

Seismic Excitation of the Polar Motion, 1977–1993

BENJAMIN FONG CHAO,¹ RICHARD S. GROSS,² and YAN-BEN HAN³

Abstract—The mass redistribution in the earth as a result of an earthquake faulting changes the earth's inertia tensor, and hence its rotation. Using the complete formulae developed by CHAO and GROSS (1987) based on the normal mode theory, we calculated the earthquake-induced polar motion excitation for the largest 11,015 earthquakes that occurred during 1977.0–1993.6. The seismic excitations in this period are found to be two orders of magnitude below the detection threshold even with today's high precision earth rotation measurements. However, it was calculated that an earthquake of only one tenth the size of the great 1960 Chile event, if happened today, could be comfortably detected in polar motion observations. Furthermore, collectively these seismic excitations have a strong statistical tendency to nudge the pole towards $\sim 140^\circ\text{E}$, away from the actually observed polar drift direction. This non-random behavior, similarly found in other earthquake-induced changes in earth rotation and low-degree gravitational field by CHAO and GROSS (1987), manifests some geodynamic behavior yet to be explored.

Key words: Earthquake, polar motion, earth rotation.

1. Introduction

The earth's rotation varies slightly with time. The 3-D earth rotation variation can be conveniently separated into two components: (i) The 1-D variation in the spin rate, often expressed in terms of the length-of-day variation. (ii) 2-D variation in the rotational axis orientation, generically called the nutation when viewed from the inertial reference frame, or the polar motion as seen in the terrestrial reference frame.

There are two dynamic types of earth rotation variations (MUNK and MACDONALD, 1960). (i) The “astronomical variations” due to external luni-solar tidal torques that change the earth's angular momentum: Well-known examples include the tidal braking that causes the earth's spin to slow down over geological times, and the astronomical precession and nutation caused by torques exerted on the earth's equatorial bulge. (ii) The “geophysical variations” caused by large-scale

¹ Geodynamics Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A.

² Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, U.S.A.

³ Beijing Astronomical Observatory, Chinese Academy of Sciences, Beijing 100080, China.

mass movement of internal geophysical processes under the conservation of angular momentum. These include tidal deformations in the solid earth and oceans, atmospheric fluctuations, hydrological variations, ocean currents, earthquake dislocations, post-glacial rebound, mantle tectonic movement, and core activities.

The present paper deals with the polar motion and its seismic excitation. Possible interactions between seismicity and earth rotation have been under consideration since the discovery of the polar motion a hundred years ago (e.g., LAMBECK, 1980). On one hand, a non-uniform earth rotation would give rise to a time-varying stress field inside the earth, which in turn may affect the triggering process of earthquakes. This effect with respect to the polar motion is in general an order of magnitude smaller than its tidal counterpart (LAMBERT, 1925), but having a longer time scale on the order of a year. CHAO and IZ (1992) conducted a statistical test in an attempt to correlate the occurrence of earthquakes with the contemporary polar motion based on nearly 10,000 earthquakes that occurred during 1977–1991; but only a weak correlation was found. A more definitive conclusion awaits further studies taking into account the tensorial nature of the seismic source mechanism and the stress field induced by polar motion.

On the other hand, the mass redistribution in the earth *as a result* of an earthquake faulting changes the earth's inertia tensor, and hence its rotation. Early simplistic earthquake faulting models considering only regional dislocations greatly underestimated the effect (MUNK and MACDONALD, 1960). After the 1964 Alaska earthquake it was recognized that the seismic dislocation, although decreasing with focal distance, remained non-zero even at teleseismic distances away from the fault (PRESS, 1965). When integrated globally (see equation (2) below) considering the size and source mechanism of the earthquake this displacement field can give finite effects (MANSINHA and SMYLLIE, 1967). SMYLLIE and MANSINHA (1971), DAHLEN (1971, 1973), RICE and CHINNERY (1972), and O'CONNELL and DZIEWONSKI (1976), among others, calculated the seismic excitation of polar motion based on realistic models. It was concluded that the great 1960 Chile and 1964 Alaska earthquakes should have produced significant changes in polar motion (see below). Unfortunately the accuracy of the polar motion record at that time was insufficient to yield any conclusive detection.

