Leading modes of torsional oscillations within the Earth's core

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[1] The fluid core motion cannot be observed directly, however, it can be deduced from magnetic observations. This motion can be approximated as a set of coaxial cylinders rotating along the Earth rotation axis. Our study shows that the actual motion in the core corresponds to a set of oscillations propagating from the core-mantle boundary to the inner core (with diminishing amplitude) at period of 85, 50, 35 and 28 years, respectively. These oscillations appear to be very robust in our study, moreover two weaker modes have also been isolated and require further study. Zatman and Bloxham (1997) isolated two modes with periods that correspond to our first two modes. Comparing the theoretically predicted modes of Mound and Buffett (2007), all three analyses (one theoretically based and two based on geomagnetic observations) agree on the periods of the isolated modes; this concurrence is exceptional and provides strong evidence of the existence of the modes. **Citation:** Dickey, J. O., and O. de Viron (2009), Leading modes of torsional oscillations within the Earth's core, *Geophys. Res. Lett.*, *36*, L15302, doi:10.1029/2009GL038386.

1. Introduction

[2] Using the surface magnetic field and its time variations, it is possible to solve for the flux inside the core, as done for instance by *Hide et al.* [2000]. *Zatman and Bloxham* [1997] have shown that this motion was consistent with two torsional oscillations traveling inside the core, with periods of 76 and 53 years, respectively. *Mound and Buffett* [2007] have shown theoretically how such oscillations are generated inside the core, and found several other periods that would likely be associated with torsional oscillation. In 2000, *Hide et al.* [2000] identified a robust observation with a torsional oscillation period of ~65 year. The later analysis of *Roberts et al.* [2007] favored a ~60 year oscillation. Note that the average of the first two modes found by Zatman and Bloxham is 60–65 years, which matches the results of *Hide et al.* [2000] and *Roberts et al.* [2007]. This is in agreement with the earlier findings of *Braginsky* [1987].

[3] Our study aims at isolating the different torsional oscillations that can be found in the observations, then to confront them with the theoretical results. We assume that the flow inside the core is adequately represented by the so-called "Taylor cylinder" flow [*Jacobs*, 1987], which implies that the velocity field is equivalent to a rigid rotation of coaxial cylinders around the Earth rotation axis and that this velocity is the mean velocity of the fluid at the intersection of the cylinder by the core. We used the core angular momentum (CAM) associated with the flow reconstructed [*Hide et al.*, 2000] from *Jackson et al.* [1995] data; here, CAM is given separately for the 20 cylinders used in the reconstruction of the flow. The raw CAM data by channels are given in Figure 1 (top).

2. Techniques Utilized

[4] The singular spectrum analysis (SSA) (and its multi-data set generalization, the MSSA) is an extension of the EOF decomposition, as first introduced by *Vautard and Ghil* [1989]. First, we have to define the maximum wavelength of the targeted signal (i.e., the window size). We compute the autocorrelation matrix on this window size, and compute its eigenvectors. The eigenvalues of the matrix are proportional to the variance explained by the eigenvector, so we sort the result by decreasing eigenvalue, so that the first eigenvector is associated with the most variability. This method is very good at retrieving coherent pattern in noisy datasets. Indeed, quasi-periodic variations and long-term polynomial behavior of the signal will be emphasized by the autocorrelation computation. Classically, a quasiperiodic signal appears as the combination of two eigenvector (one for the cosine, one for the sine), while a polynomial pattern is fully represented by only one eigenvector. The projection of the signal on the eigenvector of the auto-correlation matrix allows the isolation of the time variable amplitude of quasiperiodic signal. Experience shows that better results are obtained by retrieving only one mode at the time (i.e., two eigenvector), then subtracting the associated signal, and making a new analysis.

[5] When using the multichannel SSA, the autocorrelation is estimated on the whole set of series. As the autocorrelation is based on lagged time series, it well isolates similar variations in the different series, even if they are not in phase. For this very reason, it is very efficient to isolate propagation pattern, as we did in this study.

