ness temperature at 1.4 cm to that at 1 cm, as well as the absolute value of the brightness temperature at 1 cm.

J. B. POLLACK
*Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts 02138*
A. T. WOOD, JR.
*Harvard College Observatory*

**References and Notes**

1. Anon., *Pravda*, 2 Oct. and 1 Nov. 1967.
2. V. S. Avduevskiy, M. Y. Marov, M. K. Rozhdestvenskiy, "The model of the atmosphere of the planet Venus on the results of measurements made by the Soviet automatic interplanetary station Venera 4," preprint (1968).
3. A. Kliore, D. L. Cain, G. S. Levy, G. Fjelbo, S. I. Rasool, "Structure of the atmosphere of Venus derived from Mariner V S-band measurements," paper presented at the COSPAR Meeting, 11th, Tokyo, Japan, 1968.
4. J. B. Pollack and C. Sagan, *Astrophys. J.* **150**, 327 (1967).
5. W. Ho, I. A. Kaufman, P. Thaddeus, *J. Geophys. Res.* **71**, 5091 (1966).
6. A. H. Barrett and D. H. Staelin, *Space Sci. Rev.* **3**, 109 (1964).
7. V. K. Chung, "Microwave spectra of the planet Venus," thesis, Massachusetts Institute of Technology (1962).
8. R. Wattson, personal communication (1968).
9. M. E. Ash *et al.*, *Science* **160**, 985 (1968).
10. G. H. Pettingill, R. B. Dyce, D. B. Campbell, *Astron. J.* **72**, 330 (1967).
11. R. M. Goody, *Atmospheric Radiation*, part I, *Theoretical Basis* (Clarendon Press, Oxford, 1966), p. 12.
12. J. R. Dickel, *Icarus* **6**, 417 (1967).
13. J. E. Gibson and H. H. Corbett, *Astron. J.* **68**, 74 (1963).
14. ———, *Radio Sci.* **69D**, 1577 (1965).
15. D. H. Staelin and A. H. Barrett, *Astrophys. J.* **144**, 352 (1966).
16. P. H. Griffith, D. D. Thornton, W. J. Welch, *Icarus* **6**, 175 (1967).
17. S. E. Law and D. H. Staelin, "Measurements of Venus and Jupiter near 1-cm wavelength," in preparation.
18. J. B. Pollack, *Icarus*, in press.
19. M. Belton, D. Hunter, R. M. Goody, in *The Atmospheres of Venus and Mars*, J. C. Brandt and M. B. McElroy, Eds. (Gordon and Breach, New York, 1968).
20. Aided by NASA grant NGR 09-015-023. We thank Richard Wattson for the surface boundary conditions, Andrea Dupree for her computer program, A. Kliore for a preprint of the latest reductions of the Mariner-5 results, Carl Sagan for helpful discussions, and David Staelin for a preprint of his most recent results.

28 June 1968

## Earthquakes and the Earth's Wobble

Abstract. *Observational evidence is presented in support of the hypothesis that large earthquakes excite the earth's natural wobble and produce the observed secular polar shift. Previous theoretical calculations based on elasticity theory and earthquake statistics had predicted a significant effect. There appear to be some premonitory signs of large earthquakes in the pole path.*

It has been known for over 80 years that the earth's axis of rotation moves with respect to an observatory coordinate system. To earthbound observers this represents a variation of the astronomically determined latitude. Viewed from space, it represents a wobble of the earth about its rotation axis. The observed motion is most conveniently displayed as the path of the instantaneous north pole of rotation (Fig. 1).

In 1891, S. C. Chandler isolated a component of a 14-month period from the latitude observations (*1*). Rigid-body dynamics gives a 10-month period for the earth's natural wobble, but the longer observed period can be reconciled with theory if allowance is made for rotational deformation (*2*). The motion is now called the Chandler wobble. The accompanying rotational deformation implies that the Chandler wobble must be subject to damping, and therefore a more or less continuous excitation is required to maintain it. Identifying the source of the excitation has remained one of the principal problems in studies of the earth's rotation (*3*). We now report evidence in support of theoretical calculations (*4*) which led to the hypothesis that large earthquakes provide the hitherto unidentified excitation.

Latitude measurements are reduced independently by two organizations to produce pole paths. The International Latitude Service (ILS) collected and reduced latitude measurements from three to five observatories on a single latitude circle (39°8'N) from 1900 to 1962 (*5*). In 1962, the International Polar Motion Service (IPMS) took over this work (*6*). Using stations on a single latitude circle allows all stations to observe the same stars, avoiding dependence on the accuracy of star catalogs. Currently, mean pole positions for 0.05-year intervals are issued. The origin used is the mean pole position for the period 1900 to 1905, called the Conventional International Origin (CIO).

