New Evidence for the Fluctuation Characteristics of Intradecadal Periodic Signals in Length-Of-Day Variation

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Abstract The intradecadal fluctuations in the length-of-day variation (∆LOD) are considered likely to play an important role in core motions. Two intradecadal oscillations, with ~5.9 and ~8.5 years periods (referred to as SYO and EYO, respectively), have been detected in previous studies. However, whether the SYO and the EYO have exhibited stable damping trends since 1962 and whether geomagnetic jerks are possible excitation sources for the SYO/EYO are still debated. In this study, based on different methods and different ∆LOD records with different time spans, we showed robust evidence to prove that the SYO and the EYO have had no stable damping trends since 1962. We also found that there may be a ~7.6 years signal, but given that its average amplitude is too small, further confirmations are needed in the future. After confirming that the jerks have no special consistency with the peaks/valleys of the EYO/SYO, we further used a deconvolution process and confirmed that the geomagnetic jerks seem to be related to sudden changes in the SYO/EYO time series and their excitation series. Thus we finally suggest that jerks are possible excitation sources of the SYO/EYO. After using a deconvolution process, we estimate that the period P and quality factor Q of the SYO and the EYO are $[P = 5.85 \pm 0.06 \text{ years}, Q \geq 180]$ and $[P = 8.45 \pm 0.17 \text{ years}, Q \geq 350]$, respectively.

1. Introduction

The fluctuation characteristics and excitations of the intradecadal changes in the length-of-day variation (ΔLOD) were thought to be related to the secular variations in the core geomagnetic field and hence help to constrain the magnetic field strength in the core as well as to understand the mechanism driving the Earth's core-mantle interactions (e.g., R. S. Gross, 2015; Mound & Buffett, 2006). Two periodic signals have been detected from the ΔLOD in the intradecadal period band (i.e., the 5–10 years period band), an approximate six year oscillation (SYO, e.g., Holme & de Viron, 2013; Liao & Greiner-Mai, 1999) and an approximately 8.5 years oscillation (EYO, Ding, 2019). Their fluctuation characteristics are thought to help determine their possible mechanism (e.g., Gillet et al., 2010), but the fluctuation characteristics of these two signals are still controversial.

Liao and Greiner-Mai (1999) first found a nearly stable ~5.8 years oscillation in the 1970–1990 ΔLOD (see their Figure 5a) and suggested that the Southern Oscillation Index may have had some correlation with it. Abarca del Rio et al. (2000) also showed that the 6–7 years oscillation had no stable decreasing trend in the 1900–2000 time span (see their Figures 3 and 5), and its fluctuation characteristic was similar to a...
modulation as suggested by Ding (2019). Holme and de Viron (2013) showed that the SYO was a stable fluctuation in the 1962–2012 time span after using an iterative fitting and removal process (see their Figure 2). Chao et al. (2014) showed the Morlet wavelet spectrum of the ∆LOD in the 1962–2012 time span, and their results roughly indicated that the SYO had a decreasing trend from 1965–1997, but changed to an increasing trend after 1997 (see their Figure 1c; also similar as the finding in Ding, 2019). After using a Daubechies wavelet combined with a symmetric extension, Duan et al. (2015) used the normal Morlet wavelet (NMWT) method (Liu et al., 2007) for the extended ∆LOD time series and found that the SYO has a nearly stable decreasing trend in the 1962–2012 time span (see their Figure 9). Based on the same method and same record (1962–2012), Duan et al. (2017) further proposed a damping model and estimated that the quality factor $Q$ of the SYO was $51.6 \pm 0.4$ based on fitting the SYO envelope curve in the time domain. Based on this $Q$ value and a free decay trend for the SYO, Duan et al. (2018) and Duan and Huang (2020b) further considered electromagnetic (EM) coupling at the core-mantle boundary (CMB) under the mantle-inner core gravitational coupling mechanism. Based on the optimal sequence estimation method (Ding & Chao, 2015a; Ding & Shen, 2013), Ding and Chao (2018a) first found the SYO in global GPS and geomagnetic records, and their results showed that the SYO in ∆LOD, GPS, and geomagnetic data had a high degree of consistent synchronicity without a stable decreasing trend. Based on the AR-z spectrum method (Ding and Chao, 2015b, 2018b) and upon using a much longer ∆LOD time series (1760–2018), Ding (2019) identified nine periodic signals in the intradecadal and decadal ranges, namely, the $\sim 149$ years, $\sim 68$ years, $\sim 33$ years, $\sim 22.3$ years, $\sim 18.6$ years, $\sim 13.5$ years, and $\sim 11$ years (or the $\sim 10.6$ years signal) which has also been found in the $J_2$ time series (Chao et al., 2020 and Ding and Chao, 2018b), $\sim 8.5$ and $\sim 5.85$ years periodic signals. He first found the $\sim 8.5$ years periodic oscillation (EYO) in the ∆LOD and suggested that it could be represented by a stable cosine signal. In Ding (2019), a clean time series for the SYO was obtained after fitting and removing the other periodic signals, a similar process to that in Holme and de Viron (2013). Ding (2019) showed that the SYO has no stable decay trend in the 1962–2018 time span, a slight decreasing trend in the 1975–1995 time span, but an increasing trend after 1995. This finding was consistent with the result from Chao et al. (2014), and Ding (2019) explained this by a modulation. Based on Daubechies wavelet fitting, NMWT, and a BEME (boundary extreme point mirror-image-symmetric extension) method which was claimed to avoid edge effects in the NMWT, Duan and Huang (2020a) (referred to as DH20) analyzed the ∆LOD in the 1962–2019 time span. Their results suggested that the SYO had a stable decreasing trend and that the EYO had a stable increasing trend, and they still suggested that the SYO had a $Q$ of $\sim 51$.

