Polar Motion: Historical and Scientific Problems
ASP Conference Series, Vol. 208, 2000
S. Dick, D. McCarthy, and B. Luzum, eds.

Tectonic and Cryospheric Excitation of the Chandler Wobble and A Brief Review of the Secular Motion of Earth's Rotation Pole

S. R. Dickman

Geology Department, State University of New York, Binghamton, New York 13902-6000 USA, dickman@binghamton.edu

1. Introduction

I had originally planned to focus this talk on two novel sources of Chandler wobble excitation: *tectonic*, associated with aseismic processes occurring for example at subduction zones; and *cryospheric*, associated with the transient oceanic responses to episodes of ice-cap melting. I was also asked by the conference convenors to present a brief historical review of the secular motion of Earth's rotation pole. In the course of preparing that review, I was struck by the exceedingly controversial nature of the topic, from beginning to end; as a result, the review will be somewhat lengthy, and I will not have time to discuss cryospheric excitation of wobble.

2. Tectonic Excitation of the Chandler Wobble

The basic premise underlying this excitation source is that observed seismic activity contributes only secondarily to lithospheric plate motions. Evidence supporting this premise comes from a number of regions, where significant discrepancies exist between observed seismic slip and known plate velocities. In California, for example, measured seismic slip rates are 24–30 mm/yr but plate velocities are 48–56 mm/yr; in Iran, slip rates are also about half of the ~26 mm/yr plate velocities. In other regions, the discrepancies are much greater: 20 mm/yr of slip versus plate velocities of 53 mm/yr in central Asia; ~20 mm/yr of slip versus plate velocities exceeding 100 mm/yr in western New Guinea; and so on (see, *e.g.*, DeMets *et al.* 1990, Ekstrom and England 1989, Molnar and Deng 1984, Minster and Jordan 1978, for these and other similar results).

Various explanations of such discrepancies are of course possible. Perhaps great earthquakes, over a time scale of several centuries, manage to achieve substantial displacements in these regions, bringing their seismic slip on the average up to the level of the long-term plate motion. Alternatively, aseismic processes may be acting on all time scales to make up the difference. By "aseismic processes," geophysicists refer to several phenomena, such as "slow earthquakes" and "silent earthquakes" (in which displacement at the source is too gradual to produce significant, or even any, seismic waves at the frequencies observable by seismometers), episodic "creep", and steady "creep" (the term "creep" can itself refer to a variety of micro-scale processes).

Seismologists have accumulated a variety of evidence that such aseismic processes indeed occur. The most important evidence is associated with the great Chilean earthquake of 1960, the largest earthquake of the century. Strain data analyzed by Kanamori and Cipar (1974) and Kanamori and Anderson (1975) provided strong indications that a slow earthquake — with a seismic moment 30% larger than the observed great one — began 15 minutes earlier. Using a low-frequency seismic array, Cifuentes and Silver (1989) and Linde and Silver (1989) inferred that a slow quake, with a 30% smaller moment, occurred 19 minutes earlier.

Evidence for aseismic activity can be found in association with other large earthquakes, such as the MacQuarie Ridge earthquake of 1989 (evidence for a slow quake several minutes earlier, with a moment 70% smaller (Ihmle *et al.* 1993, Ihmle and Jordan 1994)), the Nicaraguan earthquake of 1992 (a slow quake following the main event, with a moment 100% larger (Ihmle *et al.* 1993, Ihmle and Jordan 1994)), the 1977 Sumba earthquake (aseismic slip following (Stewart 1978, Spence 1986)), and the 1970 Colombian and 1963 Peru-Bolivian earthquakes (in each case, slow prior deformation (Dziewonski and Gilbert 1974)). It is difficult to escape the conclusion that slow or silent earthquakes accompany at least some large earthquakes.

Other evidence of aseismic activity comes from geodetic data, which suggested significant aseismic slip for 20 years following the 1906 San Francisco earthquake (Thatcher 1974); shoreline data, which suggested that a slow, deep episode of creep took place prior to the 1960 Chilean earthquake; and 1978–1979 normal-mode data, which was interpreted to indicate a large number of slow and silent earthquakes during that time span (Beroza and Jordan 1990).

Further evidence of aseismic activity comes from rotational data. Smylie and Mansinha (1968) found ~4-month lags and leads in correlations between seismicity and polar motion data; Gross and Chao (1985) discovered a step-change in polar motion excitation following the 1977 Sumba event and concluded that the subducting slab had slipped aseismically over a 20-day period. Preisig (1988) found several instances (such as near the 1985 Chile earthquake) in which his refined polar motion data exhibited 'kinks' within ± 15 days of large earthquakes. By their observability, the aseismic deformations implied by these analyses must possess very large seismic moments.

Given all of these works, it is not surprising that the scientific literature is filled with suggestions that aseismic activity is capable of exciting the Chandler wobble. Early proponents include Chinnery, Dahlen, and others (quoted in Kaula *et al.* 1973), Kanamori and Cipar (1974), O'Connell and Dziewonski (1976), Kanamori (1977), Rochester (1984), and Gross (1986). For example, Rochester (1984) stated that "seismic excitation [of the Chandler wobble] may be more effective ... if there are significant pre- or post-seismic mass shifts."

In 1997, a Ph.D. student of mine named Yongming He completed an analysis of aseismic, tectonic excitation of the Chandler wobble. As you will see, the results — which have not been published elsewhere — are provocative and intriguing, and I would like to summarize his work.

