Rotational Seismology and Engineering Applications:

Proceedings for the First International Workshop
Menlo Park, California, U.S.A.—September 18 to 19, 2007

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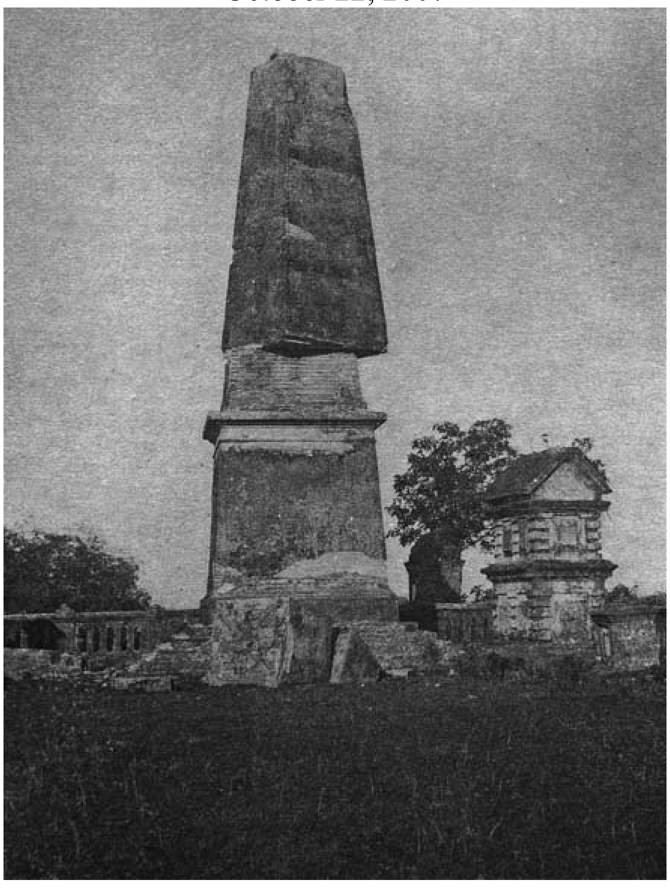

Figure 1. *Rotation of the monument to George Inglis (erected in 1850 at Chatak, India) was observed by Oldham (1899) after the 1897 Great Shillong earthquake of 1897. This monument had the form of an obelisk rising over 60 feet high from a base of 12 square feet. During the earthquake, the topmost 6-foot section was broken off and fell to the south and the next 9-foot section was thrown to the east. The rotated remnant is about 20 feet in length [Photo from Oldham, R.D. (1899): Report on the Great Earthquake of 12th June 1897. Mem. Geol. Survey India, vol. 29.]*

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Contents

Executive Summary

The *First International Workshop on Rotational Seismology and Engineering Applications* was held in Menlo Park, California, on 18–19 September 2007, as one of the activities of the *International Working Group on Rotational Seismology.* This workshop was hosted by the U.S. Geological Survey (USGS), which recognized this topic as a new research frontier enabling better understanding of the earthquake processes and reduction of seismic hazards.

The technical program consisted of three presentation sessions: plenary and oral, held during the first day, and poster, held during the second day, followed by discussions. A post-workshop session was held the following day 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.

The Workshop began with the plenary session, held in the morning of 18 September at the USGS campus, in which three lectures were presented for the general audience. William H. K. Lee of the USGS summarized recent observations of rotational ground motions from local earthquakes in Taiwan. Mihailo Trifunac of the University of Southern California lectured on rotations in structural responses. Heiner Igel of the University of Munich presented observations of rotational ground motions of earthquakes in the far-field using ring laser gyros. About 100 individuals attended this session.

The Workshop then moved to the nearby Vallombrosa Center for in-depth presentations and discussions among 63 participants. Five oral presentations were given in the afternoon on major areas of research on rotational seismology and engineering issues. The morning session of the following day, 19 September, was devoted to 30 posters covering a wide range of topics, including large block rotations in geological time scale, rotations of monuments after earthquakes, and theories, instruments, observations, and analyses of rotational motions.

In the early afternoon of 19 September, participants were divided into five panels for in-depth discussions: (1) theory, (2) far-field, (3) near-field, (4) engineering applications, and (5) instrument design and testing. This was followed by a general discussion in which the panel leaders summarized the group discussions on the key issues and future research directions. It was concluded that collaborative work is essential for nurturing this new field of inquiry, and that there are many opportunities for collaborative work across institutions, nations, and disciplines. The panel reports, and proposed future directions and research plans are described in detail in this *Report*, and the accompanying Workshop DVD disc contains all the presentation files and supporting materials.

In recognizing this emerging new field, the Seismological Society of America approved on 31 August 2007, the publication of a special issue on *Rotational Seismology and Engineering Applications* in their *Bulletin*, under the guest editorship of W.H.K. Lee, M. Celebi, M.I. Todorovska, and H. Igel, to appear in May, 2009.

1. Introduction

The foundation of seismology is based on the linear elasticity theory of simple homogeneous materials under infinitesimal strain. This theory was mostly developed in the early nineteenth century: the differential equations of the linear elastic theory were first derived by Louis Navier in 1821, and Augustin Cauchy gave his formulation in 1822 that remains virtually unchanged to the present day (Sokolnikoff, 1956). From this theory, Simeon Poisson demonstrated in 1828 the existence of longitudinal and transverse elastic waves, and in 1885 Lord Rayleigh, the existence of elastic surface waves. In 1897, Richard Oldham first identified these three types of waves in seismograms, and the linear elasticity theory has been embedded in seismology ever since.

Seismology is based primarily on the observation and modeling of three-component translational ground motions. Although effects of rotational motions due to earthquakes have long been observed (e.g., *Mallet*, 1862), *Richter* (1958, p. 213) stated that: "*Perfectly general motion would also involve rotations about three perpendicular axes, and three more instruments for these. Theory indicates, and observation confirms, that such rotations are negligible.*" However, Richter provided no references for this claim, and the available instruments at that time did not have the sensitivity to measure the very small rotation motions that the classical elasticity theory predicted.

Some theoretical seismologists (e.g., *Aki and Richards*, 1980, 2002) and earthquake engineers have argued for decades that the rotational part of ground motions should also be recorded. It is well known that standard seismometers and accelerometers are profoundly sensitive to rotations, particularly tilt, and therefore subject to rotation-induced errors (see e.g., *Graizer*, 1991; 2005; Pillet and Virieux, 2007). The paucity of observations of rotational ground motions is mainly the result of the fact that, until recently, the rotational sensors did not have sufficient resolution to measure small rotational motions due to earthquakes.

Measurement of rotational motions has implications for: (1) recovering the complete ground-displacement history from seismometer recordings; (2) further constraining earthquake rupture properties; (3) extracting information about subsurface properties; and (4) providing additional ground motion information to engineers for seismic design.

This *Report* describes the technical program, the group discussions on key issues and future directions, and some recommendations and conclusion. All the presentation files and supporting materials are collected in the Workshop DVD disc accompanying this *Report*. This disc has an "autorun" feature when it is inserted on a DVD drive. If it does not automatically start, please find the file, autohtml.exe, in the root directory and double click it with the mouse. The online version of this *Report* will appear and you can explore the contents of the DVD disc at various levels. Alternatively, you copy the entire DVD disc to a directory on your hard disk, and explore its contents manually. This DVD disc contains nearly 2 gigabytes of useful information contributed mostly by the Workshop authors, and it is intended for personal use only.

1.1 Rotational Motions in Seismology and Earthquake Engineering

In the absence of direct measurements, the rotations of ground motion and of response of structures have been deduced indirectly from accelerometer arrays, but such estimates are valid only for long wavelengths compared to the distances between sensors (e.g. Castellani and Boffi, 1986; Niazy, 1987; Oliveira and Bolt, 1989; Spudich et al., 1995; Huang, 2003; Ghayamghamian and Nouri, 2007). The rotational components of ground motion have also been estimated theoretically, using kinematic source models and linear elastodynamic theory of wave propagation in elastic solids (Bouchon and Aki 1982; Trifunac, 1982; Lee and Trifunac, 1985, 1987).

In the past decade, rotational motions from teleseismic and small local earthquakes were also successfully recorded by sensitive rotational sensors, in Japan, Poland, Germany, New Zealand, and Taiwan (e.g., Takeo and Ito, 1997; Takeo, 1998; Teisseyre et al., 2003; Igel et al., 2005, 2007; Huang et al., 2006; Suryanto et al., 2007). The observations in Japan and Taiwan showed that the amplitudes of rotations can be *one to two orders of magnitude grater than expected* from the classical linear theory. Theoretical work has also suggested that, in granular materials or cracked continua, asymmetries of the stress and strain fields can create rotations in addition to those predicted by the classical elastodynamic theory for a perfect continuum (Teisseyre and Boratńyski, 2003).

Rotational motions in the near field (within ~25 km of fault ruptures) of strong earthquakes (magnitude >6.5), where the discrepancy between observations and theoretical predictions may be the largest, have not been recorded so far. Recording such ground motions would require extensive seismic instrumentation along some well-chosen active faults and luck. To this end, several seismologists have been advocating such measurements, and a current deployment in southwestern Taiwan by its Central Weather Bureau is designed to "capture" a repeat of the 1906 Meishan earthquake (magnitude 7.1) with both translational and rotational instruments.

