Characterisation and implications of intradecadal variations in length-of-day

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Variations in Earth rotation (defined in terms of length of day - LOD) arise from external tidal torques, or from exchange of angular momentum between the solid Earth and its fluid components [1]. On short timescales (annual or shorter) the non-tidal component is dominated by the atmosphere, with small contributions from the ocean and hydrological system. On decadal time scales, the dominant contribution is from angular momentum exchange between the solid mantle and fluid outer core. Intradecadal periods have been less clear, and have been characterised by signals with a wide range of periods and varying amplitudes, including a peak at around 6 years [2–4]. Here, by working in the time domain, rather than the frequency domain, we demonstrate a clear partition of the non-atmospheric component into only three components: a decadally varying trend, a 5.9-year period oscillation, and jumps at times contemporaneous with geomagnetic jerks. The nature of the jumps in LOD changes fundamentally what class of phenomena may give rise to the jerks, and provides a strong constraint on electrical conductivity of the lower mantle, which can in turn constrain its structure and composition.

The length-of-day (LOD) fluctuations from 1962 until 2012 are corrected for atmospheric and oceanic effects using assimilating general circulation models (see supplementary material, Figure S1). This correction accounts for most of the variation at yearly and shorter periods. The remaining short-period signal is dominantly semi-annual; we therefore apply a 6-month running mean both to eliminate this signal and reduce shorter-period noise. Figure 1 shows that the data are well explained by a decadally varying signal and a constant 5.9-year periodic signal, amplitude 0.127 ms (determined iteratively – see methods section); the residual between the data and these two signals has a root mean square amplitude of less than 0.03 ms. Also plotted (vertically shifted for clarity) are the decadally varying signal alone and the data with the 5.9-year oscillation subtracted, demonstrating the separation of the oscillation from the background trend. Inference from spectral studies [5,6] suggests that the 5.9-year oscillation is also present prior to 1960.

In Figure 2, we remove the decadal signal to give the intra-decadal variability. The 5.9-year oscillation is dominant, with no indication of variation in amplitude or period (see also supplementary information, Figure S3). This argues against an origin from solar processes (e.g.[7]), as there are no variations that might correlate with variations in the solar cycle. The most likely origin of the oscillation is in association with fluid core motions [6] and inner-core coupling [8]. The harmonic signal is disturbed by small discontinuities. Also plotted are the approximate times of identified geomagnetic jerks (sharp changes in the gradient of the time derivative of the geomagnetic field – the secular variation) [9]. An extremum of the 5.9-year oscillation, or a separate feature in LOD, can be identified with each jerk, within their temporal uncertainty (about ±6 months). The best known, and most studied, geomagnetic jerks are those around 1969 and 1978. In Figure 3, we replot Figure 2 to cover these two jerks, with wavelet determinations of jerk timings at geomagnetic observatories [10]. The peaks in jerk occurrence clearly match closely peaks in the LOD signal. The

1969 and 1978 jerks have been identified as having similar spatial structure but of opposite sign; it is interesting that they match opposing peaks in the LOD signal. Further, it has been suggested that their timing is a function of location – the 1969/1978 jerk seen in Europe has been associated with a southern hemisphere signal in 1972/1982 (e.g. [11]). This splitting has been suggested as evidence of filtering by electrical conductivity in the mantle, perhaps laterally varying [10], but potentially even from laterally uniform conductivity [12]. However, the 1972/1982 timings correspond to the next peak in the LOD cycle (and separate discontinuities in LOD derivative [13]), suggesting instead that the two signals identified as parts of a global jerk instead result from two separate localised events. The histogram peak heights cannot be compared because of non-uniform sampling (geomagnetic observatory distribution) (the 1969 and 1978 jerks are seen strongly in the heavily sampled European region), but it is interesting that both the jerk histogram and LOD extrema in 1969 and 1978 are sharp (the more so when the 6-month running average of the LOD is taken into account), while the broader time distribution of jerk occurrence around 1972 and particularly 1982 events is matched by a broadening of the extremum in the LOD signal, arising from slope changes in the LOD curve.

Importantly, there is no apparent lag between the times of the rotational and magnetic signals. To explore this further, in Figure 4 we focus on the period 2002-6, for which two geomagnetic jerks (2003.5 and 2004.7) are more tightly localised in time through core-flow modelling using geomagnetic satellite data [14]. The latter time matches an extremum in LOD, and is centred additionally on a change in slope in the LOD signal. The earlier event occurs away from an extremum of the 5.9-year oscillation, but is still centred on a feature in the LOD curve, seen more clearly because it occurs away from an extremum of the oscillation. The grey lines are linear fits to the data before 2003.25 and after 2003.75; these are extended to 2003.5, and the dashed grey line applies the 6-month running average to the composite signal, giving a good qualitative fit to the data. Therefore, the data are explained by discontinuities in both LOD, of almost 0.1 ms, and its gradient, of -0.18 ms/year, centred at 2003.5. Similar features appear frequently in the LOD curve; supplementary Figure S4 shows similar analysis for 1971.0 and 1994.3. It would be of interest to recover more such features from satellite data; the upcoming ESA mission Swarm is likely to be particularly useful in this regard.