Yongming's work is based on four assumptions. Most basically, each aseismic slip episode is assumed to occur in connection with a major earthquake. Furthermore, the aseismic slip is assumed to have the same focal mechanism as that of the associated earthquake. However, the aseismic moment is assumed to be *amplified*, relative to the associated seismic moment, by a factor denoted **F**

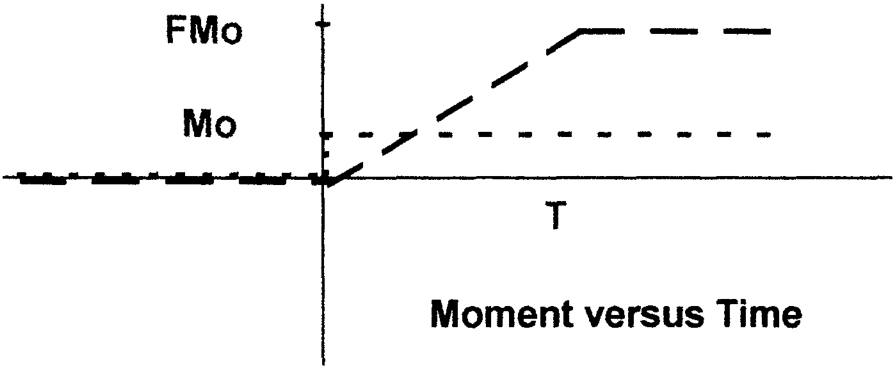

Figure 1. Sketch of seismic moment versus time, illustrating the difference between seismic and aseismic events. The earthquake occurs suddenly, with moment M_0; the aseismic episode takes place over a span of time, reaching a maximum moment $\mathbf{F}M_0$ after time **T**.

(this factor to be determined). Finally, unlike the earthquake — which occurs more or less instantaneously — the aseismic episode has a *ramp* source time function, with a duration **T**. The latter two differences between seismic and aseismic mechanisms are illustrated in Figure 1.

Yongming began by tabulating the characteristics of each of the 45 largest earthquakes that occurred during 1983–1994. The moment tensor of each seismic event, modified by the amplification factor **F**, would yield the moment tensor of the associated aseismic episode. The global displacement field of each episode could then be determined using a normal mode approach modified by the ramp-function time dependence. For each choice of **F**, integrating the displacement field would tell us the change in Earth's inertia tensor, thus the rotational excitation. Comparison with the observed rotational excitation would indicate the most appropriate amplification factor for each episode. We decided early in this research to focus on **F** but not **T**; instead, we chose a duration **T** of 6 months for each aseismic episode as a reasonable 'working value' (from the type of analysis described below, we had actually found that value to be optimum in some cases).

The rotational excitation data that we would be comparing with tectonic predictions was based on the COMB95 data set (R. Gross, personal communication 1996), which provided x and y components of polar motion during 1962–1995 at 5-day intervals. We chose this data set, despite its lower precision and time resolution compared to (*e.g.*) the SPACE95 data, because we were interested in performing the comparison also around the time of the 1964 Alaska earthquake, the second largest earthquake of the century. The data was processed first by removing the seasonal wobbles and linear trend, then by applying the digital deconvolution filter of Wilson (1985) to obtain the excitation time series. AAM "re-analysis" data provided by the NCEP (P. Nelson, personal communication 1996) — 5-day samples produced from smoothed, de-seasoned daily averages of the original 4× daily data, including wind and IB pressure

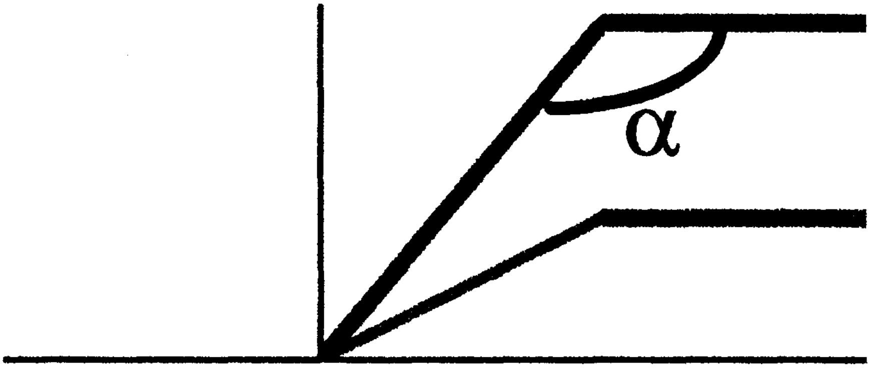

Figure 2. Sketch of aseismically produced polar motion excitation versus time, illustrating that with a larger moment amplification factor **F**, the angle α between the excitation during and after (or before and during) the aseismic episode decreases.

components — were subtracted from the polar motion excitation time series to eliminate atmospheric effects.

Yongming's comparison of predicted and observed excitations was somewhat subtle. The predicted rotational excitation function $\Psi_x + i\Psi_y \equiv \underline{\Psi}$ for an aseismic episode beginning at time $t = 0$ is

$$\underline{\Psi} = (\sigma_r/\sigma_0)/(C_M - A_M)[\mathbf{F}\underline{c}]t/\mathbf{T} \qquad 0 \leq t \leq \mathbf{T}$$

$$\underline{\Psi} = (\sigma_r/\sigma_0)/(C_M - A_M)[\mathbf{F}\underline{c}] \qquad t > \mathbf{T}$$

where $\underline{c} \equiv c_{xz} + ic_{yz}$ is the seismic change in Earth's products of inertia, σ_r and σ_0 are the Chander frequencies for a rigid Earth and as observed, respectively, and C_M and A_M are the mantle's polar and equatorial moments of inertia. This type of solution is shown schematically in Figure 2 for two hypothetical values of **F**. From Figure 2 it should also be clear that the angle denoted α — representing *either* the angle between the aseismic and post-aseismic excitation *or* the angle between the pre-aseismic and aseismic excitation — will decrease as the aseismic amplification **F** increases. It turns out that the predicted angle for a given aseismic situation is

$$\alpha_{\mathrm{PRED}} = \pi + tan^{-1}\{(\sigma_r/\sigma_0)/(C_M - A_M)[\mathbf{F}\underline{c}]/\mathbf{T}\}.$$

It follows that **F** can be estimated by comparing α_{PRED} and α_{OBS}.

