THE ATMOSPHERIC EXCITATION OF RAPID POLAR MOTIONS

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ABSTRACT. Analysis of data from new, highly accurate, geodetic techniques reveals rapid polar motions. Comparison of the new geodetic data and meteorological excitation estimates shows that the observed rapid polar motions are correlated with atmospheric pressure changes, and that these changes are related to atmospheric normal modes.

1. INTRODUCTION

The polar motion is greatly affected by the Chandler wobble resonance, which strongly amplifies the effects of eastward propagating (prograde) exchanges of equatorial angular momentum with rotational periods near 433 days. The motion is dominated by the prograde Chandler and annual wobbles, both greatly amplified by the resonance; Lambeck (1980) provides a recent review of the study of these motions. More rapid forcings are attenuated and the existence and nature of faster polar motions have long been in doubt. However, two new techniques, Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), now routinely monitor the polar motion with a demonstrated accuracy of ~ 2 milliarcseconds (or mas), roughly a factor of 5 to 10 times more accurate than data from older techniques (Robertson et al. 1985, Steppe et al. 1985). This paper concerns the meteorological excitation of polar motions at periods much shorter than one year; these motions are so small (< 10 mas amplitude) that they can be adequately observed only with the most accurate modern data.

2. ESTIMATES OF EFFECTIVE EQUATORIAL ANGULAR MOMENTUM CHANGES

2.1 EFFECTIVE ANGULAR MOMENTUM ESTIMATES FROM POLAR MOTION DATA

The relation between the polar motion and its excitation can be concisely expressed in complex notation using an Earth-fixed coordinate system, which by convention is right handed with the z axis near the mean rotation pole, the x axis near the Greenwich meridian and the y

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axis towards 90° East longitude. Let the coordinates of the rotation pole along the x and y axes be denoted by m_1 and m_2, respectively. The excitation, denoted by χ_1 and χ_2, is proportional to the components of effective angular momentum about those same axes. The response of the Earth to such excitation is

$$\frac{d\,m}{d\,t} = i\ \sigma\ (m - \chi) \qquad (1)$$

where m is $(m_1 + i\ m_2)$, χ is $(\chi_1 + i\ \chi_2)$ and σ is $(1 + i/2Q) * 2\pi / T_c$. σ represents the complex resonance frequency, with T_c being the Chandler wobble period (approximately 433 days) and Q the dimensionless quality factor (generally thought to be larger than 100).

The accuracy and precision of global geodesy has greatly increased recently, both because of the introduction of new techniques and because of the international program to Monitor Earth Rotation and Intercompare Techniques (MERIT) (Wilkins, 1984). The geodetic data showed noticeable improvements during 1983, and a high accuracy level has been maintained since; we limited our analysis to 1984 and 1985, using polar motion determinations from three independent sources. Radio interferometric polar motion estimates, based on 24 hour averages, were available every five days during this period from a reduction of VLBI data from the International Radio Interferometric Survey (IRIS) project by the U.S. National Geodetic Survey (Robertson et al., 1985). Additional information came from a JPL reduction of less frequent single baseline VLBI observations using the radio antennas of the U.S. Deep Space Network (DSN) (Eubanks et al., 1985). Polar motion estimates from Laser ranging to the Lageos satellite were provided by the University of Texas Center for Space Research solution CSR 84 L01, which only covers to the end of 1984 (Tapley et al, 1985).

In Equation (1), the polar motion arises from the convolution of the complex excitation by the impulse response of the Chandler wobble resonance; comparison of the geodetic and meteorological data thus requires either the convolution of excitation data or the deconvolution of polar motion data. We used a Kalman filter, developed at JPL in support of DSN spacecraft navigation, to deconvolve the geodetic data (see Morabito et al. (1986)).

2.2. Meteorological Excitation Estimates

While it has long been clear that surface pressure changes contribute to both the annual and Chandler wobbles (Lambeck, 1980), the study of more rapid meteorological effects has only recently been made possible by modern weather analysis / forecasting techniques (see, e.g., Barnes et al., 1983). Forecasts are made through numerical integration of atmospheric models, initialized with large quantities of meteorological data. These efforts thus provide estimates of the current atmospheric state at a dense set of grid points throughout the atmosphere; calculation of the atmospheric excitation is straightforward given such analysis fields, typically available on a daily or twice daily basis.

