Geophys. J. Int. (2005) **160,** 435–439 doi: 10.1111/j.1365-246X.2004.02510.x

FAST TRACK PAPER

Geomagnetic jerks and a high-resolution length-of-day profile for core studies

R. Holme[1] and O. de Viron[2]

[1]*Department of Earth and Ocean Sciences, University of Liverpool, 4 Brownlow Street, Liverpool L69 36P, UK. E-mail: holme@liv.ac.uk*
[2]*Royal Observatory of Belgium, 3, avenue Circulaire, B-1180 Brussels, Belgium*

Accepted 2004 October 15. Received 2004 October 11; in original form 2004 August 6

SUMMARY

By subtracting computed atmospheric angular momentum from a time-series for length-of-day variations, we obtain a high-resolution time-series that is useful for studying the effects of the core on length-of-day variations. Features in this time-series are closely correlated with the time at which geomagnetic jerks have been observed, suggesting a role for the core in angular momentum exchange within the Earth system on timescales as short as one year, and that jerks are directly related to the processes responsible for changes in core angular momentum.

Key words: core angular momentum, geomagnetic jerks, length-of-day variation.

1 INTRODUCTION

The rotation rate of the solid Earth is known to vary on all timescales, from a slow, secular increase due to the action of tidal torques (e.g. Stephenson & Morrison 1995), to periods of a year and shorter, which are dominated by the exchange of angular momentum between the solid Earth and atmosphere (e.g. Gross *et al.* 2004), but are also influenced by the oceans (Marcus *et al.* 1998), and many other smaller effects. Intermediate between these two regimes are variations on a decadal timescale, associated with angular momentum exchange between the core and mantle (e.g. Ponsar *et al.* 2003). It has also been suggested that the core might influence variations in length of day (LOD) on subdecadal timescales (Zatman & Bloxham 1997; Zatman 2001; Mound & Buffett 2003).

In the past, studies of decadal LOD have been carried out using a LOD time-series that has been low-pass-filtered (for example, the often-used series of McCarthy & Babcock 1986). This was adequate for looking at variations on a decadal timescale, but on shorter timescales, a considerable signal from the angular momentum exchange between the atmosphere and solid Earth may be included, particularly at the end of the time-series. Angular momentum exchange on subdecadal timescales has recently become of particular interest as a result of the availability of high-quality magnetic data. The Ørsted (Neubert *et al.* 2001) and CHAMP (Reigber *et al.* 2002) satellites have provided a continuous series of high-quality vector magnetic data from early 1999 to the present. These data motivate the construction of models of surface core flow with high temporal resolution. This paper aims to provide an equally high-quality time-series for LOD variation against which such models can be compared. We consider LOD after subtraction of a directly modelled atmospheric signal, bringing with it two advantages. First, the filtering will be considerably improved, because variation about the long-term trend will be significantly reduced. Secondly, atmospheric angular momentum (AAM) has been demonstrated to have power on a decadal timescale (Dickey *et al.* 2003); if not modelled, variations in AAM could contaminate the LOD curve. We then examine the improved LOD series for evidence of core influence on subdecadal LOD variations.

2 SUBTRACTION OF AAM FROM LOD VARIATIONS

For the variation of the length of day, we used the COMB2003 series (Gross *et al.* 2004), which gives daily excess LOD. This series is available from the JPL's Space Geodetic Science and Applications Group by anonymous ftp from euler.jpl.nasa.gov/keof/combinations/2003. The International Earth Rotation Service (IERS) has established the Global Geophysical Fluid Center (GGFC, see Chao *et al.* 2000), made up of six special bureaus, to stimulate research and provide data on the effect of global geophysical fluids on Earth rotation. Of particular interest for this study are the special bureau for the atmosphere (head: D.A. Salstein), for the ocean (head: R.S. Gross), and for the core (head: T. Van Hoolst). The special bureau for the atmosphere provides the scientific community with the atmospheric excitation function (defined for instance by Barnes *et al.* 1983) for some of the major atmospheric models. In our study, we used the NCEP re-analysis model (Kalnay *et al.* 1996), selected for two main reasons. First, the NCEP re-analysis is the only consistent series over the long term (covering from 1948 to the present). Secondly, Koot, de Viron & Dehant (in preparation) have shown from a tri-corner hat study that, for periods longer than 10 days, this series is the least noisy available. Data are provided with a 6-hr resolution, which we decimate to the time of the LOD data.