Figures 3 and 4 illustrate the procedure for the 1992 Sumba and 1994 Java events. Straight lines are fit to each component of the observed excitation time series under the constraint that the lines must pass through the actual datum at the time of the earthquake (clearly, alternative constraints — or no constraint — are approaches that might be worth considering). These illustrations are

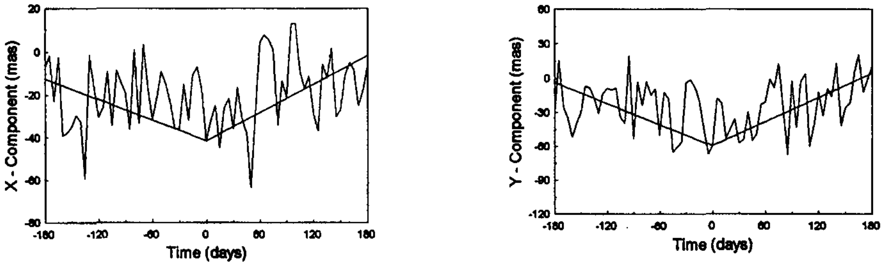

Figure 3. Polar motion excitation time series, x and y components, created as described in the text from the COMB95 data set. The straight lines are best fits to the data, constrained to equal the datum at the time of the 1992 Sumba earthquake, and may represent aseismic activity in that region associated with the Sumba event.

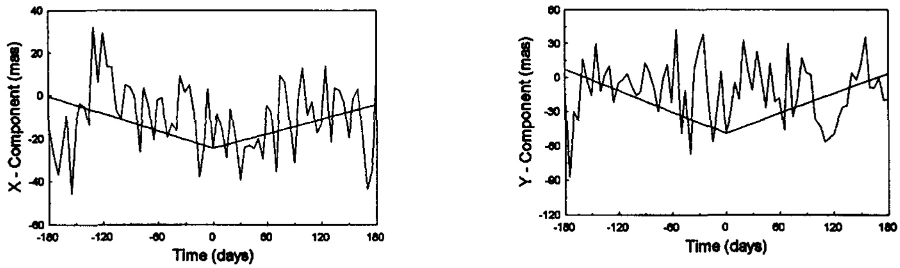

Figure 4. Same as figure 3, but around the time of the 1994 Java earthquake.

typical, in that in some cases the regressed lines do indeed follow the trends in the data, and the trends change around the time of the seismic event, but in other cases (such as the Java y-component) there is no change in trend evident in the data.

Yongming's results are listed in Table 1. The excitation time series were noisier than we had hoped, and linear patterns were often not clear. The implied amplification factors varied widely, ranging from 25 to ~1.5 million. However, the results were obtained without any constraint that the amplification factors for the x and y components be equal or nearly so, even though these components are part of the same vector excitation. It is thus surprising that — despite the wide range of amplification factors — almost 80% of the events have $\mathbf{F}_x$ and $\mathbf{F}_y$ within 1 order of magnitude of each other; and *all* of the events have $\mathbf{F}_x$ and $\mathbf{F}_y$ within a factor of 60 of each other.

Table 1 contains even more provocative results. From the amplification factors, the aseismic changes in the products of inertia can be deduced, thus the total changes; these are also listed in Table 1. We see that the implied total change $\underline{c}$ in inertia is fairly uniform for all 45 events, despite their wide range of *seismic* magnitudes and moments: for c_{xz}, all changes are no more than 3.6

Table 1. Aseismic amplification factors, implied total** change in products of inertia.

