A WORKSHOP ON ROTATIONAL GROUND MOTION

John R. Evans[1]*, A. Cochard*[9]*, Vladimir Graizer*[2]*, Bor-Shouh Huang*[3]*, Kenneth W. Hudnut*[4]*,*
Charles R. Hutt[5]*, H. Igel*[9]*, William H. K. Lee*[1]*, Chun-Chi Liu*[3]*, Robert Nigbor*[6]*, Erdal Safak*[4]*,*
William U. Savage[1]*, U. Schreiber*[10]*, Mihailo Trifunac*[7]*, J. Wassermann*[9]*, and Chien-Fu Wu*[8]
(alphabetical listing following first author)

[1] U. S. Geological Survey, Menlo Park CA 94025, USA
[2] California Geological Survey, Sacramento CA 95814, USA
[3] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
[4] U. S. Geological Survey, Pasadena CA 91106, USA
[5] U. S. Geological Survey, Albuquerque NM 87198, USA
[6] Department of Civil Engineering, University of California, Los Angeles CA 90095, USA
[7] Department of Civil Engineering, University of Southern California, Los Angeles CA 90089, USA
[8] Seismology Center, Central Weather Bureau, Taipei, Taiwan
[9] Sektion Geophysik, Ludwig-Maximilians-Universität, D-80333 München, Germany
[10] Fundamentalstation Wettzell, Technische Universität München, D-93444 Kötzting, Germany

1. INTRODUCTION

A successful workshop titled "Measuring the Rotation Effects of Strong Ground Motion" was held simultaneously in Menlo Park and Pasadena *via* video conference on 16 February 2006. The purpose of the Workshop was to summarize existing data, theory, and to explore future challenges for rotational seismology, free-field strong motion, and structural strong motion. Due to the organizers' oversight, we *ex post facto* extend the scope of this Report to include the extensive work on teleseismic rotational motions (e.g., *Igel et al.*, 2005). The Workshop and the addition of many teleseismic citations and papers to the Web site succeeded in these goals and in forging a consensus for the steps to be pursued in the near term.

There were 16 participants in Menlo Park, 13 in Pasadena, and a few on the phone bridge. The workshop was organized by William H. K. Lee and John R. Evans. The workshop was chaired by William U. Savage in Menlo Park and by Kenneth W. Hudnut in Pasadena.

To facilitate the workshop, an FTP site and a newer Web site were created for distribution of relevant materials. The FTP site still contains the Workshop agenda, PowerPoint™ presentations, many papers (use-only basis, with permission of their authors), a comprehensive citations list including both teleseismic and strong motions, an e-mail history, and representative sensor specifications. The Web site mirrors this information and adds much more:

http://www.rotational-seismology.org

ftp://ehzftp.wr.usgs.gov/jrevans/RotationsWorkshop/

In this report, we proceed from the theoretical bases for making rotational measurements (*Graizer*; *Safak*; *Trifunac*) through the available observations (*Nigbor*; *Liu et al.*), proposed suites of measurements including rotation (*Hudnut*), a discussion of teleseismic rotational seismology (*Igel et al.*), sensor-calibration issues (*Hutt and Evans*), and finally the summary and conclusions (*Savage*).

In addition to the Working Groups and continuing tests and measurements, a special session at the Fall 2006 AGU meeting is being organized, this time to include the full span of efforts.

2. THEORETICAL BASIS FOR ROTATIONAL EFFECTS IN STRONG MOTION AND SOME RESULTS — V. GRAIZER

Most instruments used to record ground motion are pivot-pendulum or linear-pendulum seismographs, velocigraphs, or accelerographs. In most cases it is assumed that these sensors respond only to translational motions. *Graizer* (1989, 2005) showed that the differential equation of small oscillations of horizontal pivot-penduli can be written (3 = vertical axis):

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2 - \psi_3'' l_1 + x_2''\theta_1 \qquad 1$$

where y_i is the recorded response of the instrument, θ_i is the angle of pendulum rotation, l_i is the length of the pivot-pendulum arm, $y_i = \theta_i l_i$ at the end of the arm, ω_i is the natural frequency, D_i is fraction of critical damping of the *i*th transducer, g is the acceleration due to gravity oriented vertically, x_i” is the linear ground acceleration in *i*th direction, and ψ_i is a rotation of the ground surface about axis x_i. Following are functions of time: θ_i (thus y_1) and x_1.