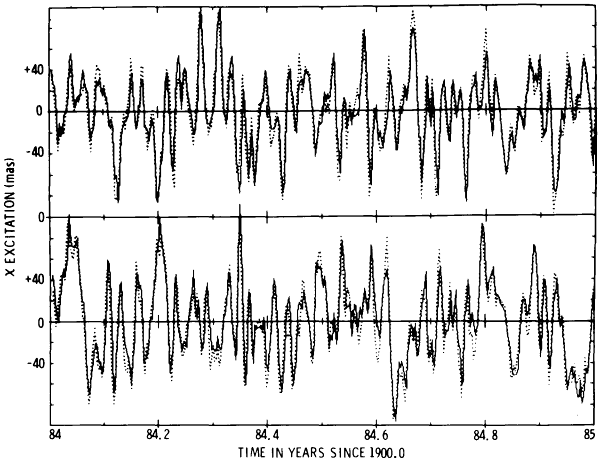

Figure 1. Determinations of the χ_1 (top) and χ_2 (bottom) atmospheric pressure term from the U.S. NMC (solid lines) and the ECMWF (dotted lines), after seasonal adjustment.

The total effective atmospheric angular momentum vector (or χ vector) includes two equatorial components (χ_1 and χ_2) associated with the excitation of the polar motion. The contributions of wind and surface pressure changes can be separated to first order, and only the χ_1 and χ_2 pressure terms are used in this analysis; Barnes et al. (1983) describe the calculation of the χ vector. Our study was conducted with excitation estimates from the global analysis fields of the U.S. National Meteorological Center (NMC) and the European Centre for Medium range Weather Forecasting (ECMWF). The twice-daily NMC estimates were sampled at noon UTC, the epoch of the ECMWF data. Occasional gaps in the NMC data were filled by linear interpolation; we also removed a sudden bias change in the ECMWF data, caused by ECMWF model changes on February 1, 1984, (K. Whysall, personal communication). Since the data show a clear seasonal cycle which could corrupt our statistics, we seasonally adjusted our data by estimating and removing a bias and annual and semiannual sinusoids from each data set. The surface pressure fields used in this analysis are actually derived from a wide variety of meteorological measurements, not just from surface pressure data. Satellite temperature measurements thus provide information about surface pressure changes, even in remote ocean regions without barometers.

3. Atmospheric Oscillations and the Meteorological Excitation

Figure 1 presents the daily χ_1 and χ_2 pressure term estimates from the NMC and the ECMWF for 1984, after seasonal adjustment. The close agreement of the results from the two weather centers evident in Figure 1 is confirmed by further statistical analysis, with the crosscorrelation between the NMC-ECMWF data being > 0.95 for both components for 1984 through 1985. The χ_1 and χ_2 pressure terms are proportional to the cosine and sine components of the P_2^1 spherical harmonic of surface air pressure, respectively, with a one mas increase being equivalent to a maximum change in surface pressure (at latitudes of +- 45^o) of ~ 0.04 millibars. The strong rapid oscillations in Figure 1, with root mean square (rms) scatters of 35 to 40 mas, thus correspond to rms surface pressure changes of ~ 1.5 millibars at mid-latitudes. Similar global variations in surface air pressure have been observed previously; their meteorological study is generally based on normal mode expansions of atmospheric pressure changes (Salby, 1984 and Madden, 1979). The low order barotropic normal modes are, at least in theory, closely related to spherical harmonics of the surface pressure (Madden, 1978), and the polar motion is primarily sensitive to one particular normal mode, called H_3^1 by Madden (1979), s = 1, l = 2 by Ahlquist (1982,1985), and the 10 day wave by Salby (1984). Ahlquist, using NMC analysis fields for 1976-1979, claimed detection of this mode, with an average amplitude of 0.6 millibars at +- 45^o latitude, and considerable amplitude variation. The barotropic modes all propagate westward, and this mode will thus excite retrograde polar motions. Ahlquist (1982) showed that there is also a red noise component of atmospheric variability present in low order surface pressure harmonics which shows no definite sense of polarization.