We have previously [9,13] identified discontinuities in the time derivative of LOD at the time of geomagnetic jerks, but the observation of a direct jump in the LOD (angular velocity) itself is new, and changes fundamentally the class of phenomena in which we can seek an origin for the jerks. A discontinuity in the derivative requires a jump in the torque, but from conservation of angular momentum, a jump in the LOD itself further implies a sudden change in the mantle moment of inertia. Large earthquakes are known to produce such a jump; for example, the Sumatra 2004 Boxing day Earthquake produced a jump of 6.8 μs in LOD [15], with smaller amplitudes estimated for the February 2010 Chile earthquake (1.25 μs) and the March 2011 Japanese earthquake (1.8 μs). However, the effect modelled here is one to two orders of magnitude larger than that of these large earthquakes, requiring a different mechanism.

What could give rise to such an effect? Occurring simultaneously with geomagnetic jerks, the LOD jumps, like the oscillation, most likely originate from the core. A sudden localised strong coupling could temporarily attach part of the fluid core to the mantle, and due to the influence of the Taylor-Proudman theorem, this would create a torsional motion, bringing all fluid with it on a cylinder concentric with the rotation axis (see, for example, the figure in [16]), in effect dragging a part of the core with the mantle and changing its moment of inertia. (This can also be viewed as the impulsive transfer of angular momentum from mantle to core.) This connection could result from a localised magnetic effect; one possible mechanism is flux expulsion [17], upwelling (vertical motions) of fluid near the core surface leading to expulsion of toroidal magnetic field (not observable) into an electrically conducting mantle and its conversion into (observable) poloidal field at the core surface. Detailed modelling of this effect is outwith the scope of this letter, but in the methods section, we present scaling arguments suggesting that torsional motions of width 10°, magnitude a fraction of a km yr^{-1} are sufficient to achieve the required angular momentum jump; a timescale for the transfer of angular momentum is of order 10 days, effectively instantaneous considering the 6-month running average of the data. Geomagnetic jerks have previously been associated with torsional flow in the core [18] although such motions cannot explain the whole signal [19]; flux expulsion necessarily involves diffusional processes, and therefore will generate secular variation which cannot be explained by torsional flows alone. Comparison with the fit of the 5.9-year oscillation in Figure 4 shows that the effect of the LOD pulse decays rapidly, with the fit to the oscillation returning within at most a year, consistent with the cylindrical perturbation reconnecting with the motion of the core. This timescale may further provide a constraint on magnetic diffusional processes at the top of the core. However, a lasting change in LOD derivative remains [9,13], and the creation and decay of the jump could excite the system; it could be that these "jerks" are the mechanism which excites the 5.9-year oscillation and prevents it from decaying.

Simultaneous observation of geomagnetic and LOD signals limits strongly the electrical conductivity of the deep mantle: substantial deep mantle electrical conductivity away from the core-mantle boundary would delay the propagation of any geomagnetic signal from a sharp change in field at the CMB to Earth's surface [20,21]. Considering a homogeneous layer of material close to the core, this lag τ is given to a first approximation by

$$\tau = \mu_0 h t \sigma = \mu_0 h G \tag{1}$$

(see Methods section) where μ_0 is the permittivity of free space, h the height of the middle of the layer above the CMB, t the layer thickness ($h > t/2$), σ the electrical conductivity of the layer, and $G = \sigma t$, its conductance. The simultaneous expression in LOD and geomagnetic field of the 2003.5 (and also 2004.7) events conservatively requires $\tau < 0.2$ years. Significant electromagnetic coupling between the core and mantle requires a conductance of $G = 10^8 S$ [22,23]. Such a layer located at the CMB (small h) would have little effect on the propagation of secular variation. However, a thin layer of high conductance more distant from the CMB, or more diffuse conductance over, for example, the thickness of D$''$, is not consistent with this small lag; if the layer is the primary source of significant electromagnetic core-mantle coupling, then its height above the CMB must satisfy $h < 50$km, with correspondingly stronger constraint if the conductance G is greater. The requirement for low electrical conductivity except close to the CMB is in agreement with bounds provided by modelling from surface observations [24,25].

One candidate for enhanced electrical conductivity in the lower mantle is a possible phase transition to post-perovskite (e.g., [26]). However, seismic transitions which might correspond to this transformation [27] are observed at more than 50km above the CMB. Thus any such layer capable of substantial EM coupling would give too great a delay time to be compatible with the timing of geomagnetic jerks, and can be ruled out. If enhanced conductivity is confirmed as a consequence of the post-perovskite transition, then the timing of geomagnetic jerks and their LOD signature would provide evidence against the wide-spread presence of post-perovskite in the lower mantle.

Methods summary The fit of the decadal trend and 5.9-year oscillation to the data was obtained iteratively. The decadal trend was fit with smoothing splines and subtracted from the data. From the initial fit to the residual, varying the period and seeking best fit, an oscillation of period 5.8 years and 0.12 ms amplitude was obtained (Figure S2 in supplementary information); this oscillation was then subtracted from the original data and the decadal trend redetermined. This two-stage process was repeated until convergence (4 stages) varying the spline knot spacing as necessary to allow good representation of the decadal variation; the fit in Figure 1 has a spacing of approximately 4 years.

