Bulletin of the Seismological Society of America, Vol. 99, No. 2B, pp. 1437–1442, May 2009, doi: 10.1785/0120080092

Short Note

Design of a Relatively Inexpensive Ring Laser Seismic Detector

by R. W. Dunn, H. H. Mahdi, and H. J. Al-Shukri

Abstract During the last decade the ability of large ring lasers to measure seismic induced ground rotation has demonstrated their potential for making contributions to the field of seismology. Unfortunately, ring lasers like many optical instruments tend to be expensive. In this technical note, we examine some design options for deploying a relatively low cost ring laser ground rotation sensor. A review of the design parameters, common to all active ring lasers, is followed by an examination of a specific relatively low cost approach currently employed in a ring laser that has been operating outside Conway, Arkansas. The article concludes with a discussion of some earthquakes detected by this instrument.

Introduction

For a number of years, there has been interest in measuring seismic induced ground rotation (Aki and Richard, 1980; Takeo and Ito, 1997). Ring lasers have measured geophysical phenomena ranging from the polar motion of the Earth (Schreiber *et al.*, 2004) to earthquake induced ground rotation (McLeod *et al.*, 1998; Pancha *et al.*, 2000; Schreiber *et al.*, 2005). In addition, ring lasers have provided measurements of rotational velocities about an axis normal to the surface of the Earth (z axis) that are consistent in waveform and amplitude with collocated standard seismograph measurements of translational ground motion (Igel *et al.*, 2005; Suryanto *et al.*, 2006).

Design Parameters

Active ring lasers have the lasing medium inside the cavity (Chow *et al.*, 1985; Stedman, 1997), which in the presence of rotation produces a frequency beat note as opposed to a shift in an interference pattern. Coherent waves of light are propagated simultaneously around the laser cavity in both a clockwise and counterclockwise direction. If the laser cavity is rotating, the time required for light to complete a path around the cavity depends on the direction of propagation. This small difference in transit time creates a frequency difference between the counter propagating waves proportional to the rotational velocity of the ring laser cavity. A small amount of light from each of the counter propagating waves is transmitted through the dielectric mirrors; the transmitted light from one of the mirrors is collimated and combined on a photodiode creating an audio frequency beat note. The beat frequency or Sagnac frequency created by Earth's rotation is given by the following equation (Stedman, 1997):

$$\Delta f = 4A\mathbf{n}\cdot\mathbf{\Omega}/\lambda p. \qquad (1)$$

In this relation, Δf is the Sagnac frequency, A is the area of the laser cavity, p is the perimeter of the cavity, λ is the laser's wavelength, and the magnitude of $\mathbf{\Omega}$ is the rotational velocity of the Earth. The symbol $\mathbf{n}$ represents the normal to the ring laser cavity, and the inner product $\mathbf{n}\cdot\mathbf{\Omega}$ gives the projection of the normal to the laser cavity on the rotation axis of the Earth. Therefore in large ring lasers, Earth's rotation creates a carrier (Sagnac) frequency that is modulated by local rotations of the cavity, changes in the area of the cavity, and variations of the inner product. In horizontal ring lasers, seismic waves primarily modulate the Sagnac frequency by introducing small rotations around the ring laser's z axis. However, like all coupled oscillators, the counter propagating beams or oscillations in an active ring laser cavity will lock to a common frequency if the coupling is too strong and/or the frequency difference is too small (Aronowitz, 1971; Chow *et al.*, 1985; Stedman, 1997). In this situation, often referred to as lock-in, the detection of rotation is impossible. One of the primary coupling mechanisms between the counter propagating beams is light backscattered from the optical elements within the cavity. Various schemes are used to overcome lock-in. In the current generation of geophysical sensors, the approach is to enlarge the ring laser cavity until the Sagnac frequency is high enough to bias the system out of lock-in (Stedman, 1997; Dunn, 1998).