Regarding the possible relationship between the SYO/EYO and geomagnetic jerks, Holme and de Viron (2005) found that the 1969, 1972, 1978, 1982, 1992, and 1999 jerks were consistent with the sudden changes in the ∆LOD in the 1962–2005 time-span. Holme and de Viron (2013) further confirmed that the sudden changes (jumps) in their cleaner SYO time series may have been triggered by geomagnetic jerks. Silva et al. (2012) also suggested that the SYO seems to have been closely related to some geomagnetic jerks. Chulliat et al. (2015) suggested that the SYO may be related to the 2006, 2009, and 2012 jerks. Soloviev et al. (2017) suggested that the SYO has some relationship with the 1996, 1999, 2002, and 2014 geomagnetic jerks. However, by using modeled torsional waves, Cox et al. (2016) found that $\sim 6$ years period torsional oscillation could not produce observed jerk signals. Ding (2019) first calculated the excitation function time series $\phi(t)$ for the SYO in ∆LOD based on a deconvolution process. He found that there was no clear relationship between the geomagnetic jerks and $\phi(t)$, but he concluded that this finding needed to be confirmed by further work. Duan and Huang (2020b) claimed that they did not identify any possible excited event for the SYO since 1962 and suggested that the EYO was discontinuously excited with a random 50–100 year time interval. Upon using 13 selected jerks, DH20 found that the peaks/valleys of the EYO were consistent with 10 of them, but they also concluded that the SYO has no such relationship with jerks. DH20 further concluded that the EYO could be used to predict jerks.

To date, there have been two disputes for the SYO and the EYO in the ∆LOD:

1. whether the SYO and the EYO have had stable damping trends since 1962 and
2. whether the geomagnetic jerks are possible excitation sources for the SYO and the EYO

In this study, we attempt to resolve these two disputes.
Whether the SYO and the EYO Have Stable Damping Trends

In this section, we will use two ∆LOD time series with different lengths as the datasets. The ∆LOD time series in Holme and de Viron (2013) and DH20 were extracted from their corresponding figures for further use.

2.1. The Used Datasets

We first extracted the residual ∆LOD time series (referred to as DH_R; 1962/01–2018/05; daily sampling) and the recovered SYO and EYO time series (referred to as DH_S and DH_E, respectively) from DH20 (see Figure S1 for the comparisons between the original figures of DH20 and our extracted results). The SYO time series (1962/01–2011/06; monthly sampling) from Figure 2 of Holme and de Viron (2013), referred to as Hid_S, was also extracted for further comparison.