In Fig. 1 we present the result of subtracting the modelled atmospheric angular momentum signal from the observed LOD variations. The reduction in variance of the LOD signal is clear.

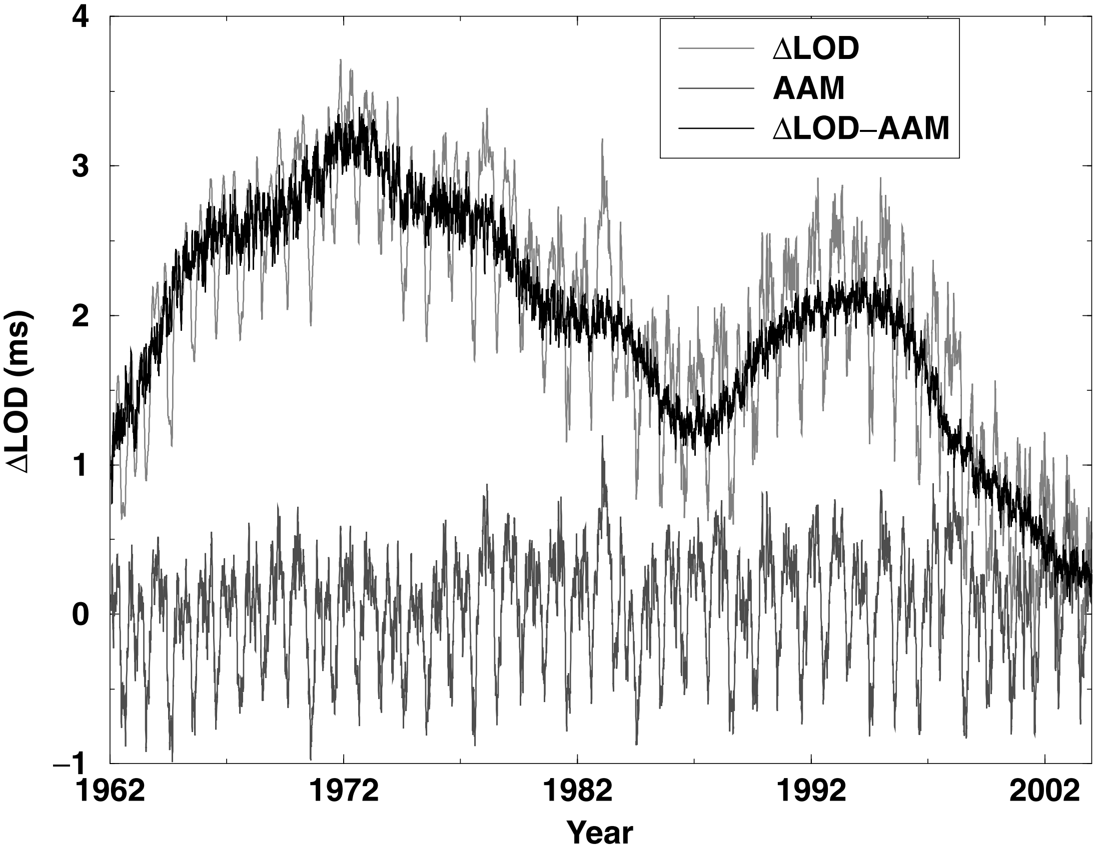

Figure 1. Variations in length of day in milliseconds from 1962 to 2004. Also plotted are the calculated atmospheric angular momentum for the same period and the residual length-of-day variation (the difference between the two signals).

However, despite this improvement, there is still clearly a strong annual signal remaining in the data, and also power at semi-annual and terannual periods, possibly due to inadequacies in modelling the atmospheric data, but also due to contributions from the ocean. We attempted to model the oceanic signal directly, using the ECCO JPL (non-assimilating) model (Gross *et al.* 2004), but this increased the variance of the residual signal, suggesting that the oceanic modelling is not yet sufficiently accurate for the signal to be subtracted in this way, or possibly the existence of a phase shift due to the influence of the core (Zatman & Bloxham 1997). Instead, we eliminate these variations by a simple 365-day running average of the data, as shown in Fig. 2. From this (admittedly) very simple filter, the improvement resulting from accounting for the AAM directly is clear. For further application of the new curve, we fit the running average with a smooth curve, using the technique of penalized least-squares splines (Constable & Parker 1988). This method fits a curve on a basis of cubic B-splines (see, for example, de Boor 1978), seeking a fit to the data while minimizing the 2-norm of the second derivative. We obtained a superior result by fitting the smooth curve to the running average rather than to the residual LOD−AAM itself, when leakage from the remaining annual variation could be clearly seen in the results. We present two fits to the data, both very close, but one slightly rougher than the other.