Our design uses a plasma tube excited by a direct current discharge, industrial grade optics, and beam lines filled with dry nitrogen. The plasma tube is ~0.75 m long with a bore of 7.7 mm. It is filled with a 16 to 1 mixture of helium and neon and is sealed at each end with a Brewster window. Single longitudinal mode operation is achieved by reducing the gain in the cavity until the laser is operating near threshold. A pressure greater than 2.9 torr is used to increase the pressure broadening linewidth of the lasing mode. Increasing the linewidth of the dominant lasing mode facilitates single-mode operation by starving the adjacent modes that fall within its linewidth (Dunn, 1998). Although the Brewster windows increase backscattered light, a plasma tube allows operation with an unevacuated cavity or a modest vacuum from a mechanical pump. If desired, the beam lines can be constructed from low cost plastic pipe (polyvinyl chloride). The earthquakes presented in this article were detected while the cavity was filled with dry nitrogen at atmospheric pressure. The laser cavity is configured as an equilateral triangle 17 m on a side and is formed from three concave dielectric laser mirrors that have radii of curvatures of 15, 15, and 50 m. At the operating wavelength of 0.6328 μm, the mirrors reflectivity is $>99.7\%$. Although a triangular design is less optimal than a square cavity in terms of the scale factor $(4A/\lambda p)$, a triangular configuration guarantees the laser cavity is planar and saves the expense of a fourth laser cavity mirror and the associated mounting system. The plasma tube is mounted midway between the two 15 m radius of curvature mirrors; at this location the laser beams have their minimum size. To achieve a measure of temperature stabilization, the beam lines are buried ~1 m below the surface. Temperature variations that cause the laser to mode hop present the primary limitation to long-term stability in a large near surface mounted ring laser. A mode hop momentarily disrupts the signal. With near surface mounting, 30 min to 1 hr between mode hops is fairly typical. The corner boxes containing the mirrors and the plasma tube are mounted in commercial drainage manholes. Located (35.09° N, 92.19° W) in a lightly populated area, the laser is attached to bedrock in a north facing ridge that has a slope of ~14°. The slope was selected to facilitate drainage during rainstorms. Because the slope reduces the angle between the normal to the laser cavity and the rotation axis of the earth from 54.9° to 40.9°, the Sagnac beat frequency created by the Earth's rotation is ~776.3 Hz.

The quality factor (Q) is used as a measure of the sharpness or selectivity of the laser cavity at resonance. It can be defined as $Q = 2\pi W/P_L$ or $Q = 2\pi f_o t_c$ (Verdeyen, 1995). In these expressions, W is the energy in the resonator field, P_L is the energy loss per cycle of oscillation, $f_o = 474$ THz is the resonator frequency, and t_c is the cavity ring down time. In this laser, the ring down time was determined by shorting the power to the plasma tube and using a digital storage scope to measure the laser output until it reached the $1/e$ point (0.368). For the 51 m perimeter ring, the ring down time was measured as $t_c \sim 900$ μsec. Employing the relation $Q = 2\pi f_o t_c$ yields a quality factor of $\sim 2.7 \times 10^{12}$. In ring laser cavities, the Q factor scales linearly with the perimeter (Stedman, 1997). Consequently, the ring laser cavity Q can be increased by enlarging the cavity perimeter and/or reducing the power losses. Quantum noise produces measurement errors that dictate a fundamental quantum limit on the sensitivity to rotation in ring lasers. Chow *et al.* (1985) and Stedman (1997) provide equivalent relations for this fundamental limit: $\Delta\Theta/\sqrt{t} = (cP/4AQ)\sqrt{(hf_o/P_L)}$. In addition to Q, P_L, and f_o defined previously, Θ is the rotation angle in radians, c is the speed of light, P is the perimeter of the cavity, A is the area of the cavity, h is Planck's constant, and $\sqrt{t}$ is the square root of the measurement time. To account for unknown losses from the Brewster windows, the measured single-mode laser output of 11 μW is doubled and the power loss per mode P_L is approximated as 23 μW. With these numerical values, the minimum resolution for detecting rotation $(\Delta\Theta/\sqrt{t})$ is ~1.4 prad$/\sqrt{\text{sec}}$. Making an estimate that the laser is operating a factor of 10 above the quantum limit, a resolution of 1.4 prad$/\sqrt{\text{sec}}$ is obtained. If the power loss is not a function of cavity perimeter, the resolution increases as the square of the perimeter of the laser cavity (Stedman, 1997). Consequently, large well-engineered ring lasers are capable of incredible sensitivity to rotation.