Event	F_x*	F_y*	F_x / F_y	Δc_{xz}	Δc_{yz}
				$\times 10^{28}$ kg m^2	$\times 10^{28}$ kg m^2
Solomon Is. 3/18/83	12741	1566	8.1	+3.5	−3.3
Costa Rica 4/3/83	941	1312	0.7	+0.5	−0.6
Japan Sea 5/26/83	777	570	1.4	−3.0	+2.3
Chile 10/4/83	1051	1354	0.8	−0.9	+3.1
Sumba 11/24/83	9018	5689	1.6	+3.3	−2.7
*****Solomon Is. 2/7/84**	**23118**	**2249**	**10**	**+5.9**	−2.7
Izu Trench 3/6/84	**7894**	**89059**	**0.09**	−3.1	−2.3
Philippines 8/6/84	**4648**	**47808**	**0.1**	−1.5	**+11.7**
Philippines 11/20/84	36133	50508	0.7	+14.2	+5.8
Chile 3/3/85	1593	608	2.6	−5.8	+6.1
Mexico 9/19/85	1058	696	1.5	+0.6	−3.5
Mexico 9/21/85	9009	3041	3.0	+1.3	−3.4
Aleutian Tr. 5/7/86	**101**	**6645**	**0.02**	−0.8	**+5.1**
Philippines 8/14/86	**1445286**	**70315**	**21**	**+9.6**	**+5.1**
Kermadec Tr. 10/20/86	3039	3841	0.8	+3.3	+9.7
Ryukyu Tr. 11/14/96	2306	2373	1.0	−0.8	+3.0
Chile 3/5/87	11597	4798	2.4	−9.0	+5.9
MacQuarie 9/3/87	9544	20889	0.5	−2.8	−4.6
Aleutian Tr. 11/30/87	1920	1220	1.6	+5.5	−1.8
Aleutian Tr. 3/6/88	6683	3896	1.7	+6.7	−7.0
Solomon Is. 8/10/88	1113	7400	0.2	+0.6	−4.9
MacQuarie 5/23/89	**58**	**662**	**0.09**	**+0.3**	−2.6
Japan Tr. 11/1/89	5699	6063	0.9	−3.7	+3.8
Philippines 12/15/89	2583	4290	0.6	−0.6	+3.9
Fiji Is. 3/3/90	31680	41929	0.8	−12.0	−7.1
Costa Rica 3/25/90	**40917**	**2445**	**17**	**+6.5**	−0.4
Mariana Tr. 4/5/90	**4756**	**453**	**11**	**+3.8**	−0.4
Philippines 4/18/90	17376	53769	0.3	−4.4	−5.8
Philippines 7/16/90	616	1159	0.5	+0.9	+1.7
Solomon Is. 12/30/90	10657	1142	9.3	−0.6	+1.2
Costa Rica 4/22/91	**306**	**5562**	**0.06**	**+0.3**	−4.0
Kurile Is. 12/22/91	8895	13765	0.6	−6.1	+18.7
Nicaragua 9/2/92	4437	503	8.8	+1.8	−0.4
Vanuatu 10/11/92	1736	10973	0.2	+0.8	−7.1
Sumba 12/12/92	2072	10880	0.2	+3.5	−9.1
Kurile Is. 1/15/93	59088	74466	0.8	+4.0	+7.0
Kurile Is. 6/8/93	2471	2213	1.1	−4.8	+2.8
Japan Sea 7/12/93	2049	955	2.1	−10.5	+4.2
Mariana Tr. 8/8/93	**1353**	**79544**	**0.02**	−2.6	**+11.5**
Fiji Is. 3/9/94	5348	3311	1.6	−4.0	−3.6
Java 6/2/94	61391	20834	2.9	+5.6	−10.4
Bolivia 6/9/94	136	25	5.4	−1.3	+0.4
Japan Sea 7/21/94	29108	47099	0.6	−12.2	+6.6
Kurile Is. 10/4/94	135	29	4.7	−2.2	+0.5
Kurile Is. 12/28/94	436	425	1.0	−0.8	+0.8

*mean value, based on range of amplification factors inferred using 95% confidence limits for fitted lines

**total is sum of seismic and aseismic changes in the products of inertia

*** bold entries correspond to events whose ratio $\mathbf{F_x/F_y}$ differs from unity by more than 1 order of magnitude times the average c_{xz}, no less than 1/13.5 times the average c_{xz}; for c_{yz}, all changes are no more than 4.0 times the average c_{yz}, no less than 1/12.9 times the average c_{yz}.

Still more intriguing, all of these changes in inertia are nearly the **same** as the total change for the great Chilean event of 1960. Using the aseismic moment for Chile estimated from Kanamori and Cipar (1974), the totals for Chile 1960 were

$$c_{xz} = 0.7 \times 10^{28} \qquad c_{yz} = 2.0 \times 10^{28};$$

the average inferred total changes for our 45 events are

$$c_{xz} = 3.9 \times 10^{28} \qquad c_{yz} = 4.6 \times 10^{28}.$$

There are thus three conclusions from our work. The consistency of our results suggests (1) that our approach may be scientifically reasonable; (2) that *all* aseismic activity (at least at subduction zones) operates at essentially the same level — a tectonically significant level; and (3) that aseismic processes may indeed have the potential to excite the Chandler wobble.

3. Secular Trend of the Rotation Pole: A Review

Historically, this subject can be divided into different "eras", reflecting the evolution of our views concerning its significance, nature, and causes; and in each era, controversies abound. Even before the establishment of the ILS — as far back as 1872 (Markowitz 1960) — there was astronomical evidence of secular changes in latitude at observatories; but the evidence was dismissed as observational error.

After Chandler's discovery of wobble in 1891, and even during the first decade of the ILS, attention was understandably focused on the periodic signals in latitude data and in the inferred position of the rotation pole. But by the middle of the second decade of the twentieth century, data analyses began to reveal clear evidence of a secular drift of the rotation pole. In fact, all of the "early" (*i.e.*, prior to 1960) analyses of ILS polar motion data, as summarized in Table 2, provided consistent determinations of that trend, at a rate of a few milliarcseconds (mas) per year in a general direction towards the east coast of North America. Nevertheless, a controversy raged following the claim by Schlesinger (1922) that the drift was merely an artifact of southward crustal motion of one ILS station, that at Mizusawa. The purported latitude shift at Mizusawa was initially claimed to be 9 mas/yr, which is equivalent to ~30 cm/yr — a rate we would (at least now) recognize as unrealistically high. The controversy continued for decades, as highlighted in Table 3, with various researchers taking opposing views (in some cases against themselves!) or compromise platforms.