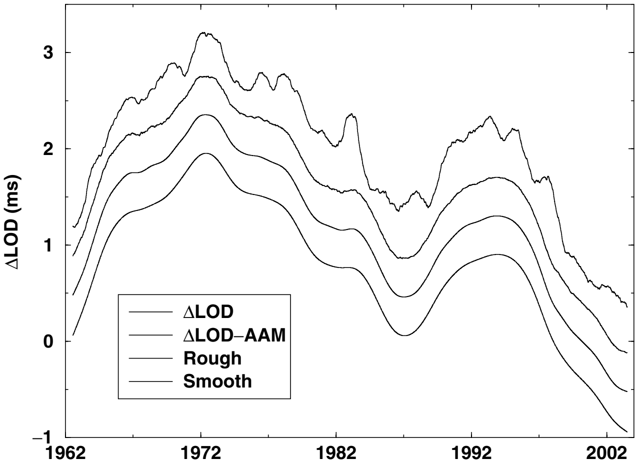

Figure 2. A 365-day running average of the raw LOD series, and the residual LOD−AAM. The uncorrected running average still includes a significant signal from AAM. Also plotted are two smooth-curve fits of the residual LOD−AAM running average, both fitting the series very closely, but one (‘Rough’) more closely than the other (‘Smooth’). Offsets between curves are for ease of plotting only. Curves are from top to bottom in the order of the legend.

3 GEOMAGNETIC JERKS

To investigate the properties of the new LOD series, we use our spline fits to estimate its time derivative, presented in Fig. 3. In addition to the general oscillatory behaviour, additional ‘wiggles’ in the series can be seen, corresponding to inflexions in the LOD−AAM series. These features could arise from many sources (for example unmodelled changes in atmospheric or oceanic angular momentum), but their timing strongly suggests a link to the Earth’s core.

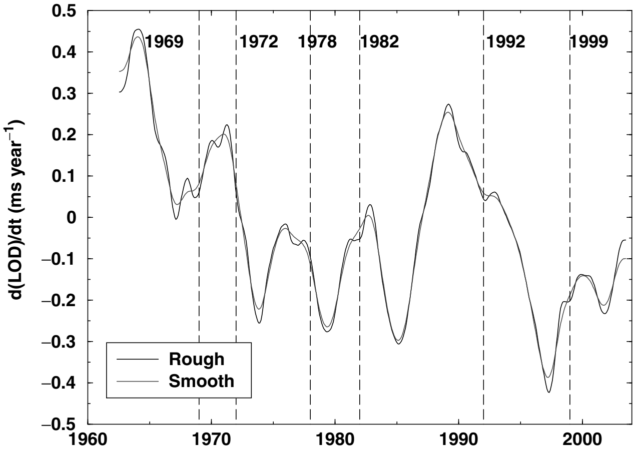

Figure 3. Time derivatives of the two smooth-curve fits to the LOD−AAM residuals. The vertical dashed lines designate geomagnetic jerks.

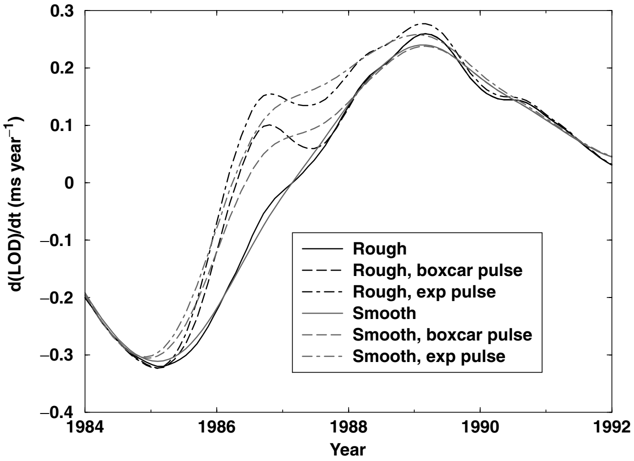

Figure 4. A synthetic jerk created by pulses in the LOD derivative.