Since late 1955, the Bureau International de l'Heure (BIH) in Paris has also been reducing latitude measurements in order to correct star-transit times for polar motion (*7*). At the beginning of 1957 information from nine stations was being processed. By early 1967, 39 observatories were contributing. Ten-day means have been published (*8*). Pole positions were referred to a moving origin. Typical comparisons between the ILS-IPMS and BIH-CIO paths are shown at the top of Fig. 1.

The motion of the pole is complicated by the presence of an annual component which beats with the Chandler component to give a 6-year periodicity to the amplitude. The annual motion has been shown (*9*) to be produced by the seasonal rearrangement of atmospheric mass. Removal of the annual component from the paths shown at the top of Fig. 1 results in those shown directly below.

A connection between earthquakes and the motion of the pole had been suggested very early in the history of latitude observations (*10*). Until recently the displacement fields of even the greatest earthquakes were thought to extend to no more than a few hundred kilometers from the focus. Thus, estimates of the contribution of earthquakes to the Chandler wobble excitation fell several orders of magnitude short of the observed level (*11*).

The prevailing view on the extent of earthquake displacement fields was drastically altered by the work of Press (*12*). Both the theoretical predictions of elasticity theory and distant strain measurements were adduced to argue that a measurable displacement field may extend to epicentral distances of several thousand kilometers for a great earthquake.

When the effect of such large-scale deformation of the earth was calculated for a number of individual earthquakes, and when an estimate of the cumulative effect was made on the basis of earthquake statistics, it was found that earthquakes could account for both the excitation of the Chandler wobble and a slow secular shift of the mean pole of rotation (*4*).

The reality of a secular motion of the pole has been the subject of some debate among observers, but there seems now to be agreement that a drift of a fraction of 1 foot (0.3 m) per year does in fact occur (*13*).

If the displacement field of an earthquake is established in a short time as compared to the Chandler-wobble period (the best estimate of the period appears to be 1.2 year), the effect on the pole path is as illustrated in Fig. 2. Before and after the quake, the pole follows a circular path (with damping, the path is actually a gentle inward spiral) in an anticlockwise sense. At the time of the earthquake, the center of rotation (secular pole) is shifted, while there is a nearly equal and opposite vector contribution to the wobble (*4*). Hence, the position of the rotation pole is left nearly unaltered; only the path