In the last three decades, the measurement of earth rotation has been progressively improved by three orders of magnitude in both accuracy and temporal resolution (e.g., EUBANKS, 1993, for a review). This is achieved through the advances in modern space geodetic techniques, primarily Very-Long-Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Global Positioning System (GPS). In fact, these techniques have measured the contemporary relative tectonic plate motions to within a few mm/year, and revealed coseismic, near-field displacements caused by recent earthquakes. The SLR technique has also greatly benefitted the determination of the earth's global gravitational field and detected slight temporal variations in the low-degree field. In the area of earth rotation measure-

ment, the current accuracy is estimated to be within 1 milliarcsecond ($1 \text{ mas} = 4.85 \times 10^{-9}$ radian, corresponding to about 3 cm of distance on the surface of the earth), while the formal errors are as low as 200 μas .

Taking advantage of these modern data as well as the seismic centroid moment tensor solutions made available in the Harvard CMT catalog (for a review, see DZIEWONSKI *et al.*, 1993), SOURIAU and CAZENAVE (1985) and GROSS (1986) calculated the seismic excitation of polar motion using DAHLEN'S (1973) formulation for post-1977 major earthquakes. It was concluded that the polar motion excited by those earthquakes were all too small to be detected even in the modern earth rotation data. CHAO and GROSS (1987) developed complete formulae for calculating the earthquake-induced changes in earth's rotation and low-degree gravitational field based on the normal mode theory of GILBERT (1970). They made calculations for the 2,146 major earthquakes that occurred during 1977–1985. In addition to confirming the above conclusion, the result indicated that earthquakes have a strong statistical tendency to make the earth rounder and more compact. It also demonstrated a similar tendency for earthquakes to nudge the rotation pole towards the direction of about 150°E . CHAO and GROSS (1995) and CHAO *et al.* (1995) extended the calculation to include 11,015 major earthquakes for the period 1977–1993 to evaluate the corresponding rotational and gravitational *energy* changes.

The present paper will study the seismic excitation of polar motion in the framework of CHAO and GROSS (1987) but making use of the updated result of CHAO and GROSS (1995). The corresponding changes in length-of-day will only be presented in passing, as they are in general two orders of magnitude smaller (that is to say, polar motion is hundreds of times easier to excite than length-of-day by earthquakes). The physical reason is the following. The geophysical excitation acts against the “inertia” of the earth system. For length-of-day the inertia is the earth's axial moment of inertia C , whereas the inertia for polar motion is the difference between the axial and equatorial moments of inertia, $C - A$ (see equation 2), which is only $1/300$ of C .

2. Dynamics and Calculation

The excitation of the polar motion is governed by the conservation of angular momentum. The equation of motion is customarily expressed as (MUNK and MACDONALD, 1960):

$$m + \frac{i}{\sigma} \frac{dm}{dt} = \Psi \quad (1)$$

where m is the complex-valued pole location measured in radian; its real part is the x component (along the Greenwich Meridian) and the imaginary part the y

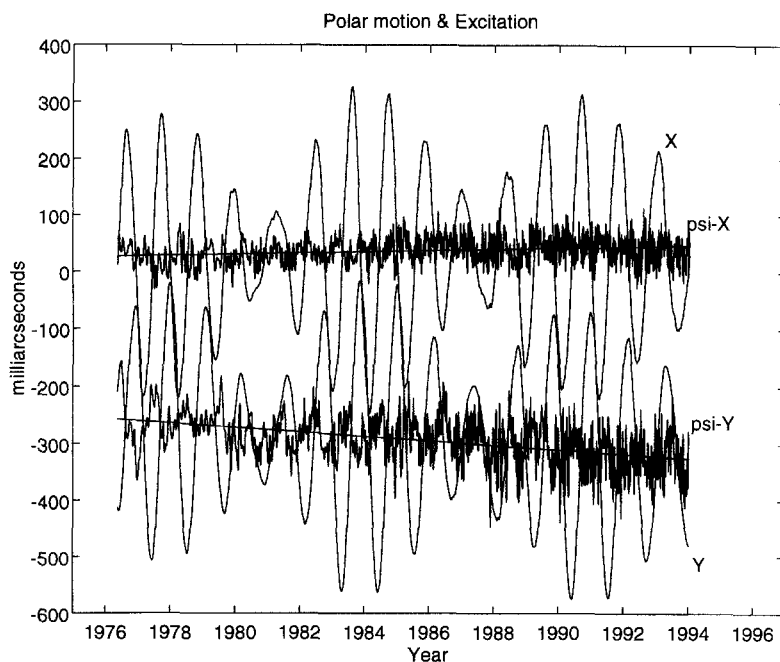


Figure 1

The x and y components of the observed polar motion and its excitation function (Ψ , obtained by deconvolution) for 1976.4–1994.0, in units of milliarseconds. The straight lines are the least-squares fit to the excitation function.