The most rapid features of the magnetic secular variation that have been identified with a source internal to the Earth are the so-called geomagnetic jerks (Courtillot *et al.* 1978; Malin & Hodder 1982; Courtillot & Le Mouël 1984), sharp changes in the gradient of the secular variation (and hence in the second time derivative of the geomagnetic field). Jerks have been observed worldwide, but particularly clearly in the *Y* (east) component of the field recorded at European magnetic observatories. During the period of interest, geomagnetic jerks are well known around 1969, 1978, 1992 and 1999 (see Mandea *et al.* 2000, and references therein). These dates match closely four of the inflexion features in Fig. 3. Furthermore, the geomagnetic jerks in 1969 and 1978 are known to have a bimodal distribution (Alexandrescu *et al.* 1996, and references therein), with many Southern Hemisphere observatories reporting the signal around 1972 and 1982, respectively. Alexandrescu *et al.* (1996) suggest that such a delay might be interpreted in terms of regional differences in mantle conductivity, leading to a longer delay time for propagation of the jerk through the mantle for the Southern Hemisphere. Fig. 3 suggests, however, that both cases consist of two separate events.

On the basis of this correlation of rapid features in the LOD derivative with geomagnetic jerks, we claim strong evidence that the core is involved in angular momentum exchange on timescales of the order of 1 yr.

4 ORIGIN OF THE SIGNALS

It is generally assumed that geomagnetic jerks are very sharp features in time, and so if the signals in Fig. 3 are associated with them, they might also be expected to be sharp. Unfortunately, both taking a running average and fitting with splines smooth any sharp signals. We investigate whether the features in Fig. 3 could be identified with sharp changes by forward modelling. First, we attempt to generate a synthetic jerk, by applying a finite pulse to the LOD derivative (equivalent to a torque). We apply two pulses, first a uniform pulse of 0.15 ms yr^{-1} lasting 1 yr:

$$f(t) = 0.15; \quad t_0 + 1 > t > t_0, \tag{1}$$

and secondly, an exponentially decaying pulse, of the form

$$f(t) = 0.3\exp[-(t - t_0)]; \quad t > t_0, \tag{2}$$

in both cases choosing $t_0 = 1986$. The effect of each pulse on LOD is calculated by direct integration, and added to the de-trended LOD−AAM signal, which is then treated as before (1-yr running average, and spline fit). The effect on the LOD derivative profile is shown in Fig. 4. Both pulses yield features that are qualitatively similar to the six ‘wiggles’ observed in Fig. 3; in particular, both the ‘rough’ and ‘smooth’ spline fits match the observed behaviour.

Secondly, we attempt to eliminate the 1969 feature, corresponding to the best known and best defined jerk, by similar application of a torque impulse. We add three different uniform pulses (similar to eq. 1) starting in 1967.6: first, a half-year pulse with amplitude −0.15 ms yr^{-1}, secondly, a 2.7-yr pulse with amplitude −0.18 ms yr^{-1}, and finally a pulse longer than the data series (effectively a step function) with amplitude −0.2 ms yr^{-1}. The altered LOD time-series is again treated with the running average and spline fit. As shown in Fig. 5, the application of each torque pulse is sufficient to eliminate the feature that we have associated with the 1969 geomagnetic jerk, and the 2.7-yr pulse also eliminates the 1972 feature. Fig. 5 also shows the difficulty in using our results to extract a timescale for the torque features: even without considering differently shaped pulses, timescales of 0.5 yr, 2.7 yr, or (for the step function) instantaneous are all consistent with the observations.

Whilst our interpretation is clearly non-unique—many other pulses would produce similar changes in shape to the corrected LOD curve, and also probably many smoother changes in $d(\text{LOD})/dt$—we may at least say that sudden changes in the LOD derivative (and

