Bulletin of the Seismological Society of America, Vol. 99, No. 2B, pp. 1082–1090, May 2009, doi: 10.1785/0120080342

A Glossary for Rotational Seismology

by W. H. K. Lee, compiler

Abstract Some common terms for rotational seismology are compiled from contributions by many authors, including R. DeSalvo, J. R. Evans, E. F. Grekova, C. R. Hutt, H. Igel, C. A. Langston, B. Lantz, E. Majewski, R. Nigbor, J. Pujol, P. Spudich, R. Teisseyre, M. D. Trifunac, R. J. Twiss, and Z. Zembaty. In addition, some glossary terms about earthquakes are excerpted from Aki and Lee (2003), Lee and Wu (2009), and others for the benefit of readers who are not seismologists. It is a first attempt to compile a glossary for rotational seismology (including some terms for continuum mechanics), and it is by no means complete. Several iterations will be required to reach a satisfactory glossary, and this compilation is just a start.

Introduction

Because standard dictionaries often do not include new technical terms without significant delay, this glossary will be a useful addition to *BSSA*'s special issue on rotational seismology and engineering applications (volume 99-2B). Precise definitions are critical for fostering collaboration and reducing misunderstandings among different disciplines. However, this is easier said than done because every scientific field seems to develop its own jargon that is difficult for outsiders to understand. Even within a given field, different authors often define technical terms differently, or a given term has different usage. This article is a first attempt to compile a glossary for rotational seismology (including some terms for continuum mechanics). It is by no means complete, and revisions will be necessary. Because several iterations will be required to reach a satisfactory glossary, see the Data and Resources section.

For terms that cannot be found here, readers may consult, in particular, the tutorials by Peters (2009), Pujol (2009), Teisseyre (2009), and Zembaty (2009a) and the review by Trifunac (2009). Evans and International Working Group on Rotational Seismology (IWGoRS, 2009) describe notation conventions for rotational seismology, while Grekova and Lee (2009) provide suggested readings in continuum mechanics (including elasticity theories) and earthquake seismology.

In addition, some selected glossary terms about earthquakes are excerpted from Aki and Lee (2003), Lee and Wu (2009), and others for the benefit of readers who are not seismologists. The glossary of Aki and Lee (2003) includes over 1200 specialized terms (including abbreviations and acronyms) that the readers may encounter in reading the literature on earthquake and engineering seismology and related fields. For each term, the authors provide a brief definition with a citation of the original paper, if known. In many cases, they also provide references for additional reading. They attempt to give commonly used definitions, but they also warn readers that a term might have different usages in some literature. They avoided introducing mathematical formulas because a companion summary of key formulas in earthquake seismology is given in Ben-Zion (2003).

Glossary Terms

Alphabetization is by glossary term; spaces between words are considered significant. For example, shorter words are alphabetized before longer words that begin with the same spelling. The alphabetization ignores punctuation within the terms. Glossary terms are indicated using **bold** font. Please note that the following glossary terms are compiled based on materials available (either from existing literature or from authors mentioned in Lee *et al.*, 2009). Because different authors may define a term differently, common usage was chosen. Occasional references have been provided.

Accelerograph: An instrument designed to record acceleration, especially for strong ground shaking on ground or in structures, caused by nearby large earthquakes (see, e.g., Trifunac, 2008). An accelerograph is one of the many types of **seismograph**.

Accelerometer: A sensor or transducer that converts acceleration of its base into an analog trace or electrical signal. The acceleration signal is normally obtained from the feedback current necessary to maintain an **inertial sensor** at its mechanical zero point. As in a linear actuator the current is equal to the applied force, this current is proportional to the acceleration within the **bandwidth** limits of the feedback. Outside the band the acceleration can still be extracted from the position signal, normally through a complicated **transfer function**. Accelerometers may be enclosed within a self-contained **accelerograph**, but for studies of structural response, they can be located remotely, with their signals being transmitted (usually by cables) to a central recorder. Unless otherwise specified, an accelerometer measures translational acceleration. However, accelerometers are also sensitive to (and thus their recorded output is affected by) rotational ground motions.

Active fault: A **fault** that has moved sufficiently in recent time that continued **slip** in the future should be expected. The length of time for a movement to be considered recent depends on the application and is often taken as being within the past 11,000 yr. Although faults that move in earthquakes today are active, not all active faults generate earthquakes—some are capable of moving aseismically (see, e.g., Johnston and Linde, 2002). More precise attempts (usually unsatisfactory) have been made to define active faults for legal and regulatory purposes. See Yeats *et al.* (1997, p. 449).

Aftershocks: Earthquakes occurring as a consequence of a larger earthquake (referred to as the **mainshock**) in roughly the same location. Aftershocks generally shows a decrease in the rate of occurrence, discovered by F. Omori in 1894, indicating a stress relaxation process as the rocks are being accommodated to their new postearthquake state. See Utsu (2002a) and equation (7.4) in Ben-Zion (2003).

Apparent velocity: If T (in s) and Δ (in km) denote the **travel time** and **epicentral distance** of a seismic phase arriving at a point on the Earth's surface, then the apparent velocity is defined as $d\Delta/dT$, and its reciprocal is called the apparent **slowness**. We note that seismic velocity should properly be seismic wave speed in many cases because it is often used as a scalar; however, traditional usage is velocity.

Array: See **Seismic array**.

Array analysis: The joint analysis of **seismograms** recorded in a small network of **seismometers** or **seismographs**, which all record with a common time base. **Seismic arrays** allow the estimation of the wavefield's gradient and thus the estimation of various components of the **strain tensor** and the vector of rotational motions.

Attenuation relation: Term used particularly in the fields of strong ground motion and earthquake engineering to describe the decay of peak ground parameters (such as displacement, velocity, or acceleration) as a function of distance from the source or a ruptured **fault**. Similar relations are expected for peak ground rotation parameters.

Axial deformation: A deformation having an axial symmetry, characterized by a lengthening or shortening parallel to a given direction or axis, with a shortening or lengthening perpendicular to the axis that is the same in all directions.

Axial tensor, vector or scalar: A tensor (vector or scalar) object that changes the sign when we change the orientation of a system of coordinates from right-handed to the left-handed or vice versa. They do not depend on the coordinate system itself. For instance, **couple-stress tensor**, **Levi-Civitta tensor**, **torque**, **rotational velocity**, and mixed product of basis vectors of the coordinate system are axial objects. Many axial objects are related to rotation. Axial objects sometimes are called pseudo objects. They cannot be equal to polar objects, which do not depend on the orientation of a coordinate system.

Axis of rotation: An axis parallel to the **rotation vector**. Each rotation can be presented in terms of angle of rotation and axis of rotation. See **rotation tensor**.

Back azimuth: The angle (usually measured from north clockwise) in the horizontal plane describing the direction of wave propagation from the earthquake source to the receiver. The back azimuth of shear energy can be estimated from collocated measurements of translation and rotations.

Bandwidth: A range between high-pass and low-pass cut-off frequencies. In seismology, bandwidth is often meant as the portion of the **frequency-response** amplitude spectrum that is approximately flat; and it is often defined as the frequency band between the upper and lower frequencies, where the amplitude falls 3 dB below its maximum value (called the -3 dB points).