component (along the 90°E longitude), σ is the frequency of the free Chandler wobble with a nominal period of 435 days and a Q value of 100, and Ψ is the complex-valued excitation function. Mechanically equation (1) is analogous to the excitation of a simple harmonic oscillator with a natural frequency σ .

The polar motion m traces out a prograde, quasi-circular path on the order of 10 m in the vicinity of the North Pole. Figure 1 shows the x and y positions of the pole at nominal daily intervals according to the “Space93” dataset (GROSS, 1994) derived from space geodetic measurements during 1976.4–1994.0. Besides a slow polar drift, the oscillation consists mainly of the annual wobble and the Chandler wobble. It is continually excited (otherwise it would decay away in a matter of decades); and the excitation function Ψ can be obtained numerically according to equation (1) in a process of deconvolution. The Ψ thus obtained is also given in Figure 1, together with the least-squares fitted straight lines representing the polar drift (see below). The geophysical problem is to identify and understand the sources of this “observed” Ψ . It is now known that a major source is the variation of the atmospheric angular momentum (e.g., CHAO, 1993; KUEHNE *et al.*, 1993). The problem is far from closed, and the earthquake dislocation remains a candidate excitation source.

The polar-motion excitation Ψ due to mass redistribution is given by

$$\Psi = 1.61(\Delta I_{zx} + i \Delta I_{yz})/(C-A) \quad (2)$$

where I denotes the inertia tensor, the factor 1.61 takes into account the earth's non-rigidity and the decoupling of the fluid core from the mantle in the excitation process. Note that Ψ should also include an additional term due to mass motion, but that term is negligible in the case of abrupt seismic sources (CHAO, 1984).

With an abrupt step-function time history (compared to the considerably longer time scale of the polar motion), an earthquake faulting generates a co-seismic, step-function displacement field \mathbf{u} (after the seismic waves have died away). Knowing the seismic moment tensor, \mathbf{u} anywhere in the earth can be evaluated by the normal mode summation scheme of GILBERT (1970). The task, then, is to calculate the seismic Ψ according to equation (2), which consists of evaluating ΔI by a properly weighted integration of \mathbf{u} over the globe. The reader is referred to CHAO and GROSS (1987) for details of the formulation and calculation method. This normal mode scheme is found to be extremely efficient.

Calculation has been conducted for 11,015 major earthquakes (with nominal magnitude greater than 5.0) that occurred during 1977.0-1993.6, using the seismic

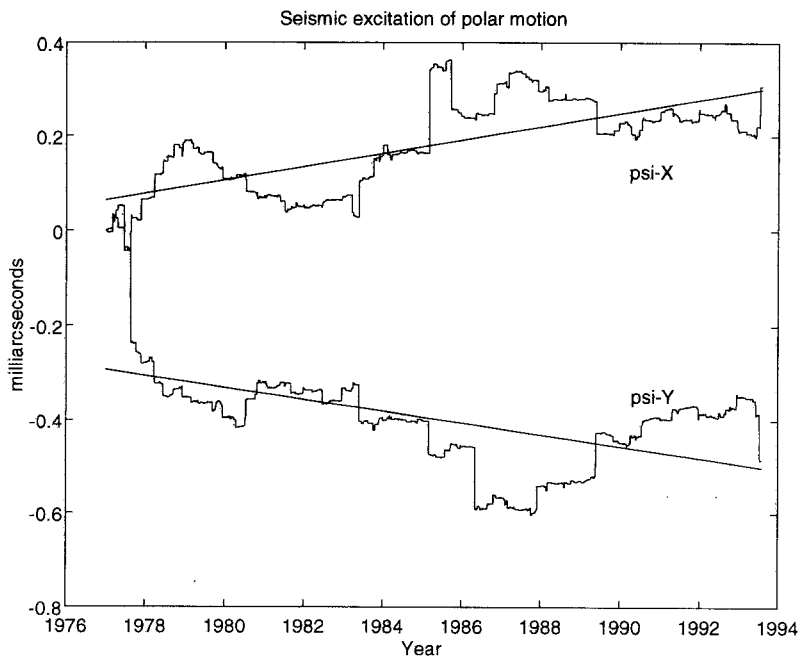


Figure 2

The x and y components of the seismic excitation of polar motion. The straight lines are the least-squares fit to the excitation function.