Figure 1a is a photograph of the triangular ring laser site. The small buildings are used to weatherproof the concrete manholes containing the mirror boxes and the plasma tube. Figure 1b shows one of the circular stainless steel mirror boxes with its cap removed. The cavity mirror is visible inside the box and the combining optics is in the background.

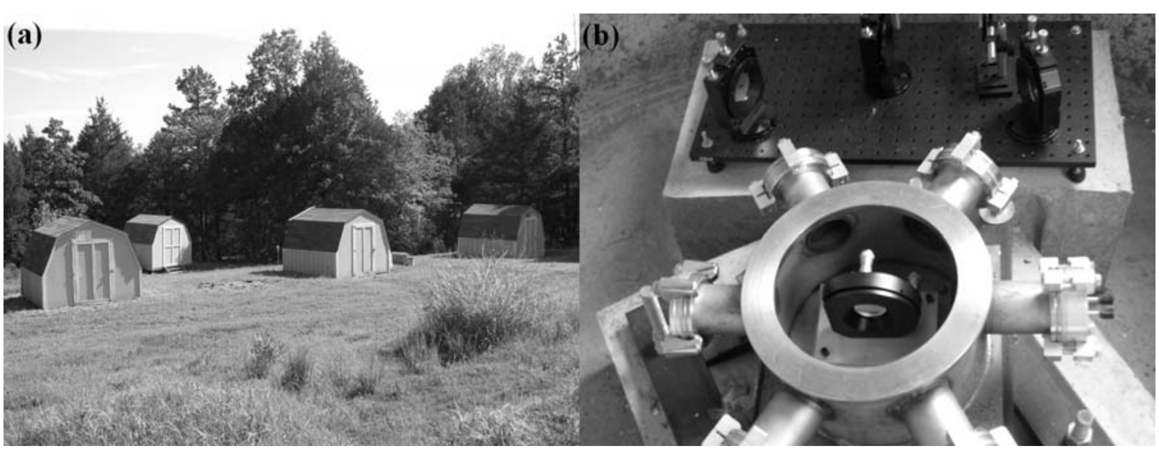

Figure 1. Ring laser site and a laser corner box with the top removed are shown in the photographs.

Typical Results

A data acquisition system, with a sampling frequency of 2500 Hz, stored the modulated Sagnac frequency and a frequency counting routine created the ring laser seismograms; the software counting routine was set to calculate the dominant frequency in each consecutive 0.1 sec interval of the raw modulated Sagnac frequency data. Fast Fourier Transform (FFT) power spectrums showing the seismic induced sidebands came directly from the raw Sagnac record; the magnitudes of the side bands are referenced to the magnitude of the Sagnac frequency. Results from a magnitude 3.3 earthquake that occurred at 13:51:13 UTC in eastern Tennessee on 7 September 2006 at a depth of 7 km are typical of the ring laser's response to seismic waves. The epicenter (36.27° N, 89.50° W) is ~284 km east of the laser site. As shown in Figure 2a, the unfiltered ring laser seismogram is centered about the Sagnac frequency. Because horizontally mounted ring lasers respond to rotation around the normal to the ring laser cavity (z axis), in theory, a ring laser would not respond to P waves. The presence of a P-wave signature apparently results from P to SH wave conversion through scattering in the Earth's crust (Igel *et al.*, 2005). A series of power spectrums associated with the 3.3 magnitude earthquake are shown in Figure 2b–d. In Figure 2b, the FFT was taken before the arrival of the P wave. Aside from some small microseisms a few tenths of a hertz from the Sagnac frequency peak, there are no sidebands prior to the arrival of the P wave. The power spectrum in Figure 2c starts with the arrival of the P wave and ends just before the arrival of the S wave; it shows the harmonic responses introduced by the P wave. Figure 2d shows the FFT of the first 20 sec after the arrival of the S wave. Figure 2e shows the ring laser seismogram from a magnitude 5.8 earthquake that occurred on 10 September 2006 at 14:56:07 UTC under the Gulf of Mexico at a depth of 10 km. Its location (26.33° N, 86.58° W) is ~1121 km from the laser site. Figure 2f shows the harmonic responses during the 20 sec period after the arrival of the S wave. The narrower frequency excursions in this power spectrum when compared with the 3.3 magnitude earthquake are consistent with the observations that the higher frequency seismic components experience a greater attenuation with distance (Bolt, 1978) and smaller earthquakes tend to generate a wider initial seismic frequency spectrum (Hough, 2002). Figure 2g shows the ring laser seismogram from a magnitude 5.2 earthquake that occurred at 09:37:00 UTC in southern Illinois on 18 April 2008 at a depth of 11.6 km. Its location (38.450° N, 87.890° W) is approximately 543 km from the laser site. Because of unusually heavy rainfall, one of the manholes shifted slightly, which correspondingly produced a small reduction in the Sagnac frequency as can be seen by comparing the results with the 3.3 magnitude earthquake. Figure 2h shows the strong harmonic responses recorded for 20 sec after the arrival of the S wave. The relatively high amplitude of these side bands allows them to be referenced to the Sagnac with a linear scale instead of a logarithmic scale. As expected, the strongest harmonic responses consistently occur with the arrival of the S wave. Although the P-wave induced sidebands are much lower in amplitude than the sidebands created after the arrival of the S wave, the locations of the frequency peaks in the respective power spectrums are similar.