Angular momentum transfer: The jump in ΔLOD is of magnitude $\Delta T = 0.1$ ms. In the methods section, we show that this could be caused by a change in velocity of 0.25 km yr^{-1}, of a cylinder of core fluid, width $10^{\rm o}$ centred on colatitude of $45^{\rm o}$, an order of magnitude less than typical azimuthal velocities of modelled surface core flows. A plausible time scale for this change is of order 10 days, in effect instantanous on the averaging time-scale of 6 months.

Electromagnetic delay time: In the methods section, we show that the delay time for signals to travel from source at the CMB to observation at Earth's surface is through a mantle layer of uniform conductivity is only a weak function of the scale of the signal, proportional to the mean height, thickness and conductivity of the thin layer.

Methods

Angular momentum transfer The jump in ΔLOD is of magnitude $\Delta T = 0.1$ ms. This corresponds to a change in angular momentum ΔL of the Earth of

$$\Delta L = I\Delta\omega = -I2\pi\Delta T/T^2 = -6.7 \times 10^{24}\text{Nms}$$

where $I = 7.1 \times 10^{37} kgm^2$ is the moment of inertia of the solid Earth, ω is angular velocity, and $T = 86400$ s is the period of 1 day. This must be taken up by the motion of a cylinder of core material, density ρ, touching the core surface (radius $c = 3.485 \times 10^6$m) at colatitude θ, width $\delta\theta$, mass $M = \rho 4\pi c^3 \cos^2\theta \sin\theta\delta\theta$. If this cylinder has a change in azimuthal velocity δv, the change in angular momentum is

$$\Delta L = Mc\sin\theta\delta v = 2.6 \times 10^{24} \sin^2(2\theta)\delta\theta\delta v$$

where $\delta\theta$ is measured in degrees and δv a core surface velocity in km yr^{-1}. Thus equating the two equations for change in angular momentum, a cylinder of width $\delta\theta = 10^{\text{o}}$ centred on colatitude of $\theta = 45^{\text{o}}$ would require a change in velocity of $\delta v = 0.23$ km yr^{-1}, an order of magnitude less than typical azimuthal velocities of modelled surface core flows.

This change in angular momentum could arise from a toroidal electromagnetic torque[22]

$$\Gamma_z = -\frac{c}{\mu_0}\int B_\phi B_r \sin\theta dS$$

Considering a patch of strong poloidal field ($B_r = 1$mT) and toroidal field (from differential rotation) an order of magnitude stronger ($B_\phi = 10$mT), then allowing for upwelling of the same dimensions as the cylinder ($\delta\theta = 10^{\text{o}}$ again at $\theta = 45^{\text{o}}$) a torque magnitude of order 7×10^{18} Nm would arise. Given that torque gives rate of change of angular momentum, the time scale for the application of this torque would be $\tau = \Delta L/\Gamma_z \sim 10^6$s = 10 days, short enough on the timescale of the 6-month running average to produce a close to instantaneous jump in LOD as seen in the current analysis. (Note that the time scale for flux expulsion into a conducting lower mantle is even shorter, similar to the delay time calculated following.)

Electromagnetic delay time The delay time for signals to travel from source at the CMB radial distance $r = c$, through the mantle to observation at Earth's surface $r = a$ is given by [21]

$$(2l+1)\tau_l = \mu_0 \int_c^a dr \sigma(r) r \left(1 - \left(\frac{c}{r}\right)^{2l+1}\right) \tag{2}$$

where τ_l is the delay time of a magnetic field component of spherical harmonic degree l, $\sigma(r)$ is the electrical conductivity of the mantle, and μ_0 is the permeability of free space. For a layer of uniform conductivity σ, of mean height above the CMB h, thickness t, this can be determined exactly, but it is nonetheless instructive to consider an alternative approximate formulation. Changing variables to distance from Earth's core $x = r - c$, and assuming $h, t \ll c$ then

$$\begin{aligned}
\tau_l &= \frac{\mu_0 \sigma c}{2l+1} \int_{h-t/2}^{h+t/2} dx \left(1 + \frac{x}{c} - \left(1 + \frac{x}{c}\right)^{-2l}\right) \\
&= \mu_0 \sigma c \int_{h-t/2}^{h+t/2} dx \left(\frac{x}{c} - l\left(\frac{x}{c}\right)^2 + \frac{2l(l+1)}{3}\left(\frac{x}{c}\right)^3 + \mathcal{O}\left(\frac{x}{c}\right)^4\right) \\
\Rightarrow \tau_l &\approx \mu_0 \sigma t h \left(1 - l\frac{h}{c}\left(1 + \frac{1}{12}\left(\frac{t}{h}\right)^2\right) + l(l+1)\frac{2}{3}\left(\frac{h}{c}\right)^2\left(1 + \frac{1}{4}\left(\frac{t}{h}\right)^2\right)\right) \\
&\approx \mu_0 \sigma t h \left(1 - l\left(\frac{h}{c}\right)\right)
\end{aligned} \tag{3}$$

Thus for large scale (small l) field components, to first order in the small parameters (h/c), (t/c), the delay time for a layer of uniform conductivity is only a weak function of degree (for scaling arguments as here the term in l can be neglected), and linearly proportional to the mean height, thickness and conductivity of the thin layer.