We chose the 1962–2020 ∆LOD time series from the EOPC04 data set (Bizouard et al., 2019), the atmospheric angular momentum (AAM) data set (Salstein et al., 1993), the oceanic angular momentum data set (OAM, R. S. Gross et al., 2005) and the hydrological angular momentum data set (HAM, based on the Land Surface Discharge Model; Dill, 2008) for further use and comparison. Note that the AAM/OAM/HAM effects are the main Earth external excitation sources of the Earth’s rotation (R. S. Gross, 2015). All those four datasets have been preprocessed (the same preprocesses can be found in Ding, 2019), and the AAM, OAM and HAM excited ∆LOD have been calculated in advance. The final used time series can be summarized as: (1) EOPC04 ∆LOD time series (1962–2020, 10 days sampling); (2) the AAM excited ∆LOD time series (1948/01–2019/03; 10 days sampling); (3) the OAM excited ∆LOD time series (1949/01–2019/02; 10 days sampling); (4) the HAM excited ∆LOD time series (1971/01–2020/06; 10 days sampling). We show those four time series in Figure 1a (here, we note that the units in the figures of Ding, 2019 were misspelled to mas); their corresponding Fourier amplitude spectra are shown in Figure 1b. We can see that the ∆LOD changes shorter than 5 years are mainly caused by AAM effects (see Figure 1b). All the AAM, HAM and OAM effects had very small contributions to the intradecadal period band (5–10 years; i.e., the 0.1–0.2 cpy frequency band), except that the ∼5 years signal in the ∆LOD was caused by the AAM (see Figure 1b). Hence, here, we only remove the AAM effect from the EOPC04 ∆LOD time series. The residual ∆LOD time series after removing the AAM effect was referred to as N_G (=∆LOD‒AAM).

As the EOPC04 ∆LOD time series only has an ∼58 years length, which may be too short to isolate two close signals by using a filter, we further chose a yearly long-term ∆LOD time series (1730–2020) (from: www.iers.org).
Note that the 1962–2020 timespan of this time series is almost the same as the yearly EOPC04 ∆LOD time series (see as Figure 3a of Ding, 2019), and the data before 1900 have estimated errors more than 0.18 ms, hence they are only used for improving the frequency-resolutions. We tend to only believe the results obtained in the 1900–2020 timespan are robust.

Before we performed further work, we listed the time series used in the following sections and their corresponding sources/preprocessing process in Table 1. Note that ‘DH_’ means that the time series was extracted from Duan and Huang (2020a), ‘Hd_’ means that the time series was extracted from Holme and de Viron (2013), and ‘N_’ denotes that the time series was newly obtained from the EOPC04 or the yearly long-term ∆LOD by us.

2.2. Reanalysis of the Results in Previous Studies

The extracted DH_S (SYO) and DH_E (EYO) time series from DH20 are shown in Figures 2a and 2b (red curve and purple curve, respectively); their corresponding Fourier spectra are shown in Figure 3a. A residual DH_R1 is obtained after applying a zero-phase high-pass filter (with a 0.14 cpy cut-off frequency) to DH_R (see Figure 2a, the black curves). The spectral results show that the SYO amplitudes in DH_R and DH_R1 are almost the same (considering the filtered noise effects; see Figure 3a) and that the phase difference between them is approximately zero (Figures 3b and 3c). These findings indicate that the applied filter does not change the real SYO signal in DH_R time series. The spectra of DH_S and DH_E time series show clear differences from that of DH_R (residual ∆LOD used in DH20). The spectrum of the residual time series DH_R–(DH_S + DH_E) clearly shows a residual peak between the two target signals (see Figure 3a; located at ~0.143 cpy, i.e., ~7 years period). The phases also show clear differences in the target frequency bands (Figures 3b and 3c). These results preliminarily indicate that the recovered SYO/EYO in DH20 cannot completely represent the real signals in their used ∆LOD.

When using the classical filtering method for isolating two close signals, the data length should preferably be longer than 2/Δf (where Δf is the frequency interval). As the DH_R time series is ~56 years long, one could safely use a classical high-pass filter to isolate the SYO. However, here we do not further filter the DH_R time series, instead of filtering the longer EOPC04 time series. After using a high-pass filter (with 0.145 cpy as the cutoff frequency) for the residual EOPC04 time series N_G (∆LOD-AAM; ~58 years long), we further apply a 6-month running mean as done by Holme and de Viron (2013), then we can obtain a residual time series in which the SYO signal is the main component, we refer it as to N_G1. From Figure 2a, we can find that N_G1, DH_R1, and Hd_S have good consistency even though different methods were used (filter method used for the N_G1 and DH_R1 time series; iterative fitting and removing method used for the Hd_S time series in Holme and de Viron, 2013), and there is no stable decreasing trend for the SYO in the 1962–2019 timespan. In fact, the DH_S obtained by DH20 shows consistency with the DH_R1 and N_G1 only in the 1970–2000 timespan (simulation tests also prove this; see Figure S6).

