EXCITATION OF EARTH'S POLAR MOTION
BY ATMOSPHERIC ANGULAR MOMENTUM VARIATIONS, 1980–1990

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Abstract. We compute the polar-motion excitation function due to the atmospheric angular momentum (AAM) for both IB (inverted-barometer) and non-IB cases, as well as the excitation function from geodetically observed Earth orientation data for the period 1980–1990. The two are then compared in studying the AAM contribution to the polar motion excitation. The polar drifts with periods longer than ~2 years have similar characteristics, but the comparison is inconclusive because of data uncertainties. For the seasonal wobble excitation, the agreement is poor except for the prograde annual wobble, indicating the influence of other geophysical excitations than AAM. For the Chandler wobble excitation, a correlation coefficient of 0.53 for non-IB and 0.58 for IB are found for 1986–1990. Together with a coherence spectral analysis, they clearly demonstrate a strong contribution of AAM to the Chandler wobble excitation.

Introduction

The Earth's rotation varies slightly with time. It varies both in its magnitude (i.e., length-of-day or LOD) and in the orientation of its axis. The latter variation with respect to the terrestrial reference frame is known as the polar motion: The Earth's rotation axis traces out in the vicinity of the North Pole a quasi-circular, prograde path with a varying amplitude of a few hundred milliarcseconds (1 mas = 0.003 cm). The polar motion consists mainly of an annual wobble and the Chandler wobble with a period of about 14 months. In addition, the mean pole undergoes a slow drift over the years.

The present paper deals with the excitation of polar motion. Without excitation any polar motion will eventually dissipate away; and the very existence of the polar motion implies continual excitation. The geophysical problem is to identify the sources of the excitation. To study excitation, one should bear in mind that the Earth's polar motion is a linear, oscillatory resonant system [Munk and MacDonald, 1960]. The observed polar motion is the temporal convolution of the excitation with the free Chandler oscillation [Chao, 1985]. Thus one derives the polar-motion excitation function by deconvolving the observed polar motion. The "observed" polar-motion excitation function is then compared directly with excitation functions computed for geophysical sources.

The specific geophysical excitation treated presently is the variation of the atmospheric angular momentum (AAM). AAM variation has been demonstrated to be the dominant cause for LOD variations shorter than a few years [e.g., Hide and Dickey, 1991]. It has also been linked to excitation of rapid polar motions [Eubanks et al., 1988], and as the major excitation source for the prograde annual wobble [e.g., Chao and Au, 1991]. Other possible polar-motion excitations include seismic movements, mass transport in the hydrosphere and post-glacial rebound; but convincing links for them have yet to be found.

Formulation and Data

The polar motion is a 2-dimensional quantity, conveniently expressed in terms of the complex angular distance \( m = m_1 + im_2 \) in radians, where subscripts 1 and 2 refer to the x (along the Greenwich Meridian) and y (along the 90°E longitude) coordinates of the terrestrial frame. The equation of motion governing the excitation of the geodetically observed \( m \) is [Barnes et al., 1983; Gross, 1992]

\[
\dot{m} = i \omega \left( m - x \right)
\]

where \( x \) is the excitation function and \( \omega \) is the complex Chandler frequency. The excitation due to AAM variation can be evaluated by [Barnes et al., 1983]

\[
\begin{align*}
\chi &= x_1 + i x_2 \\
&= \frac{1.00 R^4}{2g(C-A)} \int \sin^2 \theta e^{i \theta} d\sigma + \frac{1.43 R^3}{\Omega g(C-A)} \int (u \cos \theta + iv) e^{i \lambda} d\sigma d\lambda
\end{align*}
\]

where \( R, g, \) and \( \Omega \) are respectively the Earth's mean radius, mean surface gravity, and mean angular spin rate; \( C \) and \( A \) are the Earth's polar and equatorial moments of inertia; \( P \) is the deviation of the surface air pressure from the local mean, \( u \) and \( v \) are the eastward and northward components of the wind velocity. The first integral over the unit sphere (with surface element \( d\sigma = \sin \theta \ d\theta \ d\lambda \), where \( \theta \) and \( \lambda \) are the co-latitude and east longitude) arises from changes in the products of inertia due to air pressure changes. The second integral (which also includes the integration over the vertical height in terms of the pressure \( p \)) accounts for the relative angular momentum due to the winds.