In 1960, a thorough, thoughtful, and very persuasively written work by Markowitz (1960) seems to have firmly rebutted the possibility of Mizusawa's hypothetical southward drift. By this time, however, other doubts had been raised about the reality of the secular drift of the pole, and the issue remained clouded. One very frustrating doubt concerned the effect of changes in the star catalogues used in the ILS observational programs. Analysis of the data had led to the suggestion that the drift of the mean pole was an artifact of such changes

Table 2. Secular polar motion: early inferences. Vector mean value, excluding Sekiguchi (1956) due to its limited time span.

researcher	time span	secular polar trend rate	secular polar trend direction
Wanach (1916)	1900–1915	*3 mas / yr*	*55° W*
Lambert (1922)	1900–1917	*4.8*	*78° W*
Lambert (1922)	1900–1918	*6.6*	*81° W*
Mahnkopf (1932)	1900–1923	*5.1*	*62° W*
Kimura (1924)	1900–1923	*5.8*	*57° W*
Wanach (1927)	1900–1925	*4.7*	*42° W*
(Sekiguchi (1956)	1923–1935	*10.3*	*91° W)*
Cecchini (1952)	1900–1950	*1.8*	*38° W*
Comstock (1954) Orlov (1954)	1900–1950	*4.2*	*69° W*
Markowitz (1960)	1900–1959	*3.2*	*60° W*
AVERAGE*		**4.2 mas / yr**	**64°W**

Table 3. Interpretation of secular latitude changes.

researcher	Mizusawa displacement?	*Secular polar motion?*
Schlesinger (1922) vs. Lambert [1922]	−9 mas/yr* · no	*no* · *yes*
Kimura (1924) vs. Kimura [1940]	yes · −3.4 mas/yr	*yes* · *no*
Hattori (1946)	yes	*only 1919–1920*
Cecchini (1950) vs. Cecchini [1959]	−2.4 mas/yr · no	*slight, 1935–1950* · *slight, 1935–1950*
Orlov (1958)	−6 mas/yr	*yes*
Markowitz (1960)	no	*yes*

— despite the fact that the analysis implied a contamination in the direction normal to the trend rather than in the direction along the trend. The suggestion was investigated by Sekiguchi (1956), who found (see Table 2) that even during a limited span of time contained entirely within 1 observing program, the trend persisted, with a direction and rate similar to that gleaned from longer time spans.

It is very puzzling to read that, despite this work and despite Sekiguchi (1954) having declared the star catalogue effect to be minor, Munk and MacDonald (1960) in their landmark monograph concluded that the effect was a major one. They further declared that there was "no general agreement" (p. 76) on the existence of a secular polar trend, though (as illustrated in Table 2) all of the analyses were fairly consistent with each other. Munk and MacDonald also stated (p. 175) that "*... a glance at [the data] establishes the absence of any obvious drift.*" Indeed, there is no trend apparent in their illustration, but one is clearly seen in ILS data (even in the 1900–1960 portion) and was easily measured in all of the data analyses published up until that time!

Through the 'era' of the 1960s and 1970s, the analyses continued (see Table 4), now including other data sets besides the ILS. For example, McCarthy (1972) measured a secular change in the latitude of Washington, D.C.; since the ILS secular polar motion is directed roughly towards Washington, the drift rate he inferred would be very nearly that of the rotation pole itself, and indeed it fits in well with the polar drift rates listed in Table 4. In fact, all of the determinations in Table 4 agree well with the earlier estimates (Table 2).

Table 4. Secular polar motion: estimates continue.

researcher	**time span**	**secular polar trend rate**	**secular polar trend direction**
Markowitz (1968)	1900–1966	*3.2 mas / yr*	*60° W*
Markowitz (1970)	1900–1966	*3.5*	*65° W*
Yumi & Wako (1970)	1899–1966	*2.20*	*77.7° W*
Arur & Mueller (1971)	1900–1966	*3.3*	*75° W*
Proverbio *et al.* (1972)	1900–1962	*2.94*	*65.6° W*
Stoyko (1972)	1900–1966	*4.0*	*73° W*
Stoyko (1972)	1900–1966	*3.2*	*70° W*
McCarthy (1972)	1916–1967	*>3.01*	*(77° W)*
Proverbio & Quesada (1974)	1900–1970	*3.07*	*69.6° W*
Dickman (1977)	1900–1974	*3.41*	*76.3° W*

Yet, during this era another issue clouded our understanding of the secular polar trend. Continental drift had become fully established as a real phenomenon of the Earth, and it was a distinct possibility that the ILS trend was merely an artifact of the continental drift of the lithospheric plates to which the ILS stations are attached. This possibility was addressed, and refuted, by Soler and Mueller (1978) and Dickman (1977), who used newly constructed absolute plate velocity models to predict the amount of secular polar motion that would be produced by continental drift of the ILS stations. They found that latitude observations are affected only secondarily by continental drift; the latter contributes typically only ~10% of the observed trend. The reasons for its minor effect are that continental drift (particularly for the North American and Eurasian plates) is (1) slow and (2) primarily east-west. It follows, then, that the Earth's rotation pole really *is* moving, with respect to the surface; the secular motion of the rotation pole, measured by the ILS stations, amounts to a true polar wander (TPW) of the Earth. This TPW is of respectable magnitude: the pole is moving faster than the plates, the ILS rate of ~3.5 mas/year being equivalent to more than 10 cm/yr; the rate of true polar wander is about 1° per million years.

At the same time that the physical nature of the trend was being established, the ILS data was being re-worked (Yumi and Yokoyama 1980). The 'modern' era of determinations of the secular trend includes a number of analyses, summarized in Table 5, based on that newer, more "homogeneous" ILS data set as well as on other, more sophisticated and/or higher accuracy 'space geodetic' data sets.