Block rotation: Rotation of crustal blocks in continental areas of diffuse deformation, a very slow process not measured with **inertial sensors**. Block rotation about a vertical axis is common along strike-slip **faults**, but horizontal-axis block rotation commonly occurs in thrust and normal fault systems, and presumably oblique-axis block rotation can occur along oblique-slip faults. See Twiss *et al.* (1993).

Body waves: Waves that propagate through the interior of a body. In seismology, the Earth is usually considered an infinite, linear elastic and homogeneous continuum, and there exist only two types of body waves: (1) dilatational (P) waves, and (2) shear (S) waves.

Classical continuum: An idealized material medium (medium of mass points) that is assumed in classical mechanics (see e.g., Goldstein, 1950). The medium has a continuously distributed mass, and the **stress** is a function of 6 independent strain measures, characterizing purely translational **strain** (volumetric and shear one).

Clip level: The maximum output of a sensor. A hard clip is defined as the maximum voltage output of a sensor regardless of input. A soft clip is defined as the amplitude at which the output begins to distort into a nonlinear representation of the input waveform. For an ideal sensor, the two clip levels are (nearly) the same, with no distortion or nonlinearity before the hard clip is reached.

Coda waves: Waves recorded on a **seismogram** after the passage of **body waves** and **surface waves**. Coda waves are thought to be back-scattered waves due to the Earth's inhomogeneities. Measurements of rotations in the coda wave field may help to separate *P* and *S* energy (see Pham *et al.*, 2009).

Compatibility condition: The ability of two or more fields to fulfill the required mutual relationship. For example, a condition imposed on **strain** field so that it can be expressed by the derivatives of **displacements**.

Constitutive equation: For continuous media, an equation relating basic physical quantities characterizing the state of the material, for instance, the relation between **strains**, temperature, the gradient, and **stresses** of a continuum. Constitutive equations define the behavior of the material, and they are different for different materials. This term was introduced by Walter Noll in 1954.

Corner frequency: In earthquake source studies, a parameter characterizing the **far-field** body-wave displacement spectrum. See Figure 7 and equation (6.1) in Ben-Zion (2003).

Cosserat continuum: A continuum, whose point bodies (infinitesimal particles) possess both translational and rotational degrees of freedom. In the Cosserat continuum, the **stress tensor** is asymmetric, and there exists a **couple-stress tensor**. Apart from the full Cosserat continuum, there exist a Cosserat pseudocontinuum, in which translations and rotations are not independent (in the linear approximation, the **rotation vector** equals **curl** $\mathbf{u}/2$, where $\mathbf{u}$ is the *translational* **displacement**) and a reduced Cosserat continuum, in which rotations and translations are independent, but the **couple-stress tensor** is zero.

Cosserat elasticity: An elasticity theory introduced by the Cosserat brothers (Eugène and François Cosserat, 1909), in which each material point has six degrees of freedom, three of which correspond to translation, as in the classical theory, and the other three to rotation. See Pujol (2009).

Cosserat length: A characteristic length associated with the independent rotational field and defined for the given type of continuum.

Couple-stress tensor: Let $\mathbf{n}$ be the unit vector corresponding to the normal to an elementary material surface. A tensor $\boldsymbol{\mu}$ of second rank is called the couple-stress tensor if $\mathbf{n} \cdot \boldsymbol{\mu}$ gives the **torque** acting upon this surface. The couple-stress tensor plays the same role for **torques** as **stress tensor** does for forces.

Cross-axis sensitivity (rotation and translation): The susceptibility of a sensor to produce an additional signal in response to motion other than that for which the sensor is intended to be sensitive. There are five cross-axis sources for every sensitive axis of an **inertial sensor** (Nigbor *et al.*, 2009). A translational **accelerometer** may be sensitive to both off-axis translational axes and to rotations about any axis (Trifunac and Todorovska, 2001).

Curl: In mathematics, the curl is the vector operator describing the rotation of a vector field. Curl $\mathbf{A}$ or rot $\mathbf{A}$ is equal to $\nabla \times \mathbf{A}$, the vector product of the gradient operator and vector or tensor $\mathbf{A}$. In seismic wave-fields based on linear isotropic elasticity, the curl operator separates out the *S*-wave field because the curl of the *P*-wave field is zero.

dB: See **Decibel**.

Decibel (dB): A logarithmic measure of relative signal power defined as $10\log(P/P_o)$ or $20\log(A/A_o)$, where P_o is the power, and A_o the signal amplitude at some reference level, typically the minimum or maximum signal resolvable by the instrument ($P_o = A_o^2$).

Dirac tensors: The invariant tensors defined in four dimension with use of the numbers: 0, 1, −1, and the imaginary unit i or $-i$. These tensors remain unchanged under any transformation in 4D and help to define the invariant fields. These tensors are symmetric, antisymmetric or asymmetric.

Displacement, rotational: It is often used as a synonym for **rotation vector**. See Evans and IWGoRS (2009).

Displacement, translational: A vector from the point where a material particle initially was located, to its location after an increment of motion. Unless otherwise specified, it means *translational* displacement in seismology. In earthquake geology, displacement is a term used to describe the direction and magnitude of the movement of one side of a **fault** relative to the other. In strong motion seismology and earthquake engineering, it is the time-dependent position of a material particle during earthquake shaking relative its position at rest, typically obtained by doubly integrating the acceleration records. Recovering the long-period part of the displacement history accurately from velocity or acceleration sensors is difficult because of the sensitivity of translation sensors to rotational ground motions (Trifunac and Todorovska, 2001).

Double couple: A force system consisting of two opposing (or orthogonal) couples with the same scalar moment and opposite direction (or sign). Its equivalence to dynamic **fault slip** was first shown by Maruyama (1963) for an isotropic elastic medium, while the force system equivalent to **fault slip** for an anisotropic medium was obtained by Burridge and Knopoff (1964). See Aki and Richards (2002, pp. 42–48).

Drift: For a structural engineer, interstory drift means cord rotation defined by the difference in horizontal offsets between two elevations (floors) of a given structure. To instrumentalists, it may mean a change in sensor offset caused by a fluctuation of temperature or tilting of the base, for example. Finally, to a geologist it means a type of glacial deposit.

Earthquake sequence: A series of earthquakes originating in the same locality. See Utsu (2002a).

Elastic energy (or strain energy): The internal energy contained in an elastic material and caused by its translational and/or rotational **strain**. Elastic energy is a function of materially objective (rotating together with the material and independent of its rigid translations) **strain tensors**. Knowing this function, one may obtain the **constitutive equations** of the elastic material. In the linear material, elastic energy is a quadratic form of the linear **strain tensors** (materially objective in the linear approximation). See **principle of material objectivity**.

Epicentral distance: Distance from a site to the **epicenter** of an earthquake. Epicentral distance is commonly given in kilometers for local earthquakes and in degrees (1° is about 111.2 km) for teleseismic events or **teleseisms**.

Epicenter (earthquake): The point on the Earth's surface immediately above the earthquake-rupture initiation point (the focus or **hypocenter**).

Far field: See **near field and far field**.

Fault: A **fracture** or fracture zone in the Earth along which the two sides have been displaced relative to one another (nearly) parallel to the fracture. The accumulated **displacement** across a fault may range from a fraction of a meter to hundreds of kilometers. The type of fault is specified according to the orientation and sense of **slip** and the inclination (dip) of the fault plane (Yeats *et al.*, 1997).

Fault, active: See **active fault**.