In order to evaluate (2) one needs global atmospheric pressure and wind data. We use the ECMWF (European Centre for Medium-range Weather Forecasts) data set on a 2° latitude by 2.5° longitude grid at 12-hour intervals spanning 11 years: 1980–1990. For a more detailed description of the data and the numerical integration scheme, see Chao and Au [1991]. Two ideal cases are assumed
regarding the ocean's response to overlying air pressure loading: In the inverted-barometer (IB) case the ocean responds completely isostatically, whereas the non-IB case assumes zero yielding of the ocean to air pressure loading.

During 1980–1990 ECMWF has had several changeovers and modifications of its circulation models used in the generation of the analysis data. These changes lead to systematic errors in the form of discontinuities in the time series. The severity of the discontinuity depends on the parameter in question and the nature of the model change. In particular, we found it necessary to invoke an empirical shift at May 1 of 1985 in order to bring two sections of the AAM series to match at that junction.

Further pre-processing on the AAM $\chi$ was performed: The time series is first low-passed with a Butterworth filter of order $S$, in both forward and reverse directions to eliminate any phase distortion. The cutoff frequency is 0.1 cycle per day, or about 36 cpy (cycles per year). The series is then decimated by a factor of two into daily values. The purpose of this procedure is to facilitate later comparison with the observed data, processed as follows.

Equation (1) is the basis for the time-domain deconvolution [cf. Wilson and Haubrich [1976] used to deduce the "observed" polar-motion excitation function $\chi$, where we adopt a nominal Chandler $\omega$ corresponding to a prograde period of 433 solar days and a $Q$ value of 100 [Wilson and Haubrich, 1976]. For $m$ we use the "Space90" data set obtained by Gross and Steppe [1991] through a Kalman filter combination of all the available space geodetic measurements of the Earth orientation. The Space90 values are provided at nominal daily intervals; however, the actual temporal resolution is typically 5 days with a cutoff frequency of about 36 cpy.

Computation and Results

The task now is to compare the AAM $\chi$ series (from equation 2) with the observed $\chi$ series (from equation 1). A plot of the AAM series can be found in Chao and Au [1991] (see also Figure 3).

(a) Polar drift: First, we extract the long-period variation from each of the series. The extraction is achieved again through the application of a 2-way Butterworth low-pass filter of order $S$, at cutoff frequency of 0.5 cpy. Zero padding on both ends of the series is invoked to reduce end effects during filtering. The resultant $x$-$y$ "polar drift" paths during 1980–1990 are shown in Figure 1.

The observed polar drift path does not follow either of those predicted by AAM, IB or non-IB. However, no final conclusion can be drawn from this comparison because the AAM-predicted paths have been contaminated by the discontinuities in the AAM series due to the ECMWF analysis model changes (see above). Yet it is interesting that the drifts show similar characteristic and magnitude.

(b) Seasonal wobble excitation: Next, we remove by subtracting the above polar drift (as "noise") from our series. A periodogram is then computed: Figure 2 shows strong seasonal (annual and semi-annual) signals in both prograde (positive frequency) and retrograde (negative frequency) excitations. The prograde annual excitation is responsible for the large annual wobble (under near-resonance with the free Chandler oscillation) observed in the polar motion.

It is immediately evident from Figure 2 that for the prograde annual excitation the excitation power of AAM, both IB and non-IB, agrees well with that of the observed. However, it has been shown [Chao and Au, 1991] that there exists a substantial -40° phase difference between them. Much poorer match is seen for other seasonal excitations -- retrograde annual and semi-annual, indicating contributions of other geophysical processes that can excite the seasonal polar motion. A detailed study has been reported by Chao and Au [1991]. The geophysical budget for the seasonal polar motion is far from "closed".

(c) Chandler wobble excitation: Let us now remove the seasonal signals. We achieve that by first estimating these signals in a least-squares sense and then subtracting them.
from the time series. We can now concentrate on the remaining polar-motion excitation. The latter, by definition, is the Chandler wobble excitation because, when convolved with the free Chandler oscillation, they give rise to the Chandler wobble. Figure 3 shows the $x$ components $x_1$; the $y$ components $x_2$ are similar (not shown). The series exhibit the characteristics of a white stochastic process. Notice the amplitude differences in the overall fluctuation.