centroid moment tensor solutions published in the Harvard CMT catalog (e.g., DZIEWONSKI *et al.*, 1993). Smaller earthquakes, although numerous, have completely negligible effects. The adopted normal mode eigenfrequencies and eigenfunctions belong to the spherically symmetric earth model 1066B of GILBERT and DZIEWONSKI (1975). The net effect is then the accumulation of individual step-function contributions: $\Psi(t) = \sum_n \Psi_n H(t - t_n)$, ($n = 1, \dots, 11,015$). CHAO and GROSS (1995) have also calculated the corresponding changes in length-of-day and low-degree gravitational field.

3. Results and Analysis

Figure 2 shows the calculated polar-motion excitation function $\Psi(t)$ by the earthquakes. The starting value is arbitrarily chosen to be zero. Comparing Figure 2 with 1, it is obvious that the magnitude of the seismic excitation is insignificant during 1977.0–1993.6: It is of two orders of magnitude too small to explain the observed polar-motion excitation.

For the purpose of illustration, Table 1 lists the results for the following eight largest earthquakes in recent decades (with seismic moment M_0 exceeding 10^{21} Nm). These results have been reported elsewhere by CHAO and GROSS (1995).

- Event I: May 22, 1960, Chile
- Event II: March 28, 1964, Alaska, U.S.A.
- Event III: August 19, 1977, Sumba, Indonesia
- Event IV: March 3, 1985, Chile
- Event V: September 19, 1985, Mexico
- Event VI: May 23, 1989, Macquarie Ridge
- Event VII: June 9, 1994, Bolivia
- Event VIII: October 4, 1994, Kuril Is., Russia

The source mechanism of Events I and II, which occurred before the span of the Harvard catalog, are taken from KANAMORI and CIPAR (1974) and KANAMORI

Table 1

Magnitude and direction of polar-motion excitation by eight great earthquakes, and the corresponding length-of-day changes

Event (M_0 , 10^{21} Nm)	I (270)	II (75)	III (3.6)	IV (1.0)	V (1.1)	VI (1.4)	VII (2.6)	VIII (3.9)
ΔLOD (μs)	−8.4	6.8	0.33	−0.10	−0.089	−0.059	0.192	−0.053
$ \Psi $ (mas)	22.6	7.5	0.21	0.18	0.084	0.114	0.331	0.256
$\arg(\Psi)$ ($^\circ\text{E}$)	115	198	160	110	277	323	122	129

(1970), respectively. Events VII (a deep-focused event) and VIII in 1994 are also outside our studied period. They have the largest seismic moment since Event III in 1977.

The following facts are observed: (i) The earthquake-induced ΔLOD is small: even the largest earthquakes (Events I and II) would only cause a ΔLOD that is barely discernable even with today's measurement precision. (ii) The direction of polar motion excitation, $\arg(\Psi)$, tend to cluster in the second quadrant (see below). (iii) Although the polar motion excitations by the latest 6 events have magnitude that were hardly detectable, Events I and II, if happened today, could be readily detected in the polar motion measurement. It should be noted, however, that it is in the polar motion *excitation* that an earthquake leaves its signature as a step function. In the polar motion path itself (which represents a time integration of the excitation, see equation (1)), the earthquake manifests itself as a "kink" in the path, and hence more difficult to detect. Further difficulties arise because of the abrupt nature of the earthquake source and the relatively "gappy" sampling of earth rotation in the past. Only recently has a virtually continuous monitoring of earth rotation become feasible by means of the GPS technique.

Figure 3 compares the power spectra of the observed and the seismic excitations for the same period of 1977.0–1993.6. The spectra are computed using THOMSON'S (1982) multitaper technique after removal of the mean values. The different spectral characteristic is evident. The frequency dependence f^n of the spectrum of the seismic excitation is found to follow $n = 2.0$, similar to a Brownian motion process. The power of the seismic Ψ is in general 40–60 dB lower than that observed. In particular, the power difference at the Chandler frequency band around 0.83 cycle per year is about 45 dB. We have also calculated and examined possible correlation between the two excitation functions in the Chandler band. Only a weak coherence at a moderate confidence level was found. These findings are consistent with GROSS (1986).