For the EYO, it is not possible to completely filter the ~10.6 years signal or the possible ~7 years signal (Figure 3a) for the EYO from the DH_R or N_G time series; hence, a bandpass filter was applied to the 1730–2020 yearly ∆LOD time series. As we have noted above, we only tend to believe the results obtained in the 1900–2020 timespan are robust, and the data noise can affect the amplitude (~0.08 ms) of the EYO about 0.02 ms. The obtained result (Figure 2b; dark blue curve) shows that the EYO is almost a stable oscillation in the 1962–2019 time-span, which is consistent with the finding in Ding (2019).

The above reanalysis denotes that the SYO and EYO obtained by DH20 cannot completely represent the real signals in ∆LOD, and there seems also to be a ~7 years signal in the 5.5–10 years period band of DH_R. To confirm this, we used the same process (NMWT + BEPME) to further obtain a ~7 years signal from the residual DH_R–(DH_S + DH_E) time series (see Figure S2 and S2a), and a stable increasing time series for this ~7 years signal was obtained (see Figure S2a). Combining the NMWT spectrum of DH_R–(DH_S + DH_E) in Figure S3, we confirm that this residual peak around the ~7 years period in Figure 3a is mainly caused by the residual energy from the ~5.9 and ~8.5 years signals (since those two damping oscillations obtained by DH20 could not well represent the original signals in the residual ∆LOD).
2.3. New Results from the Classic Filter

We first applied a band-pass filter to the residual ∆LOD time series \(N_G\) (\(N_G = \Delta\text{LOD} - \text{AAM}\); the cutoff frequencies were 0.10 \(\text{cpy}\) and 0.205 \(\text{cpy}\)); the Fourier spectrum of this filtered \(N_G\) is shown in Figure 4b (and 4c; black curve). Compared with Figure 3a (the spectrum of DH_R), we can find that the ∼10.6 years signal was filtered. This ∼10.6 years signal may have originated from the solar cycle, but further confirmation is still needed (see Chao et al. 2020). We note that in Ding (2019), a 7.7 years signal was fitted and removed to obtain a cleaner SYO time series; given that the amplitude of this signal was quite small, this information was not specifically explained in Ding (2019). In the following, we will also show that there may have been a ∼7.6 years signal in the ∆LOD, not a ∼7 years signal. As the length of the \(N_G\) time series is approximately 58 years, even though there is a ∼7.6 years signal, it is still long enough to filter the SYO from the EYO and the ∼7.6 years signal. However, it is hard to isolate the EYO with a possible ∼7.6 years signal. Hence, we only use a bandpass filter (the cutoff frequencies are 0.145 \(\text{cpy}\) and 0.205 \(\text{cpy}\)) to isolate the SYO from the \(N_G\) time series, and we refer this SYO time series as \(N_S\) (see Figure 4a). Note that the average amplitude of the SYO is ∼0.12 ms in the 1962–2019 timespan, and the data noise may affect it up to ∼0.012 ms. For the EYO time series, to avoid the influence of a possible 7.6 years signal, we directly select the 1962–2019 part from the filtered result which was obtained from the 1730–2020 ∆LOD time series, that is, the \(N_E\) time series shown in Figure 2b; we also plotted this EYO time series in Figure 4a.

From Figure 4a, we clearly find that the SYO and EYO have no stable damping trends. The EYO is close to a stable oscillation, while the SYO only has a decay trend in the 1962–1990 time span but has an increasing trend in the 1990–2008 time span. The whole envelope of the SYO seems to have been a modulation phenomenon (see the envelopes denoted by the dashed curves in Figure 4a). Figure 4b shows the Fourier amplitude and phase spectra of the bandpass filtered \(N_G\), \(N_S + N_E\) (1962–2019) and the residual time series (the bandpass filtered \(N_G - (N_S + N_E)\)). The amplitudes and phases around the ∼5.9 years show that the obtained \(N_S\) (SYO) can well represent the original spectra, while the results around the ∼8.5 years show some differences between the obtained \(N_E\) (EYO) and the original signal. The residual spectra (green curve) show that there is a residual peak around the ∼7.6 years period, which is similar to Figure 3a. Given that as the AAM effects have been removed from the EOPC04 ∆LOD time series, hence the background noise level of the \(N_G\) time series around the 0.1–0.5 \(\text{cpy}\) frequency band is changed from ∼0.045 ms (in Figure 1b) to ∼0.012 ms (see Figure S4). As the ∼7.6 years residual peak has a ∼0.025 ms amplitude, we may
Figure 2. (a) DH_R: the filtered residual ∆LOD time series DH_R which was extracted from DH20; DH_S: the extracted SYO time series from DH20; N_G: filtered residual ∆LOD time series obtained from the residual EOPC04 time series N_G (ΔLOD–AAM) after using a high-pass filter (with 0.145 cpy as the cutoff frequency) and a 6-month running mean process; Hd_S: the SYO time series extracted from Holme and de Viron (2013). (b) DH_E: the extracted EYO time series from DH20; N_E: the EYO time series obtained from the 1730–2020 ∆LOD time series after using a bandpass filter with 0.109 cpy and 0.124 cpy as the cutoff frequencies. Each of the colored areas in (a) (or (b)) correspond to a fixed 5.9-year (or 8.6-year) period.