Figure 3 contains the results from a magnitude 6 earthquake that occurred in Mexico (16.35° N, 93.99° W) on 6 July 2007 at 13:09:19 UTC ~2089 km from the laser site. The ring laser seismogram shown in the top trace (Fig. 3a) can be compared with the responses from a temporarily deployed broadband seismograph. The second trace (Fig. 3b) is the radial component, and the third trace (Fig. 3c) is the transverse component. The ring laser seismogram was filtered with a high-pass Butterworth filter with a corner frequency of 0.4 Hz, and the rotated horizontal axes were high-pass filtered with a corner frequency of 1 Hz. Although the ring laser and the seismograph were collocated, the responses were recorded with different data acquisition systems.

Conclusions and Discussions

Large near surface mounted ring lasers can readily respond to seismic induced rotation; the main disadvantage is the background noise particularly during the heat of the day. A more controlled environment such as a vault would enhance the results. A discussion of what can be achieved in a vault with a system that incorporates the optimum currently available active ring laser technology is provided by Schreiber *et al.* (2009). If desired, the design discussed in this article can be deployed in a more compact package. Past experiments indicate that a Sagnac frequency of ~150 Hz can bias the relatively low-cost design out of lock-in (Dunn, 1989). Consequently, for a horizontally mounted ring laser using a triangular cavity at latitude 35° N, ~4 m on a side would be required to bias the laser out of lock-in. A square cavity would require ~2.5 m on a side to stay out of lock-in. Of course, the resolution would correspondingly decrease from the value cited for the 51 m perimeter ring. In response to a request for a cost estimate, in 2004 it took ~16,000.00 U.S. dollars to construct the 51 m perimeter ring laser as a deployment ready system. This estimate does not include the data acquisition system, the remote site preparation, or site installation costs. The labor costs for machining and assembly were at an in-house university rate.

Data and Resources

The information concerning the magnitude, location, depth, and tectonic conditions associated with the earthquakes used in this study were obtained from the U.S. Geological Survey Earthquake Hazards Program at http://earthquake.usgs.gov/ (last accessed April 2008). The ring laser data were taken from a ring laser deployed ~10 km north of Conway, Arkansas. A National Instruments data