For small oscillations of both pivot and linear penduli, the vertical accelerometer is almost insensitive to tilts. Neglecting the cross-axis sensitivity terms, the differential equation of the horizontal pendulum (Eqn. 1) simplifies to:

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2 \qquad 2$$

while that of the vertical pendulum is becomes

$$y_3'' + 2\omega_3 D_3 y_3' + \omega_3^2 y_3 = '' - x_3'' \qquad 3$$

Thus, in a typical strong-motion tri-axial instrument both horizontal sensors are responding to a combination of horizontal accelerations and tilts, while the vertical sensor is responding almost entirely to the vertical acceleration.

Tilting of the accelerograph’s base can, therefore, significantly impact its response to ground motions. As it was shown by *Graizer* (2005, 2006), the presence of unknown tilts in the record makes calculation of residual displacements from accelerograms impossible from only the linear-acceleration records. Consequently, direct methods of displacement calculation from linear acceleration (*Graizer*, 1979; *Iwan et al.*, 1985; *Boore*, 2001) are not applicable to those records. A conservative procedure based on filtering out the low-frequency portion of linear ground motion, developed by *Trifunac* (1971), and similar methods, are the only way to routinely process existing strong-motion data.

A method for evaluating tilts using uncorrected strong-motion accelerograms was first suggested by *Graizer* (1989), and later tested in a number of laboratory experiments with different strong-motion instruments. The method is based on the difference in the tilt sensitivity between the horizontal and vertical penduli (equations (2) and (3)). This method was applied to a number of the largest-amplitude records, including from the $M_W = 6.7$ Northridge earthquake of 1994. Residual tilt extracted from the strong-motion record at the Pacoima Dam (upper left abutment) reaching 3.1° in the N45°E direction, and was a result of tilt induced directly by this local earthquake during high amplitude shaking. This estimate is in agreement with residual tilt as measured by an electronic level a few days after the earthquake (*Shakal et al.*, 1994). Applied to records of Northridge earthquake, estimated tilt reached 2.9° on the ground floor of a 12-story hotel in Ventura. In contrast, processing most of the largest-amplitude records of the Northridge earthquake shows that free-field tilts, when present, were within the error of the method, less than about 0.5°.

Tilt estimates using existing strong-motion records demonstrate the importance of independent measurements of rotations. It may be especially important in recording the seismic response of buildings because structures can have significant rotational components even in cases when the corresponding free-field ground motion is purely translational.

3. SIGNIFICANCE OF ROTATIONAL MOTIONS IN STRUCTURES — E. SAFAK

Rotational motions in structures are generated by the rotational components of ground shaking and by the dynamic characteristics (e.g., mass and stiffness distribution) of the structure. Body *P* and *SV* waves and surface waves (Love and Rayleigh) are the main sources of rotational excitations. Rayleigh waves cause horizontal-axis rotational excitations at the base of any multi-story building (see Figure 2 of PowerPoint™, "Safak_RotationalWorkshop.ppt" at the FTP or Web site). Similarly, Love waves can create rotational excitations with respect to vertical axis (i.e., torsional vibrations). The significance of rotational excitations varies with the wave lengths and dominant frequencies of surface waves and the foundation geometry and the natural frequencies of the structure. For tall buildings, Rayleigh-wave induced rotations can create significant "P-Δ Effects", which are the overturning moments and horizontal shear forces generated by drift and the weight of the building (see Figure 3 of PowerPoint™).