Despite the small magnitude, the seismic excitations Ψ collectively are interesting in their own right. Following CHAO and GROSS (1987), we shall now conduct statistical analyses to reveal their peculiar behavior.

Figure 4 shows the angular histogram ("rose diagram") of the arguments of the 11,015 Ψ 's in thirty-six 10° increment bins. Apart from a concentration around 15°E , an abnormally large number of Ψ 's cluster around 140°E . The distribution pattern is remarkably similar to the 2,146 Ψ 's analyzed by CHAO and GROSS (1987), indicating that this pattern is robust with respect to time and number of earthquake samples. In fact, the statistical tendency of this angular anomaly is stronger now with the substantially greater number of samples: the normalized χ^2 found here is as high as 14.1, compared to 3.81 found in CHAO and GROSS (1987). Compared with, say, the 1% significant level of 1.64 or the 0.1% significant level of 1.90 for a random distribution (at 35 degrees of freedom), this asserts the extremely non-random nature of the distribution of Figure 4.

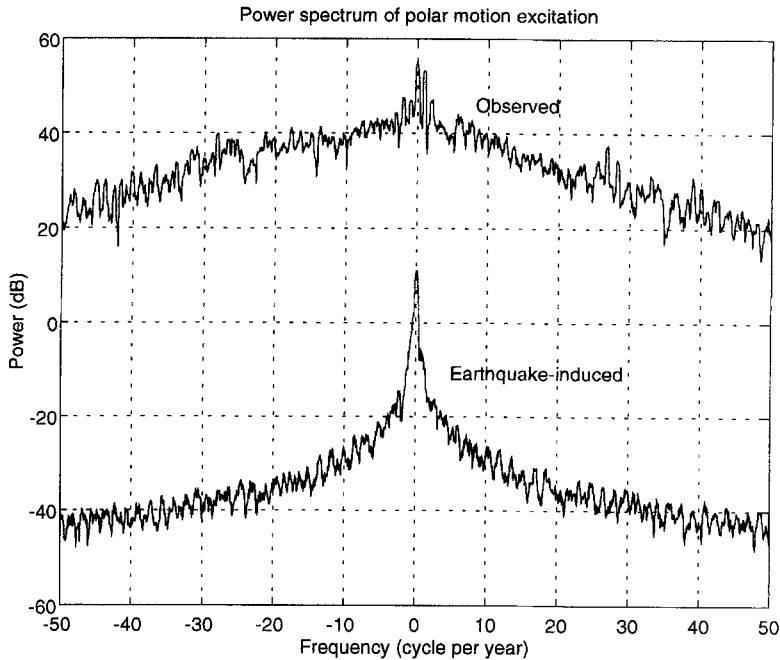


Figure 3

The (multitapered) power spectrum (in dB units of mas^2/cpy) of the observed polar-motion excitation compared with that induced by earthquakes during 1977.0–1993.6. Mean values have been removed from the time series.

The preference of earthquakes in nudging the rotation pole towards $\sim 140^\circ\text{E}$ is also evident in Figure 2. The straight lines are the least-squares fit to the curves; their slopes give the velocity of the polar drift induced by earthquakes. This polar drift velocity vector (0.019 mas/yr , 131°E), as plotted in Figure 5, indeed points to that general direction. The magnitude of the vector is here magnified by 100 times, in order to be shown against other vectors:

The one labeled “O&D” (4.5 mas/yr , 148°E) is that similarly obtained using O’CONNELL and DZIEWONSKI’s (1976) calculation for 30 great earthquakes during 1900–1964. So it appears that the earthquake-induced polar drift has continued its journey toward $\sim 140^\circ\text{E}$ at least since 1900 when fairly reliable seismic records had become available. It should be cautioned, however, that O’CONNELL and DZIEWONSKI may very well have greatly, and presumably to different extent, overestimated the sizes of their studied earthquakes (KANAMORI, 1976). Even though the directions of the polar excitation by *individual* earthquakes, which are determined by the source mechanisms according to plate tectonics, are realistic, the (vectorial) cumulative drift direction may be biased. However, closer examination of these individual directions indicates that this bias is not severe: Figure 6 plots the