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Author contributions R.H. performed the primary analysis and led the writing of the manuscript. O.dV. provided the original data with corrections for atmophere and ocean and contributed to writing the manuscript.

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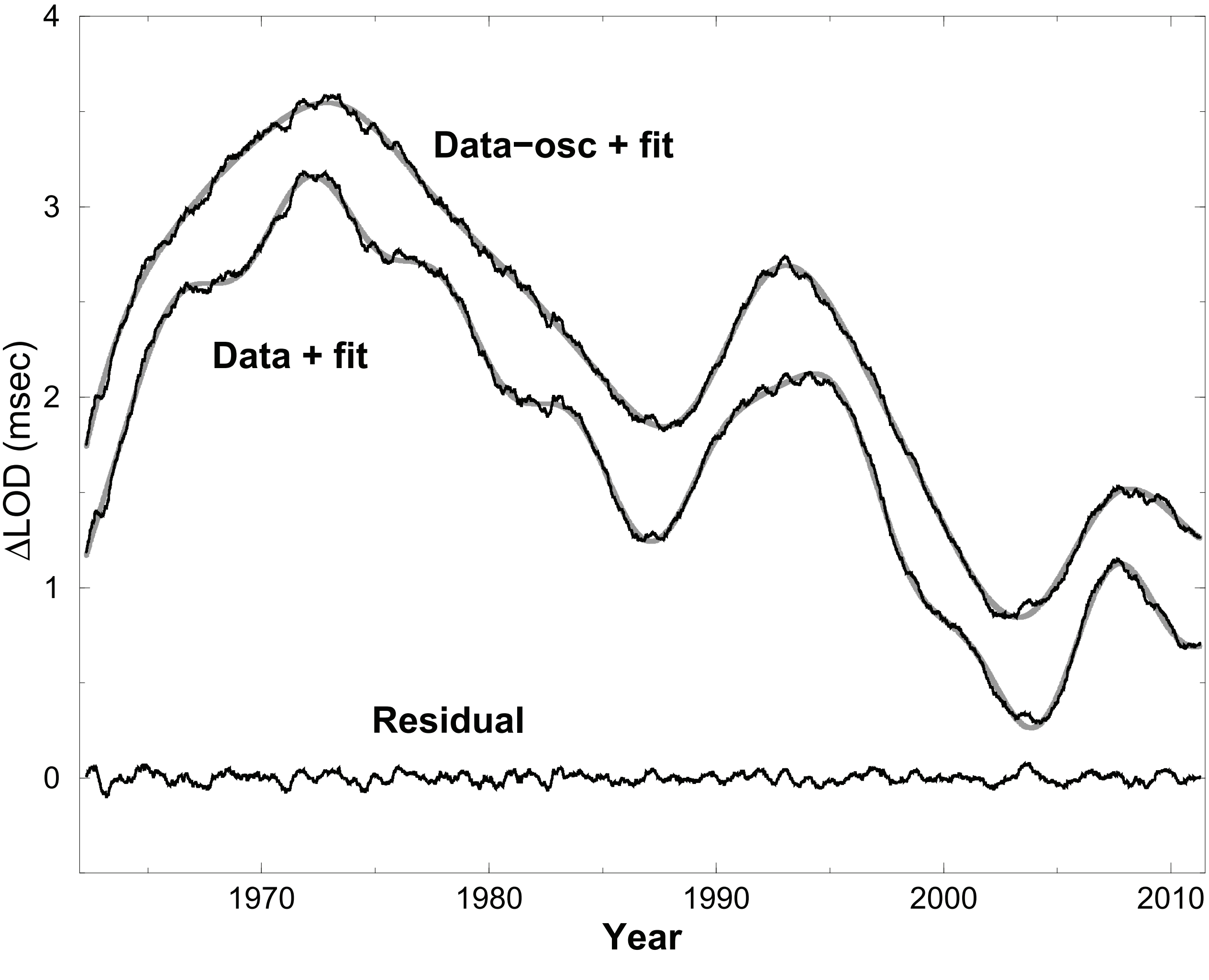
Figure 1 Fit to ΔLOD data (black line) of 5.9-year oscillation and decadal trend (grey line). Also plotted are the residual, and data and fit with the oscillation removed, shifted upwards by 0.5s for clarity.