Mass and stiffness characteristics of structures determine the amounts of rotation in various structural components and their connections, such as the rotations of floor slabs or of beam-column connections. These rotations significantly influence the structure's natural frequency, which is a key parameter used to calculate seismic design forces. In multi-story buildings, for example, it is often assumed for design calculations that the floor slabs remain horizontal — that there are no rotations at beam-column connections. In reality, beam-column connections do rotate, and the amount of rotation is determined by the relative stiffness of beams and columns and the presence of any shear walls in the building. Indeed, in a multiple-story building the assumptions of no-rotations *versus* free-rotations at the beam-column connections can make more than a factor of two difference in the calculated natural frequencies of the structure (see Figures 4 and 5 of PowerPoint™). Moreover, knowing rotations in a structure (e.g., rotations of beam-column or beam-shearwall connections, or in plane rotations of floor slabs) allows us to calculate more precisely the distribution of seismic forces among various components, such as between frames and shear walls (see Figures 6 and 7 of PowerPoint™).

The discussion above indicates a need for measuring rotational motions during earthquakes, both on the ground and within the structure. Currently, rotational motions are not measured but are calculated by taking differences between measured horizontal linear motions. This differencing operation amplifies the noise in the records significantly, particularly for vertical motions. Thus, there is a need for affordable sensors that measure rotations directly and accurately.

4. MEASUREMENT OF ROTATIONS: *CONDITIO SINE QUA NON* FOR COMPREHENSIVE INTERPRETATION OF STRONG MOTION — M. D. TRIFUNAC

In traditional earthquake engineering, structures are designed to resist only simplified representations of strong ground motions — horizontal translational accelerations. Occasionally, in the design of important, long-span structures, the vertical component of linear excitation also may be considered. Rotational excitation by torsional and rocking components of strong ground motion is almost never considered.

Recognition that the rocking response of structures is caused not only by the compliance of the soil (soil-structure interaction) but also by the rocking of foundations caused by the passage of P, SV, and Rayleigh waves started to appear in the literature in the mid-1980s (*Trifunac*, 1982; *Castellani and Bofi*, 1986, 1989; *Lee and Trifunac*, 1987). Many studies showed the significance of those rocking excitations for both contiguous and base-isolated structures (e.g., *Todorovska and Trifunac*, 1990*a,b*; 1992*a,b*; *Todorovska and Trifunac*, 1993). Separating the effects of rocking excitation and rocking associated with soil-structure interaction is essential for interpreting observed inter-story drift. With current instrumentation (in tall buildings typically consists only of translational transducers) this separation cannot be carried out even approximately (*Trifunac et al.*, 2001). For buildings with large floor plans, warping and deformation of the foundation (*Trifunac et al.*, 1999), differential translational, and rocking seismic motions further complicate both recording and analysis of structural response. Further work is needed in this area before the role of rocking excitation can be understood and included in engineering design.

In the absence of recorded rotational components of strong motion, it is important for engineering studies of response to have at least preliminary, physically realistic simulations of such motions. The method of *Lee and Trifunac* (1985, 1987) for generating artificial torsional and rocking accelerograms meets most of these requirements. This method is an exact analytical solution if it is accepted that (1) the motion occurs in a linear elastic, layered half space and (2) that synthetic ground motion can be constructed by superposition of P, SV, and Rayleigh waves for rocking (*Lee and Trifunac*, 1987), and by SH and Love waves for torsion (*Lee and Trifunac*, 1985). This method has been extended to predict associated strain (*Lee*, 1990) and curvature over time near the surface (*Trifunac*, 1990) during the passage of seismic waves.

Simple structural systems are often modeled as a rigid foundation slab supporting a one-dimensional set of lumped masses interconnected by massless springs, and with dashpots to simulate local dissipation of vibrational energy. Such models have been used to analyze elementary consequences of soil-structure interaction and are commonly used in studies and applications of the Response Spectrum Method. These models have also been studied and used to evaluate the effects of torsional excitation (*Gupta and Trifunac*, 1987, 1989, 1990) and of rocking excitation (*Gupta and Trifunac*, 1988, 1991). These studies have shown that torsional and rocking excitations can be significant and which combinations of structural and soil properties are important for such excitation. For example, rocking excitation becomes important for tall structures supported by soft soil while torsional excitations can dominate in the response of long and stiff structures supported by soft soils.