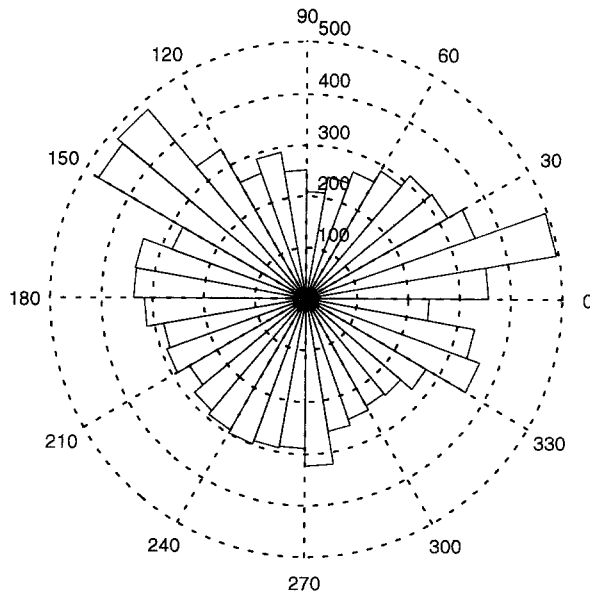


Figure 4

The angular histogram (“rose diagram”) for the direction of the seismic excitation of polar motion by major earthquakes for 1977.0–1993.6, in 36 angular bins with respect to the terrestrial coordinate system.

rose diagram (in 20° bins) of O’CONNELL and DZIEWONSKI’s 30 polar excitation directions and their cumulative polar drift. The directions have the same heavy clustering in the second quadrant, and hence the cumulative drift is largely unidirectional.

The other two vectors in Figure 5 are from polar motion observations; they agree well with each other. The one labeled “Space93” (3.84 mas/yr , -68°E) is simply obtained from the fitted line in Figure 1. The one labeled “Pole93” (3.22 mas/yr , -81°E) is similarly obtained from a polar motion dataset for 1900–1993, primarily based on the International Latitude Service data since 1900. It is seen that the observed polar drift directions are roughly opposite to those induced by earthquakes.

4. Conclusions

The direction of the seismic excitation depends on the focal location and source mechanism. Through computation, it is found that, at least since 1900, the seismic excitations collectively have a statistically strong tendency to nudge the pole towards $\sim 140^\circ\text{E}$, away from the actually observed polar drift direction. This non-

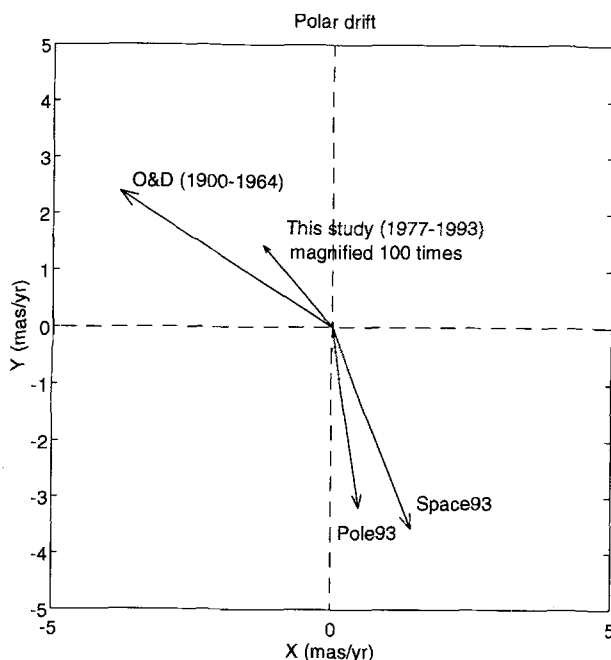


Figure 5

The calculated polar drift velocity induced by major earthquakes for 1977.0–1993.6, magnified 100 times, in comparison with O’Connell and Dziewonski’s estimate (labeled “O&D”) and the observed polar drift (labeled “Space93” and “Pole93”).

random behavior is similar to other earthquake-induced changes computed for length-of-day and low-degree gravitational field, which indicate a strong tendency for the earthquakes to make the earth rounder and more compact (CHAO and GROSS, 1987). Specific questions arise: Why do earthquakes seem to “recognize” the existence of the rotation axis? Is there any as yet unseen, dynamic connection between the pole position and the occurrence and source mechanism of earthquakes? Or are they manifestations of some behind-the-scene geophysical processes? The dynamic reasons for such peculiar behavior of earthquakes are not clear in terms of the grand scheme of the plate tectonics. At the present time these remain mere speculations.