Fault slip: The relative **displacement** of points on opposite sides of a fault, measured on the fault surface. See Aki and Richards (2002, figure 4.13, pp. 101), and figure 13 in Ben-Zion (2003).

Foreshocks: Relatively smaller earthquakes that precede the largest earthquake (which is termed the **mainshock**) in an **earthquake sequence**. Not all mainshocks have foreshocks. See Utsu (2002a).

Fracture: A general term for discontinuities in rock; includes faults, joints, and other breaks. See Section 4 in Ben-Zion (2003).

Fragmentation: Deformations and failures in which the rotational structures in the material undergo microcrushing or crushing under high compressive load.

Frequency response (amplitude and phase): For a typical inertial seismometer (e.g., an **accelerometer** or rotational sensor), the frequency response is the complex **transfer function** relating the input ground motion (translational acceleration or **rotational velocity**) to the output signal (usually voltage). This transfer function is typically measured in terms of amplitude and phase spectra. For analog-output sensors, the measured frequency response is generally modeled in the Laplace domain with a best-fit pole-zero model (Nigbor *et al.*, 2009).

Gain: Used to describe an amplifier or filter gain, not the sensitivity of a sensor.

Gradiometry (seismic wave): The study of the compatibility relationship between a wave field and its spatial and temporal gradients. Spatial gradients of the wave field may be constructed using a dense seismic array of instruments or obtained from **strain** or rotation measurements. The compatibility relationship requires a model for a propagating seismic wave in 1, 2, or 3 dimensions that can be used to determine wave propagation azimuth, wave slowness, change in geometrical spreading, and change in azimuthal radiation pattern. See Langston (2007).

Green's function: In seismology, the vector **displacement** field generated by an impulsive force applied at a point in the Earth. When combined with the source function describing the discontinuities in displacement and traction across an internal surface, a Green's function can represent the seismic displacements caused by earthquake faults and buried explosions. Green's function was first introduced by George Green (1793–1841) as a solution to an inhomogeneous hyperbolic equation for a point source in space and time. See Aki and Richards (2002, pp. 27–28).

Ground motion: Vibration of the ground primarily due to earthquakes. It is measured by a **seismograph** that records acceleration, velocity or displacement. In engineering seismology, it is usually given in terms of a time series (an accelerogram), a response spectrum or Fourier spectrum. See Anderson (2003). If not specified, ground motion generally means translational ground motion. See also **rotational ground motion**.

Gyroscope (Gyro): A device measuring or compensating for rotational motions; commonly used for navigation which contains fast rotating axial-symmetric body. The principle of its action is based on the law of balance of **kinetic moment**. Because this term can mean both a stable platform and a rotational sensor, it should be avoided or defined by the authors.

Hypocenter (focus): Point in the Earth where the rupture originates during an earthquake. Its position is determined from arrival times recorded by **seismographs**. The point on the Earth's surface vertically above the hypocenter is called the **epicenter**.

Identity tensor: A tensor of second rank, possessing the following property: the scalar product (from right or left side) of this tensor and of any vector (tensor) gives the same vector (tensor). The identity tensor is equal to $\mathbf{ii} + \mathbf{jj} + \mathbf{kk}$, where $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ are orthogonal unit vectors, and the sign of the tensor product is omitted.

Inertial sensor: A translational or rotational-motion sensor sensitive to accelerations or velocities, affixed and referenced to some stated frame (generally to the noninertial frame of the rotating, gravitating Earth or a built structure), and generally measuring one of the six degrees of freedom of whole-body motion. Inertial sensors respond to accelerations but, because of the inductive readout method, often output a signal proportional to ground-motion velocity. A well-built inertial sensor has a bob moving freely in only one degree of freedom and is sensitive to accelerations in that degree of freedom. Because of hinging effects, very often inertial sensors intrinsically mix the linear acceleration and angular acceleration. To make sure that this does or does not happen, one has to examine the hinging mechanism of the sensor.

Inertia tensor: See **tensor of inertia**.

Intensity (earthquake): Rating of the effects of earthquake shaking at a specified location. Historically, intensity was a qualitative rating assigned by observers using a descriptive scale with grades given in Roman numerals I to XII for the commonly used Modified Mercalli scale. Intensity is now also quantitatively estimated using ground-motion measurements; such quantitative intensity measurement is called instrumental intensity to distinguish it from the qualitative seismic intensity. See Musson (2002).

International System of Units (SI): An internationally agreed-upon system of units, abbreviated SI for Le Système International d'Unités and recommended for use in all scientific and technical fields (National Bureau of Standards, 1981). The international system of units comprises seven base units: (1) length in meters (m), (2) mass in kilograms (kg), (3) time in seconds (s), (4) electric current in amperes (A), (5) thermodynamic temperature in kelvins (K), (6) amount of substance in moles (mol), and (7) luminous intensity in candela (cd). SI also has a number of derived and supplementary units including: (1) frequency in hertz (Hz), (2) force in newtons (N), (3) pressure or stress in pascals (Pa), (4) energy, work, or quantity of heat in joules (J), (5) power in watts (W), (6) electric charge in coulombs (C), and (7) electric potential in volts (V). See Lide (2002) for a detailed review of SI and conversion factors.

Kinetic moment: Rotational analogue of impulse. It is equal to the sum of moment of momentum and of proper kinetic moment (sometimes called dynamic spin). Kinetic moment of a body is calculated relatively to a fixed point in a system of reference and depends upon the chosen pole (another point, fixed in the body). For a rigid body, if its center of mass is taken as a pole, and the origin of an inertial system of reference is taken as a fixed point, the kinetic moment is equal to $\mathbf{r} \times \mathbf{p} + \mathbf{J}\boldsymbol{\omega}$, where $\mathbf{r}$ is the radius-vector of the center of mass, $\mathbf{p}$ is the momentum (impulse) of the body, $\mathbf{J}$ is the **tensor of inertia** calculated relative to the center of mass, and $\boldsymbol{\omega}$ is the angular velocity of the body. The time derivative of the kinetic moment represents the inertial term in the law of balance of **torque** (the **torques** must be calculated relative to the same fixed point). In **micropolar** theories, the existence of proper kinetic moment of particles and resistance of the medium to their rotation causes the existence of **rotational waves**.

Lamé constants: Two physical constants that linearly relate **stress** to **strain** in a homogeneous and isotropic elastic solid in the classical elasticity theory.

Levi-Civitta tensor: A tensor that is equal to $-\mathbf{I} \times \mathbf{I}$, where $\mathbf{I}$ is the **identity tensor**. Its components are known as Ricci symbols. It appears in expressions including vector products.

Magnitude (earthquake): A quantity intended to measure the size of an earthquake independent of the place of observation. Richter magnitude (M_L) was originally defined in 1935 as the logarithm of the maximum amplitude (in millimeters) of seismic waves in a **seismogram** written by a Wood–Anderson seismograph at a distance of 100 km from the **epicenter**. Empirical tables were constructed to reduce measurements to this standard distance; the zero of the scale was fixed arbitrarily to fit the smallest earthquakes then recorded. Many types of magnitudes were subsequently introduced, such as body-wave magnitude (m_b), surface-wave magnitude (M_S), and moment magnitude (M_w). According to Hagiwara (1964), earthquakes may be classified by magnitude (M) as *major* if $M \geq 7$, as *moderate* if M ranges from 5 to 7, as *small* if M ranges from 3 to 5, as *micro* if M ranges from 1 to 3, and as *ultra-micro* if $M < 1$. Later usages include: as *nano* if $M < 0$, as *great* if $M \geq 8$ (or sometimes $7\frac{3}{4}$), and as *mega* if $M \geq 9$. See Utsu (2002b) for a discussion of magnitude scales and their relationships.