The rotations in structural response, and the contributions to the response from the rotational components of the ground motion have also been of interest for many decades (e.g. Newmark, 1969; Luco, 1976; Rutenberg and Heidebrecht, 1985). Recent reviews on rotational motions in seismology and on the effects of the rotational components of ground motion on structures can be found, for examples, in Cochard et al. (2006) and Pillet and Virieux (2007), and Trifunac (2006), respectively.

The present Workshop is intended to survey our present knowledge about rotational motions in seismology and earthquake engineering, and to discuss key issues and future research direction. We will discuss how this Workshop came about in the next section.

1.2 Growing Interests and Formation of the International Working Group on Rotational Seismology (IWGoRS)

Various factors, such as the growing number of successful direct measurements of rotational ground motions (e.g., by ring laser gyros, fiber optic gyros, and sensors based on electro-chemical technology), and the rising awareness about the usefulness of the information they provide (e.g., in constraining the earthquake rupture properties, extracting information about subsurface properties, and about deformation of structures during seismic and other excitation), and about the limitations of the information that can be extracted from the translational sensors due to their sensitivity to rotational motions (e.g., computation of permanent displacements from accelerograms (e,g., Graizer, 1991; Trifunac and Todorovska, 2001; Graizer, 2005; Boroschek and Legrand, 2006; Pillet and Virieux, 2007)), lead to a spontaneous interest to organize the scientific and engineering community interested in rotational motions.

A series of events led to the present Workshop. First, a monograph on *Earthquake Source Asymmetry, Structural Media and Rotation Effects* was published, edited by Teisseyre et al. (2006), with contributions from many authors of different countries. A small workshop on Rotational Seismology was organized by W.H.K. Lee, K. Hudnut, and J. R. Evans of the USGS on 16 February 2006 in response to grass roots interest. It was held at the USGS offices at Menlo Park and Pasadena, California, with about 30 participants from about a dozen institutions participating *via* teleconferencing and telephone (*Evans et al.*, 2007). These events further led to the formation of the *International Working Group on Rotational Seismology* in 2006, inaugurated at a luncheon during the AGU 2006 Fall Meeting in San Francisco.

The *International Working Group on Rotational Seismology* (IWGoRS) aims at promoting investigations of rotational motions and their implications, and sharing experience, data, software and results in an open web-based environment. It consists of volunteers and has no official status. H. Igel and W. H. K. Lee are serving as "co-organizers". Its charter is accessible on the IWGoRS web site (http://www.rotational-seismology.org). The Working Group has a number of active members leading task forces focusing on the organization of workshops and scientific projects including: testing and verifying rotational sensors, broadband observations with ring laser systems, and developing a field laboratory for rotational motions. The IWGoRS web site also contains the presentations and posters from related meetings, and eventually will provide access to rotational data from many sources.

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 et al., 2007). The goal of this session was to discuss rotational sensors, observations, modeling, theoretical aspects, and potential applications of rotational ground motions. A total of 21 papers were submitted for this session, and over 100 individuals attended the oral session.

The interest in this session demonstrated that rotational motions are of current interest to a wide range of geophysical disciplines, including strong-motion seismology, exploration geophysics, broadband seismology, earthquake engineering, earthquake physics, seismic instrumentation, seismic hazards, geodesy, and astrophysics, confirming the timeliness of IWGoRS. At this meeting, it became apparent that there is a need for longer organized meetings dedicated specifically to this topic, to allow sufficient time for communication between investigators from different countries and from different fields to discuss the many issues of interest, and to draft a research plan. This led to a plan to hold periodic workshops, the first one to be held in the United States, and the next one in Germany. The present Workshop is a realization of the first part of this plan.

2. Organization of the 2007 Workshop

At the IWGoRS inauguration luncheon it became clear that to establish an effective international collaboration within the IWGoRS, a larger workshop (originally proposed by Maria Todorovska) was needed to allow sufficient time to discuss the many issues of interest and to draft research plans for rotational seismology and engineering applications.

Since holding a workshop would need funding, we were very fortunate that David Applegate, the USGS Earthquake Program Coordinator, provided us with a funding of $25,000 on 23 March 2007. We were then faced with the difficult task of organizing and holding the workshop in less than six months, so that the available fund could be spent by the end of the government fiscal year (i.e., 30 September 2007).

In early April, we organized an Advisory Committee to provide us guidance with Leon Knopoff (UCLA) as the Honorary Chair, and members Roger Borcherdt (USGS), Yun-tai Chen (Peking University, China), Ramanath Cowsik (Washington University at St. Louis), Robert Page (USGS), Minoru Takeo (University of Tokyo, Japan), Roman Teisseyre (Polish Academy of Sciences, Poland), and Ta-Liang Teng (USC).

To plan the workshop technical program, we established a Program Committee consisting of: Mehmet Çelebi (USGS), Alain Cochard (University of Strasbourg, France), Bor-Shouh Huang (Academia Sinica, Taiwan), Ken Hudnut (USGS), Heiner Igel (University of Munich, Germany), Willie Lee (USGS, Chair), Ulli Schreiber (Technical University of Munich, Germany), Maria Todorovska (USC), and Mihailo Trifunac (USC).

A Local Organizing Committee was established to handle the workshop details, with Gerry Brady, Michael Diggles, John R. Evans (Chair), Sheri Farris, Susan Garcia, Tran Huynh (Workshop Coordinator), Marty Sanders, Stan Silverman, Chris Stephens (Vice-Chair) and Steve Walter.

We selected the Vallombrosa Center as the workshop site because it is designed for small group meetings and is in close proximity to USGS. Vallombrosa provides both meals and lodging in a beautiful site highly conducive to participant interactions.

3. Technical Program of the Workshop

The Program Committee, in consultation with the Advisory Committee, organized a technical program with the following goals:

- Present three general introductory lectures on rotational seismology and engineering applications geared to a general scientific audience. Treat these lectures as USGS' Earthquake Hazards (EHZ) seminars. These seminars are open to the public at the USGS auditorium, archived and with video broadcasting, maximizing the audience. This event coincided with the 40th anniversary of the USGS earthquake seminars.
- Present six oral presentations to bring workshop participants up-to-date on major areas of research in rotational seismology and corresponding earthquake-engineering matters.
- Present thirty poster presentations to cover all areas of rotational seismology and engineering, and allow enough time for participants to interact with poster presenters and one another.
- Divide the participants into five groups (of their choice) for in-depth discussions of key issues and directions for future research. Each group to be chaired by a group leader who would then present the individual group discussions in the final session with all the participants. Allow sufficient time for reaching consensus on the key issues and future directions.

With the above mentioned goals, a technical program was organized consisting of three sessions: (i) plenary, (ii) oral, and (iii) poster. The plenary session, open to the public, was held at the USGS headquarters in the morning of the first day, and was attended by about 100 individuals. Following a welcome speech by R.D. Catchings, the Chief Scientist of the USGS Earthquake Hazards Team, and an introduction by W.H.K. Lee, three lectures were presented during the Plenary Session, by W.H.K. Lee on observations of local earthquakes in Taiwan, M.D. Trifunac on rotations in structural response, and H. Igel on observations of rotational ground motions using ring laser gyros.

The remaining part of the workshop was held at the nearby Vallombrosa Center, and was attended by 63 participants. The Oral Session was held in the afternoon of the first day, and consisted of five presentations, by Y.T. Chen on the single couple component of the far field radiation from dynamical fractures, R. Teisseyre on fundamental deformations in asymmetric continua, K.U. Schreiber on Sagnac interferometry for the determination of rotations in seismology, S. Pezeshk on the engineers' perspective and experience on rotational measurements in structures, and M.I. Todorovska on instrument correction for 6DOF seismic sensors.

The Poster Session was held in the morning of the second day of the meeting, and consisted of 30 poster presentations, listed in the technical program (Appendix 1).

The afternoon of the second day of the workshop was devoted to in-depth discussions on the key outstanding issues and future directions. The participants could join one of five panels on the following topics: (1) theoretical studies of rotational motions (chaired by L. Knopoff), (2) measuring far-field rotational motions (chaired by H. Igel), (3) measuring near-field rotational motions (chaired by T.L. Teng), (4) engineering applications of rotational motions (chaired by M.D. Trifunac), and (5) instrument design and testing (chaired by J.R. Evans). The panel reports on the key issues and unsolved problems, and on research strategies and plans can be found in Appendices 2.1 through 2.5. Following the in depth group discussions, the panel chairs reported on the group discussions in a common session, with further discussions among all the participants.

We were delighted that nearly all principal researchers on rotational seismology and engineering accepted our invitation. One oral presentation (by Hudnut and Borsa) and one poster presentation (by Ghayamghamian and Nouri) were not delivered at the Workshop due to a last minute schedule conflicts and insufficient time for visa processing, respectively, but are included on the Workshop DVD disc.

A post-workshop session was held on 20 September on the Laser Interferometer Gravitational-wave Observatory (LIGO) project. This ambitious project aims at measuring gravitational waves (predicted by Einstein) from astrophysical sources, and using these measurements to open a new observational window on the universe. LIGO physicists are pushing the limits of technology in trying to measure a predicted motion of less that 10 picometers rms between 1 and 100 Hz.