We note that the two statements, ‘Whether the SYO and EYO have decreasing or increasing trends in the time domain observation’ and ‘Whether the SYO and EYO are attenuated oscillations’, are different. The former focuses on the fluctuation characteristics of the SYO and EYO in the time domain, while the latter focuses on the quality factor Q of the SYO and EYO. Generally, if the Q of an oscillation is larger than zero, this oscillation is a decaying oscillation. In the Earth system, almost all the well-known oscillations or normal modes have positive Q values. In the time domain (real observations), decreasing or increasing characteristics are not necessary for an attenuated oscillation. For example, the Chandler wobble has a ∼20–170 Q value (see Ding and Chao, 2017), but its amplitude is time-varying rather than damped in the time domain. If an oscillation is continuously excited, one cannot estimate its Q value from directly fitting its envelope in the time domain (similar to the case for the Chandler wobble). The above analysis only focuses on the fact that the SYO and EYO have no damping trend in the time domain. We will attempt to estimate the Q values for the SYO and EYO in Section 4.

3. SYO and EYO Decay Trends

The above sections showed that all the results from the classic filter and from Holme and de Viron (2013) have no stable damping trend for the SYO and EYO. This begs the question of why did the SYO and EYO recovered in DH20 have stable damping trends. Supplementary Figure s3, 9-10, 14, and 15 in DH20 clearly showed that edge effects were still present even when the NMWT + BEPME method was used. More importantly, their Figures S14a and S15a showed that the recovered signals had clearly increased and slightly decreased amplitudes, respectively, even though the input signals were stable sine signals. In light of this, we suspect that the damping trends for their SYO and EYO results should have been affected by the methods that they used.

We reproduced the same processing strategy explained in DH20 (Daubechies wavelet fitting + NMWT + BEPME) and tested it. Two-time series, S(t) and S_d(t), were simulated. S(t) contained nine zero-phase and stable cosine signals, similar to those in DH20 except for the random noise term (see their Supplementary Information). S_d(t) also contained the same nine periodic signals, but the amplitudes and phases were estimated by using a least-square process to fit the observed ∆LOD (see the dark blue curve in Figure 5a). Both of these two simulated time series contained a 5.9 years cosine signal and a 8.6 years cosine signal. The restored 5.9 and 8.6 years signals from S_d(t) (+random noise) are shown in Figure 5b (green curves), and our restored results are almost the same as those extracted from DH20 (red curves in Figure 5b). Note that the same signals and same process were used in DH20, and just the used random noise could not be the same. This finding proves that we fully reproduced the processing strategy used in DH20.

We further use the same process to analyze S(t). Interestingly, we obtained a decreasing 5.9 years signal and an increasing 8.6 years signal for the input stable cosine signals (see Figure 5c). Hence, we further compare...
the recovered 5.9 years/8.6 years signal from S2(t) and DH_R time series (extracted from DH20). We first use the same process for S1(t)/S2(t) to analyze DH_R. The new recovered SYO and EYO are shown in Figures 6a and 6b (green curves), respectively; the extracted SYO (DH_S)/EYO (DH_E) from DH20 (red curves) and

Figure 3. (a) Fourier amplitude spectra of DH_R, DH_R+, DH_S, DH_E and DH_R-(DH_S + DH_E) time series; (b) Phase spectra of DH_R, DH_R+, DH_S and DH_E time series; (c) shows the phase differences between DH_R+/DH_S and DH_R time series around the ~0.17–0.18cpy frequency band. Note that the phase unit is rad.