Table 5. Secular polar motion: modern determinations.

researcher	**time span**	**secular polar trend rate**	**secular polar trend direction**
Wilson & Vicente (1980)	1900–1977	*3.4 mas / yr*	*66° W*
Dickman (1981)	1900–1979	*3.52*	*80.1° W*
Gross (1982)	1899–1979	*3.96*	*69.3° W*
Chao (1983)	1900–1979	*3.52*	*79.4° W*
Okamoto and Kikuchi (1983)	1899–1979	*3.46*	*80.6° W*
Zhao & Dong (1988)			
ILS+others	1900–1978	*1.59*	*71° W*
Poma *et al.* (1991)	1900–1979	*3.4*	*79° W*
Vondrák *et al.* (1995)			
HIPPARCOS(-)	1900–1990	*3.31 mas/yr*	*78.1° W*
McCarthy & Luzum (1996)			
ILS+BIH+NEOS	1899–1994	*3.33*	*75.0° W*
NEOS	1976–1994	*3.39*	*85.4° W*
Gross (1998)			
ILS	1900–1979	*3.8*	*75.5° W*
Space96	1976–1997	*4.123*	*73.9° W*
HIPPARCOS	**1899–1992**	**3.51**	**79.2°W**

It is worth noting three points. First, these modern determinations of the secular polar motion are consistent with all of the previous estimations. Second, even in the midst of this modern era doubt was cast on the reality of the secular trend. For example, the IAPSO Advisory Committee on Tides and Mean Sea Level (1985) stated "It may even be that the entire apparent secular motion of the pole is an artifact of systematic [errors] in the ILS pole position determinations."

Third, the most recent and perhaps best estimates of the trend may be those based on the Hipparcos data set (Vondrák 1991 and later papers), the most sophisticated re-working and expansion of the original ILS observations to date. The analysis by Gross (1998) (see also Gross and Vondrák (1999)), which accounted comprehensively for the presence of other signals in the data, yielded a polar drift rate of 3.5 mas/yr in the direction towards 79° W.

date. The analysis by Gross (1998) (see also Gross and Vondrák (1999)), which accounted comprehensively for the presence of other signals in the data, yielded a polar drift rate of 3.5 mas/yr in the direction towards 79° W.

3.1. Cause(s) of the Secular Polar Motion: The Controversies Continue

Even before the trend was recognized as a true polar wander, there were geophysical attempts to discover its cause (see, *e.g.*, Munk and MacDonald 1960). Through most of the modern 'era,' one excitation source has maintained its position as the preferred explanation of the secular polar motion. In the words of Lambeck (1988),

> "All solutions of the equations of polar motion driven by realistic models of the deglaciation of the ice sheets predict a shift of the mean rotation pole in a direction of about 70° west..., and this is remarkably close to the observed shift since about 1900.... *The agreement in the phase of the pole shift therefore suggests that the primary excitation is the Late Pleistocene deglaciation.*"

There are a few reasons why Pleistocene deglaciation is the trend's most likely excitation source. Because the mantle is viscous, we *expect* true polar wander to be excited by (surface) mass re-distributions. And, when a reasonable viscosity is chosen (or, more specifically, when reasonable viscosities for the upper and lower mantle are chosen), forcing by the known late-Pleistocene ice history does indeed yield a TPW with the observed (ILS) rate and direction (Lambeck and Nakiboglu 1980, Sabadini and Peltier 1981, *etc.*). Additionally, that true polar wander direction is towards Laurentia (the Hudson's Bay region of Canada), the center of the largest Pleistocene ice sheet.

But even this candidate has become controversial. This past year, research has focused on the 'reasonable' upper mantle viscosity employed by essentially all TPW analyses, questioning the need for those analyses to treat it as a fixed constraint. And, in recent years, the assumption that the southern hemisphere has contributed negligibly to the forcing has begun to be questioned as well.

So, what about *other* excitations? And, if other excitation sources exist, how small can they be and still affect the secular polar motion? At one extreme, the Earth might be rotationally unstable, tending to overturn catastrophically even when a tiny mass — such as "Gold's beetle" (Gold 1955) — shifts its location a bit on the surface; at the other extreme, the Earth will be stable to all but the largest mass re-distributions.

One point we do understand is that non-isostatic processes will have a greater effect than isostatic processes (*e.g.*, Vermeersen and Vlaar 1993). Thus, for example, continental drift represents a negligible mass re-distribution in terms of its ability to excite TPW (Soler and Mueller 1978, Dickman 1979), as does isostatically compensated erosional processes, which Destrigneville *et al.* (1987) found to be 100 times too small to explain the ILS trend.

Other excitations could be long-term, *e.g.* tectonic, or present-day, *e.g.* global warming. If the long-term sources are more effective, then we would have to recognize (as many have) that "a considerable fraction of the current polar motion may represent a secular trend that has existed for millions of years" (Steinberger and O'Connell 1997).

Overall, if other sources are contributing non-negligibly to the secular polar motion, then we are faced with the most geophysically frustrating question: how do all of the various contributions to the observed TPW affect the inference of mantle viscosity? This question remains unanswered as of today; but I would like to give you a brief appreciation of the variety of disciplines that may play a role in the answer.

On-going seismo-tectonic excitations of the secular polar motion might include

- seismic activity. For example, Gross and Chao (1999) found seismic effects during 1977–1998 to be fairly negligible, with a TPW towards 153°E at a rate of ~0.07 mas/yr. On the other hand, the net shift in the rotation pole from the 1960 Chile and 1964 Alaska events, the two largest earthquakes of this century, has been predicted to be 30 mas; clearly, with a seismicity that is sufficiently intense, earthquakes have the potential to affect the secular polar motion.
- aseismic activity. Boschi *et al.* (1985) found the ability of asthenospheric viscosity to amplify seismic deformation to be small, leading to a TPW drift rate of ~0.17 mas/yr (thus, a few percent of the observed rate). Alfonsi and Spada (1998) found the effects of deeper mantle viscosity to be fairly negligible during the past two decades, the resulting TPW being towards 50°W at a rate of ~0.08 mas/yr.
- mountain building. Vermeersen and Vlaar (1993) found the effects of steady uplift of the Himalayas to be quite non-negligible, yielding a TPW towards 97°W at a rate of ~0.7 mas/yr (thus, perhaps 20% of the observed secular polar motion).
- subducting slabs. Even in the early days of plate tectonics, the effects of subduction on TPW was recognized as potentially important (Takeuchi and Sugi 1972). Spada *et al.* (1992) found that a 'rain' of lithospheric slabs descending into the mantle would produce a significant true polar wander, with a drift rate of ~1.8 mas/yr (half of the observed net motion).
- mantle convection. Steinberger and O'Connell (1997) found that convective re-distributions of mass would be able to cause a significant TPW, towards 24°W at a rate of ~1.4 mas/yr.