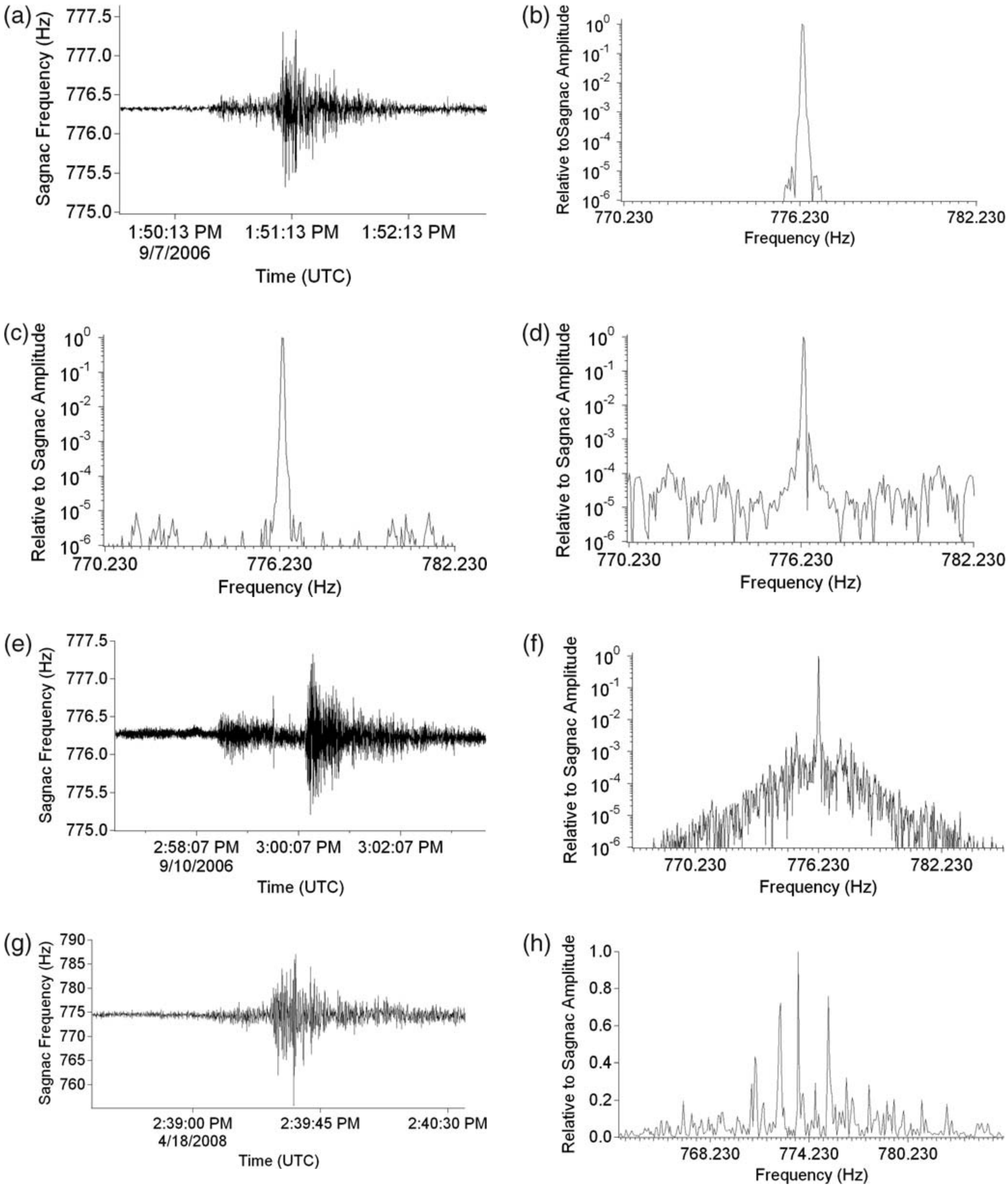

Figure 2. Seismic responses from three typical earthquakes detected by the ring laser are shown. (a) The ring laser seismogram from a magnitude 3.3 earthquake located ~284 km from the laser site. The maximum ground rotation rate detected by the ring laser in this event is ~1 nrad/sec. (b) FFT taken before the arrival of the *P* wave. (c) FFT of the *P* wave before the arrival of the *S* wave. (d) FFT taken during the first 20 sec after the arrival of the *S* wave. (e) Ring laser seismogram for a magnitude 5.8 earthquake located under the Gulf of Mexico ~1121 km from the laser site. The maximum ground rotation rate detected by the ring laser for this event is ~1 nrad/sec. (f) The accompanying FFT for the first 20 sec after the arrival of the *S* wave. (g) The ring laser seismogram of a magnitude 5.2 earthquake ~543 km from the laser site. The maximum ground rotation rate detected by the ring laser for this event is ~11 nrad/sec. (h) The FFT, with a linear scale, of the first 20 sec after the arrival of the *S* wave.