Observations of building response to earthquake shaking led to similar findings. For example, for a seven-story, symmetric, reinforced concrete structure (damaged by the 1971 San Fernando earthquake and again by the 1994 Northridge earthquake) torsional response contributed up to 40% of the motion at the roof (*Trifunac and Ivanovic*, 2003). Including the non-linear response of soils and large eccentricities in soil-structure interaction, torsional and rocking excitations contributed to significant damage in this building. In another well-studied building (the Hollywood Storage building in Los Angeles), asymmetry of the foundation and strong torsional excitation by surface waves propagating approximately along the longitudinal axis of the building resulted in a large torsional response (*Trifunac et al.*, 2001).

Recording, analysis, and interpretation of the contributions of torsional and rocking excitations to total inter-story drift are essential for future development of earthquake-resistant design codes. Without proper consideration of these contributions, observed drifts may erroneously be assumed to result only from relative displacement of structures, leading to false confidence that current design methods are "conservative" (*Trifunac and Ivanovic*, 2003).

5. OBSERVATIONAL EXPERIENCE WITH ROTATIONAL STRONG MOTION — R. NIGBOR

Over the past 13 years we have attempted to monitor the three rotational components of strong ground motion along with traditional translational acceleration measurements. Interest in monitoring rotational strong ground motion grew from the theoretical results of *Bouchon and Aki* (1982) and *Lee and Trifunac* (1985). Both studies concluded that rotational components of ground motion may be important for a complete description of strong motions in the near field. *Graizer* (1989) suggests methods for inertial seismometry for weak and strong motions. Estimates of peak rotational velocities in these papers were on the order of 0.1 rad/s, within the range of available inertial sensors. Additional questions about the effects of rotations on measured strong ground motions arose as higher resolution digital accelerographs appeared in the 1980s.

Nigbor (1994) documents early efforts to measure rotational strong ground motion. Early in 1993, Systron-Donner™ had just developed their MEMS-based “GyroChip™” Model QRS11™ rotational-velocity sensor. An early production version was obtained and integrated into a prototype 6-DOF (six degree of freedom) measurement system. The sensor’s range (0.2 rad/s clip and 100 μrad/s resolution) was appropriate for strong ground motions, based on theoretical results of *Bouchon and Aki* (1982) and others. The system was deployed in the garage of a private home north of Landers, California, 2 km from the fault trace of the 1992 Landers Earthquake. During two months of monitoring, six aftershocks were recorded, with a maximum PGA of 0.02 g. No rotational motions were resolved above the ~1 mrad/s noise level.

On 22 September 1993, the Department of Energy conducted a “Non-Proliferation Experiment” (NPE) at the Nevada Test Site. It was a one-kiloton chemical explosion 390 m underground at Rainer Mesa. This event was densely monitored by the seismological community (*Zucca*, 1993). The prototype 6-DOF accelerograph was deployed on bedrock 1 km from the epicenter of this large chemical explosion. The digital recorder successfully recorded excellent quality data for all six sensors, including the three components of rotation. Peak rotational velocity was 400 mrad/s, while peak acceleration was 0.8 g horizontal and >1 g vertical.

The rotational sensor package was moved permanently to the surface station of the Borrego Valley Downhole Array in Southern California. Since 1994, several hundred earthquakes have been recorded by the BVDA array, with a maximum PGA of 0.2 g, yet no rotational motions have been resolved above the approximately 1 mrad/s peak sensor noise.