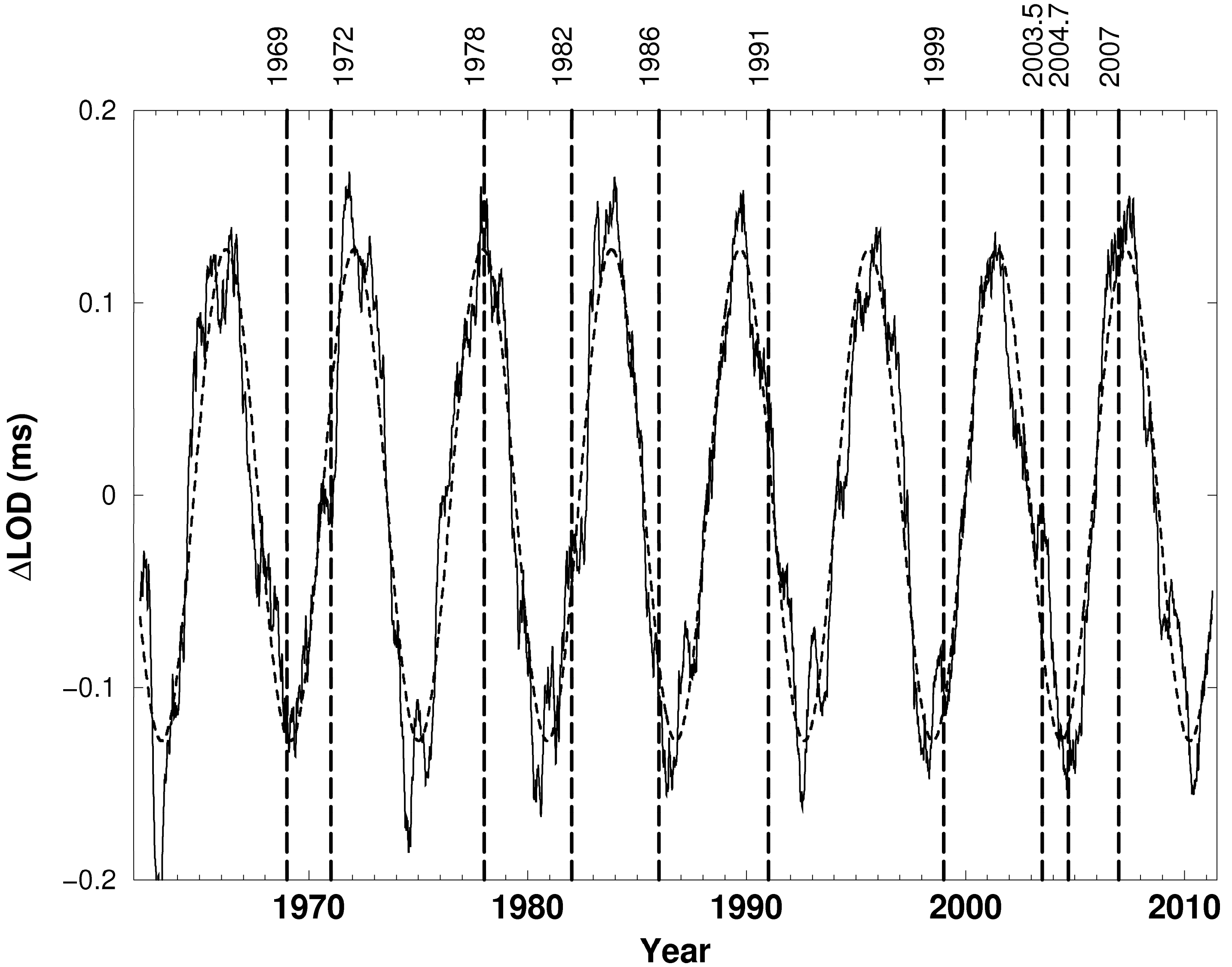
Figure 2 Decadally detrended LOD data (with 6 month running average), plotted with 5.9-year oscillation fit (dashed line). Vertical lines shows best determinations of geomagnetic jerk timings.

Figure 3 Focus on 1965-1985, to show correlation between the 5.9-year LOD oscillation and a histogram of wavelet-determined geomagnetic jerk occurrence times [10].