Finally, various short-term excitation sources operating today may be envisioned as well, including

- surface water fluctuations. For example, Chao (1983) estimated that lowering of the Caspian Sea during 1930–1955 caused a definitely non-negligible secular polar motion, towards 130°E at a rate of ~0.7 mas/yr.
- groundwater storage. Work such as that by Kuehne and Wilson (1990) and many others will eventually allow us to quantify the long-term (from a hydrological point of view) global changes in groundwater storage.
- cryospheric changes. Melting of ice caps, and the associated global rise in sea level, was explored as a potential excitation of the secular rotational trend by a number of authors in the 1950s (see, *e.g.*, Munk and MacDonald 1960 for references and for their own development of the subject). Its potential importance has continued to the present time, especially in association with a

postulated global warming (*e.g.*, Trupin 1993, James and Ivins 1997, *etc.*). Ongoing glaciological and impending satellite gravity measurements may allow the mass budgets of the ice caps and also mountain glaciers to be better quantified during the next few years, and in combination with altimetry measurements of global sea level should allow their effects on the secular polar motion to be predicted better.

The potential excitation sources of secular polar motion that I have mentioned reflect the variety of Earth systems that evolve and interact. It is not yet apparent which will turn out to be most important, or whether some will cancel each other out. But the direction of the ILS secular trend ends up pointing towards Hudson's Bay, so it may well end up that the most preferred candidate is also the most enduring.

Acknowledgments. I am grateful to A. Feingold for assistance with LaTeX, and to S. Dick and D. McCarthy for their invitation to speak in Cagliari.

References

Alfonsi, L. & Spada, G. 1998, *J. Geophys. Res.*, **103**, 7351.

Arur, M. & Mueller, I. 1971, *J. Geophys. Res.*, **76**, 2071.

Beroza, G. & Jordan, T. 1990, *J. Geophys. Res.*, **95**, 2485.

Boschi, E., Sabadini, R., & Yuen, D. 1985, *J. Geophys. Res.*, **90**, 3559.

Cecchini, G. 1950, *Bull. Geodes.*, **17**, 325.

Cecchini, G. 1952, *Bull. Geodes.*, **26**, 423.

Cecchini, G. 1959, Pubbl. Uffico Centrale Latit., Pino Torinese.

Chao, B.F. 1983, *J. Geophys. Res.*, **88**, 10299.

Cifuentes, I. & Silver, P. 1989, *J. Geophys. Res.*, **94**, 643.

Comstock, G. 1954, *Astron. J.*, **12**, 24.

DeMets, C., Gordon, R., Argus, D., & Stein, S. 1990, *Geophys. J. Int.*, **101**, 425.

Destrigneville, C., Pinet, P., & Souriau, A. 1987, The influence of erosion on the polar secular drift, preprint.

Dickman, S.R. 1977, *Geophys. J. Roy. Astr. Soc.*, **51**, 229.

Dickman, S.R. 1979, *Geophys. J. Roy. Astr. Soc.*, **57**, 41.

Dickman, S.R. 1981, *J. Geophys. Res.*, **86**, 4904.

Dziewonski, A. & Gilbert, F. 1974, *Nature*, **247**, 185.

Ekstrom, G. & England, P. 1989, *J. Geophys. Res.*, **94**, 10231.

Gold, T. 1955, *Nature*, **175**, 526.

Gross, R.S. 1982, A determination and analysis of polar motion, Ph.D. dissert., University of Colorado, Boulder.

Gross, R.S. 1986, *Geophys. J. Roy. Astr. Soc.*, **85**, 161.

Gross, R.S. 1998, EOS, Fall Meeting.

Gross, R.S. & Chao, B.F. 1985, *J. Geophys. Res.*, **90**, 9369.

Gross, R.S. & Chao, B.F. 1999, IUGG XXII General Assembly, Birmingham, A67.

Gross, R.S. & Vondrák, J. 1999, *Geophys. Res. Lett.*, **26**, 2085.

Hattori, T. 1946, *Proc. Imp. Acad. Japan*, **22**, 151.

IAPSO, Advisory Committee on Tides and Mean Sea Level. 1985, EOS, **66**, 754.

Ihmle, P., Harabaglia, P., & Jordan, T. 1993, *Science*, **261**, 177.

Ihmle, P. & Jordan, T. 1994, *Science*, 266, 1547.

James, T.S. & Ivins, E.R. 1997, *J. Geophys. Res.*, **102**, 605.

Kanamori, H. 1977, *J. Geophys. Res.*, **82**, 2981.

Kanamori, H. & Cipar, J. 1974, *Phys. Earth planet. Int.*, **9**, 128.

Kanamori, H. & Anderson, D. 1975, *J. Geophys. Res.*, **80**, 1075.

Kaula, W., Lambeck, K., Markowitz, W., Mueller, I., & Smylie, D. 1973, EOS, **54**, 792.