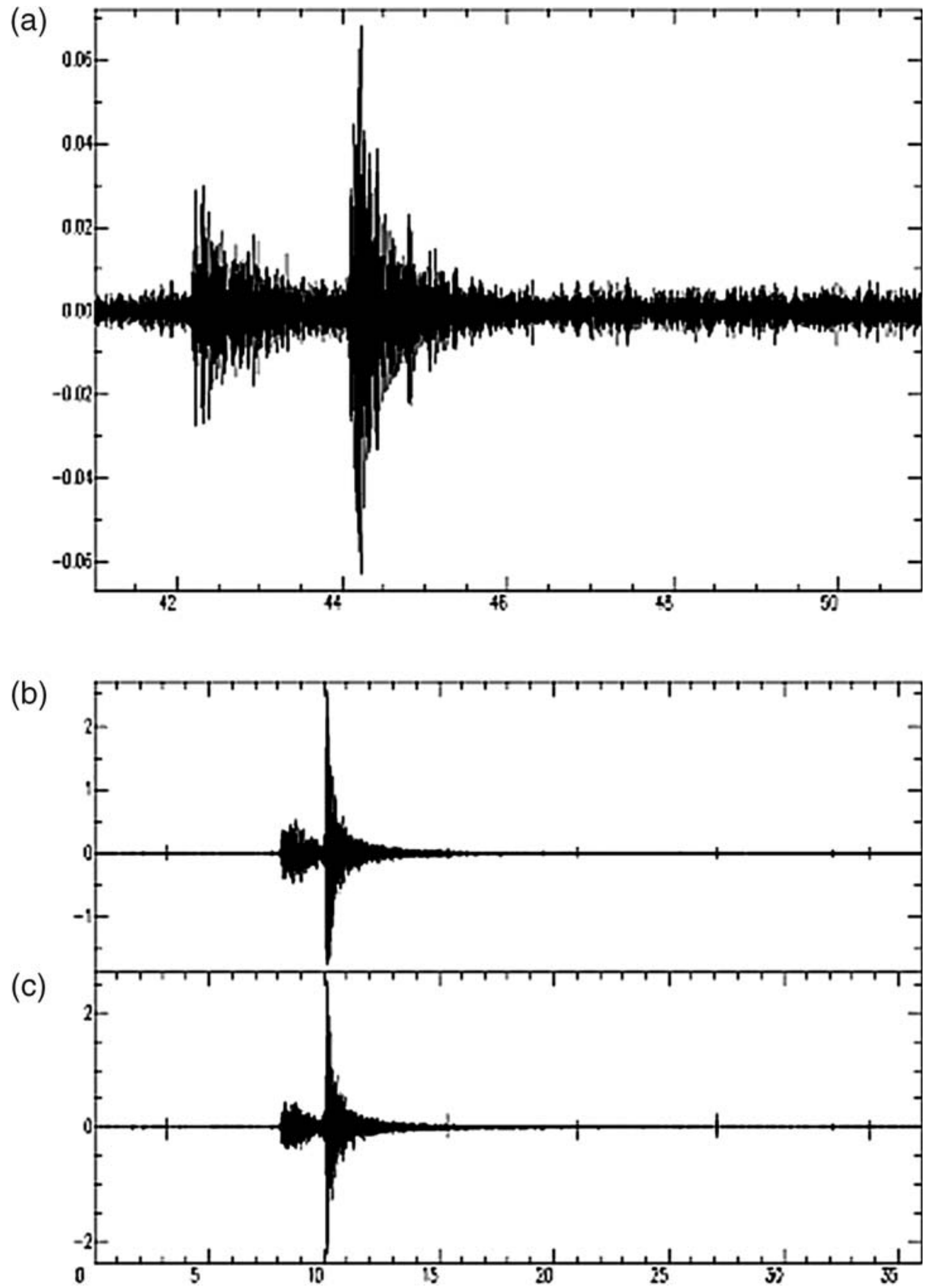

Figure 3. A comparison is shown between a ring laser seismogram shown in the top trace and the rotated horizontal axes from a collocated standard seismogram for a magnitude 6.0 earthquake located in Mexico ~2089 km from the laser site. The second trace is the radial component, and the third trace is the transverse component of the seismograph. The maximum ground rotation rate detected for this event is ~0.3 nrad/sec.

acquisition system and a National Instruments software counting routine were used to store the data and prepare the rotational seismograms. A Wave Metrics IGOR Pro software package created the FFT responses. The seismograms were taken with a Guralp broadband seismometer.