3. Analysis and Results

[6] When MSSA is applied to the CAM series corresponding to each of the 20 cylinders, this technique allows us to retrieve propagation patterns associated with angular momentum transfer among the different cylinders and between the liquid core and the mantle or the solid inner core. Three distinct regions (see Figure 1, top) exist within the 20 Taylor cylinders: innermost (1–3, IC), the "mid-latitude" (4–15, MLC) and the outer (16–20, OC) regions [*Hide et al.*, 2000]. The innermost cylinder lies within the projection of the inner core itself, thus would only be affected by a minute amount. On the other hand, the mid-latitude and outer cylinder would be outside of the inner core projection and would be affected. The

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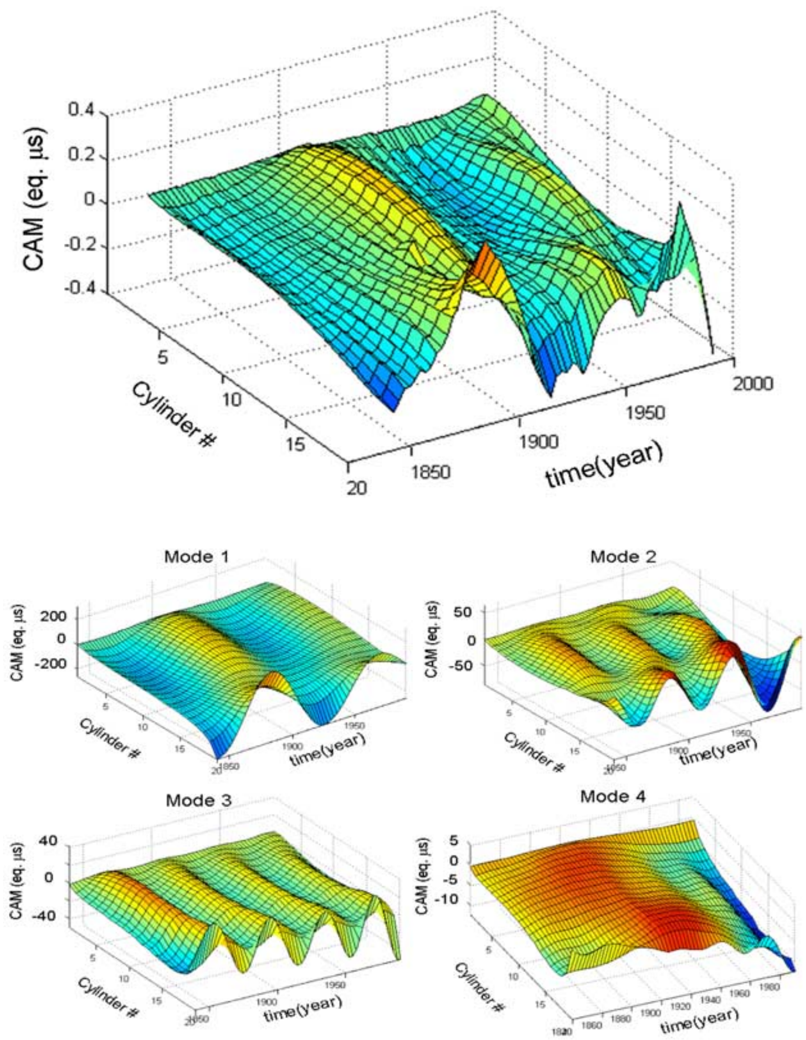

Figure 1. (top) The CAM of each cylinder is drawn, as computed by D.H. Boggs using the Taylor cylinder hypothesis [*Hide et al.*, 2000]. The cylinder 20 is close to the equator and to the CMB in the equatorial plan, and the cylinder 1 is close to the pole, and near the center of the Earth in the equatorial plan. The data are the values of the CAM on 20 cylinders (Taylor cylinder approximation) every 2.5 years from 1840 to 1987.5 (61 points). The CAM is in equivalent millisecond, i.e., 6×10^{28} Nms. (bottom) The first four reconstructed pairs of the CAM. The data are the value of the CAM on 20 cylinders (Taylor cylinder approximation) every 2.5 years from 1840 to 1987.5 (61 points). The CAM is in equivalent millisecond, i.e., 6 10^{28} Nms.