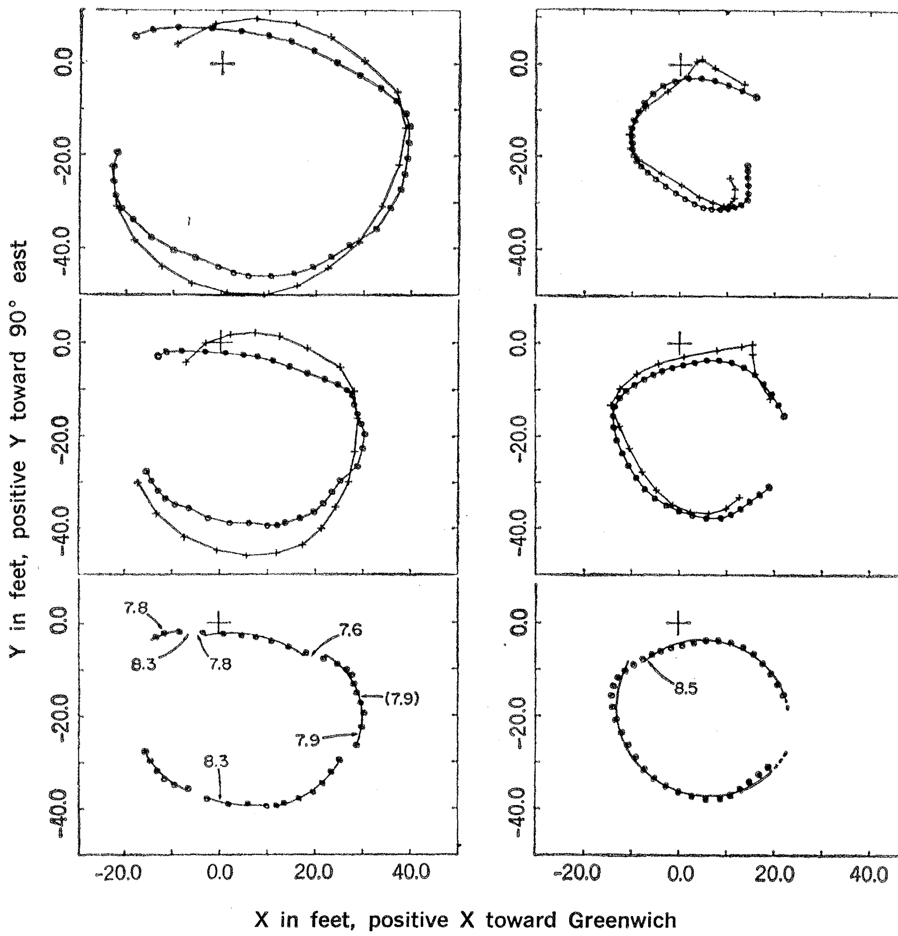


Fig. 1. Pole paths for 1957 (left) and 1960 (right). Pole motion is anticlockwise. (top) Independent determinations of the International Latitude Service (ILS-IPMS) and the Bureau International de l'Heure (BIH). The same paths with the annual motion removed are shown directly below. In the lower part of the figure circular arcs have been fitted to the BIH path after removal of the annual variation. All earthquakes of magnitude $M > 7.5$ are indicated. The one which bears no relation to a break in the fitted arcs is in parentheses. Solid circles, BIH-CIO; crosses, ILS-IPMS.

it describes in time is changed. On the basis of this theoretical model, we have constructed an observational test of the hypothesis that earthquakes are responsible for the excitation of the Chandler wobble and the observed secular polar shift.

If the period of the Chandler Wobble is taken to be fixed, in the absence of excitation and after the annual wobble has been removed, successive mean pole positions should be equally spaced along a nearly circular arc (Fig. 3). The angle $\alpha$ subtended at the center of the arc by neighboring pole positions is just that fraction of $2\pi$ given by the ratio of the time interval between pole

Table 1. Pole path breaks in relation to large earthquakes (1957.0 to 1968.0). R.P., random probability.

| Earthquakes | | | Three closest pole path breaks | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | BIH | | | ILS-IPMS | | |
| Date | Region | Magnitude | Days before quake | Days before quake | Days after quake | Days before quake | Days before quake | Days after quake |
| | | | | $M \geq 8.00$ | | | | |
| 9 Mar 57 | Aleutians | 8.3 | | 12 | 28 | | − 32 | 124 |
| 4 Dec 57 | Outer Mongolia | 8.3 | 72 | 2 | 38 | 91 | − 55 | 164 |
| 6 Nov 58 | Kurile Islands | 8.7 | 79 | 19 | 81 | 63 | − 10 | 120 |
| 22 May 60 | Off Chile | 8.5 | 162 | − 8 | 358 | 78 | 42 | 50 |
| 13 Oct 63 | Kurile Islands | 8.25 | 261 | 1 | 149 | 57 | 2 | 71 |
| 28 Mar 64 | Southern Alaska | 8.5 | 168 | 18 | 242 | 60 | 5 | 68 |
| | | | | R.P. = 0.09% | | | R.P. = 71% | |
| | | | | $8.00 \geq M > 7.75$ | | | | |
| 27 Jun 57 | Lake Baikal, U.S.S.R. | 7.9 | 82 | 12 | 88 | 78 | − 14 | 69 |
| 28 Jul 57 | Guerro, Mexico | 7.9 | 113 | 43 | 57 | 109 | 17 | 38 |
| 29 Nov 57 | Southern Bolivia | 7.8 | 67 | − 3 | 43 | 86 | − 60 | 169 |
| 17 Dec 57 | Santa Cruz Island | 7.8 | 85 | 15 | 25 | 104 | − 42 | 151 |
| 19 Jan 58 | Off Ecuador | 7.8 | 48 | 8 | 32 | 137 | − 9 | 118 |
| 10 Jul 58 | SE Alaska | 7.9 | 73 | − 40 | 100 | 54 | − 1 | 56 |
| 4 May 59 | Off Kamchatka | 8.0 | 98 | − 2 | 82 | 60 | − 13 | 105 |
| | | | | R.P. = 3.4% | | | R.P. = 60% | |
| | | | | $7.75 \geq M > 7.50$ | | | | |
| 24 Sep 57 | Off Mindanao | 7.6 | 101 | 1 | 69 | 75 | 20 | 126 |
| 26 Apr 59 | Off Formosa | 7.5–7.75 | 90 | − 10 | 90 | 52 | − 21 | 113 |
| 14 Sep 59 | Kermadec Islands | 7.75 | 51 | − 9 | 89 | 120 | 28 | 81 |
| 8 Sep 61 | Sandwich Islands | 7.5–7.75 | 116 | 16 | 104 | 114 | − 50 | 306 |
| 15 Aug 63 | Peru-Bolivia | 7.75 | 202 | − 58 | 208 | 163 | − 2 | 57 |
| 26 May 64 | S. Sandwich Islands | 7.5–7.75 | 227 | 77 | 183 | 64 | − 9 | 100 |
| 24 Jan 65 | Ceram Sea | 7.6 | 320 | 60 | 150 | 88 | − 40 | 149 |
| 4 Feb 65 | Santa Cruz Island | 7.75 | 331 | 71 | 139 | 98 | − 30 | 139 |
| 28 Dec 66 | Off N. Chile | 7.75 | 143 | −117 | 197 | 133 | 79 | 140 |
| | | | | R.P. = 29% | | | R.P. = 68% | |