Brian Lantz of Stanford University first explained why gravitational-wave physicists would attend a Workshop on rotational ground rotations. Very simply, good measurements of ambient ground tilt (that is, rotation around the horizontal axes at the Earth's surface) in LIGO facilities will make it easier, even possible, to operate Advanced LIGO with sufficient sensitivity and accuracy. Then, he presented an introduction to gravitational waves and their detection, performance of the initial LIGO instruments and predictions for Advanced LIGO, and discussion of the seismic isolation subsystem used. Riccardo DeSalvo of Caltech then reviewed LIGO accelerometer developments and possible use of LIGO and its seismic isolators to extract signals of geophysical interest. Extensive discussions took place during and after the presentations.

4. Group Discussions on Key Issues and Future Directions

4.1 Panel Discussions

In the early afternoon of the second day of the Workshop (19 September), the participants were divided into five groups of their own selection for in-depth discussions: (1) theory, (2) far-field studies, (3) near-field studies, (4) engineering applications, and (5) instrument design and testing. Finally, all participants met again to hear reports from the group leaders and for general discussion of key issues and future research directions:

(1) Theory. Substantial new work is being done to extend the classical linear elasticity theory. A key question is whether the rotational wavefield is merely the curl of the displacement field or there is something more. The classical theory doesn't allow for stored torques but they are permitted in asymmetric elasticity theories for granular materials, for example. There is a clear need for solutions to "benchmark" problems. There is also a need to pose one or more problems amenable to testing with observed data as a guide for the work of observational seismologists. The details are given in Appendix 2.1.

(2) Weak-motion measurements. Impressive progress has been made in developing high-resolution ring laser gyros, originally for measuring the Earth's axial rotations and motions of the axis. Four such instruments are now in operation, in Germany, New Zealand, Arkansas, and California. Rotational motions from earthquakes measured at teleseismic distances are consistent with translational motions using linear elasticity theory. Recent studies show the potential for use of collocated measurements of translations and rotations for recovering subsurface information. These should evolve into several six-component observatories equipped with both ring laser gyros and broadband seismometers and the sharing of these data with the broader seismological community in near real time. The details are given in Appendix 2.2.

(3) Strong-motion measurements. Rotational ground motions from local earthquakes have been measured in Japan and Taiwan using commercially available rotational sensors. These records are puzzling from the point of view of linear elasticity theory and array-derived rotation estimates because the observed rotations are 10 to 100 times larger than those deduced from either theoretical considerations or translational accelerometer arrays. This dichotomy suggests that nonlinear elastic theory and local (receiver) site conditions may be crucial to rotational motions. There is wide agreement that measuring all six components of motion (three translational, three rotational) in the near-field, particularly along active faults, is a critical goal. Participants in this group, echoed by the instrument design and testing group, noted that field-worthy rotational seismometers and proper field deployment techniques are yet to be developed. The details are given in Appendix 2.3.

(4) Earthquake engineering. The average rotation between adjacent floors in a structure ("drift") is *the key variable* governing the engineering design of structures to withstand destructive motions. During strong earthquakes, this rotation results from: (i) rotational components of seismic waves, (ii) soil-structure interaction, and (iii) relative deformation of the structure by the inertial loads. Accurate prediction of *all* contributions to the drift is essential. Current, simplified engineering design methods, which consider only translational components of motion, leads to serious underestimation of the response amplitudes of structures in the near-field. Critical issues include (i) that rotational components of motion be recorded *both* in the soil and in the structures, and (ii) that rotational motions be included in the building code design formulae. The details are given in Appendix 2.4.

(5) Instrument design and testing. The panel finds an immediate need for a frequency *versus* response "rotational-sensor space" being defined, as has existed many decades for translational sensors. This new sensor space would span 10^{-6} to 10^{2} Hz and 10^{-12} to 10^{0} rad/s/Hz$^{1/2}$. Strong-motion seismology and engineering applications will occupy the upper right quadrant. A rotational high noise model (rHLM), rotational low-noise model (rLNM), and the needs of weak-motion seismology and Advanced LIGO would occupy the lower half of this space. Second, extant standards and testing methodologies, primarily from translational seismology, are to be extended and new sensors and test equipment developed through focused research in this emerging field. The details are given in Appendix 2.5.

4.2 Other Discussions

(1) The International Working Group on Rotational Seismology (IWGoRS)

Heiner Igel presented an overview of IWGoRS, which was organized by Heiner Igel and Willie Lee in 2006. It is a grass roots effort with no official affiliation or officers. It is a Web-based volunteer group to share ideas, data, software, and results at: http://www.rotational-seismology.org/. This Working group has many activities (organized under various task forces), and one of which is this Workshop. Any one can join, but active participation in an existing or a new task force is encouraged.

(2) "Capturing" Major Earthquakes with Arrays of Many Different Types of Instruments.

There are about 16 major earthquakes (Magnitude ≥7) occurring worldwide every year, and data from these major earthquakes are most important for engineering design and also for seismological research. At the Workshop, we discussed the need to "capture", with as many instruments (of different types, but co-located) as possible, one or more future major earthquakes. For example, William H. K. Lee described a multi-institutional effort to intensify monitoring of the Meishan fault in southwestern Taiwan, where an M7.1 earthquake occurred in 1906, rupturing ~25 km of the fault. This group is now installing an array of modern digital instruments to include both array and point measurements of rotational motions. The Taiwan group welcomes others to deploy instruments in the same location in order to create a truly international field laboratory.

(3) Special BSSA Issue on Rotational Seismology and Engineering Applications

In recognizing this emerging new field, the Seismological Society of America approved on 31 August 2007, the publication of a special issue on rotational seismology and engineering applications in their *Bulletin*. Call for papers will be announced shortly so that this special issue can be published in May 2009, under the guest editorship of W.H.K. Lee, M. Celebi, M.I. Todorovska, and H. Igel. We are expecting an issue of about 500 printed pages with supporting materials posted online in the BSSA Electronic Supplements. It may contain about 15 original papers, 25 short notes, 4 reviews and 6 tutorials. Researchers on rotational motions in seismology and earthquake engineering are encouraged to submit their manuscripts by May 31, 2008.

(4) Post-workshop Session: Advanced LIGO Project

The Laser Interferometer Gravitational-wave Observatory (LIGO) is a project to measure gravitational waves from astrophysical sources (predicted by Albert Einstein in 1916). LIGO physicists are pushing the limits of technology in trying to measure a predicted motion of less that 10 picometers rms between 1 and 100 Hz. Due to its late addition to the Workshop program, only about half the Workshop participants were able to attend the post-workshop session addressing the initial and Advanced LIGO projects.

After talks by Brian Lantz of Stanford and by Riccardo DeSalvo of Caltech on their work on the LIGO project, extensive discussions took place during and after the presentations. For more information about the LIGO project, please visit the following website: http://www.ligo-la.caltech.edu/contents/overviewsci.htm

5. Recommendations and Conclusion

Several recommendations emerged from this Workshop:

- Since the classical linear elasticity theory is clearly inadequate, more realistic theory should be developed, especially for rotational motions in the near-field.
- Using existing data and collecting more data from existing rotational instruments, establish one or more rotational motion noise models (low noise, high noise). Update the noise models as more data become available.
- Routinely record 3-component ground rotation (using commercially available rotation sensors) at operating seismological stations, especially near active

seismic zones. This should be done at perhaps a dozen stations on a trial basis in order to collect enough rotational motion data on which to base future deployments.

- Install and routinely operate a large ring laser (at least one component, preferably three components) at one or more high quality seismological observatories. For those interested in tilt signals (LIGO, USGS/ASL), comparing rotation about one or both horizontal axes to the output of high-quality very broad-band horizontal instruments, like the STS-1H/VBB seismometer, will be important.

- Routinely record rotational motion in a few structures and at depth below, especially those in active seismic zones. Rotational sensors should be placed strategically in such a way as to produce maximum knowledge gain.

- Encourage development of higher quality, lower cost rotational sensors than those now commercially available. This may require some R&D funding since the market for rotational sensors is currently quite small.

- Continue development of techniques and facilities for rotational sensor testing.

- Urge funding agencies to support: (i) deployment of rotational sensors on the ground and in structures, and (ii) research involving the rotational components of ground motion and of the response of structures, and the effects of these motions.

In order to share presentations and papers, we collected large amounts of supporting materials for this *Report,* mostly contributed by the Workshop participants on a DVD disc. Several participants also contributed "tutorials" to help students to better understand some fundamental topics. The preliminary disc was distributed at the Workshop. After the Workshop, many authors updated their materials and we corrected some errors. The final Workshop DVD disc is accompanying this *Report,* and its contents are listed in Appendix 3. It contains nearly 2 gigabytes of files, and is intended for personal use only.

Throughout the Workshop, participants had many opportunities to interact because the Vallombrosa Center provides a good environment. It was the first time that nearly all principal researchers in this emerging field gathered to share their ideas, experience, and results. A list of the Workshop participants is given in Appendix 4.

In conclusion, it was recognized that collaborative work will be essential to nurturing this new field of inquiry, and we see many opportunities for collaborative work across institutions, nations, and disciplines.

Acknowledgements

We thank David Applegate and Bill Leith for providing the funding to host this workshop and members of the Advisory, Program, and Local Organizing Committees for making this workshop possible. We also thank the Southern California Earthquake Center and the International Working Group on Rotational Seismology for their collaborations.

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[Note: For the convenience of the readers, many references cited below can be found on the Workshop DVD disc under the directories of the first authors in: \Supplemental_Materials\2007_Workshop_Participants_and_Contributors, OR \Supplemental_Materials\Supplemental_Papers_by_Others].