mid-latitudes, not intercepting the inner core and with only a small interface with the D″ layer (at bottom of the mantle), would be able to exercise a relatively free motion about the solid inner core and have vigorous oscillations in phase with the decadal LOD [*Hide et al.*, 2000]. An analogy would be the motion of the Antarctic Circumpolar Ocean Current (ACC) that travels completely around the Earth without any land obstacles in its path. Because of this, the ACC is extremely strong and produces powerful winds and storms in the Southern Oceans. The equatorial outermost cylinders would have the most contact with the D″ layer causing eddies, currents and turbulence which would affect nearby cylinders explaining the discontinuity in the outer cylinders (16–20) and a common pattern distinct from the mid-latitude cylinders. This provides a rationale for these 3 different regions; we see in Figure 2 the mid-latitude region that is in phase with the length-of-day, as one would expect. In contrast, the outer region intercepts the lower mantle and is out of phase with LOD leading it by about 20–25 years (centered around 22 years), which may be related to a solar effect [*Mursula et al.*, 2002].

[7] Here, we are able to isolate 6 torsional waves or modes. The 3-dimensional CAM associated with each of the wave was then reconstructed (see Figure 1, bottom). Note that the results for the second mode are shown in Figure 3 as

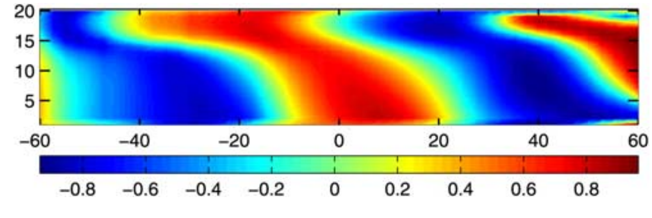

Figure 2. Correlation of LOD with the CAM as a function of the lag of the CAM with respect to LOD.

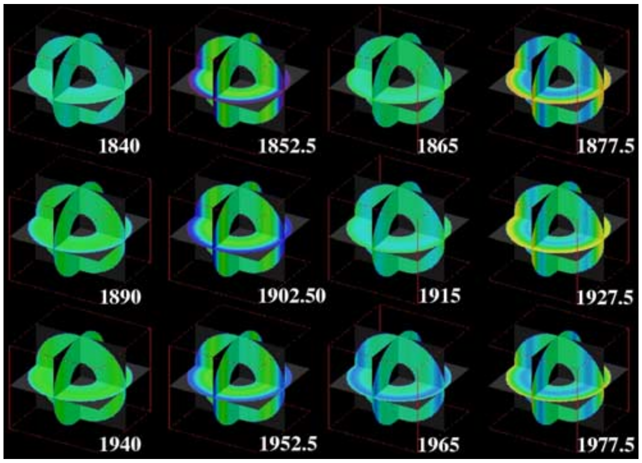

Figure 3. Three-dimensional representation of the propagation of the second modes. The propagation from the CMB to the ICB can be observed. The 50 yr period is also noticeable from the similarity of 1877.5, 1925.5 and 1977.5.

a series of snap shots from 1840 to 1977.5 with the time steps of 12.5 years and with each row covering 50 years. The anomaly in the CAM can be seen created at the Core Mantle Boundary (CMB) and propagating to the Inner Core Boundary (ICB), fading out. As the only spatial degree of freedom is the CAM of each cylinder, we can represent these waves in a more compact way: the abscissa being the cylinder number and the ordinate, time. Mode 2 with a period of 50 years can be easily seen by examining the cylinders (Figure 3). For example, strong yellow amplitudes are observed at t = 1877.5, 1927.5 and 1977.5, while robust minima (blue-purple) are evident at 1852.5, 1902.5 and 1952.5. The four modes (Figure 1, bottom) have periods of 85, 50, 35, and 27.5 years respectively. Most of those modes are propagating from the Core Mantle Boundary (CMB) to the Inner Core Boundary (ICB). The fifth and sixth modes were isolated; however, they are less robust and require further study.