In 2004, rotational sensors were included in the SFSI (soil-foundation-structure interaction) test structure at the Garner Valley Digital Array in Southern California, as part of the George E. Brown, Jr., Network for Earthquake Engineering Simulation, one of two permanent field stations operated by the University of California at Santa Barbara (http://nees.ucsb.edu). Three Model ATA™ ARS-09™ magneto-hydrodynamic (MHD) rotational-velocity sensors are installed on the bottom slab of the 4 m × 4 m × 4 m test structure sitting on native soft soil. This structure is heavily instrumented. In particular, four vertical accelerometers in the corners of the foundation slab can be used independently of the ARS-09™ sensors to measure rotational motions. Data from active (shaker) and passive (earthquake and microtremor) monitoring have been gathered for two years. In small earthquakes and low-level forced vibration testing, rocking motion of the structure has been measured using vertical accelerometers, with peak values of rotational velocity on the order of 100 μrad/s. However, to date no rotational data have been resolved above the ~1 mrad/s peak noise of the rotational sensors.

Lessons learned from the 13 years of experience with COTS rotational sensors include:

- Actual resolution is ~1 mrad/s for both the GyroChip™ and ATA™ sensors.
- Small rotational foundation motions can be resolved using closely-spaced vertical accelerometers. Obtaining all axes of motion will be difficult using this method because the signal subtraction is affected by measurement and off-axis noise.
- The NEES SFSI test structure at GVDA can be a useful field test site for rotational sensors.

6. A PRELIMINARY REPORT OF TWO TAIWAN EARTHQUAKES RECORDED BY BOTH BROADBAND AND ROTATION SENSORS — C. C. LIU, B. S. HUANG, AND W. H. K. LEE

Richter (1958) wrote, “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, the 50+ near-field strong-motion records from the 1999 Chi-Chi (Taiwan) earthquake indicate that ground motions along the 100-km long rupture are complex and might have included significant rotations.

C. C. Liu began recording earthquakes with triaxial rotation transducers at station HRLT near Hualien on 12 December 2000 using (1) a 12-channel, 19-bit Kinemetrics™ K2™ data logger, (2) an FBA, (3) a PVC-5™ rotation transducer **(**0.2 V/rad/s), and (4) a GyroChip™ rotational transducer (1.43 V/rad/s). Triggered recording was at 200 sps. No useful rotation data were obtained after five years of observation. After obtaining a more sensitive triaxial rotational transducer (eentec/PMD™ model R-1™), C. C. Liu began observations at station HGSD near Cheng-Kung, 01 July 2004. The sensitivity of the R-1™ is 50 V/rad/s, ~35 times higher than the GyroChip™ and 250 times higher than the PVC-5™. Two earthquakes yielded rotation data.

At the Houtzshan station (HGSD) in eastern Taiwan, a six-channel digitizer (Quanterra™ model Q330™) is being used to collect seismic data from two sets of sensors: (1) a three-component Guralp™ CMG-3TD™ broadband velocity seismometer (down hole at 100-m depth) and (2) a triaxial eentec/PMD™ model R-1™ rotational transducer (at the surface). Data are continuously sampled at 100 sps and 24-bit resolution. At 18:50:20.3 UTC, 26 September 2005, an $M_w = 5.1$ earthquake occurred ~29 km south of the station. The epicenter was 23.23° N, 121.40° E, and the focal depth 21 km (CWB Earthquake Report No. 94139). At 17:01:37.2 UTC, 08 January 2006, an $M_w = 4.6$ earthquake occurred ~36 km south of the station. The epicenter was 23.16° N, 121.42° E, and the focal depth 8.7 km (CWB Earthquake Report No. 95002). Preliminary observations of peak rotational velocities from these earthquakes are:

Earthquake	Epicentral Distance (km)	Maximum Rotation (μrad/s)		
Component		EW	NS	Vertical
26 September 2005	29	306	499	1863
09 January 2006	36	98	183	217

We performed some simple data analysis for these data. Preliminary results are described here for the 26 September 2005 earthquake. To integrate the rotation velocity data, we first removed the trend and then high-pass filtered the data (corner frequency 0.2 Hz). The maximum rotation is a few tens of μrad for the east-west and north-south component and about 100 μrad for the vertical component. Since 1 μrad in-plane tilt will introduce about 1 μg to a horizontal accelerometer, our observation, if real, indicates that the effects of angular rotation for an earthquake of $M_w \approx 5$ in the middle-field cannot be ignored in double integration of translational acceleration.