Figure 4. (a) The new obtained SYO (N_S) and EYO (N_E) from the ΔLOD time series based on the classic filter process. (b) The amplitude and phase spectra of the band-pass filtered N_G and SYO + EYO time series; the amplitude spectrum for the residual time series (the band-pass filtered N_G-(SYO + EYO)) is also shown in (b). (c) is similar to (b), but further considering the fitted 7.6 years signal.
the 5.9 years (corresponding to SYO)/8.6 years (corresponding to EYO) signals recovered from $S_2(t)$ (cyan curves) are also plotted in Figure 6. Note that DH_S and DH_E time series extracted from DH20 were also based on the DH_R time series. Therefore, our new recovered SYO/EYO time series from DH_R are almost the same as DH_S/DH_E (see the comparisons between the red and green curves in Figure 6). More importantly, the SYO/EYO recovered from $S_2(t)$ are similar to the DH_S/DH_E time series, especially the SYO recovered from $S_2(t)$ which almost overlap with DH_S. Thus, we conclude that the damped nature of the SYO/EYO was only an artifact of the method used in DH20 (More evidence can be obtained from the test codes in the Supplementary Information).

4. The Relationship Between Jerks and EYO/SYO

4.1. Comparing Jerks with the SYO/EYO in the Time Domain

As we reviewed in Section 1, it is debatable whether the SYO/EYO has certain relationships with jerks. In this section, we first follow the thoughts outlined in DH20 by comparing the peaks/valleys of the SYO and the EYO with the jerks, but we will consider more jerks. In DH20, only 13 jerks were selected (see the yellow areas in Figure 7), although many jerks have been identified in recent decades. Even though
the jerk bounds in the 1968–2010 time span reviewed in Brown et al. (2013) were not considered, at least the 1963 and 1965 jerks were missed in DH20 (see the gray areas in Figure 7). A given jerk will not occur at the same time in different regions of the Earth’s surface as it has 1–2 years uncertainty (Brown et al., 2013; Chulliat & Maus, 2014).

In Figure 7, we show two residual time series for the EYO and SYO; we directly used the six-month smoothed N_G time series to obtain them to keep the high-frequency information for some sudden changes. For the EYO time series, the obtained SYO (N_S; see Figure 4a) was first removed from the smoothed N_G time series, and then a high-pass filter with a 0.1 cutoff frequency was used (see Figure 7a, the dark blue curve); for the SYO time series, we directly use the N_G 1 time series which has been shown in Figure 2a (also see Figure 7b). As references, in Figures 7a and 7b, we also respectively plot the EYO (N_E) and SYO (N_S) time series (see the dashed green curves in Figure 7), which have been shown in Figure 5a.

The 13 jerks used in DH20 are indicated by the yellow areas in Figure 7, and some of them were also used in Holme and de Viron (2013) (see the corresponding years are marked with blue fonts at the top of Figure 7a). The gray areas in Figure 7 are the geomagnetic jerk bounds (and jerks) referred from Brown et al. (2013) (before 2010), Chulliat et al. (2015), and Torta et al. (2015) (after 2010). Comparing the peaks/valleys of the SYO and EYO with the 13 jerks and the 1963 and 1965 jerks, our findings differ from DH20 as we find that only the 2017 jerk is consistent with the EYO peak (see the red arrow in Figure 7a), while seven jerks are consistent with the peaks/valleys of the SYO (see the red arrows in Figure 7b) including the best known and most studied 1969 and 1978 jerks (see also in Figure 3 of Holme and de Viron, 2013). However, DH20 concluded that there is no such consistency between the jerks and the SYO peaks/valleys. Until now, there is no robust evidence to prove that the EYO must be caused by a torsional oscillation in the fluid outer core, although DH20 has suggested this as Duan et al. (2018) have suggested for the SYO. If the EYO is increased by jerk excitations, as claimed in DH20, the SYO should also be increased by jerk excitations (contradicting the decreased SYO obtained by DH20). Considering that different jerks generally have 1–3 years intervals and there is only the 2017 jerk that corresponds to the EYO peak, the EYO seems to offer no remarkable help in predicting jerks.

According to Cox et al. (2016) and Pinheiro et al. (2019), jerks may be somewhat smoother than what is often considered, and Pinheiro et al. (2019) found that the jerk duration time can be up to 4.7 years. Hence,
even with the above, we do not recommend such comparison. More reasonable comparisons should be determined by comparing the sudden changes in the SYO/EYO time series with jerks (similar to that done by Holme and de Viron, 2013) or comparing their excitation sequences with jerks (similar to that done by Ding, 2019).