The AAM-induced and the observed Chandler excitation are then subject to two (complementary) correlation analyses: The time-domain complex correlation function which gives an overall correlation estimate as a function of relative time lag, and the frequency-domain complex coherence spectrum which provides a spectral decomposition of the overall correlation [e.g., Chao, 1988]. Figure 4 shows the correlation magnitude versus the time lag of the observed relative to the AAM series, for both IB and non-IB cases. The period selected is 1986–1990, during which the AAM series are relatively uniform in the underlying models (see above). The result for the entire period of 1980–1990 is similar (but with somewhat lower correlation coefficient, see below). Figure 5 shows the corresponding squared coherence spectra. Here we used the multitaper technique of Thomson [1982] which provides robust and minimum-leakage spectral estimates. Seven orthogonal tapers with time-bandwidth product of $4\pi$ were adopted in the analysis, so that the spectral resolution is 8 elementary frequency bins. The degree of freedom is 7 and the corresponding 99% confidence threshold for the squared coherence is 0.54 [e.g., Chao, 1988]. The geophysical significance of these results is discussed in the next section.

Conclusions

We have computed the AAM-induced polar motion excitation for both IB and non-IB cases using the ECMWF meteorological data for the period 1980–1990. We also computed the "observed" polar motion excitation function from geodetically measured Earth orientation data for the same period. The two are then compared in studying the AAM's contribution to the polar motion excitation. For the polar drift with periods longer than ~2 years, the comparison is inconclusive because of systematic errors in the ECMWF AAM series during 1980–1990, even though the drifts show similar characteristic and magnitude (Figure 1). For the prograde annual wobble excitation, the agreement is good in the amplitude with a ~40° phase discrepancy, whereas the agreement for the retrograde annual wobble and the semiannual wobbles is rather poor (see Figure 2, and Chao and Au [1991]), indicating the influence of other geophysical excitations than AAM.

Our main result is with respect to the Chandler excitation. The comparison is fruitful in that it clearly demonstrates a strong influence of AAM on the Chandler wobble (Figures 4 and 5). The correlation at zero time lag is striking, reaching a correlation coefficient of 0.53 for non-IB and 0.58 for IB during 1986–1990 (no significant correlation can be found at other time lags). The
correlation coefficient for 1980–1990 is somewhat lower: 0.45 for non-IB and 0.52 for IB, presumably degraded by systematic errors in the AAM series in earlier years. Of course, observational and processing errors have further degraded the correlation estimates. The extent of the degradation is difficult to assess, but the actual correlation is certainly higher than the estimates quoted above. It should be noted that the above correlation estimates represent average values over the study period because the "instantaneous" correlation may well be time-variable at sub-yearly time scales [Kuehne et al., 1992].

Perhaps equally striking from Figure 4 is the sharpness of the correlation peak. The half width of the peak is only ~10 days. This indicates that the correlated energy between the AAM-induced and the observed Chandler excitation is largely concentrated in periods shorter than, say, a month, supporting a previous finding by Eubanks et al. [1988].

A considerable portion of the coherence spectrum in Figure 5 exceeds the 99% confidence threshold. (The high coherence around zero frequency is spurious as there exists virtually no energy after the removal of the polar drift as above.) The phase values cluster around 0° (not shown), instead of randomly distributing in (-180°,180°] as would result from two uncorrelated series. This also vindicates the significance of the correlation.

Finally, it is interesting to note that the IB effect consistently yields a higher correlation estimate than the non-IB case. The difference, over 10%, is significant (barring possible systematic errors arising from undertaking the IB procedure). This can be enigmatic because, as argued above, a major portion of the correlation comes from periods shorter than a month — an unfavorable condition for the IB effect to take place. Similar situation has been found with respect to the Earth's J_2 variations caused by atmospheric mass redistribution [Nerem et al., 1992]. Incorporation of realistic ocean models should be able to resolve this enigma, leading to a more accurate assessment of the role played by the atmosphere and oceans in the excitation of the Earth's rotational (and gravitational) variations.

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References


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