Mainshock: The largest or principal shock in an **earthquake sequence**.

Micromorphic (continuum): A continuum in which each material point is equipped with a kind of microstructure described in a local system of coordinates, whereby each of its points comprises a microvolume with microdisplacements, microrotations, microdeformations, and micro-inertia tensor (see **tensor of inertia**). A number of material constants permit the description and solution of many complicated problems in which materials display nonclassical responses to applied external loads (Eringen, 1999).

Micropolar (continuum): A continuum defined similarly to the **micromorphic continuum**, but for which only microdisplacements and microrotations of the microelements are permitted, but not microdeformations, that is, the microelements are taken to be rigid. Each material point is equipped with three degrees of freedom for rigid rotation in addition to the classical translational degrees of freedom (Eringen, 1999). A synonym for the **Cosserat continuum** (Pujol, 2009).

Moment of inertia: A component of **tensor of inertia J**, calculated as $\mathbf{k} \cdot \mathbf{J} \cdot \mathbf{k}$, is called moment of inertia relative to the axis with unit vector $\mathbf{k}$.

Near field and far field: Locations more than about ten source dimensions from the source are in the *far field*, and those within one to several dimensions are in the *near field*. There is inadequate consensus on these terms at present, although many authors argue that the case is clear enough. They state that source terms that decay, for example, as r^{-1} are far-field terms, while those scaling as r^{-2} are near-field terms. More simply, those a few wavelengths from the source are considered far field, and those within a fraction of a wavelength are near field with intermediate distances requiring examination of the effects of individual terms (Aki and Richards, 1980, pp. 88 and equations 4.23 and 4.35). Under the present circumstances, it is best for all authors to specify their meaning.

Noise level (of an instrument): See **self noise**.

***P* wave:** Compressional elastic waves are called *P* waves in seismology, with *P* standing for primary (*Primae* in Latin). In a homogeneous, isotropic, linear elastic body, the velocity of *P* waves is equal to $\sqrt{[(\kappa + 4/3\mu)/\rho]}$, where κ, μ, and ρ are bulk modulus, rigidity, and density, respectively. The particle **displacement** associated with *P* waves (for a classical linear elastic continuum in an isotropic **far field**) is parallel to the direction of wave propagation. For this reason, *P* waves are sometimes called longitudinal waves. See Aki and Richards (2002, pp. 122). In isotropic media, the **curl** of the *P*-wave field (i.e., rotational motion) is zero. However, this is not so in general, for instance, for anisotropic or **Cosserat continua**.

Pendulum: In relation to design of **inertial sensors**, either (1) a mass moving strictly in a translational manner (Fig. 1, bottom) as in most simple geophones; or (2) a mass attached by a rigid arm to a pivot axis orthogonal to that arm and to the active axis of the sensor as in many **accelerometers** and broadband velocity sensors (Fig. 1, top). A mass moving on a simple cantilever, as in many micro-electro-mechanical

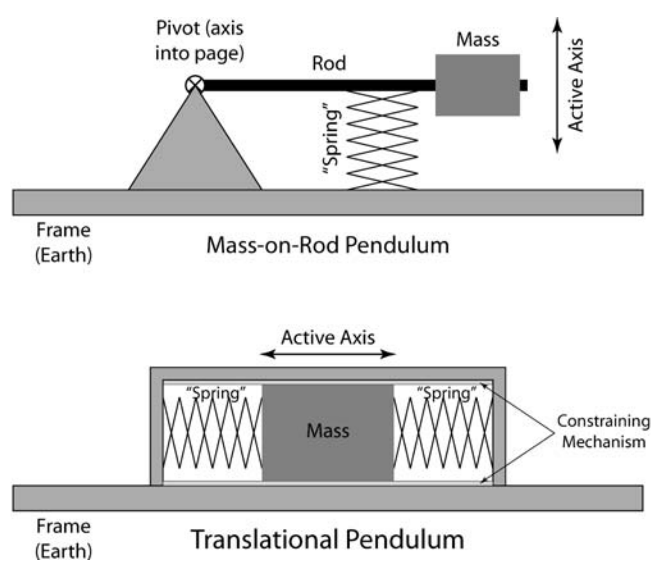

Figure 1. Schematic diagrams of a mass-on-rod pendulum (top) and a translational pendulum (bottom). The mass-on-rod pendulum moves in a circular arc about its pivot, here pointing into the page, and is parallel to the putative active axis only while at zero deflection. The translational pendulum is constrained by its suspension to move only in the active-axis direction. Spring is shorthand for all mechanical and force feedback restoring forces in combination.

systems (MEMS) devices, is equivalent to (2), whereas the restoration of classical pendulums derives solely from the gravitational force with springs either acting alone or in conjunction with gravity, providing the restoring force in common seismic pendulums. Nearly all pendulums are purposely damped by some means. The intended direction of (infinitesimal) mass motion relative to the instrument frame (thus the ground) is the *active axis* of the pendulum. Most seismic sensors are based on one or the other of these forms of constrained pendulums, although a few are based on magneto-hydrodynamic and other phenomena.

Pendulum, gravitational type: A classic instrument first studied by Galileo and Newton, a structure without springs in which the line between the rotation axis (in the original, a fixed point) and the center of mass oscillates with dampened simple harmonic motion (in the linear approximation for plane motion) about the direction of the local gravitational field of the Earth. Its equilibrium orientation is the plumb line.

Pendulum, mass-on-rod: A pendulum (Fig. 1, top) that rotates about some axis with the mass on the other end of a rigid rod or else a mass at the end of a stiff cantilever spring (the pendulum of many modern force-balance **accelerometers** and broadband seismometers). Because the rod can rotate away from the normal to the active and axes, this design may be affected by translational accelerations along the axis of the rod while it is offset, although such offsets are minimized in force-feedback and stiff (e.g., MEMS) designs. Mass-on-rod pendulums also are directly affected by **rotational accelerations** about the pivot axis.

Pendulum, translational: A mass-on-spring pendulum (Fig. 1, bottom) where the mass moves only along a linear translational path relative to the sensor's case (the mass and multiple constraining cantilever springs of a common geophone or a few MEMS devices in which multiple cantilevers and careful design obviate any effects of rotation). This design has minimum sensitivity to off-axis translational and **rotational accelerations** but is sensitive to Coriolis forces.

Point rotation: Rotational motions nominally of an infinitesimal point, generally measured by a dedicated **rotational sensor** either deployed on a small rigid pad or attached to some point in a structure.

Point seismic array: Colocated, inertial three-component seismograph, rotational sensor, and/or strain meter that can be used to perform seismic wave gradiometry. Although wave measurements are taken at a single observation point on the Earth, wave **gradiometry** produces estimates of wave parameters, such as horizontal slowness and azimuth, similar to large-aperture arrays of seismographs constructed for beam forming or frequency-wave-number analysis.

Point string deformation: The point deformation with the simultaneous extension and contraction perpendicular to each other and of the equal values.

Polar tensor (vector or scalar): An object which does not depend on the orientation of a co-ordinate system. Examples of polar objects: **stress tensor**, force, translational velocity, and mass. Polar objects cannot be equal to axial objects and are often related to the **translational motions**.