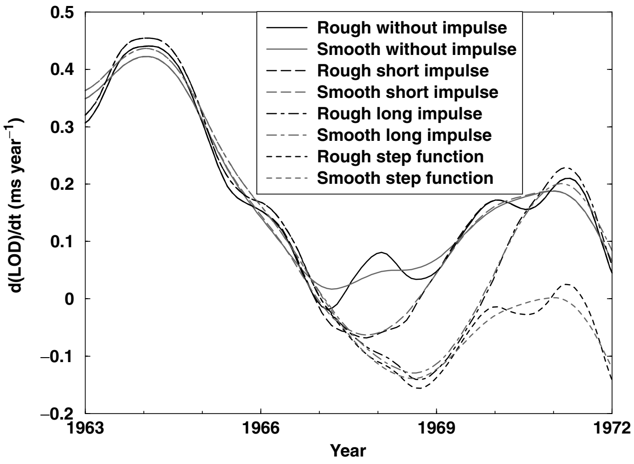

Figure 5. Three synthetic jerks to eliminate the effect of the 1969 jerk.

by implication, torque on the solid Earth) are a possible source of the features near jerk times in the LOD curve.

5 DISCUSSION

We have argued that we can see a direct connection between the timing of geomagnetic jerks and features in changes in LOD. Such claims are not new: Backus (1983) argued that features in the LOD curve in 1956 might be associated with the 1969 geomagnetic jerk, while Courtillot *et al.* (1978) argued that jerks lead extrema in ΔLOD by a few years (see also Le Mouël *et al.* 1981). However, we believe our results to be the first evidence of a direct, rapid link between geomagnetic jerks and variations in LOD.

We have argued that the jerk-like features in the LOD curve can be generated by a discontinuity in torque. This is equivalent to saying that the ΔLOD curve has a discontinuity in its slope. Such a statement is fully consistent with our understanding of the generation of secular variation at the top of the core. Changes in the radial component of the field at the CMB (from which we may calculate all three field components at the Earth's surface) arise from two processes, namely advection of the field by the core surface flow, and field diffusion:

$$\dot{B}_r + \nabla_{\mathrm{H}}(\mathbf{u}B_r) = \frac{\eta}{r}\nabla^2(rB_r), \tag{3}$$

where B_r is the radial field, **u** the core surface flow, η the magnetic diffusivity, and ∇_{H} the horizontal projection of the gradient operator. It is thought that decadal variations in core angular momentum are carried by motions constant on cylinders, so-called torsional oscillations (Braginsky 1970). If this is true, then the core surface flow will reflect changes in the flow throughout the core, which allows the estimation of core angular momentum from core surface flow (Jault *et al.* 1988; Jackson *et al.* 1993). Then a discontinuity in the rate of change of LOD will be reflected by a similar discontinuity in surface flow **u**, and from eq. (3), assuming that diffusion is slow-acting, a matching discontinuity in $\dot{B}_r$. A discontinuity in the gradient of secular variation, however, is precisely the definition of a geomagnetic jerk. Based on the reverse analysis, Le Huy *et al.* (2000) predicted just the sort of LOD discontinuity that could explain the signal that we see here. Recently, Bloxham *et al.* (2002) have argued that geomagnetic jerks may originate primarily precisely from such torsional motions, which they model with torsional waves. While we have concentrated on abrupt changes, we have not ruled out the smoother (but nontheless rapidly changing) wave processes proposed by Bloxham *et al.* (2002), and we support the conclusion that processes giving rise to geomagnetic jerks and decadal variations in LOD may have a common origin.

We have postulated short periods of torque on the mantle giving an acceleration on the solid Earth of the order of 0.1 ms yr^{-1} in the length of day. Assuming a moment of inertia for the mantle of 7.2×10^{37} kg m^2, this acceleration requires a torque of approximately 2×10^{17} Nm. How large is this? Buffett (1996) has argued that gravitational coupling between the inner core and mantle can in principle give rise to very large torques, of the order of 10^{21} Nm per radian displacement between mantle and inner core. Hence, a torque of 2×10^{17} Nm requires a displacement of the inner core with respect to the mantle of only 0.01°. Using a dynamo simulation, Buffett & Glatzmaier (2000) predict a rate for steady inner core rotation of $0.01^\circ\ \mathrm{yr}^{-1}$ due to competition between magnetic and gravitational torques and viscous inner core relaxation. A change in the balance between these competing processes could therefore produce the required jump in torque. Alternatively, the signal could come about from the response of the core to a sharp angular momentum forcing from the atmosphere or ocean.

A similar discontinuity in torque has previously been investigated by Bellanger *et al.* (2001) to explain the correlation between geomagnetic jerks and changes in phase of the Chandler Wobble (Gibert *et al.* 1998), although the torque discussed was significantly greater (of the order of 10^{20} Nm) than considered here. The close coincidence of discontinuities in three separate physical time-series (length of day, magnetic secular variation and polar motion) is particularly provocative, and suggests that their origin should be sought in a common mechanism.