Spectral analysis of the NMC data supports the normal mode explanation of the rapid variations observed in Figure 1. Figure 2 shows prograde and retrograde power spectral density estimates based on 9 years of NMC χ pressure term data (1977 to 1986), after seasonal adjustment. For comparison, the power spectral density expected for a random walk is also shown, together with 99% confidence limits. While the prograde power spectrum is consistent with a random walk model at periods less than ~ 40 days, there is a strongly significant enhancement in retrograde power near the theoretical normal mode period of 10 days.

4. COMPARISONS OF THE GEODETIC AND METEOROLOGICAL DATA

The χ excitation functions were estimated for noon UTC of each day in 1984 and 1985 from a Kalman deconvolution of the geodetic data. Direct comparison of raw and smoothed data can be misleading, and so the meteorological data were smoothed by convolution with Equation (1) and deconvolution with the Kalman filter; care was taken to apply exactly the same smoothing to the geodetic and meteorological data. Figure 3 shows the results after seasonal adjustment. It seems clear that there is some relationship between the geodetic and meteorological data, and that the agreement is better in the χ_2 component; these conclusions are supported by statistical analysis. The crosscorrelation between the geodetic and meteorological data is 0.41 for χ_1 and 0.55 for χ_2 at zero lag. A statistical test of no correlation, based on 100 degrees of freedom in the smoothed data, has a three sigma upper bound of 0.30, and so the observed correlation, although moderate, is statistically significant; such correlation is not found at other lags.

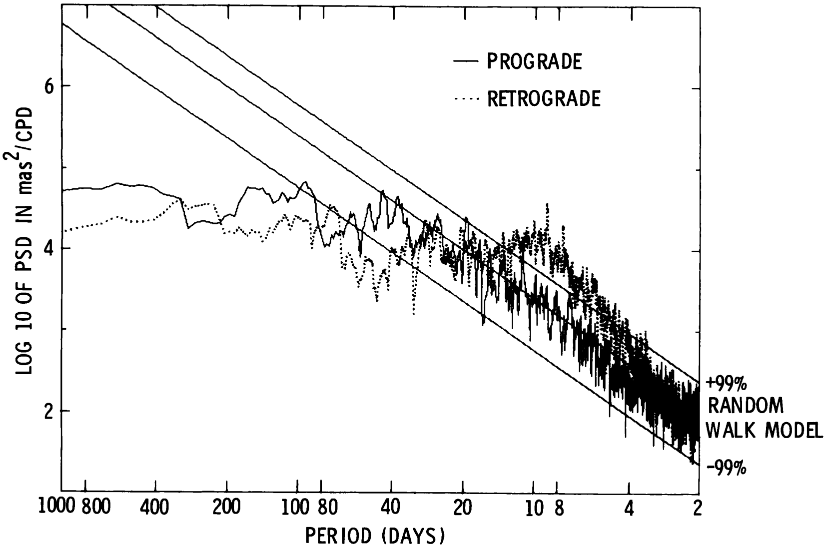

Figure 2. Power spectral density estimates for the prograde (solid) and retrograde (dotted) components of the χ pressure data, based on a seven point spectral smoothing of seasonally adjusted data from 1977 through 1985, together with a random walk spectral model.