Acknowledgments

This work was supported by the National Science Foundation under Award Number EAR-0321183. Any opinions, findings and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation. Support was also provided by the NASA Arkansas Space Grant Consortium under Collaborative Proposal Award HC18819. We thank these organizations for their support.

References

Aki, K., and P. G. Richards (1980). *Quantitative Seismology, Theory and Methods*, Freeman, San Francisco.

Aronowitz, F. (1971). The laser gyro, in *Laser Applications*, Vol. **1**, M. Ross (Editor), Academic Press, New York, 133–200.

Bolt, B. A. (1978). *Earthquakes: A Primer*, Freeman, San Francisco.

Chow, W. W., J. Gea-Banacloche, L. M. Pedrotti, V. E. Sanders, W. Schleich, and M. O. Scully (1985). The ring laser gyro, *Rev. Mod. Phys.* **57,** 61–103.

Dunn, R. W. (1989). Multimode ring laser lock-in, *Appl. Opt.* **28,** 2584–2587.

Dunn, R. W. (1998). Design of a triangular active ring laser 13 m on a side, *Appl. Opt.* **37,** 6405–6409.

Hough, S. E. (2002). *Earthshaking Science What We Know (and Don't Know) about Earthquakes*, Princeton Press, Princeton, New Jersey.

Igel, H., U. Schreiber, A. Flaws, B. Schuberth, A. Velikoseltsev, and A. Cochard (2005). Rotational motions induced by the *M* 8.1 Tokachi-oki earthquake, September 25, 2003, *Geophys. Res. Lett.* **32,** L08309, doi 10.1029/2004GL022336.

McLeod, D. P., G. E. Stedman, T. H. Webb, and K. U. Schreiber (1998). Comparison of standard and ring laser rotational seismograms, *Bull. Seismol. Soc. Am.* **88,** 1495–1503.

Pancha, A., T. B. Webb, G. E. Stedman, D. P. McLeod, and K. U. Schreiber (2000). Ring laser detection of rotation from teleseismic waves, *Geophys. Res. Lett.* **27,** 3553–3556.

Schreiber, K. U., J. N. Hautmann, A. Velikoseltsev, J. Wassermann, H. Igel, J. Otero, F. Vernon, and J.-P. R. Wells (2009). Ring laser measurements of ground rotations for seismology, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1190–1198.

Schreiber, K. U., H. Igel, A. Cochard, A. Velikoseltsev, A. Flaws, B. Schuberth, W. Drewitz, and F. Müller (2005). The GEOsensor project: rotations—a new observable for seismology, in *Geotechnologies*, J. Flury, F. Rummel, C. Reiber, M. Rothacher, G. Boedecker, and U. Schreiber (Editors), Springer, New York, 427–443.

Schreiber, K. U., A. Velikoseltsev, M. Rothacher, T. Klügel, G. E. Stedman, and D. L. Wiltshire (2004). Direct measurement of diurnal polar motion by ring laser gyroscopes, *J. Geophys. Res.* **109,** B06405.

Stedman, G. E. (1997). Ring laser tests of fundamental physics and geophysics, *Rep. Prog. Phys.* **60,** 615–688.

Suryanto, W., H. Igel, J. Wassermann, A. Cochard, B. Schuberth, D. Vollmer, F. Scherbaum, U. Schreiber, and A. Velikoseltsev (2006). First comparison of array-derived rotational ground motions with direct ring laser measurements, *Bull. Seismol. Soc. Am.* **96,** 2059–2071.

Takeo, M., and H. M. Ito (1997). What can be learned from rotational motions excited by earthquakes?, *Geophy. J. Int.* **129,** 319–329.

Verdeyen, J. T. (1995). *Laser Electronics*, Prentice Hall, Upper Saddle River, New Jersey.

Department of Physics
Hendrix College
Conway, Arkansas 72032
dunn@hendrix.edu
(R.W.D.)

Graduate Institute of Technology
University of Arkansas at Little Rock
Little Rock, Arkansas 72204
mahdi@seism.ualr.edu
(H.H.M.)

Applied Science Department
University of Arkansas at Little Rock
Little Rock, Arkansas 72204
hjalshukri@ualr.edu
(H.J.A.)

Manuscript received 30 May 2008