positions to the period of the wobble. For the ILS-IPMS data, $\alpha$ is 15° since it is given at 0.05-year intervals, whereas for the BIH data, given at 10-day intervals, $\alpha$ is 8.21°. With $\alpha$ known, a unique circular arc can be fitted to two observational points. A prediction of the location of the next observational point can then be made by extrapolating along this circular arc through the angle $\alpha$. In our procedure, if the observed point is more than 2 feet from its position predicted by extrapolation, a new arc is fitted to this and succeeding points. If it is less than or equal to 2 feet from the predicted position, it is included and a new circular arc is fitted by least squares. The circle of acceptance shown in Fig. 3 is thus given a radius of 2 feet. The arcs so fitted to the BIH paths for 1957 and 1960 are shown in the lower part of Fig. 1.

For the period 1957.0 to 1968.0, the ILS-IPMS data gives 41 breaks in the fitted circular arcs, while there are 32 breaks in the arcs fitted to the BIH data. Table 1 lists large earthquakes over the same period in relation to the nearest breaks in the fitted circular arcs. A complete listing of quakes of magnitude $M$ over 7.5 is given (*14*). Each of those with $M$ greater than 8.0 occurs close to a break in the circular arcs fitted to the BIH data. The probability that 6 days drawn at random would fall within 20 days of an arc break is only 0.07 percent. By allowing a similar tolerance of 0.10 year (twice the interval between measured pole positions) for the ILS-IPMS data, only four of the six quakes correlate with arc breaks. The probability of obtaining this correlation or a better one on a random selection of 6 days is 74 percent. The correlation of breaks in the BIH path with earthquakes is also much higher than that expected on a random basis in the magnitude range $8.0 \geqslant M > 7.75$. No significant correlation with the ILS-IPMS breaks in this magnitude range is found. In the magnitude range $7.75 \geqslant M > 7.50$, the correlation of the BIH breaks nearly disappears while that for the ILS-IPMS data is again insignificant.

A comparison of the ILS-IPMS and BIH pole paths (Fig. 1) reveals significant systematic differences between the two determinations. The disagreements range up to 10 feet, whereas characteristics of the two paths, such as curvature, seem to bear only the occasional resemblance. Without making a judgment on the quality of the observational work, the ILS-IPMS pole paths show features that might be expected of a few stations making a limited number of observations. In contrast, the BIH data does not show the more extreme variations, possibly reflecting the use of a much larger number of stations and observations.

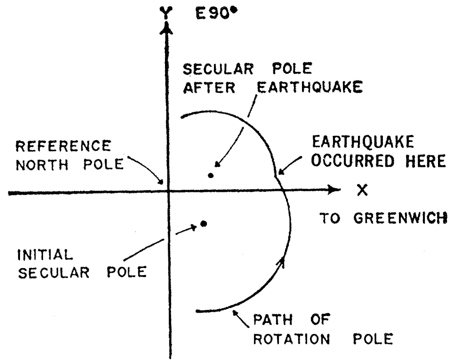


Fig. 2. Effect of an earthquake on the pole path. Displacement field is assumed to be established suddenly.

Changes in the BIH path have been found to correlate closely with the occurrence of 15 out of a total of 22 earthquakes with magnitude $M$ greater than 7.5 that occurred in the period examined, 1957.0 to 1968.0. Evidence of a systematic deviation of the pole path, not revealed by breaks in the least-squares-fitted arcs, can be found for each of the remaining seven earthquakes. Breaks which do not correlate with large earthquakes may arise from the presence of systematic errors, smaller earthquakes, and gradual strain release not associated with shocks. No significant relation between changes in the ILS-IPMS pole path and earthquakes is found.