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Appendix 1. Workshop Technical Program

All technical presentation files listed in Appendix 1 are included on the Workshop DVD disc in the sub-directories of the first authors under \Supplemental_Materials\ 2007_Workshop_Participants_and_Contributors.

General Session: Tuesday Morning, 18 September 2007

(Conference Room A, Building 3, USGS Menlo Park) *Maria Todorovska (USC) and Mehmet Çelebi (USGS), Chairs* [Speakers are underlined]

9:00 – 9:10 Welcome (<u>R. D. Catchings</u>, Chief Scientist, Earthquake Hazards Team, USGS)

9:10 – 9:35 An Introduction to the Workshop on Rotational Seismology and Engineering Applications (<u>W. H. K. Lee</u>, M. Çelebi, and M. I. Todorovska)

9:35 – 10:00 Observations of Rotational Ground Motions from Local Earthquakes in Taiwan (<u>W. H. K. Lee</u>, B. S. Huang, C. C. Liu, T. L. Teng, and C. F. Wu)

10:00 – 10:20 Break

10:20 – 11:10 Rotations in Structural Response (<u>M. D. Trifunac</u>)

11:10 – 12:00 Observations of Rotational Ground Motions using Ring Laser Gyros (<u>H. Igel</u>, A. Cochard, A. Flaws, W. Suryanto, B. Schuberth, U. Schreiber, D. N. Pham, and , A. Velikoseltsev)

12:00 – 13:30 Lunch at the Vallombrosa Center

Oral Session: Tuesday Afternoon, 18 September 2007

(Library of the Vallombrosa Center) *Heiner Igel (U. Munich), Chair*

13:30 – 13:50 The Single-Couple Component of the Far-Field Radiation from Dynamical Fractures (<u>L. Knopoff</u> and Y. T. Chen)

13:50 – 14:10 Fundamental Deformations in Asymmetric Continua: Motions and Fracturing (<u>R. Teisseyre</u> and M. Gorski)

14:10 – 14:30 Sagnac Interferometry for the Determination of Rotations in Seismology (K. U. Schreiber, J.-P. Wells, A. Carr, H. Igel, S. Voigt, and A. Velikoseltsev)

14:30 – 14:50 Integrating GPS with Rotational and Inertial Sensors (K. Hudnut and A. Borsa) [not presented due to author's last minute schedule conflict, but included on the Workshop DVD disc].

14:50 – 15:10 Rotational Measurements in Structures — Why and How? — Engineers' Perspective and Experience (M. Celebi and S. Pezeshk)

15:10 – 15:30 Instrument Correction for 6DOF Seismic Sensors (M. I. Todorovska and M. D. Trifunac)

15:30 – 18:00 Reception at the Vallombrosa Mansion and Poster Previews

Poster Session: Wednesday Morning, 19 September 2007

(East Parlor and Stage Room, Vallombrosa Mansion) *John Evans (USGS), Chair*

9:00 – 12:00 Author should be at his/her poster for at least two half-hour periods. Please post those times on the poster panel.

1. *Boroschek, R.:* Engineering Implications of Rotational Sensitivity of Translational Accelerometers.
2. *Cadena-Isaza, A., F. J. Sánchez-Sesma, L. Godinho and P. A. Mendes:* Rotational Ground Motion at Topographical Features for Incident Elastic Waves Using Boundary Integral Formulations.
3. *Castellani, Alberto and Marco Stupazzini:* Response spectrum of rotation: elaboration of cross power spectra got from closely spaced instruments.
4. *DeSalvo, Riccardo* (for the SAS team): The SAS Primary Seismic Attenuation System for Advanced LIGO.
5. *Dunn, R. W.:* Ground Motion Sensing in a 51-m Perimeter Triangular Ring Laser.
6. *Evans, John R., Ramanath Cowsik, Charles R. Hutt, C.-C. Liu, Robert Nigbor, Ulrich Schreiber, Frank Vernon, and Erhard Wielandt:* Development of Methods for Testing Rotational Sensors.
7. *Gičev, V., and M. D. Trifunac:* Rotations in a Seven-Story Building Caused by Nonlinear Waves During Earthquake Excitation.
8. *Górski, Marek, and Krzysztof P. Teisseyre:* Rotation Measurements in Seismological Observatories: Ojcow (Poland), Ksiaz (Poland), L'Aquila (Italy) and on Pasterze Glacier (Austria).
9. *Graizer, Vladimir:* Rotational Effects in Seismology and Engineering.
10. *Hautmann, Jan, Robert Barsch, Joachim Wassermann, Heiner Igel, Susanne Lehndorfer, Alex Velikoseltsev, Ulrich Schreiber:* Rotation Data from RingLaser Gyroscopes: Online Visualisation and Processing.
11. *Jeremić, Boris:* Computational Tools for Seismic Nonlinear Wave Propagation, Including Surface (Rotational) Effects and Soil-Structure Interaction.
12. *Johnston, Malcolm:* Broad-band Rotations and Strains from Local and Teleseismic Earthquakes — The Pisco, Peru, M8 earthquake of August 15, 2007, as an Example.

13. *Kalkan, Erol:* Rotational Components and Their Impacts on Structural Systems.
14. *Kozak, Jan T.:* Earthquake Rotational Effects — Historical Examples.
15. *Lehndorfer, S., J. Hautmann, W. Suryanto, D. N. Pham, A. Cochard, J. Wassermann, H. Igel, and U. Schreiber:* New Zealand Ring Lasers: Rotational Motions Around Horizontal Axes.
16. *Lee, V.W.:* Rotational Components of Elastic Waves on the Half-Space Surfaces.
17. *Liu, C. C., B. S. Hunag, W. H. K. Lee, and T. L. Teng:* Measuring Rotational Motions from Local Earthquakes at the HGSD Station in Taiwan.
18. *Musson, R. M. W., and S. L. Sargeant:* Rotational Earthquake Motions Observed in the UK.
19. *Nigbor, R. L., Evans, J. R., and Hutt, C.R.:* Laboratory and Field Testing of Commercial Rotational Seismometers.
20. *Pham, N.D., H. Igel, A. Cochard, U. Schreiber, A. Velikoseltsev, M. Käser, J. de la Puente, and F. Gallovic:* Rotational Signals in the *P* Coda.
21. *Pillet, Robert, Jean Virieux, and Yves Guglielmi:* Evidence of the Torsion Motion (Rotation Around the Vertical Axis) on Seismic Recordings.
22. *Shamsabadi, Anoosh, and Liping Yan:* Rotational Response of Skewed Bridges Subjected to Near-Field Ground Motions.
23. *Spudich, Paul, and Jon B. Fletcher:* 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.
24. *Takamori, Akiteru, Akito Araya, and Yuji Otake:* A Rotational Seismometer Utilizing the Pinning Effect of a Superconductor.
25. *Takeo, Minoru:* Rotational Motions Observed During an Earthquake Swarm in April, 1998, at Offshore Ito, Japan.
26. *Teisseyre, Roman:* Physics of Rotation Motions: Spin and Twist.
27. *Wassermann, J., S. Lehndorfer, and J. Hautmann:* Global Observation of Rotation Ground Motions: Towards a Unified Data Portal and "Real-Time" Analysis.
28. *Wells, Ray E. and Robert McCaffrey:* Rotation of Crustal Blocks in the Western U.S.
29. *Zembaty, Zbigniew:* Stochastic Approach in the Analysis of Rocking Ground Motion.
30. *Ghayamghamian, M. Reza, and G. R. Nouri:* An Estimation of Torsional Motion Using Dense Array Data and Its Effect on the Structural Response [not presented due to delay in visa processing, but included on the Workshop DVD disc].

12:00 – 13:30 Lunch at the Vallombrosa Center

Key Issues and Future Research Plans: Wednesday Afternoon, 19 September 2007

(Vallombrosa Center) *Willie Lee (USGS) and Maria Todorovska (USC), Chairs*

13:00 – 13:10 Assignment of 5 Locations for Individual Group Discussions

13:10 – 15:10 Participants may join any one of the following groups for discussions on key issues and plans for future research:

1. Theoretical Studies of Rotational Motions (*L. Knopoff*, Group Leader)
2. Measuring Far-Field Rotational Motions (*H. Igel*, Group Leader)
3. Measuring Near-Field Rotational Motions (*T. L. Teng*, Group Leader)
4. Engineering Applications of Rotational Motions (*M. Trifunac*, Group Leader)
5. Design and Testing Rotational Sensors (*J. Evans*, Group Leader)

15:10 – 15:30 Break

15:30 – 17:00 Group Leader Summaries, and General Discussion

17:00 – Workshop adjourns

Post-Workshop Special Session with LIGO Physicists: Thursday Morning, 20 September 2007

(EHZ New Situation Room, Room 3-252C, Building 3, USGS Menlo Park) *Willie Lee (USGS), Chair*

"The Laser Interferometer Gravitational-wave Observatory (LIGO) is an ambitious project to measure gravitational waves from astrophysical sources and use these measurements to open a new observational window on the universe." LIGO physicists are pushing the limits of technology in trying to measure a predicted motion of less that 10 picometers rms between 1 and 100 Hz. We are fortunate to have *Riccardo DeSalvo* and *Brian Lantz* to share their experience with us in a small group meeting.