Much work remains to be done. Importantly absent is in-field calibration of the rotational transducer. At present, we are not sure that the measurements are real, and the deployment is not optimal. We plan to deploy another triaxial rotational transducer (PMD™ model R-1™) in a new experiment for which we invite suggestions. The Central Weather Bureau (CWB), which has the seismic monitoring responsibility for the Taiwan region, will make two similar deployments later this year. If rotations prove to be significant, then we will recommend that CWB includes rotational transducers in their purchase of new accelerographs (about 50 to 100 units per year).

7. INTEGRATING GPS, ROTATIONAL, AND INERTIAL SENSORS — K. HUDNUT

While some focus on GPS and others on seismic sensors, it is fair to say that no one sensor can do everything. Earthquake-related motions of interest occur over a very wide range of amplitudes and periods. Technologies evolve quickly, so there is an ongoing need to identify promising new devices and develop more capable earthquake-monitoring systems. An important goal is a single sensor package that measures body and surface waves of teleseisms while also recording near-field strong-motion and permanent displacements. The instrument ought not to clip, even for the largest motions; for this GPS and gyros can be important augmentations to weak motion sensors and accelerometers (e.g., *Boore*, 2003). One can argue that no site will be well suited to all requirements — quiet across the entire spectrum — and that there is complexity associated with upgrading existing seismic or GPS sites for greater capability. However, there is room for innovation and improvement, particularly in the rapidly developing area called "inertial-aided GPS".

In many consumer products, from aircraft avionics to automobile navigation systems, technological developments in GPS and inertial measurement units (IMUs) are progressing rapidly. The need for position and motion data under all conditions is leading to integration of GPS, gyros, and accelerometers (the 6-DOF system and GPS covering each other's weaknesses). Through the combination of these sensors, an inexpensive navigation unit can maintain position information as it passes by objects that obstruct GPS signals, as well as providing higher frequency information for anti-skid, dynamic suspension, and other uses. Even cell phones now commonly contain GPS receivers and soon will add inertial sensors to aid the GPS. These and other markets have led to rapid improvements in performance and to decreased cost.

Simultaneously, algorithms for processing and combining data in real-time from multiple sensors have improved greatly (e.g., *Jekeli*, 2001).

The USGS requires such innovative instrumentation for applications including earthquake early warning and fault slip quantification (for use in rapid finite-fault source modeling and DamageMap). DamageMap is an automatic, preliminary tagging of structures as red, yellow, or green following a large event, based on the rotations, accelerations, and displacements (drift) of the structure. Th DamageMap system is envisioned as a major new data product of USGS for urban areas (e.g., *Safak and Hudnut*, 2006). For DamageMap, testing has shown that current GPS and accelerometer systems are each inadequate, in isolation, for recording complete building motions, motions that translate into structural damage estimates. In particular, torsional and rocking modes of building motions are not uniquely measured by GPS or accelerometers. Therefore, sensitive gyros should be included in building monitoring systems. Additionally, less costly gyros will improve the redundancy and robustness of DamageMap, fault slip, and early-warning instrument packages. Thus, with current ANSS structural instrumentation funding, a development and testing program has been initiated for GPS “Point Positioning” and extended “Real-Time Kinematic” GPS methods at the UCLA Factor building, and gyros will be purchased and tested in the upcoming year. Partly through interactions at this workshop, new ideas went into a new NASA proposal by JPL and USGS, to expand development efforts in support of DamageMap.