Power spectral density (PSD): A functional method for specifying a signal in the frequency domain, related to the power of the signal as a function of frequency. For example, the distribution of Earth motions at different frequencies. For discretely sampled data of finite duration, there are several similar methods for estimating the PSD. These methods typically involve the time averaged value of the absolute value squared of the Fourier transform of the time record, corrected by the **transfer function** of the instrument. These calibrated frequency domain components are typically displayed on a log-log plot. The abscissa may be either in terms of frequency or period, and the ordinate is usually specified in dB.

Principal axes: In general, the principal axes are the eigenvectors of a symmetric tensor. They can, for example, characterize the orientation of the **stress** and the **strain** at a point and need not be tied to the geographic co-ordinate system. As proposed by Penzien and Watabe (1975), they are system of Cartesian coordinates on the ground surface for which three seismic signals, viewed as stochastic processes along respective axes $u_x(t)$, $u_y(t)$, and $u_z(t)$, are least correlated. The system of principal axes is expected to be situated in such a way that one of the three axes is perpendicular to ground surface and one is directed toward the **epicenter** (figure 1, Zembaty, 2009a).

Principle of material objectivity (material frame indifference): The constitutive laws governing the internal interactions between the parts of a physical system should not depend upon the external frame of reference used to describe them. For continuous media, this implies that **stress** and **couple-stress tensors** have to rotate together with the material when subjected to a rigid motion and not depend upon its translational part.

Pseudovector: A quantity that behaves as a vector as long as the handedness of the co-ordinate system (i.e., it is right or left handed) remains unchanged. Changing the handedness changes the direction of the quantity. For this reason, vectors cannot be equated to pseudovectors (see Pujol (2009) for an example). An example of pseudovector is the vector product of two polar vectors. Pseudovectors are also known as axial vectors. See **axial tensor, vector, or scalar**.

Ring laser: An instrument that detects the Sagnac beat frequency of two counter-propagating light beams (see **Sagnac effect**). This beat frequency is directly proportional to the **rotation rate** around the surface normal to the ring-laser system.

Rocking: Rotation about horizontal axis or, as often used by engineers, of a whole structure about a horizontal axis. The term rocking should be used only with full, graphically supported definitions inclusive of frequency band according to Evans and IWGoRS (2009).

Rotation angles (rotational motions): The **rotational displacements** indicated θ_X, θ_Y, and θ_Z in figure 1 of Evans and IWGoRS (2009). Terms like X rotation may be used as shorthand though rotation angle θ_X is more formal. Authors are cautioned that the term, **rotational displacement**, has other meanings and should be defined (e.g., P. Spudich, personal comm., 2008; B. R. Julian, personal comm., 2008). Rotation angles are generally given in units of radians. For example, $\theta_X$is the right-handed rotation angle about the X axis. The **SI** abbreviation for radians is rad, for seconds it is s (not sec), thus units in the style mrad/s are preferred to milli-radians/sec. In continuum mechanics, rotation angle and **axis of rotation** define the **rotation tensor**.

Rotation, average (volume or area): Rotation of an extended region or some extended portion of a structure, often inferred from measured **translational motions** at the periphery.

Rotation, block: See **block rotation**.

Rotation, point: See **point rotation**.

Rotation rate: In the linear approximation, the first-time derivative of **rotational displacement**. Angular velocity or **rotational velocity** is an acceptable synonym for rotation rate. In the nonlinear theory, it is defined via **rotation tensor**.

Rotation tensor: A mathematical object that may refer to many kinds of physical rotations, in particular to the rotational part in the polar decomposition of the gradient of the radius vector in the **classical continuum**, to the (independent) rotation of a point body in the **Cosserat continuum**, or to any other rotation, for instance, to the rotation of a rigid body, of a coordinate system, etc. In the following discussion, it is an orthogonal tensor characterizing rotation of vectors and rigid bodies. If **d** is a vector subjected to rotation, the rotated vector equals $\mathbf{d}' = \mathbf{P}\mathbf{d}$, where **P** is the rotation tensor, $\det \mathbf{P} = 1$. Each rotation tensor may be represented via **rotation angle** and **axis of rotation** (theorem by Leonhard Euler), $\mathbf{P} = (1 - \cos\theta)\mathbf{nn} + \cos\theta\mathbf{I} + \sin\theta\mathbf{I} \times \mathbf{n}$, where **I** is the identity tensor ($\mathbf{Id} = \mathbf{d}$ for each vector **d**), **n** is the **axis of rotation**. For linear motions, **P** is approximately equal to $\mathbf{I} + \theta\mathbf{n} \times \mathbf{I}$. The rotation tensor is also called the turn tensor in the literature. In **micropolar** media, one has to distinguish the rotation of the background continuum, related to the gradient of translational deformation, and the proper rotation of particles. In linear elasticity and seismology the rotation tensor refers to a different object, and the expression for **P** is simplified by the infinitesimal nature of the **rotation angle**, not the translational motion. See Pujol (2009).

Rotation vector: In continuum mechanics, it is the vector $\theta\mathbf{n}$, where θ is the **rotation angle**, and $\mathbf{n}$ is the unit vector along the **axis of rotation**. It corresponds to the **rotation tensor**, $\mathbf{P} = (1 - \cos\theta)\mathbf{nn} + \cos\theta\mathbf{I} + \sin\theta\mathbf{I} \times \mathbf{n}$.

Rotational acceleration: The time derivative of the **rotational velocity**. In the linear approximation, the second time derivative of a **rotational displacement**. Angular acceleration is often used for rotational acceleration.

Rotational displacement: It is often used as a synonym for **rotation vector**. See Evans and IWGoRS (2009). See also **rotation angles**.

Rotational ground motion: The rotational components of **ground motion**. In classical elasticity and assuming infinitesimal deformations, $\boldsymbol{\omega} = \frac{1}{2}(\nabla \times \mathbf{u}(\mathbf{x}))$, where $\boldsymbol{\omega}$ is a **pseudovector** and represents the angle of rigid rotation generated by the disturbance, $\nabla\times$ is the **curl** operator, and $\mathbf{u}$ is the **displacement** of a point at $\mathbf{x}$. See Aki and Richards (2002, pp. 13), and Cochard *et al.* (2006, pp. 394).

Rotational-motion sensors: A rotational sensor (often generically known as a **gyroscope** or inertial angular sensor) that can measure angular displacement, velocity (often called rate), acceleration, or jerk (rate of change of acceleration). Such sensors may or may not have response down to zero frequency. This term is widely used in aerospace, automotive, and mechanical engineering. In earthquake studies, the term **rotational seismometer** is preferred.

Rotational response spectrum: A plot of maxima of rotational responses of oscillators as a function of their natural periods (or frequencies). It is generalized from the conventional, translational response spectrum (see, e.g., Kalkan and Graizer, 2007; Zembaty, 2009b).

Rotational seismic solitons: A finite number of rotational pulses excited in the earthquake source; they can have a form of **spin** or **twist** solitons (see Majewski, 2006, 2008).

Rotational seismic waves: They are **rotational waves** excited in the earthquake source as a result of rotational vibrations, including rotational longitudinal waves, and rotational transverse waves. See Majewski (2006).

Rotational seismology: An emerging field of inquiry for studying all aspects of **rotational ground motions** induced by earthquakes, explosions, and ambient vibrations.

