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Modern observations of the effect of earthquakes on the Chandler wobble

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ABSTRACT

Earthquakes have long been postulated as the source of excitation of the Chandler wobble (Mansinha and Smylie, 1967). More recently, the classical astronometric observations of the polar motion have been replaced by very long baseline interferometric (VLBI) observations with an improvement in accuracy by a factor of several thousand. We analyze the record of nearly 29 years of VLBI polar motion observations from the Goddard Space Flight Center.

In addition to the Chandler wobble, the polar motion has annual components making the analysis more difficult. The present study extends the polar motion sequence in both directions by the maximum entropy method (MEM). This allows the annual components, both the prograde motion and a weaker retrograde motion, to be identified and removed, leaving a pure Chandler wobble and secular polar shift. In the absence of excitation, the free Chandler wobble is closely a prograde circular motion. Circular arcs are fitted to the pole path, free of the annual components, to determine breaks corresponding to sudden excitations. The event times of earthquakes of magnitude greater than or equal to 7.5 are shown on the plotted pole paths. Often, the effects on the pole path precede the earthquake by many days, confirming the establishment of the far-field displacements in advance of the earthquake. The precursory rise in P-wave attenuation before the 2004 Parkfield earthquake, as discovered by Chun et al. (2010), may indicate a similar effect from local deformations.

1. Introduction

Modern observations of the polar motion by the very long baseline interferometric (VLBI) technique have revolutionized the study of the effects of earthquakes on the pole path. The astronometric observations previously made by the International Latitude Service (ILS), the International Polar Motion Service (IPMS) and the Bureau International de l'Heure (BIH) often differed by up to 10 cs (centiseconds) of arc or 3 m of polar displacement (Smylie and Mansinha, 1968). In contrast, VLBI observations have error levels as small as 0.009 cs of arc or 2.7 mm of polar displacement. A recent review of the evolution of polar motion measurements has been published by Smylie and Zuberi (2009).

The simplest model of the effect of earthquakes on the polar motion takes the displacement field to be established as a step function at the time of the earthquake. The effect would be a step-function shift in the secular pole and nearly an equal and opposite change in the pole path, thus producing a second-order discontinuity in the pole path as outlined most recently by Smylie and Zuberi (2009). In this model the pole would proceed at a uniform rate along a circular arc centred at the secular pole until the exact time of the earthquake. At the time of the earthquake, the secular pole would shift and the pole would proceed at a uniform rate along a new circular arc centred at the new secular pole. A first indication that this model might be wrong was given by Smylie and Mansinha (1968) who found that, for earthquakes of magnitude greater than 8, the break in the BIH pole path occurred as much as 19 days before the earthquake. The probability of this being a random result was found to be 0.09%. At the time, the error level of the measured pole positions was so high that the result was considered doubtful.

The history of the calculation of the effect of earthquakes on the polar motion is a complicated one. The original calculation by Smylie and Mansinha (1971) correctly took account of the static boundary conditions for the fluid outer core but failed to take full

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account of the tensor nature of the focal force system. Dahlen (1971) used a normal mode expansion to represent the effect on the polar motion, but it was shown that this was incomplete because in static deformation the variable y_1, in the notation of Alterman et al. (1959), is discontinuous. Dahlen (1973) later corrected his calculation, but the same erroneous assumption has recently been made by Gross and Chao (2006). Israel et al. (1973) accepted the discontinuity in y_1 but showed that there is a corresponding discontinuity in the variable y_6. Mansinha et al. (1979) corrected the calculation to include the tensor nature of the focal force system and took account of the discontinuities of both y_1 and y_6. They found a polar shift of 2.6 cs of arc towards 110°E for the 1960 Chile event and 1.2 cs of arc towards 193°E for the 1964 Alaska event. Dahlen (1973) found computed shifts in the same directions but of magnitude 1.02 cs of arc for the Chile event and 0.48 cs of arc for the Alaska event, consistently a factor of 2.5 smaller. A recent review of the effects of earthquakes by Xu et al. (2013) suggests that simplifications in the Dahlen model may lead to underestimates. Nonetheless, a considerable range of uncertainty in computed polar shifts exists. Kanamori and Cipar (1974) suggest there might be significant preseismic energy release in major earthquakes. For the 1960 Chile earthquake they estimate that the main shock and a precursory event 15 min before the main shock might lead to a seismic moment more than 12 times larger and a polar shift of 8.62 cs of arc towards 114°E.

The role of the atmosphere and oceans in the excitation of the annual wobble has long been investigated (see Chapter 7 in the book *The Earth's Variable Rotation* (Lambeck, 1980) for a review). While this source of excitation peaks near the annual period, it has also been investigated as responsible for the excitation of the Chandler wobble. Gross (2000) found that atmospheric wind and pressure fluctuations alone do not have sufficient power to excite the Chandler wobble, but including the effects of oceanic currents and ocean-bottom pressure fluctuations could result in matching the observed power of the Chandler wobble. A more recent review (Liao et al., 2003) comes to the same conclusion. In contrast to seismic effects with directly observable signatures on the pole path, excitations by the atmosphere and oceans tend to exist uniformly over a broad spectrum with no observable signature on the pole path.