9:00 – 9:05 Welcome (*Willie Lee*, USGS)

9:05 – 9:35 An Introduction to Einstein's Gravitational Waves (*B. Lantz*, Stanford)

9:35 – 10:15 Seismic Isolation System for the Advanced LIGO Project (*B. Lantz*, Stanford)

10:15 – 10:30 Break

10:30 – 11:10 Review of accelerometer developments and possible use of the control signals of Gravitational Wave Interferometer seismic isolators to extract signals of geophysical interest. (R. DeSalvo, Caltech)

11:10 – 12:00 Discussions

12:00 – 13:00 Lunch at USGS

13:00 Session adjourns, but additional discussions may continue.

Appendix 2. Summaries from Group Discussions

Appendix 2.1 Future Directions in Theoretical Studies of Rotational Motions

Panel Members: A. Cochard, A. Cadena-Isaza, Y. T. Chen, M. Gorski, **L. Knopoff (Chair)**, F. J. Sánchez-Sesma, and R. Teisseyre.

I. Fundamental theory

1. If rotational energy is stored in a fault zone, how is it stored?
2. How is stored rotational energy relaxed in a fault zone?
3. Is there a quadratic rotation-energy relation, in the sprit of Green's strain-energy relation, coupled to it or independent of it? Can we write a rotation-torque formula analogous to Hooke's law for linear elasticity in the form

$$L_{ij} = d_{ijkl}\ \omega_{kl} \tag{1}$$

   where ω_{kl} is the rotation, $\omega_{kl} = ½\,(u_{k,l} - u_{l,k})$; L_{ij} is the torque density; and d_{ijkl} is the coefficients of rotational elasticity. How are the d's related to the usual c's of elasticity?

4a. We can easily write the p.d.e. for rotation since

$$\mathbf{\Omega}_j = \varepsilon_{ikl}\ u_{k,l} = ½ \text{ curl } \mathbf{u} \tag{2}$$

   where ε is the levi-Civita pseudo tensor density. The p.d.e. is [see Note 1]

$$-v_s^2 \text{ curl curl } \mathbf{\Omega} = \partial^2\mathbf{\Omega}/\partial t^2 - ½\,\rho^{-1} \text{ curl } \mathbf{f} \tag{3}$$

   where the torque density is curl $\mathbf{f}$, $\mathbf{f}$ is the body force density, and ρ is density of the medium. This shows that rotational waves propagate with S-wave velocity and that it may be possible to store torques.

4b. How is stored (pre-)torque density relaxed in an earthquake? The storage suggests granular locking in a fault zone.

5. Granular media.
   a. Equations of state for deformation. Constitutive laws similar to rate-state laws of frictional stress as a function of slip velocity?
   b. Nature of dynamical fracture (unlocking) of granular media.

c. Locking of granular materials: Is there a problem of “Apollonian packing” for unlocking of rotations in granular media?

d. Friction laws for granular media.

e. Relevance of laws such as non-symmetric stresses or Cosserat elasticity to the problem of stored torques.

f. Importance of non-linear effects.

II. Laboratory Experiments

Experiments in the 1940’s and 1950’s showed that the deformation of (beach) sand with interstitial water was remarkably similar to that of saturated sandstone. Microscopic examination showed significant rotations of sand grains adjoining fracture surfaces.

1. What is the geometry of (quasi)static rotations in granular media? What is the influence of fluids?
2. Is there precursory rotational creep? (The prediction problem.)
3. Rotational strength weakening?

III. Applied Mathematics

Solution of p.d.e. of rotation for simple geometries

a. Scattering

b. Diffraction

c. Establishment of “benchmark” solutions as targets for numerical simulations [see Note 2].

d. Rotation of a rod

2. Radiation from relaxation of fault rotations in an earthquake.
3. Calculation of rotations in the intermediate and near-field.

Note 1. Derivation Equation (3) by Paco Sanchez-Sesma

For homogeneous, isotropic, elastic medium Navier equation can be written by means of

$$\mu\nabla^2\mathbf{u} + (\lambda+\mu)\nabla(\nabla\cdot\mathbf{u}) + \mathbf{f} = \rho\frac{\partial^2\mathbf{u}}{\partial t^2} \quad \rightarrow \quad (\lambda+2\mu)\nabla(\nabla\cdot\mathbf{u}) - \mu\nabla\times\nabla\times\mathbf{u} + \mathbf{f} = \rho\frac{\partial^2\mathbf{u}}{\partial t^2}$$

Because $\nabla^2\mathbf{u} = \nabla(\nabla\cdot\mathbf{u}) - \nabla\times\nabla\times\mathbf{u}$.

If we define rotation vector as

$$\Omega = \frac{1}{2}\nabla \times \mathbf{u},$$

considering that $\nabla \times (\nabla \cdot \mathbf{u}) = 0$ we have $\nabla \cdot \Omega = 0$ and then

$$-\mu\nabla \times \nabla \times \Omega + \frac{1}{2}\nabla \times \mathbf{f} = \rho\frac{\partial^2\Omega}{\partial t^2} \quad \rightarrow \quad -\nabla \times \nabla \times \Omega + \frac{1}{2\mu}\nabla \times \mathbf{f} = \frac{1}{\beta^2}\frac{\partial^2\Omega}{\partial t^2}$$

$$\nabla^2\Omega + \frac{1}{2\mu}\nabla \times \mathbf{f} = \frac{1}{\beta^2}\frac{\partial^2\Omega}{\partial t^2} \quad \text{and} \quad \nabla \cdot \Omega = 0.$$

From the equations above

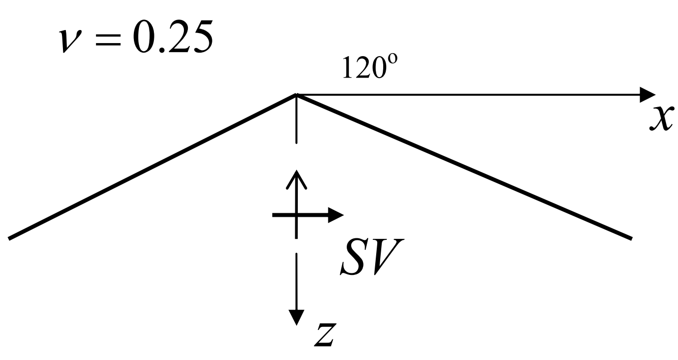
$$-\mathrm{v_s}^2 \text{ curl curl } \mathbf{\Omega} = \partial^2\mathbf{\Omega}/\partial t^2 - \tfrac{1}{2}\rho^{-1} \text{ curl } \mathbf{f}$$

Note 2. Comments by Paco Sanchez-Sesma

Paco suggested that analytical solutions could be used to test numerical methods to compute rotations in irregular topographies. For incoming SV upon infinite wedge topography analytical solutions exist (see *Sanchez-Sesma*, 1990) for the following two cases:

1. The internal angle of wedge is 120°, it is the free surface, and the Poisson ratio of the elastic material is 0.25 and thus $\alpha = \sqrt{3}\beta$, where α, β are the propagation velocities of P and S waves, respectively. Incidence is as depicted in figure. In this case, because of the geometry and material properties (we have two cases of total mode conversion in the reflection) the complete displacement field for an incoming plane SV wave of form $u^{(i)}(x,z,t) = f(t + z/\beta)$ is given by

$$u(x,z,t) = f(t+z/\beta) + f(t-z/\beta) + f(t+x/\alpha) + f(t-x/\alpha)$$
$$w(x,z,t) = 0$$

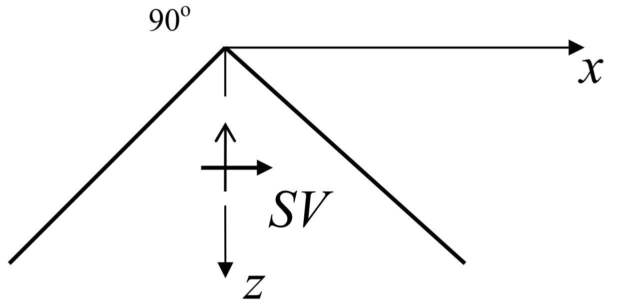


The rotation is $\omega_2 = \frac{1}{2}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right) = \frac{1}{2\beta}\left(f'(t+z/\beta) - f'(t-z/\beta)\right)$ and is null at vertex.

2. For an internal angle of 90°, for any Poison ratio, the total displacement field is:

$$u(x,z,t) = f(t + z/\beta) - f(t - z/\beta)$$

$$w(x,z,t) = f(t - x/\beta) - f(t + x/\beta)$$



The rotation is

$\omega_2 = \frac{1}{2}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right) = \frac{1}{2\beta}\left(f'(t + z/\beta) + f'(t - z/\beta) + f'(t + x/\beta) + f'(t - x/\beta)\right)$. It can be seen that at the surface (x=z) we have $\omega_2 = \left(f'(t + x/\beta) + f'(t - x/\beta)\right)/\beta$ and thus at vertex the rotation is $\omega_2 = 2f'(t)/\beta$.

These two analytical solutions can be used as a benchmark for analytical solutions aimed to compute rotations at the surface of topographical irregularities. These elementary solutions can be obtained using geometrical means. As there is no diffraction, Rayleigh waves do not appear.

Reference

Sanchez-Sesma, F. J., Elementary solutions for the response of a wedge-shaped medium to incident SH and SV waves, Bulletin of the Seismological Society of America, 80, pp. 737–742, 1990.