Rotational seismometer: A **rotational sensor** specifically designed as a **seismometer** for measuring rotation motions associated with seismic waves from earthquakes or explosions. A commercial example of a rotational seismometer is the model R-1 made by eentec (see Data and Resources section).

Rotational sensors: See **rotational-motion sensors**.

Rotational velocity: The first-time derivative of **rotation angles**; an acceptable synonym for **rotation rate** and **spin**, if the latter term refers to the antisymmetric part of the velocity gradient tensor. In nonlinear case, it is defined as vector $\boldsymbol{\omega}$ satisfying the equation $d\mathbf{P}/dt = \boldsymbol{\omega} \times \mathbf{P}$, where $\mathbf{P}$ is the **rotation tensor**, t is time.

Rotational waves: Motions of a continuum, where the rotational dynamics is present. Term sometimes used in connection with **micropolar** media to describe rotation waves in a medium in which each point has degrees of freedom related to rotational motions. It is important not to confuse rotational waves with **rotational ground motions** appearing as the **curl** of the wavefield in linear elasticity with a symmetric **stress tensor** (e.g., ***S* waves**).

***S* wave:** Elastic waves producing shear and no volume change are called *S* waves (*S* standing for Latin *Secundae* or secondary). In a classical homogeneous, isotropic, linear elastic body, the velocity of *S*-waves is equal to $\sqrt{(\mu/\rho)}$, where μ and ρ are the rigidity and density, respectively. For a classical isotropic linear elastic media (in an isotropic **far field**), the particle displacement associated with *S*-waves is perpendicular to the direction of wave propagation, so they are sometimes called transverse waves. See Aki and Richards (2002, pp. 122) and Ben-Zion (2003, equation 1.9b). In an isotropic full space, only *S* waves generate rotational motions. For isotropic **Cosserat continua**, *S* wave becomes a mixed shear-rotational wave. In anisotropic media, it couples also with ***P* wave**.

Sagnac effect (Sagnac interference): An interferometric phenomenon encountered in rotating systems as in **ring-laser** and fiber-optic **gyroscopes**. In seismology, these phenomena are most often described and measured in the frequency domain (a beat frequency) rather than in the spatial domain (interference fringes).

Seismic array: An array of seismometers distributed over the surface or volume (with bore-hole sites) of the Earth whose outputs are transmitted to and recorded at a central station. See also **point seismic array**.

Seismic spin solitons: A kind of **rotational seismic waves** in a form of a finite number of spin pulses excited in the earthquake source as a result of spin vibrations. See Majewski (2006, 2008).

Seismic tomography: The process of recovering information on the Earth's three-dimensional seismic velocity structure from observations of **travel times** and/or seismic waveforms. It can be shown that collocated measurements of the ratio of rotations (or **strain**) and corresponding components of **translational motions** contain information on the subsurface velocity structure (e.g., Fichtner and Igel, 2009).

Seismic twist solitons: A kind or **rotational seismic waves** in a form of a finite number of twist pulses excited in the earthquake source as a result of twist vibrations. See Majewski (2006; 2008).

Seismogeodetic method: A term introduced by Bodin *et al.* (1997) to describe the method used by Spudich *et al.* (1995) to infer the spatially uniform strain and rigid-body rotation as functions of time that best fit ground translations recorded by a **seismic array**, essentially doing a geodetic inversion at every instant of time. The seismogeodetic method uses a generalized inversion of the data and accounts for the data covariances.

Seismogram: Record of **ground motion** made by a **seismograph**.

Seismograph: Instrument that detects and records **ground motion** (and vibrations due to earthquakes) along with timing information. It consists of a **seismometer** (or sensor), a precise time source, and a recording device.

Seismometer: A sensor that responds to point ground or structural acceleration and produces a signal that can be recorded in terms of displacement, velocity, or acceleration. Until recently seismometer meant only a translational sensor that senses one of the three components of **translational motions**. More recently, a **rotational seismometer** may also be deployed to complement such translational seismometers and allow for measuring all six components of point motion.

Self noise: The frequency-dependent electronic and mechanical noise at the output of a **seismometer** or recorder in the presence of zero input signal. Self noise is the portion of a **seismometer** or **seismograph** output signal not related to input motions (Lee *et al.*, 1982). Evans *et al.* (2009) provide a more detailed definition and methods for measurement and analysis of **accelerometer** self noise. The self noise of an **accelerometer** is typically measured at a seismically quiet site using a single sensor (if sensor noise is higher than seismic noise) or two or three sensors (if the sensors' self noise is below seismic noise). Weak-motion seismometers require two or three-sensor methods to isolate self noise from ambient Earth noise.

Sensitivity: The scalar value used to convert the measured output signal (usually in voltage) to motion units. It is equivalent to the sensitivity scale factor of a normalized Laplace **transfer function**. For a sensor with a flat **frequency response**, the sensitivity corresponds to some midfrequency level of the frequency-response amplitude for a specified frequency, often 1 Hz. Sensitivity has units of volts per input unit (e.g., volt per g for **accelerometers**, or volt per rad/sfor rotational sensors).

Sensitivity kernels: Term often used in connection with the seismic tomography problem. Sensitivity kernels are functions of space quantifying the influence of points in space on observable quantities (arrival times, translational or rotational amplitudes, or combinations of these).

SI: An acronym for Système International d'Unités. See **International System of Units**.

Slip: See **fault slip**.

Slowness: The inverse of velocity, often annotated as scalar s (related to vector **k**, the wave-number vector).

Solitons (or solitary waves): A special kind of localized waves that propagate undistorted in shape. They are essentially nonlinear waves. They can be treated as nondispersive localized packets of energy moving with uniform velocity. Solitons are exact solutions of nonlinear wave equations. See Majewski (2006).

Spectral ratio: The ratio of two amplitude (or power) spectra. In classical linear theory, the ratio between transverse acceleration and **rotation rate** for time windows containing **surface waves** is proportional to the dispersion curves, the frequency-dependent local phase velocities (see Lee and Trifunac, 2009).

Spin: A term that is unclear at present, at least in English, but widely used in the European literature. In physics, it is used for **rotational velocity**. In continuum mechanics, it is the antisymmetric part of the velocity gradient tensor and may be also used for the proper **kinetic moment** of particles. In quantum physics, it is an intrinsic property of the elementary particles. When publishing in English, this term either should not be used or should be well defined by the authors.

Spinor: A geometrical object similar to a tensor that describes a rotational state. Some authors believe that spinors are more fundamental objects than tensors. See Majewski (2008).

Strain (strain tensor): Change in shape and/or size of an infinitesimal material element per unit length or volume. In elasticity theory, the strain is generally referred to a reference state in which the material has zero stresses (natural configuration). For small deformation, the complete description of strain at a point in three dimensions requires the specification of the extensions (change in length/length) in the directions of each of the reference axes and the change in the angle between lines, which were parallel to each pair of reference axes in the reference state. Diagonal components of the strain tensor describe normalized changes in length; off-diagonal components describe changes in angle.

Stress (stress tensor): Force, resolved into normal and tangential components, exerted per unit area on an infinitesimal surface. A complete description of stress (i.e., stress tensor) at a point in a 3D reference frame requires the specification of the three components of stress on each of three surface elements orthogonal to one of the reference axes. Hence, there are nine components of stress. For classical continua, consisting of point masses, the balance of **torque** implies the symmetry of the stress tensor and therefore reduces the stress description to six independent components. In **micropolar** theory, stresses may be nonsymmetric. Stress is distinguished from traction, which describes a force per unit area acting on any specified surface.