The magnitude of individual earthquake effect, on the other hand, depends largely on the seismic moment of the event. The rule of thumb is that the seismic moment of 10^{22} Nm would roughly produce 1 mas in polar-motion excitation and $1 \mu\text{s}$ in length-of-day change; the actual values depend on the focal location and seismic source mechanism. The polar motion excitations produced by the largest earthquakes during 1977–1993 were still an order of magnitude too small to be detected even with today’s measuring accuracy of about 1 mas. However, it was calculated that the 1960 Chile event should have produced a discontinuity as large

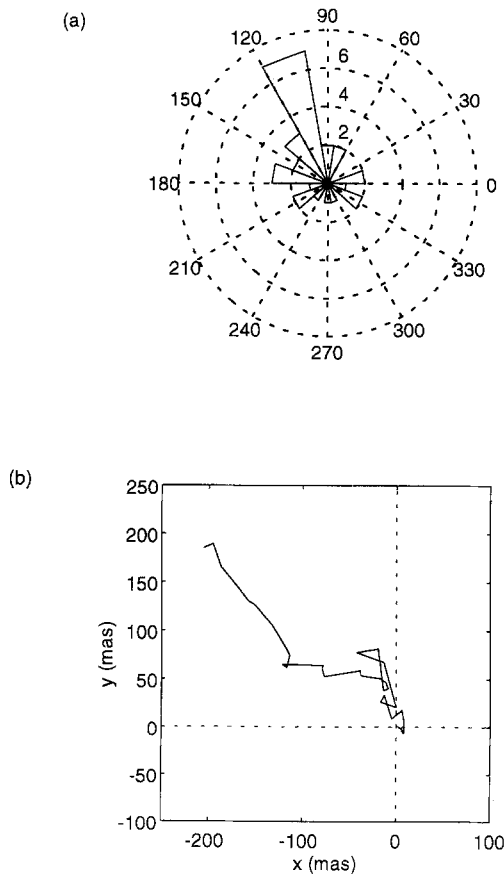


Figure 6

(a) The rose diagram for the direction of the seismic excitation of polar motion by 30 great earthquakes during 1900–1964 studied by O'Connell and Dziewonski, in 18 angular bins. (b) Their cumulative polar excitation in the terrestrial coordinate system.

as 23 mas in the polar-motion excitation function (but only $8 \mu\text{s}$ in ΔLOD). So an earthquake of only one tenth the size of that event, if happened today, could be comfortably detected in polar-motion observations, especially now that the GPS technique routinely provides sub-daily temporal resolutions. Further improvements in observation should allow detection of smaller (and hence potentially more numerous) earthquake signatures in the future.

Acknowledgments

The seismic centroid-moment tensor catalog is kindly provided via Internet by A. Dziewonski and his group at the Harvard University under support from the

National Science Foundation. The 1066B Earth Model is courtesy of R. Buland. The work of a co-author (RSG) described in this paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). This study is supported by the NASA Geophysics Program and the Beijing Astronomical Observatory of the Chinese Academy of Sciences.