Geomagnetic jerks have been used as a probe of mantle conductivity. Mantle filter theory (e.g. Backus 1983) has been used to argue that the sharpness of observed jerks would be difficult to reconcile with a highly conducting deep mantle. The observed sharpness suggests an electromagnetic delay-time constant for the mantle of the order of 1 yr or less (Mandea Alexandrescu *et al.* 1999). Our analysis provides a more direct estimate of this delay time. By comparing the centre of the ΔLOD 'wiggle' with the time of the observed jerk, we estimate the time as again of the order of 1 yr, in agreement with the value of Mandea Alexandrescu *et al.* (1999). A more precise constraint will require better localization in time of the LOD gradient discontinuity (and possibly the time of the geomagnetic jerk); this improvement will probably require direct modelling of the oceanic LOD signal to eliminate the need for taking a running average of the data.

To attempt to extend the period of analysis, we investigated the use of proxies for AAM, for example a Hadley centre estimation of AAM from sea-surface temperature data only. This failed: as for the oceanic LOD prediction, the variance in the residual LOD signal was higher than before applying the correction.

6 CONCLUSION

By extracting the AAM signal from LOD variations, we have presented evidence of the involvement of the Earth's core in LOD variations with timescales of 1 yr, or even less. The time-series derived are well suited for examining these processes in detail, as well as decadal variations in LOD. They are available, with accompanying software that enables the calculation of the residual LOD and its derivatives, from the website of the Special Bureau of the Core (http://www.ksb.be/SBC/main.html).

ACKNOWLEDGMENTS

We thank I. Wardinski for useful discussions. OdV acknowledges the financial support of the Belgian Service Public Fédéral de Programmation Politique Scientifique.

REFERENCES

Alexandrescu, M.M., Gibert, D., Hulot, G., Le Mouël, J.-L. & Saracco, G., 1996. Worldwide wavelet analysis of geomagnetic jerks, *J. geophys. Res.,* **101,** 21 975–21 994.

Backus, G.E., 1983. Application of mantle filter theory to the magnetic jerk of 1969, *Geophys. J. R. astr. Soc.,* **74,** 713–746.

Barnes, R.T., Hide, R., White, A.A. & Wilson, C., 1983. Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, *Proc. R. Soc. Lond.,* A, **387,** 31–73.

Bellanger, E., Le Mouël, J.-L., Mandea, M. & Labrosse, S., 2001. Chandler wobble and geomagnetic jerks, *Phys. Earth planet. Inter.,* **124,** 95–103.

Bloxham, J., Zatman, S. & Dumberry, M., 2002. The origin of geomagnetic jerks, *Nature,* **420,** 65–68.

Braginsky, S.I., 1970. Torsional magnetohydrodynamic vibrations in the Earth's core and variations in day length, *Geomag. Aeron.,* **10,** 1–8 (English translation).

Buffett, B.A., 1996. A mechanism for decade fluctuations in the length of day, *Geophys. Res. Lett.,* **23,** 3803–3806.

Buffett, B.A. & Glatzmaier, G.A., 2000. Gravitational braking of inner-core rotation in geodynamo simulations, *Geophys. Res. Lett.,* **27,** 3125–3128.

Chao, B.F., Dehant, V., Gross, R.S., Ray, R.D., Salstein, D.A., Watkins, M.M. & Wilson, C.R., 2000. Space geodesy monitors mass transports in global geophysical fluids, *EOS, Trans. Am. geophys. Un.,* **81,** 247–250.

Constable, C.G. & Parker, R.L., 1988. Smoothing, splines and smoothing splines: Their application in geomagnetism, *J. comput. Phys.,* **78,** 493–508.

Courtillot, V. & Le Mouël, J.-L., 1984. Geomagnetic secular variation impulses, *Nature,* **311,** 709–716.

Courtillot, V., Ducruix, J. & Le Mouël, J.-L., 1978. Sur une accélération récente de la variation séculaire du champ magnétique terrestre, *C. R. Acad. Sci. Paris. Ser. D,* **287,** 1095–1098.

de Boor, C., 1978. *A Practical Guide to Splines,* Springer-Verlag, New York.