8. BROADBAND OBSERVATIONS OF ROTATIONAL MOTIONS — DIRECT VS. ARRAY MEASUREMENTS — H. IGEL, U. SCHREIBER, A. COCHARD, AND J. WASSERMANN

In recent decades ring laser technology for the Earth Sciences was developed primarily to detect small variations of the Earth’s rotation rate. The high resolution of these instruments led to the first, somewhat accidental measurements of earthquake-induced rotational ground motions, first observed at the ring laser site in Christchurch, New Zealand (*Schreiber et al.*, 2006). At teleseismic distances the seismic wave field can be well approximated by plane waves and under this approximation a direct comparison between rotation rate around a vertical axis and transverse acceleration (recorded by a standard seismograph) is possible — translations and rotations are in phase and their amplitudes scale by twice the horizontal phase velocity. Similar relations hold for strains and translations. A systematic study of collocated translations and rotations was carried out with measurements from the 4×4-m ring laser at Wettzell, southeast Germany. These observations showed over a very broad frequency range (1–150 s period) that the waveforms have the expected relation and the amplitude ratios allow a surprisingly accurate estimate of horizontal phase velocities (*Igel et al.*, 2005; *Cochard et al.*, 2006), confirmed by sophisticated numerical modeling of rotations and translations of the observed M8.3, Tokachi-oki event of 25 September 2003. An increasing number of local and distant events are being accumulated in a rotational-translational data base. These observations have led to the design of a purpose-built ring laser system for seismology. One such 2×2-m prototype is now operational at the Piñon Flat Observatory, California.

In principle, the vertical component of rotation rate can be estimated from seismic array data (e.g., *Huang*, 2003), but — due to the lack of resolution of rotation sensors — were never compared to direct measurements of rotations. Therefore, a star-shaped seismic array with an aperture of 3 km was installed around the ring laser at Wettzell for four months recording several large earthquakes. The recorded with the best signal-to-noise ratio (M6.3, Al Hoceima, 24 February 2004) was modeled with synthetic seismograms, and the influence of noise on individual array stations systematically investigated. While the results indicate typical problems that occur when using only a few noisy stations, the final comparison between directly measured rotation rate (ring laser) and array-derived rotations (using all nine stations) show a surprisingly good match (maximum correlation coefficient of 0.94). While direct measurements are more practical, this result indicates that accurate small-scale array measurements can be used to test and validate rotational instruments (the method also can be used for rotations around horizontal axes, as vertical components are expected to be less noisy).

Future studies will focus on the estimation of Love-wave dispersion curves (and other wavefield properties) from collocated measurements of translations and rotations. Eventually these new processing tools will be applied to the events in the data base.

9. PLAN FOR INSTRUMENT TESTING IN THE ANSS PROJECT — C. R. HUTT AND J. R. EVANS

The Albuquerque Seismological Laboratory (ASL) of the U.S. Geological Survey is being updated with new facilities and capabilities to provide a National testing capability for the ANSS (Advanced National Seismic System), providing ANSS with the ability to verify and maintain a wide variety of sensors, including broadband, strong motion, and perhaps rotational.

ASL is located about 15 miles southeast of Albuquerque, just south of Kirtland AFB on the Isleta Indian Reservation. It is a seismologically quiet site with a large vault consisting of two rooms and a cross tunnel between them, ~15 m deep in granite. It also has downhole broadband instruments in granite (~100–200 m) and a set of WWSSN piers on the surface on granite. The underground facilities have excellent long- and short-term temperature stability in addition to noise signatures near the Low Noise Model (*Peterson*, 1993).

ASL has a series of reference instruments, including an STS-1™ in the vault within a super-isolated chamber (a sealed, barometric pressure resistant vessel) and both a Geotech™

KS54000™ and a Guralp™ CMG-3TB™ downhole (GSN site ANMO). ASL has several Quanterra™ Q680™, high-resolution, 24-bit, 12-channel recorders. Personnel experienced in calibration issues are present, as is software for computing self noise, power spectra, and digital filters, and for performing automated calibration analyses. We have a low-distortion oscillator for testing linearity and distortion in recorders, but this device needs replacement. The facility has one standard Lennartz™/Wielandt step table that can be used to calibrate broadband and, perhaps, rotational sensors. ASL has two Russian-made shake tables that may be useful as isolators but would need substantial refurbishment to be useful as shakers and then would probably have too much cross-axis noise for many high-resolution calibration procedures.