There are premonitory indications of changes in the BIH pole path 5 to 10 days before a high proportion of the large recorded quakes (Table 1). If these indications are confirmed with an increased number of observations, a change in the pole path might be a valuable signal that a very large scale strain release is about to occur. In combination with instrumentation (*15*) in active fault zones, such indications would provide information on the likely size of an impending quake.

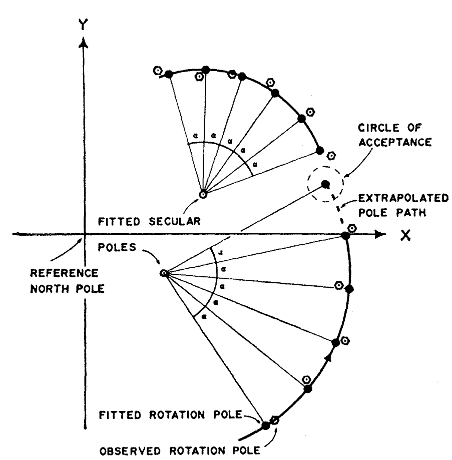


Fig. 3. Method of fitting theoretical pole path to observed path. Angles $\alpha$ are equal.

Finally, the observational evidence found in the BIH pole path strongly supports the theoretical prediction (*4*) that the excitation of the Chandler wobble and the observed secular polar shift are due to large earthquakes. Because the theoretical calculations were based on the very extensive displacement fields given by elasticity theory, the reality of the extent of these fields, both in depth and at distance, is confirmed.

L. MANSINHA
D. E. SMYLIE
*Department of Geophysics, University of Western Ontario, London, Canada*

### References and Notes

1. S. C. Chandler, *Astron. J.* **11**, 65 (1891).
2. S. Newcomb, *ibid.*, p. 81.
3. W. H. Munk and G. J. F. MacDonald, *The Rotation of the Earth* (Cambridge Univ. Press, London, 1960), pp. 163–167.
4. L. Mansinha and D. E. Smylie, *J. Geophys. Res.* **72**, 4731 (1967).
5. The monthly mean values for the period 1900 to 1954 are given by A. M. Walker and A. Young, *Mon. Not. Roy. Astron. Soc.* **117**, 122 (1957). For the period 1900 to 1962 tenth yearly means are to be found in S. Iijima, *Ann. Tokyo Astron. Observ.* **9**, 155 (1965).
6. S. Yumi, *Annual Reports of the International Polar Motion Service for the Years 1962 to 1965* (Central Bureau of the IPMS, Mizusawa, Japan, 1964 to 1967).
7. A. Stoyko and N. Stoyko, *Bull. Astron.* **21**, 205 (1957).
8. Circulaires Nos. 1–140 (Service International Rapide des Latitudes 1956–1967) and Circulaires D1–D20 (Bureau International de l'Heure, Paris, 1966–1968). Professor N. Stoyko supplied the coordinates required to convert the BIH path to the CIO path.
9. W. Munk and E. S. M. Hassan, *Geophys. J.* **4**, 339 (1961).
10. J. Milne, Bakerian Lecture of the Royal Society, *Proc. Roy. Soc. London, Ser. A* **77**, 365 (1906).
11. W. H. Munk and G. J. F. MacDonald, *The Rotation of the Earth* (Cambridge Univ. Press, London, 1960), pp. 163–164.
12. F. Press, *J. Geophys. Res.* **70**, 2395 (1965).
13. W. Markowitz, N. Stoyko, E. Federov, *Research in Geophysics*, H. Odishaw, Ed. (M.I.T. Press, Cambridge, Mass., 1964), vol. 2, pp. 149–162.
14. Magnitudes for the period 1957.0 to 1966.0 were taken from "Principal Earthquakes of the World," *United States Earthquakes* (U.S. Coast and Geodetic Survey, 1957 to 1965 inclusive). The one for 1966 was taken from Seismological Notes, *Bull. Seismol. Soc. Amer.* **57**, 567 (1967).
15. F. Press and W. F. Brace, *Science* **152**, 1575 (1966).
16. We thank R. W. Tanner of the Dominion Observatory, Ottawa, for discussions concerning observations. Supported by the National Research Council of Canada.

3 May 1968