Appendix 2.2 Future Directions in Measuring Far-Field Rotational Motions

Panel Members: J. Hautmann, **H. Igel (Chair)**, S. Lehndorfer, D. N. Pham, J. Wassermann.

Key issues and unsolved problems to be discussed:

(1) Can we extract reliable *additional* information (source or structure) from collocated measurements of rotations and translations compared to translations only?
(2) Can we develop structural inversion strategies incorporating rotations?
(3) How does scattering affect rotations and do rotations allow tighter constraints on subsurface scattering properties?
(4) How does structural and material complexity (strong lateral heterogeneities, cavities, anisotropy) affect rotation measurements (body waves, surface waves)?
(5) Under what circumstances are array-derived rotations useful/sufficient?
(6) What can we learn from ambient noise measurements of rotations?
(7) How can we make use of the horizontal components of rotation (tilts) in far-field measurements? Are they sensitive to local structure?
(8) Additional items for discussions.

Research Strategy and Plans:

Some main steps:

(1) Extend the global network of high-resolution rotation sensors (ring lasers).
(2) Build complete 6-C high-resolution observing sites using ring laser technology.
(3) Standardize transfer protocols, data formatting and archiving (in line with common seismological practice).
(4) Provide rotation data through Web interfaces (e.g., seismological data centers).
(5) Define and develop standard processing steps for event data (collocated translations and rotations).
(6) Adapt simulation tools to multi-component requirements (displacement, strain, and rotations).
(7) Model rotation data (events, noise) with appropriate simulation tools (3-D, anisotropic, scattering theory, etc.) and demonstrate the potential for seismology, geodesy, and earthquake physics. Compare results for rotations with translations.

(1) requires a joint international effort. The Munich/Strasbourg/SCRIPPS groups are attempting to implement steps (2)-(6). Point (7) will strongly depend on the availability of high-quality data from several sites.

Summary

Impressive progress has been made in developing stable, broadband, observatory sensors for rotation about the vertical. Four observatory instruments are now in operation in Germany, New Zealand, Arkansas and California. Data from these instruments has been shown to have promise for new developments in structural inversion, scattering and wave propagation. The need is to provide better access to the data (and metadata) to stimulate research by the global seismological community. Steps are being taken to solve this problem. Data access shall be initially made through www.rotational-seismology.org.

The next big step instrumentation would be to construct a 6C ring laser gyro/broad band seismometer observatory. At an initial stage, such an observatory would benefit from a dense 3C array deployment to provide data for comparison of point measurements of rotation, wave slowness and back azimuth with the same quantities derived from the spatial gradient of the wavefield. Such an observatory would also provide critically needed information about the coupling between tilt and ring laser gyros. Measuring rotations about horizontal axes at very long period could greatly improve the resolution of horizontal motions, particularly at very long period, where the tilt/acceleration coupling for conventional broadband seismometers remains a major source of long period noise. This could greatly increase the sensitivity of seismometers to Love waves. Fiber optic ring laser gyros also remain attractive instruments because of their cost, but more work must be devoted to improving their performance.

To understand the potential in particular for structural inversion, the sensitivity of rotation measurements with respect to scattering media, topography, anisotropy etc. needs to be studied. In particular, the benefits of 4-6C recordings over classical 3C recordings must be investigated and highlighted.

Appendix 2.3 Future Directions in Measuring Near-Field Rotational Motions

Panel Members: R.E. Abbott, R. D. Catchings, B. Chouet, W. Ellsworth, J. B. Fletcher, V. Graizer, B. S. Huang, J. Kozak, W. H. K. Lee, T. Ohminato, D. H. Oppenheimer, German Prieto, M. Takeo, S. L. Sargeant, P. Spudich, C. Stephens, **T.-L. Teng (Chair)**, and R. E. Wells.

Key issues and unsolved problems to be discussed:

1) Why the rotation motions observed from local earthquakes in Japan and Taiwan are 10 to 100 times larger than that from theoretical considerations or from the rotation motions of the 2004 Parkfield earthquake in California deduced from the observations of an accelerometer array nearby?
2) Why we cannot integrate acceleration data to displacement for large earthquakes in the near field? Are rotational motions an important factor?
3) How to effectively measure rotational motions in the near-field?
4) How can we sort out the source, propagation, and local site effects from rotational measurements in the near-field?
5) Should we try multiple instruments and/or methods?
6) Additional items for discussions.

Research Strategy and Plans:

1) Since rotational sensors are expensive and field sites (geology, topography and sediment cover) can be complex and spatially variable, what are the best strategies and site conditions for field deployment so that uncontaminated [One person's contamination is another's most critical observation! Bad choice of adjective.] rotational measurements are secured?
2) The Taiwan group (Huang, Liu, and Lee) is now running multiple instruments (including a rotation sensor) at the HGSD station in eastern Taiwan. How should they develop the current instrumentation into a good plate boundary observatory?
3) The Taiwan group (Wu, Huang, Liu, Lee, and Teng) is now planning to deploy an integrated array in southwestern Taiwan in order to "capture" the next M7+ Meishan earthquake. What is the best strategy/plan to "capture" a major earthquake that has large engineering and social impact?
4) Strategy and Plans from other groups.

Summary (prepared by Bill Ellsworth):

The ~15 participants in the breakout session engaged in a lively and productive discussion covering a wide range of issues related to field studies of rotational motions. The three main topic areas considered were i) instruments; ii) experiments; and iii) experimental sites.

There was broad agreement that measuring all six components (6C) of the displacement field at non-observatory sites is a worthy goal. There was also broad agreement that much work remains to be done before rotation sensors can be considered as field-worthy instruments in the same class as seismometers and accelerometers. It took many decades of work to develop both the sensors and field installation techniques that now permits the routine recording of rectilinear motions (3C) over a very broad frequency and amplitude range. Laboratory and field testing of individual rotation sensors should be coordinated to accelerate the development of field-worthy instruments operating in the bandwidth from a few tens of seconds to a few tens of Hz with the ability to resolve a μrad/s to a few tens of mrad/s. The need for standardized laboratory and field calibration procedures was noted. There was also a call for better characterizing seismometers and accelerometers to quantify their cross coupling to rotation, and to invest some effort in identifying those sensors that are least contaminated by rotation or cross-axis displacements (for example, are four-point suspended masses less susceptible to rotations than are penduli?).

There will be a need to conduct a series of validation experiments with candidate instruments to show that rotational motions can be reliably measured under field conditions. These experiments should ideally include redundant instruments and/or alternative designs. Experiments to compare field deployment techniques would also be valuable. An early experiment should embed a 6C point measurement within a well-designed array of 3C instruments for direct comparison of the point rotation with that derived from the curl of the displacement field. Concern was expressed about site effects and local heterogeneity upon the data and experiments with multiple sensors in both geologically simple and complex environments should be considered. Co-location with strainmeters should also be pursued where practical.

Scientific experiments should be guided by the potential to learn something that cannot be easily obtained from 3C seismology. There are clear needs for data to define ground-motion models for rotational motions (distance dependence of rotation as a function of earthquake magnitude), as earthquake engineers are not in agreement on the importance of rotations as input motions to structures. Results from an experiment with a 3C array and embedded 6C sensors will be important for determining the best approach for collecting this type of data. The most promising area for earthquake experiments would appear to be in the near-field. The 2004 Parkfield, CA, earthquake demonstrated the value of a dedicated array for understanding near-field motions using accelerometers. Rotation sensors should be considered for future experiments using dense deployments of accelerometers, as this would provide the best opportunity to determine if the stress glut

(*Backus and Mulcahy*, 1976) can contain a component of torque, or if rotational waves are preferentially excited by geometric or other complexities in the rupture. Perhaps some of the most valuable scientific return would be in volcano seismology as both single forces and torques represent body-force equivalents of volcanic sources. Here, the requirement will be for high-sensitivity rotation sensors, rather than strong motion sensors as would be needed for near-source earthquake seismology.

A number of suggestions were offered for candidate experimental sites. A number of the instrumental development experiments would be facilitated by conducting them at a location with frequent earthquakes and an observatory-class rotation sensor. The Piñon Flat, CA, observatory would be a good candidate site, as it has a vertical axis rotation sensor and multiple strain and tiltmeters. The test site of the Plate Boundary Observatory borehole strainmeter network on the Olympic Peninsula, WA, would provide another potential experimental site. The Parkfield strong motion array has already been noted, and a similar array is now being discussed for the southern Hayward Fault in the eastern San Francisco Bay Area. This earthquake ruptured in an M6.8 earthquake in 1868 and paleoseismic studies show that the mean recurrence time is 150–170 years. Promising field sites are also available in Taiwan, building on experience already gained with the R-1 rotation sensor. Taiwan also has the advantage of a high level of regional earthquake activity, although the capturing of any specific earthquake in its near field (such as the 1999 Chi Chi, Taiwan earthquake) will take a major commitment of resources. Well-instrumented volcanoes would be another logical target for studying both volcanic signals and tectonic earthquakes, including volcanoes in Japan, Hawaii, and Washington State. Industrial sources of torque waves should also be considered for study.

One strategy would be to think globally, and identify the 5, 10, or even 20 most likely source faults for a major (M6.5+?) earthquake in the next decade, and coordinate resources from the worldwide community to capture one or more of them. Such an experiment would undoubtedly focus on 3C accelerometers, but 6C sites would be valuable additions.

However we proceed, it is clear that rotational seismology must be firmly connected to what is being done today in rectilinear seismology and strain.