Surface waves: Waves that propagate along the surface of a body. In layered half space, there are two surface waves, Rayleigh and Love (both named after their discoverers, Lord Rayleigh, and A. E. H. Love, respectively). Both Love and Rayleigh waves generate **rotational ground motions**.

Swarm (of earthquakes): A sequence of earthquakes occurring closely clustered in space and time with no clear **main shock**.

Tectonic rotational solitons: Rotational (spin or twist) **solitons** generated by past earthquakes and propagating slowly (about 1 km/day) along a fractured earthquake **fault** and triggering new earthquakes. See Majewski (2006).

Tectonics: The branch of Earth Science that deals with the structure, evolution, relative motion, and deformation of the outer part of the Earth or the lithosphere on a regional to global scale for time scales ranging from very short up to thousands of millions of years (technically, active tectonics refers to tectonic movements that occur on a time scale of up to thousands of years, and neotectonics refers to tectonic movements on a scale of thousands of years to a few million years). The lithosphere includes the Earth's crust and part of the Earth's upper mantle and averages about 100 km in thickness. Plate tectonics is a theory of global tectonics in which the Earth's lithosphere is divided into a number of spherical plates that undergo dominantly rigid-body translation on the sphere. The relative motions of these plates cause earthquakes and deformation along the plate boundaries and in adjacent regions.

Teleseism: An earthquake at an **epicentral distance** larger than about 20° or 2000 km from the place of observation.

Tensor of inertia: Rotational analogue of mass. This is a symmetric (maximum six components), positively defined tensor that describes the distribution of mass in a rigid body. This tensor rotates together with the body if it moves, and its eigenvalues are called principal moments of inertia (diagonal components of the symmetric tensor). The tensor of inertia multiplied by the vector of **rotational velocity** is a part of the **kinetic moment**. In **micropolar** theories, inertial characteristics of each particle are density and density of tensor of inertia.

Tilt: A term that to some authors seems to mean long-period rotations about a horizontal axis, to others only static rotations, and to yet others rotations at any frequency. The term tilt should be used only with full, graphically supported definitions inclusive of frequency band, according to Evans and IWGoRS (2009).

Tiltmeter: An instrument designed to measure changes in the direction of (or angle to) the local surface normal. **Tilt** at the Earth's surface is equivalent to the horizontal components of rotation. Mechanically based tiltmeters are in general sensitive to horizontal acceleration according to the separation distance of axis and center of mass. At long periods (Earth's eigenmodes, tides) the horizontal components of **ground motion** recorded by **inertial sensors** may contain substantial contributions due to **tilts**.

Torque: Torque is a cause of the rotational motion of a body (i.e., rotational analogue of force). Torque is equal to the moment of force plus proper torque, which does not depend upon forces. Moment of force is the tendency of a force applied to an object to cause the object to rotate about a given point, and this tendency is expressed by the equation, $\mathbf{N} = \mathbf{r} \times \mathbf{F}$, where **N** is the torque, **r** is the position vector from the origin to the point of application of force, and **F** is the total force acting on the point (Morris, 1992, pp. 2235; Goldstein, 1950, pp. 2). Independent (proper) torques were introduced for the first time by Leonhard Euler in the theory of rods. In **micropolar** theories, each elementary material volume is subjected to forces as well as to independent torques (which may be caused, for instance, by moment of forces on the next micro level or may have another origin).

Torque waves: Knopoff and Chen (2009) showed that frictional torques accumulated in a fault zone of finite width are relaxed through the development of **torque** or rotation waves radiated as shear waves during the fracture process near the tips of advancing cracks.

Torsion: A term that seems to mean rotations or **strains** about the vertical axis of a structure (but with the same variance as **tilt** in the implied frequency band). The term torsion should be used only with full, graphically supported definitions inclusive of frequency band, according to Evans and IWGoRS (2009).

Torsion balance: Also called a torsion pendulum, an instrument used to measure small forces. Invented by John Michell, it was used by Coulomb to establish the electrostatic force law and by Henry Cavendish to measure the Earth's density. The Cavendish balance is also used to measure the universal gravitational (fundamental) constant, G. The restoring **torque** that acts on the boom of the balance depends upon the shear modulus of the fiber that supports it. An instrument similar to the classic torsion balance is the Wood–Anderson seismometer used to define the Richter scale.

Transfer function: Laplace or Fourier transform of the impulse response of a linear system (filter, sensor, etc.), which is equivalent to the Laplace or Fourier transform of a broadband output signal divided by that of the input signal. In seismology and earthquake engineering, **frequency response** is typically used as a synonym for transfer function; the modulus of the complex function is usually considered while phase information is ignored.

Translational motions: The in-line **displacements** indicated u_X, u_Y, and u_Z in figure 1 of Evans and IWGoRS (2009). Translational is strongly preferred over linear because the latter conflicts with matters of linearity versus nonlinearity in soils, instruments, mathematics, and so forth. If displacements, velocities, and accelerations are not otherwise qualified, they are assumed to refer to translational motions.

Travel time: High-frequency seismic waves in a smoothly varying medium propagate like a particle approximately without dispersion along a ray. The travel time is the time taken for the seismic waves to propagate from one point to another along the ray.

Twist: A term that is used to describe a shear deformation caused by torsional moment. It is widely used in the European literature.

Twistor: A geometrical object that consists of a pair of **spinor** fields. Twistors describe rotational states. See Majewski (2008).

Velocity, apparent: See **Apparent velocity**.

Data and Resources

Because several iterations will be required to reach a satisfactory glossary, readers may visit the Web site of the International Working Group on Rotational Seismology (http://www.rotational-seismology.org/, last accessed February 2009) for updates. A commercial example of a rotational seismometer is the model R-1 made by eentec (http://www.eentec.com/, last accessed February 2009).

Acknowledgments

I wish to thank R. DeSalvo, J. R. Evans, E. F. Grekova, C. R. Hutt, H. Igel, C. A. Langston, B. Lantz, E. Majewski, A. J. Michael, R. Nigbor, F. Pollitz, J. Pujol, P. Spudich, R. Teisseyre, M. Todorovska, M. D. Trifunac, R. J. Twiss, and Z. Zembaty for their contributions of glossary terms, and/or for their suggestions and comments on the manuscript draft. We thank Ray Hardesty for his excellent technical editing of this manuscript. Not all the suggested glossary terms are included due to space limitation.

References

Aki, K., and W. H. K. Lee (2003). Glossary of interest to earthquake and engineering seismologists, in *International Handbook of Earthquake and Engineering Seismology, Part B*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 1793–1856.

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

Aki, K., and P. G. Richards (2002). *Quantitative Seismology*, Second Ed., University Science Books, Sausalito, California.

Anderson, J. G. (2003). Strong-motion seismology, in *International Handbook of Earthquake and Engineering Seismology, Part B*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 937–965.

Ben-Zion, Y. (2003). Key formulas in earthquake seismology, in *International Handbook of Earthquake and Engineering Seismology, Part B*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 1857–1875.

Bodin, P., J. Gomberg, S. K. Singh, and M. Santoyo (1997). Dynamic deformations of shallow sediments in the Valley of Mexico, Part I: Three-dimensional strains and rotations recorded on a seismic array, *Bull. Seismol. Soc. Am.* **87,** 528–539.