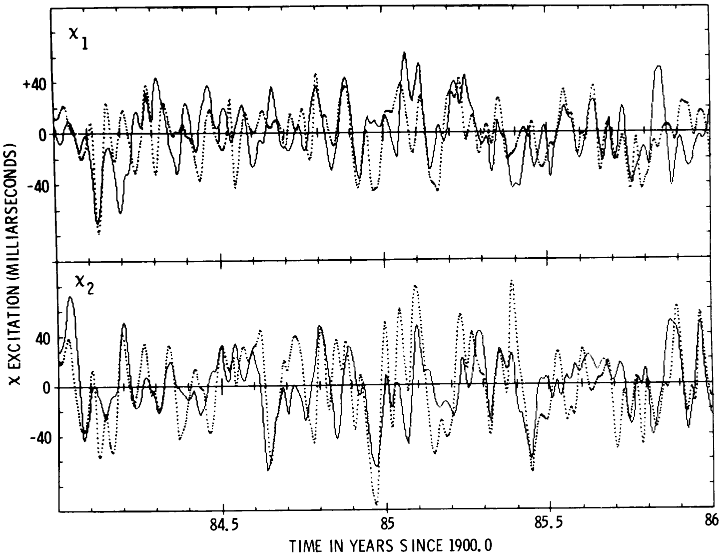

Figure 3. Kalman smoothed estimates of the NMC χ pressure terms (solid lines), together with the Kalman deconvolution of the combined geodetic data set (dotted lines), after seasonal adjustment. χ_1 is at the top and χ_2 the bottom.

Although atmospheric pressure variations are one source of rapid polar motions, the agreement with the geodetic data is not perfect, which suggests another source of rapid equatorial angular momentum exchanges. Atmospheric winds should contribute to rapid polar motions, but the χ_1 and χ_2 wind data are not correlated with the geodetic results. It is possible that these data are degraded by aliasing of the strong diurnal cycle found in meridional winds, given that samples are only available once or twice daily. By contrast, we do find evidence of significant oceanic exchanges of equatorial angular momentum at high frequencies; this is the subject of a paper now in preparation.

5. CONCLUSIONS

Rapid polar motions are at least partially driven by surface air pressure changes. The new geodetic data thus provide a novel means of studying one particular atmospheric normal mode. The polar motions induced by this normal mode are small, and typical motions, with periods of ~ 10 days and inferred polar motion amplitudes < 1.0 mas, are still not fully observable geodetically. An intensive polar motion monitoring campaign, with daily measurements of milliarcsecond accuracy, should be feasible with the new geodetic technology and would enable geodetic observation of virtually all normal mode oscillations.

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REFERENCES

Ahlquist, J.E., 1982, J. Atm. Sci. 39, 193-202.

Ahlquist, J.E., 1985, J. Atm. Sci. 42, 2059-2068.

Barnes, R.T.H., Hide, R., White, A.A., & Wilson, C.A., 1983, Proc. R. Soc. Lond. A 387, 31-73.

Eubanks, T.M., Steppe, J.A., and Spieth, M.A., 1985, Annual Report for 1984, Bureau International de l'Heure, D19-23.

Lambeck, K., 1980, The Earth's Variable Rotation, Cambridge University Press, Cambridge.

Madden, R.A., 1979, Rev. Geophys. Space Phys. 17, 1935-1949.

Morabito, D.D., Eubanks, T.M., and Steppe, J.A., 1986, this volume.

Robertson, D.S., Carter, W.E., Tapley, B.D., Schutz, B.E., and Eanes, R.J., 1985, Science, 229, 1259-1261.

Salby, M.L., 1984, Rev. Geophys. Space Phys. 22, 209-236.

Steppe, J. A., Eubanks, T. M., and Spieth, M. A., 1985, Proc. Inter. Conf. Earth Rotation and Terr. Ref. Frame, Vol. 2, 622-636, Ohio State University, Columbus.

Tapley, B.D., Schutz, B.E., and Eanes, R.J., 1985, J. Geophys. Res., 90, 9235-9248.

Wilkins, G.A., 1984, Phil. Trans. R. Soc. London, A313, 85-94.

DISCUSSION

Herring: How much of the annual polar motion is explained by annual atmospheric excitation?

Reply by Eubanks: The amplitudes of the observed geodetic and meteorological excitations agree rather well, but there is roughly a 40° difference in phase. Addition of ground water excitation estimates improves the agreement somewhat.

Grafarend: You have mentioned the spheroidal terms of degree 2 and order 1 (P21) mainly driving polar motion. In my paper yesterday, I tried to show that a large part of the polar motion signal is due to the toroidal modes. Are there toroidal modes in the atmospheric excitation?

Reply by Eubanks: As I understand it, your paper refers to a vector spherical harmonic analysis of the atmospheric vorticity field, and thus to atmospheric winds. My talk dealt with the P21 terms in a scalar spherical harmonic expansion of atmospheric surface pressure fields, while the role of atmospheric winds remains unproven.