Backus, G., and M. Mulcahy, Moment tensors and other phenomenological descriptions of seismic sources. I. Continuous displacements, *Geophys. J. R. Astr. Soc.*, **46**, 341–361, 1976.

Appendix 2.4 Future Directions in Engineering Applications of Rotational Motions

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Key Issues and unsolved problems discussed:

1. How large are the ground rotations exciting structures?
    a. Which conditions lead to large initial ground velocity ($\sim \sigma\beta / \mu$) and rotations near faults?
    b. How do vibrating blocks, liquefaction, and nonlinear soil motions near faults contribute to large rotations?
    c. How do soil and rock inhomogeneities and topography contribute to large rotations?
    d. To what extent can rotations be inferred from measurements of translations?
2. Ground rotations as excitation of structures:
    a. How much do ground rotations contribute to the total excitation of structures?
    b. For what kind of structures and under what conditions are rotational ground motions significant for the relative response?
3. Recording rotations in structures:
    a. How representative are average rotations (drifts) inferred from translational sensors?
    b. How can measurements of point rotations be used in structural health monitoring to identify the location and the extent of strain localizations?
    c. What is the optimal configuration for installing rotational sensors in structures? How many are needed and where should they be installed?
    d. How can information on rotation be inferred from existing translational data recorded in structures?
    e. Can rotational sensors give information about curvature of the response of structures?

f. How can data from rotational sensors in and around structures be used to constrain and validate detailed finite element models of structures and soil-foundation-structure systems.

4. Effects of the rotation of the instrument box on recorded translations:
    a. Theoretical and experimental studies have shown that the rotation of the instrument box affects significantly the displacements obtained by double integration of the recorded acceleration, and that permanent displacement (of the ground and in structures) cannot be computed from recorded three components if translation only. It is necessary to record all six components of motion to be able to correct the recorded translations for such effects.
    b. Such effects exist also during linear response in flexible structures, which exhibit large deformations under wind or earthquake excitation and need to be quantified.
    c. The errors in using such "contaminated" records of translations (e.g., in calibration of structural models) must be quantified.

5. Vibrational (mode superposition) *versus* wave propagation formulation of the response of structures:
    a. The vibrational formulation is inadequate for representing the structural response to near-field strong motion pulses.
    b. Is the vibrational formulation of response limiting progress in more realistic and complete representation of response?
    c. What is the required resolution for theoretical wave propagation models of structural response to near-field strong motion pulses?
    d. Mechanisms should be devised for systematic introduction and use of wave propagation methods in structural analysis.

Research Strategy and Plans:

1. Develop a focused research program to:
    a. Understand and quantify rotational ground motions and their significance for structural design.
    b. Understand and quantify the significance of recording rotational motions in structures for advanced studies, such as structural health monitoring (e.g., detecting strain localizations due to damage), wave propagation methods for analysis of the seismic response of structures, calibration and validation of detailed finite element models of structures, foundations and soil-foundation-structure systems, and performance based design.
    c. Derive simplified formulae to account for the effects of rotations in routine applications, and implementation in the building design codes.

2. Toward the above mentioned objectives:

a. Conduct studies using analytical and numerical models for elastic an inelastic response of soils and soil-structure systems.
b. Measure ground rotations and rotations in structures.
c. Compare the observed rotations with predictions using theory and recorded translations. Use the lessons learned to extend the information that can be obtained from existing strong motion data (of translational motions).

Specific tasks:

1. Set up special purpose arrays in selected buildings, including rotational sensors and high resolution GPS, to provide data for advanced studies of structural response, such as structural identification and health monitoring, wave propagation methods for analysis of structural response, and performance based design.
2. Upgrade the recording systems in many buildings to measure their rotational response during strong shaking, with the objective to observe and identify the interaction of the structure with the foundation soil, and establish the role of soil-structure interaction in the response of full-scale structures.
3. Set up detailed networks of rotational transducers in the free field, preferably collocated with existing arrays that have previously recorded useful data on strong motion translations. Use the recorded data to verify numerical simulation models, and calibrate relationships for estimating rotations from recorded translations, and future empirical scaling models for the amplitudes of the ground rotations.
4. Establish permanent structural sites (buildings, bridges, dams, …) in seismically active regions of the world to serve as full-scale laboratories for studies of the response of structures in their damaging, nonlinear range of response.
5. Develop guidelines for structural array configuration and practical installation of rotational sensors in structures. This task can be facilitated by conducting analyses of numerically simulated structural response, and full-scale tests.
6. Investigate the effect of the rotation of the instrument box on the recorded translations (of the ground and in structures), and upon displacements computed by double integration of the recorded accelerations. Investigate the implications of the errors in calibration of structural models from using liner vibrational records in structures.
7. Investigate how information from rotational sensors can be used for validation of detailed finite element models of structures, foundations and soil-foundation-structure systems.
8. Carry out detailed numerical simulations of the nonlinear response of soil-structure systems to understand the basic properties of their rotational motions. Compare these simulations to results based on different modeling techniques

(significant variations may exist depending on the choice of input model parameters and modeling technique).

9. Carry out detailed numerical simulations of the effects of topography and inhomogeneity of soils and rocks beneath structures on the ground rotations exciting structures, and identify conditions that enhance the amplitudes of the ground rotations.
10. Further analyze data from existing dense arrays of translational sensors to estimate ground rotations using spatial derivatives.
11. Further develop modeling techniques for simulation of the rotational components of strong ground motion.
12. Set up a Web site(s) for free dissemination of translational and rotational strong motion data.
13. Promote various aspects of research and education dealing with rotational strong motion.

Summary:

The average rotation between floors in a structure (drift) is the key variable that governs the engineering design of structures to withstand destructive motions caused by earthquakes, strong winds, and explosions. During strong earthquakes, this rotation results from: (i) the rotational components of seismic waves, (ii) the interaction of the structure with the flexible soil, and (iii) the relative deformation of the structure by the inertial loads. Accurate prediction of all of those contributions to the average rotations (drift) is essential for the engineering design to be conservative.

However, the lack of recorded data on the rotational components of strong motion, and the complexity of the treatment of the interaction between vibrating structures and the supporting flexible soil have resulted in simplified engineering design such that considers only the translational components of the strong ground motion and of the structural response. This approximation may be adequate only at large distances from the earthquake fault but lead to serious underestimation of the response amplitudes in the near field and adjacent to the fault.

To properly include the effects of the rotational components of strong ground motion in realistic design criteria of structures, it is essential that: (1) the rotational components of motion are recorded both in the soil and in the structures, and (2) engineering education be modernized to be more rigorous and include in the building code design formulae the rocking and torsional motions resulting from soil structure interaction.

These objectives can be accomplished during the next several decades by initiating and maintaining comprehensive observational and educational programs. Besides for building codes, which are concerned with minimum design to insure life safety, recording rotations in structures is also necessary for advanced uses of vibrational records in structures, such as those [I am uncertain of Misha's intended meaning here] that require detailed description of the structural response for accurate estimation of the structural parameters and its performance. Such advanced uses are structural health monitoring and early warning of earthquake damage in a structure, performance based design, and system identification for calibration of detailed soil-structure models.

Appendix 2.5 Future Directions in Design and Testing Rotational Sensors

Panel Members: R. Cowsik, D. DeBra, R. DeSalvo, **J. R. Evans (Chair)**, C. R. Hutt, E. R. Jensen, B. Kilgore, M. Johnston, B. Lantz, D. Lockner, C. C. Liu, R. Nigbor, U. Schreiber, and A. Takamori.

Key issues and unsolved problems:

1) Many rotational sensors have no DC response (have a low-cut filter) and require dynamic testing. In all cases, dynamic testing is desirable to demonstrate fidelity and establish transfer functions.
2) How can we generate clean rotational signals in the band and amplitude ranges required for strong-motion and teleseismic rotational sensors? Is Earth rotation a sufficient test signal for teleseismic sensors?
3) Will the strong-motion dynamic-test system be sufficient to obtain an absolute transfer function?
4) How should we test properly for cross-axis sensitivities — particularly linear-to-rotational cross axis sensitivities (but note that there are $6^2 = 36$ cross-axis sets)?
5) How do we do self-noise testing for teleseismic sensors? (Strong motion sensors can be done at any quiet site, e.g., ASL vault, however a good ambient noise spectrum should first be obtained with a teleseismic instrument.)

Research Strategy and Plans:

The constant-velocity rotational table at Physikalisch Technische Bundesanstalt (PTB) in Germany is very helpful for assessing the linearity of sensor responses as a function of amplitude and to a lesser extent as a function of frequency (the PTB table has limited accelerations). ASL is building a strong-motion rotational table from a thrust bearing, long, stiffened lever arm, and linear shake table (linear-electric-motor driven precision linear slide) which is capable of higher accelerations and may permit absolute calibration and rotation-to-rotation cross-axis tests. The main concern is the stiffness and resonances of the lever arm, which is being reengineered to raise the fundamental above its current 12.5 Hz.

We need rotational ambient noise spectra at the ASL vault and other vaults likely to be used for such work. Such spectra are becoming available from weak-motion rotational sensors in observatories.