The VLBI polar motion observations are freely available on the Goddard Space Flight Center website (http://gemini.gsfc.nasa.gov/solutions). Conveniently, standard errors for each pole position are given on the website. In this study, we analyze the VLBI pole path from 8 August 1983 through 19 June 2012, a sequence just short of 29 years in length. The average standard error for the whole record is 0.048 cs of arc or 14.6 mm of polar displacement. For the latter part of the record from 1987.0 onwards that is used for the pole path plots shown here, the average standard error is 0.044 cs of arc or 13.4 mm of polar displacement. The polar motion has three distinct components: an annual motion excited by the seasonal variations of atmospheric and oceanic mass distributions; the Chandler wobble, a natural motion of the Earth; and the secular polar shift or permanent offset of the pole. The Chandler wobble has a period of 436 days and its spectral proximity to the annual motion makes that difficult to separate from the Chandler wobble by conventional spectral analysis. The spectral density found by singular value decomposition with pole positions weighted by the inverse of the square of the standard error is shown in pages 279–285 in the book *Earth Dynamics* (Smylie, 2013). While the maximum entropy method (MEM) yields spectra without confidence intervals, it does resolve the annual components and the Chandler resonance (Smylie, 2013, Fig. 4.8). The fit to the Chandler resonance (Smylie, 2013, Fig. 4.9) yields a period of 435.8 days and a Q of 228. This large Q is compatible with values for the mantle and crust found from seismic wave attenuation (Lambeck, 1980, p. 202. In conventional spectral analysis, windowing to prevent finite record effects limits frequency resolution. Even with a 'good' window such as the Parzen window, to see a Q this large would require a record length of 990 years (Smylie, 2013, p. 302).

To remove the annual components from the polar motion we use the maximum entropy method (MEM) to extend the sequence in both directions (Smylie et al., 1973). This allows the annual components, both prograde and retrograde, to be resolved in a periodogram of the polar motion sequence and be removed by subtraction of terms in the discrete Fourier transform (DFT).

The resulting polar motion sequence, free of annual components, is then spline interpolated to daily values. Then, following the practice in the original BIH data, the daily values are reduced to 10-day means. This allows a clearer display of the rate of progression along the pole path at equally spaced time intervals. Since, in the absence of excitation, the Chandler wobble is a uniform motion along a circular arc, an arc is fitted by least squares to determine sudden breaks in the pole path, and hence sudden excitations. Lists of earthquakes of magnitude 7.5 and greater are obtained from the United States Geological Survey (USGS) website. The event times of these are indicated directly on annual plots of the polar motion free of annual components.

It is found that substantial changes in the polar motion often occur many days before the largest earthquakes. In addition, earthquakes not only seem responsible for excitation of the Chandler wobble but also, in at least one instance, seem responsible for its de-excitation. When the secular polar shift caused by an earthquake is in the direction of the current pole position, the result is a diminution of the amplitude of the Chandler wobble, or a de-excitation.

2. The VLBI pole path

As mentioned above, the VLBI pole path can be downloaded from the Goddard Space Flight Center website (http://gemini.gsfc.nasa.gov/solutions/2012a). The raw file gives 4838 pole positions and their standard errors from 3 August 1979 to 14 June 2012. The raw file has 346 null values, leaving 4492 points. Of these, 555 pairs of points have timestamps differing by less than a day, which are averaged and replaced by single values, leaving 3937 points. Then, the pole co-ordinates are converted to centiseconds of arc subtended at the geocentre, the sign of the second co-ordinate is reversed for a right-hand co-ordinate system, the time base is changed to years, and Julian days are converted to calendar days. Details of these operations are given in pages 278–279 in the book *Earth Dynamics* (Smylie, 2013).

The early part of the VLBI pole path is sparsely sampled, so we take the record for analysis to begin at point 48, which is 4.011652 years into the path at 8 August 1983, and to end at point 3936, which is 32.856959 years into the path at 12 June 2012. Thus, the equivalent record is taken to start at 4.0 years and to end at 32.9 years for a total record length of 28.9 years sampled at 3889 points. The end point is chosen so that the number of sample points is odd, facilitating the interpretation of the DFT.

In order to apply the maximum entropy method, we do a natural spline interpolation to 3889 equally spaced internal samples on a record extending from 4.0 years to 32.9 years. The first and last internal samples are one-half sample interval from the ends of the record. Function values at the ends of the record are found by the assumption that first derivatives are constant in the first two and last two subintervals of the record, supplying