In Figure 7b, the dashed gray ellipses indicate the sudden changes in the SYO time series which may correspond to the jerks used in Holme and de Viron (2013). We can see that only the 1995 jerk has no clear sudden change in the SYO time series. The purple ellipses in Figure 7b indicate the sudden changes in the SYO, which may correspond to the other jerks. In Figure 7a, it seems that all 15 jerks have corresponding sudden changes in the EYO (the dashed gray rectangles). Based on the results in Figure 7, we may conclude that the jerks seem to correspond to the sudden changes in the SYO and EYO time series.

We also note that it is not easy to determine ‘sudden changes’ in the SYO and EYO time series, which are probably just caused by high frequency noise. To further confirm the possible relations, we will compare the excitation time series of the SYO and EYO with jerks.

4.2. Comparing Jerks with the Excitation Time Series of the SYO/EYO

Before we calculate the excitation time series of the SYO and EYO, we first attempt to estimate their $Q$ values.

As we confirmed that the SYO and EYO were not caused by the Earth external excitation sources (see Figure 1), we can reasonably assume that they must have been caused by some core motions (Of course, the more detailed mechanism needs to be further studied in the future). Namely, the SYO and EYO in the $\Delta$LOD can physically be treated as normal modes of the Earth; hence, they can be equal to the temporal convolution of harmonic oscillations with the ‘excitation function’ $\varphi(t)$ (B. F. Chao, 2017):

$$m(t) = -i\omega e^{i\omega t} \int_{0}^{t} e^{i\omega \tau} \varphi(\tau) d\tau.$$  \hspace{1cm} (1)

where $\omega = 2\pi / P (1 + i/2Q)$, $P$ is the period. Here a deconvolution method can be used to estimate the $P$ and $Q$ values of the SYO and EYO. This deconvolution method has been successfully used in Furuya and Chao (1996), R. S. Gross (2005), and B. F. Chao and Chung (2012) for the Chandler wobble, in B. F. Chao and Hsieh (2015) for the free core nutation, and in Ding (2019) for the SYO. A detailed introduction to this method can be found in B. F. Chao and Chung (2012) and Ding (2019). Here, we only provide a short introduction.

Suppose the true values of $P$ and $Q$ are not known in advance, and we can choose a set of $(P, Q)$ as the input parameters for the deconvolution. If the used $(P, Q)$ has deviations from the true values, then the deconvolution notch filter would be somewhat off the target and unable to remove the resonance power completely (Chao & Hsieh, 2015). Therefore, some extra power will still be present in the obtained excitation function $\varphi(t)$. If the excitation is statistically independent of the observation noise, the spectral power around the target frequency bin will be significantly improved. Given this, if a deconvoluted $\varphi(t)$ has the least power in the target frequency band, the corresponding input $(P, Q)$ will correspond to the correct values.