Burridge, R., and L. Knopoff (1964). Body force equivalents for seismic dislocations, *Bull. Seismol. Soc. Am.* **54,** 1875–1888.

Cochard, A., H. Igel, B. Schuberth, W. Suryanto, A. Velikoseltsev, U. Schreiber, J. Wassermann, F. Scherbaum, and D. Vollmer (2006). Rotational motions in seismology: Theory, observation, simulation, in *Earthquake Source Asymmetry, Structural Media and Rotation Effects*, R. Teisseyre, M. Takeo, and E. Majewski (Editors), Springer, Heidelberg, 391–411.

Cosserat, E., and F. Cosserat (1909). *Theorie des corps deformables*, Hermann, Paris (available from the Cornell University Library Digital Collections).

Eringen, A. (1999). *Microcontinuum Field Theories. I. Foundation and Solids*, Springer, Berlin.

Evans, J. R., and International Working Group on Rotational Seismology (IWGoRS) (2009). Suggested notation conventions for rotational seismology, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1073–1075.

Evans, J. R., C. R. Hutt, J. M. Steim, and R. L. Nigbor (2009). Method for Calculating Self-Noise Spectra and Operating Range for Seismographic Sensors and Data Acquisition Units, *Seism. Res. Lett.* (in press).

Fichtner, A., and H. Igel (2009). Sensitivity densities for rotational ground-motion measurements, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1302–1314.

Goldstein, H. (1950). *Classical Mechanics*, Addison-Wesley, Cambridge.

Grekova, E. F., and W. H. K. Lee (Compilers) (2009). Suggested readings in continuum mechanics and earthquake seismology, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1076–1081.

Hagiwara, T. (1964). Brief description of the project proposed by the earthquake prediction research group of Japan, in *Proc. U.S.-Japan Conf. Res. Relat. Earthquake Prediction Problems*, 10–12.

Johnston, R. J. S., and A. T. Linde (2002). Implications of crustal strain during conventional, slow, and silent earthquakes, in *International Handbook of Earthquake and Engineering Seismology, Part A*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 589–605.

Kalkan, E., and V. Graizer (2007). Coupled tilt and translational ground motion response spectra, *J. Struct. Eng. ASCE* **133,** 609–619.

Knopoff, L., and Y.-T. Chen (2009). Single-couple component of the far-field radiation from dynamical fractures, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1091–1102.

Langston, C. A. (2007). Wave gradiometry in two dimensions, *Bull. Seismol. Soc. Am.* **97,** 401–416, doi 10.1785/0120060138.

Lee, V. W., and M. D. Trifunac (2009). Empirical scaling of rotational spectra of strong earthquake ground motion, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1378–1390.

Lee, V. W., M. D. Trifunac, and A. Amini (1982). Noise in earthquake accelerograms, *ASCE, EMD* **108,** no. 12, 1121–1129.

Lee, W. H. K., and Y. M. Wu (2009). Earthquake monitoring for prediction research and early warning, in *Encyclopedia of Complexity and Systems Science*, R. A. Meyers (Editor), Springer, Berlin (in press).

Lee, W. H. K., M. Çelebi, M. I. Todorovska, and H. Igel (2009). Introduction to the special issue on rotational seismology and engineering applications, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 945–957

Lide, D. R. (2002). *CRC Handbook of Chemistry and Physics*, Eighty-Third Ed., CRC Press, Boca Raton.

Majewski, E. (2006). Seismic rotation waves: spin and twist solitons, in *Earthquake Source Asymmetry, Structural Media and Rotation Effects*, R. Teisseyre, M. Takeo, and E. Majewski (Editors), Springer, Berlin, 255–272.

Majewski, E. (2008). Twistors as spin and twist solitons, in *Physics of Asymmetric Continuum: Extreme and Fracture Processes: Earthquake Rotation and Soliton Waves*, R. Teisseyre, H. Nagahama, and E. Majewski (Editors), Springer, Berlin, 273–284.

Maruyama, T. (1963). On the force equivalents of dynamic elastic dislocations with reference to the earthquake mechanism, Tokyo University, *Bull. Earthq. Res. Inst.* **41,** 467–486.

Morris, C. (1992). *Dictionary of Science and Technology*, Academic Press, San Diego.

Musson, R. M. W. (2002). Macroseismology, in *International Handbook of Earthquake and Engineering Seismology, Part A*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 807–822.

National Bureau of Standards (NBS) (1981). The International National System of Units (SI), National Bureau of Standards Special Publication 330, U.S. Government Printing Office, Washington, D.C.

Nigbor, R. L., J. R. Evans, and C. R. Hutt (2009). Laboratory and field testing of commercial rotational seismometers, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1215–1227.

Penzien, J., and M. Watabe (1975). Characteristics of 3-dimensional earthquake ground motion, *Earthq. Eng. Struct. Dyn.* **3,** 365–373.

Peters, R. D. (2009). Tutorial on gravitational pendulum theory applied to seismic sensing of translation and rotation, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1050–1063.

Pham, N. D., H. Igel, J. Wassermann, M. Käser, J. de la Puente, and U. Schreiber (2009). Observations and modeling of rotational signals in the *P* coda: constraints on crustal scattering, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1315–1332.

Pujol, J. (2009). Tutorial on rotations in the theories of finite deformation and micropolar (Cosserat) elasticity, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1011–1027.

Spudich, P., L. K. Steck, M. Hellweg, J. Fletcher, and L. M. Baker (1995). Transient stresses at Parkfield, California, produced by the M 7.4 Landers earthquake of June 28, 1992: Observations from the UPSAR dense seismograph array, *J. Geophys. Res.* **100,** 675–690.

Teisseyre, R. (2009). Tutorial on new developments in the physics of rotational motions, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1028–1039.

Trifunac, M. D. (2008). 75th Anniversary of strong motion observation—a historical review, *Soil Dyn. Earthq. Eng.* **29,** no. 4, doi 10.1016/j.soildyn.2008.05.011, 591–606.

Trifunac, M. D. (2009). Review: rotations in structural response, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 968–979.

Trifunac, M. D., and M. I. Todorovska (2001). A note on the useable dynamic range of accelerographs recording translation, *Soil Dyn. Earthq. Eng.* **21,** no. 4, 275–286.

Twiss, R., B. Souter, and J. Unruh (1993). The effect of block rotations on the global seismic moment tensor and patterns of seismic P and T axes, *J. Geophys. Res.* **98,** 645–674.

Utsu, T. (2002a). Statistical features of seismicity, in *International Handbook of Earthquake and Engineering Seismology, Part A*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 719–732.

Utsu, T. (2002b). Relationships between magnitude scales, in *International Handbook of Earthquake and Engineering Seismology, Part A*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Academic Press, Amsterdam, 733–746.

Yeats, R. S., K. Sieh, and C. R. Allen (1997). *The Geology of Earthquakes*, Oxford University Press, New York.

Zembaty, Z. (2009a). Tutorial on surface rotations from wave passage effects: stochastic spectral approach, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1040–1049.

Zembaty, Z. (2009b). Rotational seismic load definition in Eurocode 8, Part 6, for slender tower-shaped structures, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1483–1485.

862 Richardson Court
Palo Alto, California 94303
lee@usgs.gov

Manuscript received 1 December 2008