Kimura, H. 1924, *Japanese J. Astr. Geophys.*, **2**, 140.

Kimura, H. 1940, *Results Int. Latit. Serv.*, **8**, 232.

Kuehne, J. & Wilson, C.R. 1990, in *Variations in the Earth's rotation*, ed. D. McCarthy, W. Carter, AGU Monogr. 59, 147.

Lambeck, K. 1988, *Geophysical Geodesy*, Oxford University Press.

Lambert, W. 1922, *Astron. J.*, **34**, 103.

Linde, A. & Silver, P. 1989, *Geophys. Res. Lett.*, **16**, 1305.

Mahnkopf, H. 1932, Ergebn. Int. Breitendienst., **6**, 232.

Markowitz, W. 1960, in *Methods and Techniques in Geophysics*, I, ed. S.K. Runcorn, Interscience, N.Y., 325.

Markowitz, W. 1970, in *Earthquake Displacement Fields and the Rotation of the Earth*, eds. L. Mansinha, D. Smylie, & A.E. Beck, D. Reidel, Dordrecht, 69.

McCarthy, D.D. 1972, in *Rotation of the Earth*, eds. P. Melchior & S. Yumi, Dordrecht, 86.

McCarthy, D.D. & Luzum, B.J. 1996, *Geophys. J. Int.*, **125**, 623.

Minster, J.-B. & Jordan, T. 1978, *J. Geophys. Res.*, **83**, 5331.

Molnar, P. & Deng, Q. 1984, *J. Geophys. Res.*, **89**, 6203.

Munk, W.H. & MacDonald, G.J.F. 1960, *The Rotation of the Earth*, Cambridge University Press (reprinted with corrections, 1975).

Nakiboglu, S. & Lambeck, K. 1980, *Geophys. J. Roy. Astr. Soc.*, **62**, 49.

O'Connell, R. & Dziewonski, A. 1976, *Nature*, **262**, 259.

Okamoto, I. & Kikuchi, N. 1983, *Publ. Int. Latit. Obs. Mizusawa*, **16**, 35.

Orlov, A. 1954, Sur le but et le programme d'observation du ILS, Moscow, 86.

Orlov, A. 1958, Service des latitudes, Moscow, 102.

Poma, A., Proverbio, E., & Uras, S. 1991, *Pubbl. Staz. Astron. Carloforte-Cagliari*, **14**, 119.

Preisig, J. 1988, Relationships of earthquakes (and earthquake-associated mass movement) and polar motion as determined by Kalman-filtered, very-long-baseline-interferometry group delays, Ph.D. dissert., State University of New York at Binghamton.

Proverbio, E., Carta, F., & Mazzoleni, F. 1972, in *Rotation of the Earth*, eds. P. Melchior & S. Yumi, Dordrecht, 97.

Proverbio, E. & Quesada, V. 1974, *J. Geophys. Res.*, **79**, 4941.

Rochester, M.G. 1984, *Phil. Trans. Roy. Soc. Lond., A*, **313**, 95.

Sabadini, R. & Peltier, W.R. 1981, *Geophys. J. Roy. Astr. Soc.*, **66**, 553.

Schlesinger, F. 1922, *Astron. J.*, **34**, 42.

Sekiguchi, N. 1954, *Publ. Astron. Soc. Japan*, **5**, 109.

Sekiguchi, N. 1956, *Publ. Astron. Soc. Japan*, **8**, 1.

Smylie, D. & Mansinha, L. 1968, *J. Geophys. Res.*, **73**, 7661.

Soler, T. & Mueller, I. 1978, *Bull. Géodés.*, **52**, 39.

Spada, G., Ricard, Y., & Sabadini, R. 1992, *Nature*, **360**, 452.

Spence, W. 1986, *J. Geophys. Res.*, **91**, 7225.

Steinberger, B. & O'Connell, R. 1997, *Nature*, **387**, 169.

Stewart, G. 1978, EOS, **59**, 326.

Stoyko, A. 1972, *Vistas Astron.*, **13**, 51.

Takeuchi, H. & Sugi, N. 1972, in *Rotation of the Earth*, eds. P. Melchior & S. Yumi, Dordrecht, 212.

Thatcher, W. 1974, *Science*, **184**, 1283.

Trupin, A.S. 1993, *Geophys. J. Int.*, **113**, 273.

Vermeersen, L.L.A. & Vlaar, N. 1993, *Geophys. Res. Lett.*, **20**, 81.

Vondrák, J. 1991, *Bull. Astron. Inst. Czech.*, **42**, 283.

Vondrák, J., Ron, C., Pesek, I., & Cepek, A. 1995, *A&A*, **297**, 899.

Wanach, B. 1916, Veroff. Zent-bur. Int. Erdmess., **5**, 220.

Wanach, B. 1927, *Zeitschr. Geophys.*, **3**, 103.

Wilson, C.R. & Vicente, R.O. 1980, *Geophys. J. Roy. Astr. Soc.*, **62**, 605.

Yumi, S. & Wako, Y. 1970, in *Earthquake Displacement Fields and the Rotation of the Earth*, eds. L. Mansinha, D. Smylie, & A.E. Beck, D. Reidel, Dordrecht, 82.

Yumi, S. & Yokoyama, K. 1980, Results of the International Latitude Service in a Homogeneous System, 1899.9–1979.0, *Publ. Int. Latit. Obs. Mizusawa*, Mizusawa, Japan, 199 pp.

Zhao, M. & Dong, D. 1988, in *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*, ed. A. Babcock & G. Wilkins, D. Reidel, Dordrecht, 385.