REFERENCES

- CHAO, B. F. (1984), *On Excitation of Earth's Free Wobble and Reference Frames*, Geophys. J. Roy. Astron. Soc. 79, 555–563.
- CHAO, B. F., and GROSS, R. S. (1987), *Changes in the Earth's Rotation and Low-degree Gravitational Field Induced by Earthquakes*, Geophys. J. Roy. Astron. Soc. 91, 569–596.
- CHAO, B. F., and IZ, H. B. (1992), *Does Polar Motion Influence the Occurrence of Earthquakes*, EOS, Trans. Am. Geophys. Union 73, 79.
- CHAO, B. F. (1993), *Excitation of Earth's Polar Motion by Atmospheric Angular Momentum Variations, 1980–1990*, Geophys. Res. Lett. 20, 253–256.
- CHAO, B. F., and GROSS, R. S. (1995), *Changes of the Earth's Rotational Energy Induced by Earthquakes*, Geophys. J. Int., in press.
- CHAO, B. F., GROSS, R. S., and DONG, D. N. (1995), *Global Gravitational Energy Changes Induced by Earthquakes*, Geophys. J. Int., in press.
- DAHLEN, F. A. (1971), *The Excitation of the Chandler Wobble by Earthquakes*, Geophys. J. R. Astr. Soc. 25, 157–206.
- DAHLEN, F. A. (1973), *A Correction to the Excitation of the Chandler Wobble by Earthquakes*, Geophys. J. R. Astr. Soc. 32, 203–217.
- DZIEWONSKI, A. M., EKSTRÖM, G., and SALGANIK, M. P. (1993), *Centroid Moment Tensor Solutions for October–December, 1992*, Phys. Earth Planet. Int. 80, 89–103.
- EUBANKS, T. M., *Variations in the orientation of the earth*. In *Contributions of Space Geodesy to Geodynamics: Earth Dynamics* (eds. Smith, D. E., and Turcott, D. L.) (AGU, Washington, D.C. 1993), pp. 1–54.
- GILBERT, F. (1970), *Excitation of the Normal Modes of the Earth by Earthquake Sources*, Geophys. J. R. Astr. Soc. 22, 223–226.
- GILBERT, F., and DZIEWONSKI, A. M. (1975), *An Application of Normal Mode Theory to the Retrieval of Structural Parameters and Source Mechanisms from Seismic Spectra*, Phil. Trans. R. Soc. London A-278, 187–269.
- GROSS, R. S. (1986), *The Influence of Earthquakes on the Chandler Wobble during 1977–1983*, Geophys. J. R. Astr. Soc. 85, 161–177.
- GROSS, R. S. (1994), *A combination of Earth Orientation Data: Space 93*, IERS Technical Note 17: Earth Orientation, Reference Frames and Atmospheric Excitation Functions, Obs. de Paris.
- KANAMORI, H. (1970), *The Alaska Earthquake of 1964: Radiation of Long-period Surface Waves and Source Mechanism*, J. Geophys. Res. 75, 5029–5040.
- KANAMORI, H., and CIPAR, J. J. (1974), *Focal Process of the Great Chilean Earthquake May 22, 1960*, Phys. Earth. Planet. Int. 9, 128–136.
- KANAMORI, H. (1976), *Are Earthquakes a Major Cause of the Chandler Wobble ?* Nature 262, 254–255.
- KUEHNE, J., JOHNSON, S., and WILSON, C. R. (1993), *Atmospheric Excitation of Nonseasonal Polar Motion*, J. Geophys. Res. 98, 19973–19978.
- LAMBECK, K. *The Earth's Variable Rotation* (Cambridge Univ. Press, New York 1980).
- LAMBERT, W. D. (1925), *The Variation of Latitude, Tides, and Earthquakes*, Proc. 3rd Pan-Pacific Science Congress, Tokyo, 1517–1522.
- MANSINHA, L., and SMYLLIE, D. E. (1967), *Effects of Earthquakes on the Chandler Wobble and the Secular Pole Shift*, J. Geophys. Res. 72, 4731–4743.

- MUNK, W. H., and MACDONALD, G. J. F., *The Rotation of the Earth* (Cambridge University Press, New York 1960).
- O'CONNELL, R. J., and DZIEWONSKI, A. M. (1976), *Excitation of the Chandler Wobble by Large Earthquakes*, *Nature* 262, 259–262.
- PRESS, F. (1965), *Displacements, Strains, and Tilts at Teleseismic Distances*, *J. Geophys. Res.* 70, 2395–2412.
- RICE, J. R., and CHINNERY, M. A. (1972), *On the Calculation of Changes in the Earth's Inertia Tensor due to Faulting*, *Geophys. J. R. Astr. Soc.* 29, 79–90.
- SMYLIE, D. E., and MANISINHA, L. (1971), *The Elasticity Theory of Dislocations in Real Earth Models and Changes in the Rotation of the Earth*, *Geophys. J. Res.* 23, 329–354.
- SOURIAU, A., and CAZENAVE, A. (1985), *Reevaluation of the Chandler Wobble Seismic Excitation from Recent Data*, *Earth Planet. Sci. Lett.* 75, 410–416.
- THOMSON, D. J. (1982), *Spectrum Estimation and Harmonic Analysis*, *Proc. IEEE* 70, 1055–1096.

(Received October 10, 1994, accepted April 30, 1995)