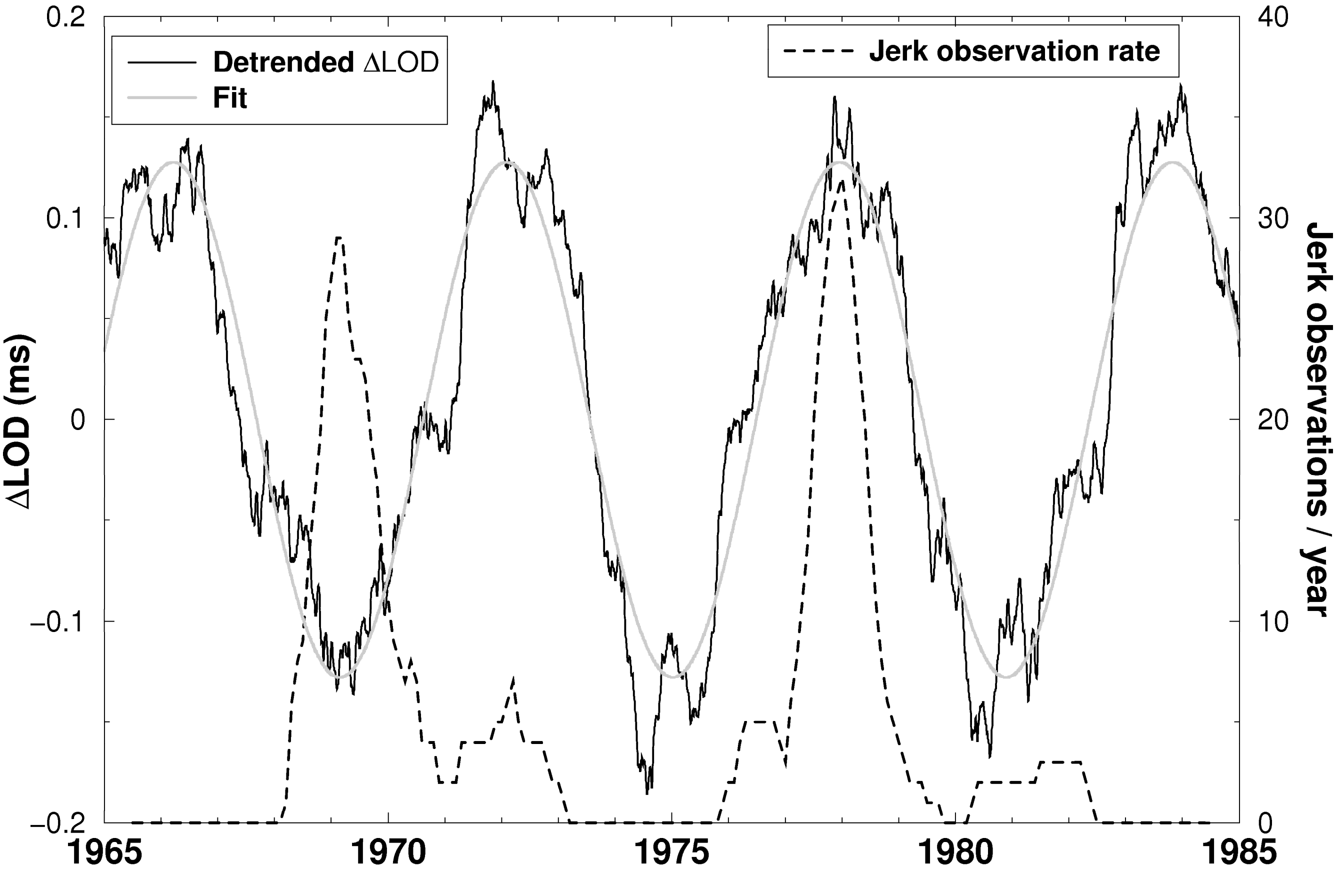
Figure 4 Focus on 2002-2006 to compare LOD series with well-constrained geomagnetic jerk times (long dashes; short dashes these times $\pm$ 3 months). Grey lines are linear fits near the jerk; grey dashed line the running average applied to these fits.



4
3
2
1
0
Data−osc + fit
Data + fit
Residual
ΔLOD (msec)
1970
1980
1990
2000
2010
Year



1969
1972
1978
1982
1986
1991
1999
2003.5
2004.7
2007
0.2
0.1
0
−0.1
−0.2
ΔLOD (ms)
1970
1980
1990
2000
2010
Year



Detrended ΔLOD
Fit
Jerk observation rate
ΔLOD (ms)
Jerk observations / year
Year
0.2
0.1
0
−0.1
−0.2
40
30
20
10
0
1965
1970
1975
1980
1985

0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
−0.12
−0.14
−0.16
ΔLOD (msec)
2002
2002.5
2003
2003.5
2004
2004.5
2005
2005.5
2006
Year