4. Tests of Robustness

[8] We have no error estimates for the core velocity fields or for the CAM of the cylinders. Further, no robust test exists at present for the significance of the MSSA. On the other hand, we know that a solution is robust only if the isolated modes could not have been misinterpreted random signal. In our case, this seems unlikely, as the variance explained by the mode is a very important part of the signal, which would not be the case if those modes were absent. In order to further test the robustness, we perturbed the signal and tried to retrieve the same modes as before. In our first test, we combine the datasets two by two, by adding the CAM associated with two successive cylinders. This should not perturb truly propagating modes, instead it would cancel part of the random variations. The fact that our four first modes were unchanged with this perturbation is an indication of their robustness. As a second test, we added noise uniformly distributed to each data point at the level of the standard deviation of its time series, and tried to retrieve the same modes as before. Again, this perturbation should not

Table 1. Tests of Robustness

	Number of Cylinders 20	Number of Cylinders 10	Noise Addition Random $\sigma/2$	Noise Addition Random σ	Noise Addition Random $3\sigma/2$	Dataset Length 1–50	Dataset Length 10–60	Dataset Length 1–40	Dataset Length 20–60	All in 1 run	Small Window (25y)	Small Window (37y)	Other large Window (120y)
1st mode	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2nd mode	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3rd mode	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓	✓
4th mode	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓	×	×

Table 2. Period of Torsional Oscillations in the Earth's Core (Years)

Normal Modes	*Zatman and Bloxham* [1997]	*Mound and Buffett* [2007]	This Paper
1	76.2	79.5	85
2	52.7	46.1	50
3		31.5	35
4		23.6	27.5

affect true propagating modes, but would change the characteristics of a random signal, and consequently change the property of a mode created by the data processing technique. Our results showed no change at all for the retrieved modes with noise added at the level of sigma/2 and sigma. When we add noise at the level of 3/2 sigma, the fourth mode is lost.

[9] As a third test, we applied the MSSA to a shorter dataset, after removing the beginning or the end of the data set. We first removed 10 data points out of 60, and observed no effect. We then removed 10 additional points, keeping only two thirds of the data set. This resulted in major changes in Mode 3 (and Mode 4 when the shortening was done at the end, where data set is stronger given improvements in observations and the geographical measurement distribution). The next test we did was to change the window size: the window size is central to the SSA technique; it is actually the only free parameter of the method. A large window size will emphasize long term pattern, while a shorter one will follow the dataset variability more closely. Again, the Modes 1 and 2 appear very robust, while Mode 3 was missed with the shortest window, the only scenario to catch mode was Mode 4. As a last test, we tried to retrieve the modes not one by one as explained here above, but all together, in one run of the MSSA. This was a success for Modes 1 to 3, but failed with Mode 4. All those tests are summarized in Table 1.

5. Discussion and Summary

[10] Next, we compare the three strongly confirmed modes with the theoretical results of *Mound and Buffett* [2007] and the observational analysis of *Zatman and Bloxham* [1997] (see Table 2). We find excellent agreement among these three sources. The first mode has periods ranging from 76.2 to 85 years, while the period of the second mode ranges between 46 and 53 years. The third mode (not found by *Zatman and Bloxham* [1997]) is clearly seen in both the *Mound & Buffett* and our results. The agreement between observational-based results with those of a model analysis is exceptional and provides strong confirmation of these modes.

[11] In summary, three distant regions exist within the 20 Taylor cylinders: innermost (1–3), the mid-latitude (4–15) and the outermost (16–20) regions (4). The IC cylinders have lowest variability, while the MLC intercept the liquid outer core and have robust unhampered oscillations with a strong common pattern and are in phase with the decadal LOD [*Hide et al.*, 2000]. At the very top of the liquid core is the D$''$ layer that has the greatest cross-sectional area in common with cylinder 20; this causes cylinder 20 to have the largest magnitude, which affects nearby cylinders (16–19). The MSSA technique allowed us to retrieve 6 CAM waves propagating from one cylinder to the other, mainly from the CMB to the ICB. The two first modes are similar to those obtained by *Zatman and Bloxham* [1997]. The four first modes are significant with the first 3 being exceptional robust; the fifth and sixth modes are subject to caution and require further study. The periods found for the significant modes are about 85, 50, 35 and 28 years, respectively. The outstanding agreement shown here between two observational-based studies and theoretical results adds further substantiation to our findings. We cannot statistically demonstrate the robustness of the retrieved modes; as such tests do not exist for MSSA. Nevertheless, we tried many perturbations of the signal, and the fact that the modes were not changed by the perturbations confirm their robustness.

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