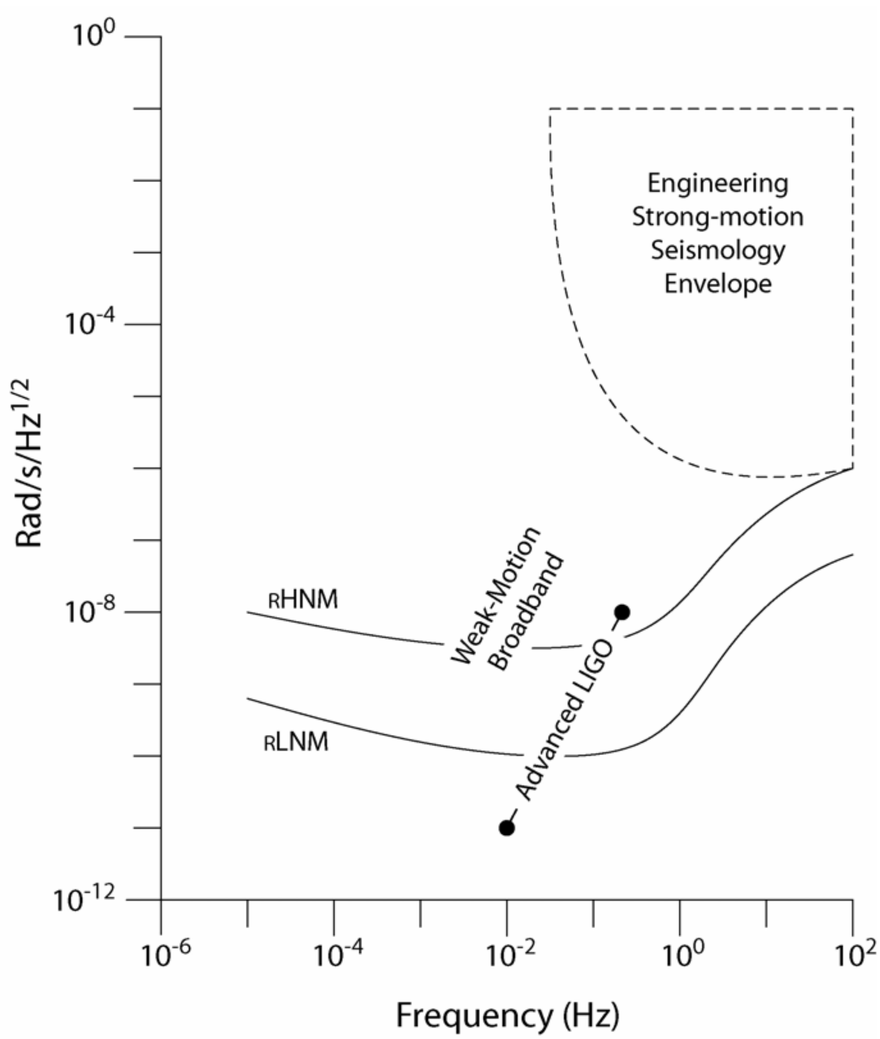
The ASL linear-motion Russian shake table, driven harmonically, may be sufficient for linear-to-rotational cross-axis measurements but appears to have rotational modes obviating such use. If that table is unacceptable, what method should be used for such tests?

Teleseismic sensors will soon have the option of two-sensor self-noise measurements between differing designs — ring laser gyro and precision torsion balance. This test should be performed and would yield both self noise and relative transfer functions between the designs, the latter possibly requiring some sort of active source.

Summary:

Goals

- Principal design goal: In units of rms rad/s/√Hz, characterize both available and desirable rotational-sensor frequency-sensitivity ranges for particular applications, as in the following sketch:



- To facilitate the above, measure an ambient low-noise model to be designated the "rLNM" (rotational Low-Noise Model). Use noise recorded at the ring laser gyros at Wettzell, Piñon Flat, Arkansas, Christchurch, etc., as the first pass at this model. Possibly use comparisons with the (linear) Low-Noise Model to estimate a rotational High-Noise Model (rHNM) as well.

- Self noise measurements for sensors: Compare two or more sensors on a single, stationary platform. Use the “blocked mass” method if feasible, otherwise an incoherence method. Strong-motion sensors generally can be evaluated with a single-sensor method.

- Measure cross-axis sensitivities of both linear and rotational sensors to both linear and rotational inputs. Between three linear and three rotational components there can be 6^2 (36) cross-axis terms; however, a more general characterization may be adequate. The key terms are rotation-to-rotation and linear-to-rotation maxima for rotational sensors, and rotation-to-linear sensitivities for linear sensors (linear-to-linear is already done routinely). These terms are likely to be functions of input acceleration rather than velocity.

- Measure the linearity and the transfer function (sensitivity and phase response over the frequency range).

- Measure the clipping level of sensors (combined with self noise, clipping implies the sensor’s dynamic range). As with linear sensors, apply the ANSS standard of rms noise (*not* integrated over partial octaves) compared to the rms of a just-clipping sine wave.

- Determine the environmental sensitivity for such parameters as temperature, pressure, power supply voltage, EMI/RFI, etc.

- Determine the stability of various specifications over time.

- Fiber optic gyros may suffice as primary reference sensors, although they generally are somewhat noisy. In any case, a well-tested weak-motion sensor can be used as a reference in some strong-motion tests.

- In addition to experience with linear sensors, a possible source for test standards is: IEEE-SA Standards Board, IEEE standard specification format guide and test procedure for non-gyroscopic inertial angular sensors: Jerk, acceleration, velocity, and displacement, *IEEE Std.*, **671-1985**, 69 pp., 1985.

Methods

- The rLNM is essentially available but will be collated and disseminated shortly by the Wettzell/München group and collaborators. In addition to direct observation, it should be possible to estimate ambient *z*-axis rotational noise from horizontal components of linear motions, however this method is subject to tilt contamination and would be only an upper limit. Other methods of estimation for the rHNM should be evaluated.

- Self noise measurements will be accomplished in a manner very similar to the methods already used for linear sensors.

- Cross-axis characterization requires both very pure rotational and very pure translational tables capable of both constant-velocity and accelerating motions. Use of granite slabs (circular and rectilinear) on air bearings was discussed.

- Broadband dynamic tests, with and without accelerations, are required to estimate transfer functions and linearity. These are best performed on the ASL long-arm rotational table, but that table must be made much stiffer and provided with a superior bearing. The table should be made large enough and powerful enough for testing smaller torsion-balance and ring laser gyro sensors (≥1 m across mounting surface). The PTB table is viable for testing at constant rotational velocities and may be used similarly for "static" linearity and clipping tests. If feasible, a machinist's NC turntable should be obtained and evaluated for similar uses (as well as for tilt testing linear accelerometers). Results from these various rotational shake tables should be compared as verification.

- Exciting sensor by rotation through a known angle and integrating the record to estimate this angular offset is a thoroughgoing test of sensitivity, linearity, and fidelity and should be performed on all such sensors (equivalent to double-integration testing of accelerometers and single-integration testing of linear broadband sensors). Prior correction for phase and amplitude variations near any low-cut filter corner are likely to be requisite.

- Clipping levels are best tested on the ASL long-arm table.

- An environmental chamber should be equipped with a constant-velocity rotational table (perhaps the proposed machinist's NC turntable). Extant laboratory equipment is viable for all other tests except pressure. Pressure testing chambers or services may be leased as needed and will require a mounted rotational shake table inside. Functionality and oberservations of unusual noise, offset, and sensitivity at one frequency of sine wave or one constant rotational velocity should be adequate.

Appendix 3. Contents of the Workshop DVD Disc

The accompanying Workshop DVD Disc (version 2.0) is an updated and corrected version of the DVD distributed at the Workshop. It contains all presentation files and supporting materials. This revised DVD has an automatic-start feature when it is inserted on a DVD drive. If it does not start automatically, please locate the file *autohtml.exe* in the root directory start it manually. The online version of this *Report* will then appear and you may explore the DVD disc at various levels. Alternatively, you may copy the entire DVD to a directory of your hard disk, and explore its contents manually. This DVD contains nearly two gigabytes of useful information contributed mostly by the Workshop authors, and is intended for personal use only.

The root directory includes both html and PDF versions of this *Workshop Report*. In addition, it contains a 20-minute movie, *Einstein's Messengers* — a National Science Foundation presentation on gravity waves.

The supplemental materials are grouped into four directories:

(1) *2006_AGU_Session_Presentations*: presentation files from the *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 et al.*, 2007).

(2) *2006_USGS_Video_Conference_Presentations*: presentation files and auxiliary information from a small workshop on rotational seismology organized by W. H. K. Lee, K. Hudnut, and J. R. Evans on 16 February 2006 at the USGS offices at Menlo Park and Pasadena, California, *via* teleconferencing and telephone (*Evans et al.*, 2007).

(3) *2007_Workshop_Participants_and_Contributors*: This directory contains 58 folders named by author's last name. Each folder contains files contributed by the Workshop participants and a few contributors who could not attend the Workshop.

(4) *Supplemental_Papers_by_Others*: This directory contains 50 PDF files of papers or reports written by authors who did not participate in the Workshop but which are of interests to Workshop participants. Many of these papers are old and may be difficult to locate away from a major Earth-science library.

We have chosen the PDF format with embedded fonts for this DVD so that all files can be read reliably by as many different computer systems as possible. Original files of other formats are also included if submitted by the authors. Some authors, however, contributed files that require specific commercial software (e.g., Microsoft's PowerPoint), and equivalent PDF files were prepared. Due to occasionally conversion problems, users are advised to use the original formatted files if a PDF file does not appear to be correct.

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