Supplementary information

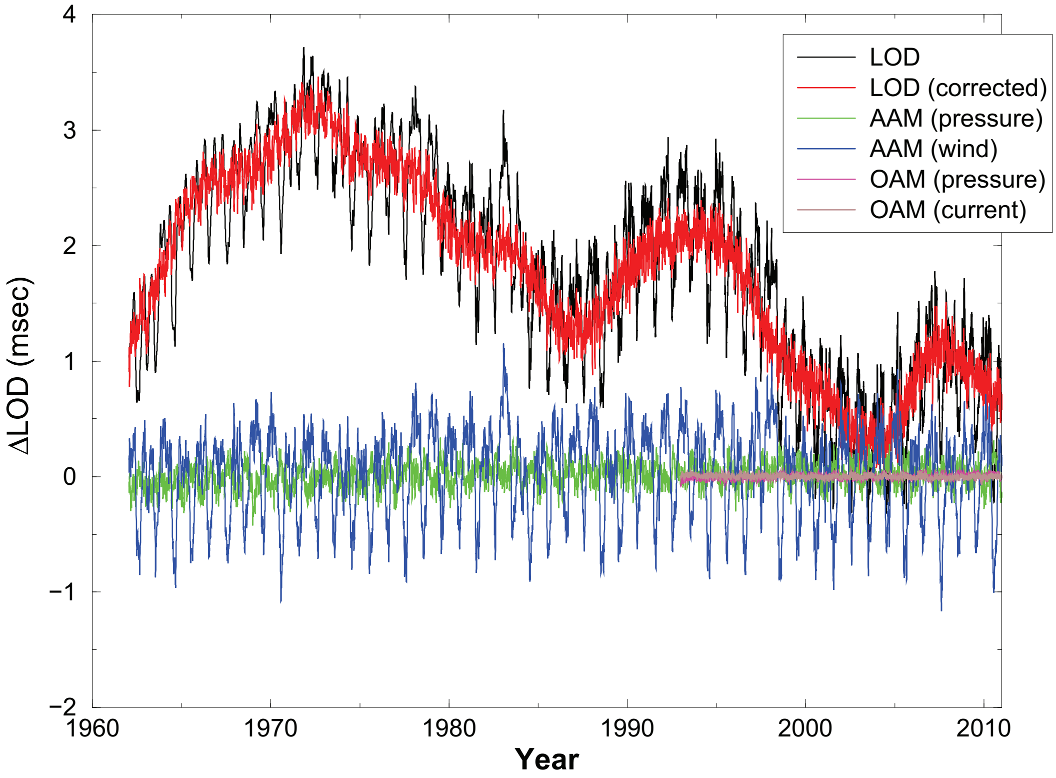


Figure S1: LOD observations, atmospheric and oceanic signals, and predictions. Here we show influence of removing atmospheric and oceanic predictions from the LOD time series, from the NCEP (28) and ECCO (kf80 version) (29) models respectively. We prefer the NCEP model prediction to that of the ERA40 re-analysis (30), thought possibly to better represent variation at longer periods, because of a significantly better fit of periods of variation around 1 year, allowing simple smoothing with a 6-month running average. The oceanic estimate is small (also for other oceanographic and hydrological predictions), probably less significant than the uncertainty in the atmospheric prediction.

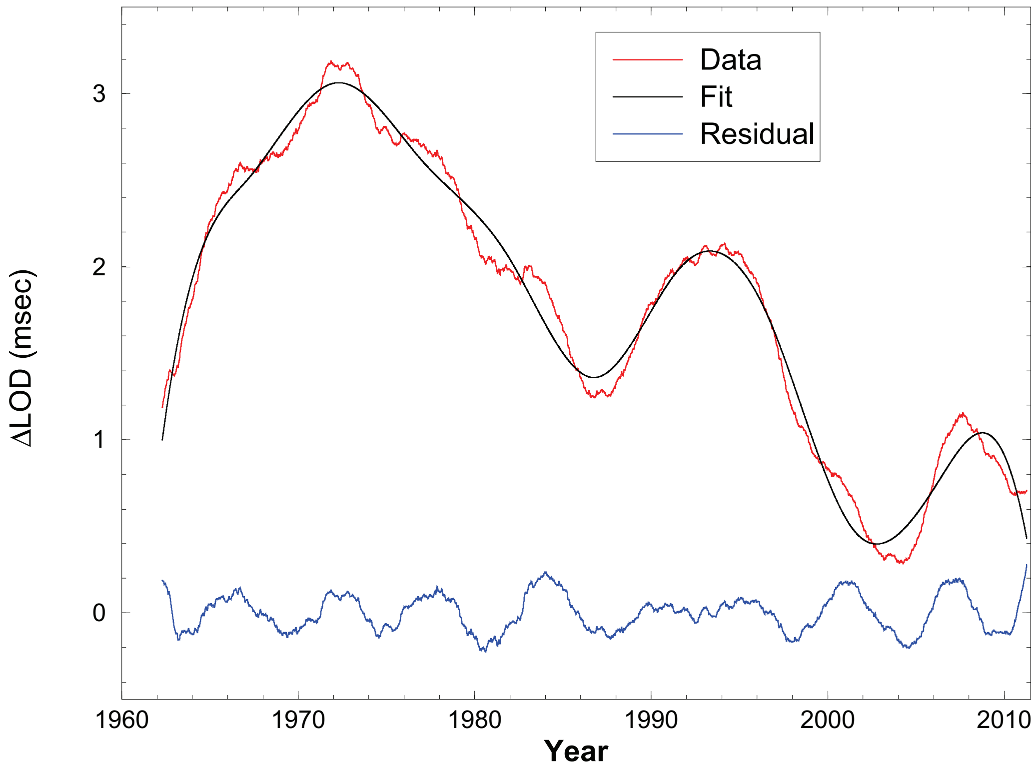


Figure S2: Varying amplitude of the oscillation? Here we show the fit to the total ΔLOD of smoothing splines with 5-year knot separation (allowing representation only of periods of 10 years or more) demonstrating the presence of a periodic residual with approximate 5.8 year period, but of varying amplitude, particularly low in the 1990s (5). However, during this decade, the oscillation anticorrelates with the decadal trend, thus allowing potential cancellation between the two signals. This accounts for previous claims of variation of amplitude of the oscillation (e.g.,(5)), although as we have shown, such variation is not required by the data. Methodologically, to model the oscillation, we must detrend the data of the decadal variation, but also to model the trend, we must detrend of the oscillation.