Dickey, J.O., Marcus, S.L. & de Viron, O., 2003. Coherant interannual and decadal variations in the atmosphere-ocean system, *Geophys. Res. Lett.,* **30,** 1573, doi:10.1029/2002GL016763.

Gibert, D., Holschneider, M. & Le Mouël, J.-L., 1998. Wavelet analysis of the Chandler wobble, *J. geophys. Res.,* **103,** 27 069–27 089.

Gross, R.S., Fukumoria, I., Menemenlis, D. & Gregout, P., 2004. Atmospheric and oceanic excitation of length-of-day variations during 1980–2000, *J. geophys. Res.,* **109,** B01406, doi:10.1029/2003JB002432.

Jackson, A., Bloxham, J. & Gubbins, D., 1993. Time-dependent flow at the core surface and conservation of angular momentum in the coupled core-mantle system, in *Dynamics of the Earth's Deep Interior and Earth Rotation,* pp. 97–107, eds Le Mouël, J.-L., Smylie, D.E. & Herring, T., AGU/IUGG, Washington, DC.

Jault, D., Gire, C. & Le Mouël, J.L., 1988. Westward drift, core motions and exchanges of angular momentum between core and mantle, *Nature,* **333,** 353–356.

Kalnay, E. *et al.,* 1996. The NCEP/NCAR 40-year reanalysis project, *Bull. Am. met. Soc.,* **77,** 437–471.

Le Huy, M., Mandea, M., Le Mouël, J.-L. & Pais, A., 2000. Time evolution of the fluid flow at the top of the core. Geomagnetic jerks,, *Earth Planets Space,* **52,** 163–173.

Le Mouël, J.-L., Madden, T. R., Ducruix, J. & Courtillot, V., 1981. Decade fluctuations in geomagnetic westward drift and Earth rotation, *Nature,* **290,** 763–765.

McCarthy, D.D. & Babcock, A.K., 1986. The length of day since 1656, *Phys. Earth planet. Inter.,* **44,** 281–292.

Malin, S.R.C. & Hodder, B.M., 1982. Was the 1970 geomagnetic jerk of internal or external origin?, *Nature,* **296,** 726–728.

Mandea, M., Bellanger, E. & Le Mouël, J.L., 2000. A geomagnetic jerk for the end of the 20th century?, *Earth planet. Sci. Lett.,* **183,** 369–373.

Mandea Alexandrescu, M., Gibert, D., Le Mouël, J.-L., Hulot, G. & Saracco, G., 1999. An estimate of average lower mantle conductivity by wavelet analysis of geomagnetic jerks, *J. geophys. Res.,* **104,** 17 735–17 745.

Marcus, S.L., Chao, Y., Dickey, J.O. & Gregout, P., 1998. Detection and modelling of nontidal oceanic effects on Earth's rotation rate, *Science,* **281,** 1656–1659.

Mound, J.E. & Buffett, B.A., 2003. Interannual oscillations in length of day: Implications for the structure of the mantle and core, *J. geophys. Res.,* **108,** 2334.

Neubert, T. *et al.*, 2001. Ørsted satellite captures high-precision geomagnetic field data, *EOS, Trans. Am. geophys. Un.,* **82,** 81–88.

Ponsar, S., Dehant, V., Holme, R., Jault, D., Pais, A. & van Hoolst, T., 2003. The core and fluctuations in the Earth's rotation, in *Earth's Core: Dynamics, Structure, Rotation,* Vol. 31, pp. 251–261, eds Dehant, V., Creager, K.C., Karato, S.-I. & Zatman, S., Geodyn. Ser., AGU, Washington DC.

Reigber, C., Lühr, H. & Schwintzer, P., 2002. Champ mission status, *Adv. Space Res.,* **30,** 129–134.

Stephenson, F.R. & Morrison, L.V., 1995. Long-term fluctuations in the Earth's rotation—700 B.C. to A.D. 1990, *Phil. Trans. R. Soc. Lond., A,* **351,** 165–202.

Zatman, S., 2001. Phase relations for high frequency core-mantle coupling and the Earth's angular momentum budget, *Phys. Earth planet. Inter.,* **128,** 163–178.

Zatman, S. & Bloxham, J., 1997. The phase difference between length of day and atmospheric angular momentum at subannual frequencies and the possible role of core-mantle coupling, *Geophys. Res. Lett.,* **24,** 1799–1802.