Upgrades for proposed ANSS testing include ASL acquisition of: additional low-noise high-resolution recorders (either some of the Q680's™ being retired from GSN or purpose-bought Q330HR's™, both high-resolution Quanterra™ recorders); new reference sensors dedicated to calibration and testing (STS-2™ and Honeywell™/Sundstrand™ QA2000-300™ accelerometers). ASL may also acquire an environmental test chamber (temperature ± humidity ± pressure), Agilent™ precision sampling multimeter (3458A™) and dynamic signal analyzer (35670™). A combination of a high-precision tilt table and a high-precision strong-motion shake table would allow for separation of linear and rotational sensitivities and cross-axis sensitivities of both accelerometers and rotational sensors. Additional upgrades may include EMI/RFI/magnetic field generation and test equipment, an additional, larger Lennartz™/Wielandt step/tilt table, a new low-distortion oscillator, an interferometric rotational reference sensor, a centrifuge, and new, GUI-based software for standardized testing following ANSS guidelines and those of the Guidelines for Seismometer Testing Workshop (May, 2005, Albuquerque). Finally, it may be appropriate to fit the Russian shake tables as isolation tables and possibly as functioning shake tables.

We note that site noise may also be a limiting factor in the measurement of rotations just as it can be for linear-motion sensors, but we know little about what ambient-noise levels to expect, particularly in urban areas. At quiet sites at least, the best instruments can measure the rotation of the Earth, 72 μrad/s (0.004 °/s) as well as the rotational motions associated with large teleseisms. The sensitivity required for strong motion is comparable to the rotational velocity of the Earth.

Finally, we mention that there has been significant work on the difficult method of measuring rotation by comparing adjacent linear sensors on the same pier (e.g., *Huang et al.*, 2003; *Suryanto et al.*, 2006).

10. DISCUSSION AND CONCLUSIONS — W. U. SAVAGE

The focus of our general discussion at the Workshop was the immediate future, the near-term after the Workshop. The following comments and suggestions were made.

We agreed to prepare this summary of our deliberations to inform and to include the larger community in subsequent discussions and developments; W. H. K. Lee and J. R. Evans took the lead. We recommend forming an International Working Group to implement our recommendations, to guide future developments, and to help promote theoretical and experimental contributions to the subject of rotational ground motion.

Our consensus for the immediate future is to evaluate existing data and to collect additional data with both current instruments and with new rotational sensors at sites, in structures, and at near-field free-field sites.

The impact of rotational data on engineering design and analysis needs to be explored further, theoretically and through experiments. Prior to a large-scale deployment of rotational sensors, define the ultimate societal uses and benefits from expanded measurements should be studied. The Working Groups should review the objectives and benefits of making such measurements.

Additional data are needed to evaluate a wide variety of available sensors and to be certain what is being measured. We should take advantage of both US and international testing and deployment capabilities as well as sensors already owned by any of us. Manufacturers should be invited to participate in development and testing of these systems.

GPS is efficacious in static displacements, with both fact and promise of higher frequency observations. GPS has the advantage of being independent of and complementary to inertial systems. We recommend that GPS be incorporated in ANSS guidance material.

Further evaluation of rotational sensors and rotational measurements can be accelerated by bench testing prior to deployment. These laboratory calibrations would help to verify the data from existing installations. Similarly, field calibration methods must be developed.

Simultaneous measurement of acceleration, rotation, and GPS are needed to sort out tilt from the passage of seismic waves, to certify total displacements, and to broaden the bandwidth of the combined data. GPS is best at long periods while the high-frequency data are also needed and will come primarily from inertial sensors —1000-Hz GPS is in development but more testing is needed for confident use of high-frequency GPS instrumentation.

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