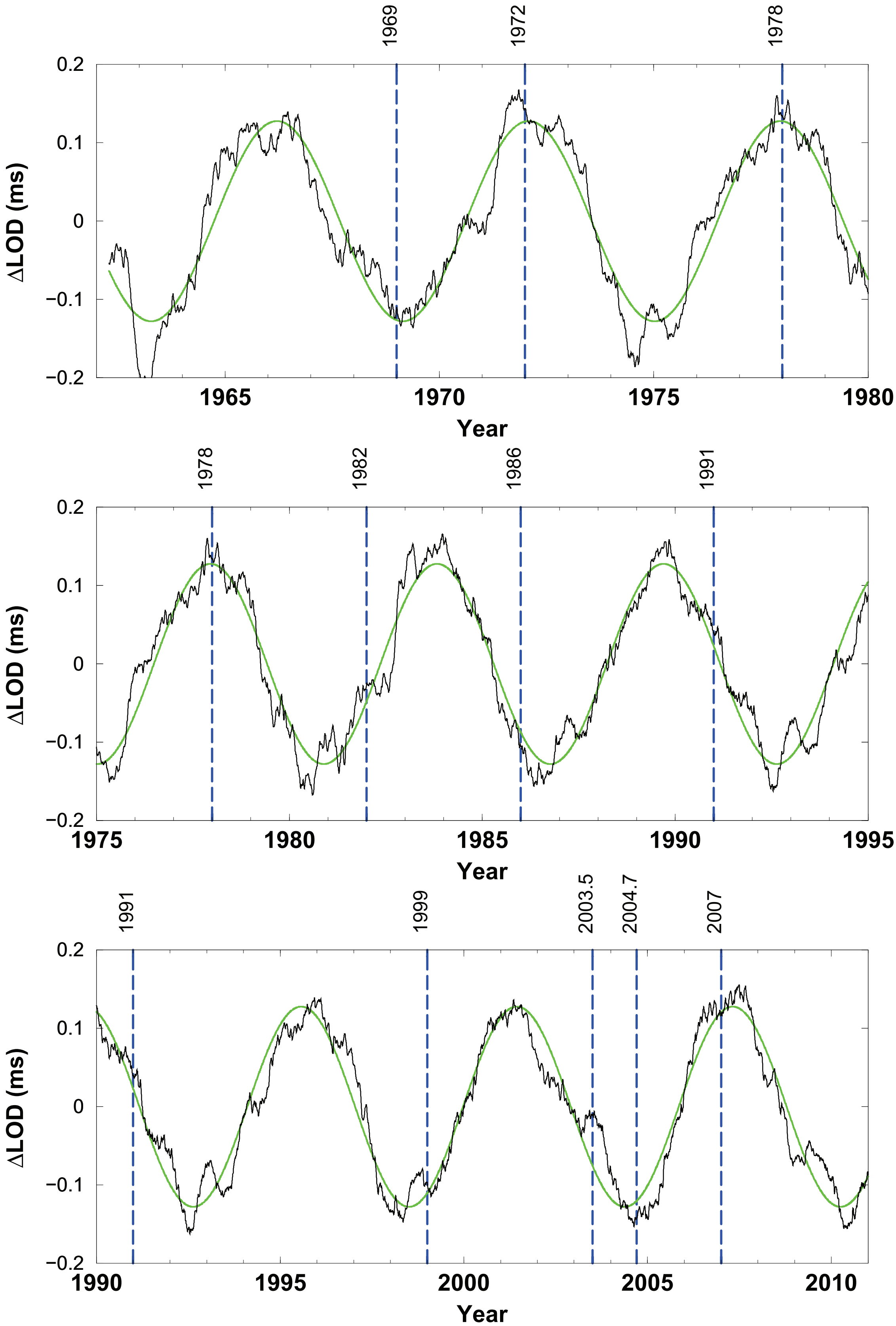


Figure S3: Expanded version of Figure 2 from main paper.

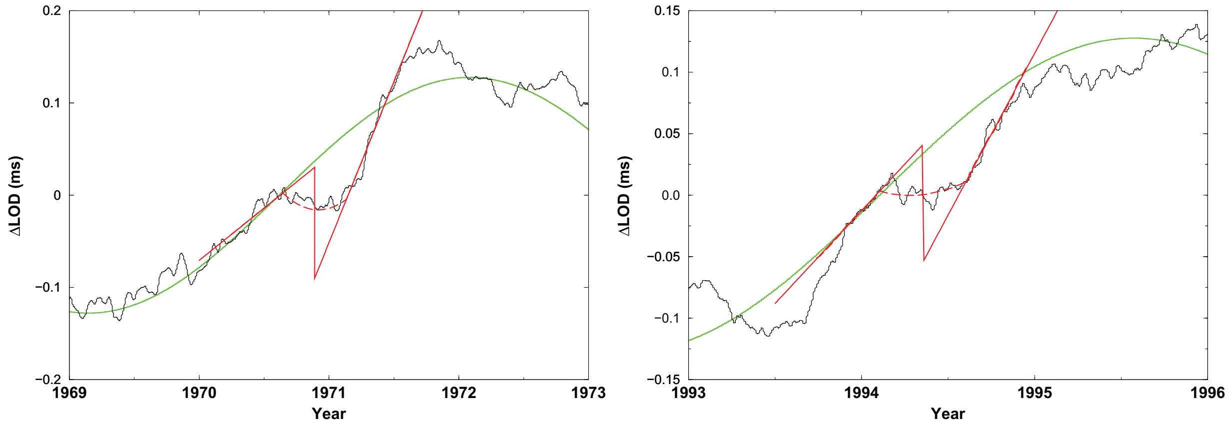


Figure S4: Modelling of LOD features in 1971 and 1994.3 with jumps,following Figure 4. Solid lines are model; long dashed lines are 6-month running averages to mimic the data. 1971 shows a jump in LOD of 0.120 ms, and in gradient of 0.236 ms / year; 1994.3 shows a jump of 0.093 ms and a jump in gradient of 0.112 ms / year. These values are broadly consistent with the well-defined jerk in 2003.5

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