Here, we set $P$ from 5.6 years to 6.1 yr and from 8.1 yr to 8.8 years for the SYO and EYO, respectively. The period interval is 0.02 year for both of them. Meanwhile, we set $Q$ from 1 to 3,000 with 10 intervals for both of them. For the chosen SYO and EYO time series, to be more generous, we choose the same time series used in Figure 7 but without a six month smoothing in order to keep higher frequency signals. After the deconvolution process, the resultant mean excitation power as a function of the input $(P, Q)$ is shown in Figure 8. The results show that no minimum can be determined in Figures 8a and 8b. However, around $P \approx 5.85$ and $Q \geq 180$ in Figure 8a and around $P \approx 8.46$ and $Q \geq 350$ in Figure 8b, the mean excitation powers are clearly lower than the others, which means that the $Q$s of SYO and EYO should be larger than 180 and 350, respectively. In Ding (2019), the $Q$ for the SYO was suggested to have been larger than 200. Considering that different lengths were used (1962/01–2016/07 in Ding (2019) and 1962/01–2019/02 in this study) and the estimate errors, such a difference is acceptable. For the more precise periods, we finally obtain that $P = 5.85 \pm 0.06$ years for the SYO (almost the same as that given in Ding, 2019, 5.85 ± 0.03 years) and $P = 8.45 \pm 0.17$ years for the EYO.
After determining \((P, Q)\) for the SYO and EYO, we can further calculate their excitation function sequence according to Equation 1. Here, we use \((P = 5.85, Q = 180)\) for the SYO and \((P = 8.45, Q = 350)\) for the EYO. The chosen SYO and EYO time series are the same as those used for determining \((P, Q)\) in Figure 8. The obtained excitation time series \(\phi_S(t)\) and \(\phi_E(t)\) for the SYO and EYO are shown in Figure 9a. We observed that \(\phi_S(t)\) and \(\phi_E(t)\) almost overlapped with each other. This finding is easily understood, given that the high-frequency (>2 cpy) components of the chosen SYO and EYO time series are the same. The \(\phi_S(t)\) (and \(\phi_E(t)\)) series has no very significant spike, which means that the SYO and EYO should have been continuously excited. Only from \(\phi_S(t)\) and \(\phi_E(t)\), it seems no more useful information can be obtained for the possible excitation sources; hence, we further use a 1D median filter (with a \(n = 18\) window) to the excitation time series \(\phi_E(t)\) to show some small perturbations (As \(\phi_S(t)\) and \(\phi_E(t)\) are almost the same, so we can only do this for one of them). The obtained filtered \(\phi_{E1}(t)\) is shown in Figure 9b. Some sudden changes can be found in Figure 9b (see changes around 1972, 1995, and 2014 for examples) which differ from Ding (2019). This is mainly because a \(n = 105\) window for the 1D median filter was used in Ding (2019); this window is almost 3 years and too wide to show some local changes. To more clearly show the sudden changes in \(\phi_{E1}(t)\), we further calculate its first derivative \(\phi_{Ed}(t)\), and the result is shown in Figure 9c. From the envelopes shown in Figure 9c (yellow curves), the epochs of the first five maximum envelopes (except the envelope at around 1967, which marked by the red arrow) are well consistent with the 1963, 1972, 1982, 1995, and 2005 jerks; and envelopes are generally well consistent with the jerks or jerks bounds (gray areas). Figure 9d further shows the NMWT spectrum of the sequence \(\phi_{Ed}(t)\) in Figure 9c. The spectral values in Figure 9d are shown on the log2 scale, which is the same as Alexandrescu et al. (1995), (1996). If we follow the inferences from Alexandrescu et al. (1995), (1996), the jerks or jerk bounds (gray areas) in Figure 9d seem to be well consistent with the sudden changes in \(\phi_{Ed}(t)\).

From the above analysis in Sections 4.1 and 4.2, it seems that the geomagnetic jerks do relate to the SYO and EYO, although we do not know the possible mechanisms. Therefore, we finally suggest that the geomagnetic jerks may be one kind of excitation source of the SYO and EYO.

5. Discussions and Conclusions

The fluctuation characteristics of the SYO and EYO will affect the understanding of their physical mechanisms. To confirm these fluctuation characteristics, we reanalyzed the ∆LOD records used in previous studies (Duan and Huang, 2020a and Holme and de Viron, 2013) and further analyzed the EOPC04 ∆LOD time series based on the classic filter process. Our results show that the results for the SYO from the classic filter process are well consistent with the corresponding results in Holme and de Viron (2013) and
Ding (2019) (both studies used a fitting and removing process). The spectra result reveal that the stable damping SYO and EYO suggested by DH20 cannot represent the real signals that are contained in their used ∆LOD record (DH_R). Although there was a residual peak around $\sim 7$ years period in the spectrum of DH_R–(DH_S + DH_E) (in Figure 3a), we confirmed that it was just caused by the residual energy of the $\sim 5.9$ and $\sim 8.6$ years signals (see Figures S3 and S4). Our results from the classic filter process based on the EOPC04 ∆LOD time series and a much longer yearly ∆LOD time series also showed that the amplitudes of the SYO and EYO did not have stable damping trends in the 1962–2019 time span. We also found that a $\sim 7.6$ years signal may also have been present in the ∆LOD time series. Although a 7.7 years signal has been fitted and removed in Ding (2019) to obtain a cleaner SYO time series, the amplitude of this signal is only about 0.025 ms (which is much less than the amplitudes of the SYO and EYO) which Ding (2019) did not specifically explain. In addition, because the mean amplitudes of the residual SYO and EYO in the DH20 results were about 0.042 ms, this $\sim 7.6$ years signal was also impossible to find in spectra of DH20. Although the average amplitude ($\sim 0.025$ ms) of this $\sim 7.6$ years spectral peak is about twice the background noise level ($\sim 0.012$ ms; see Figure S4) in the N_G (∆LOD-AAM) time series (in the 0.2–0.5 cpy frequency band), we tend not to claim that this $\sim 7.6$ years spectral peak must correspond to a stable periodic signal; we only show the simply fitted result for it in Figure S5 and suggest that further confirmations are need to verify it.

For the possible relationship between jerks and SYO/EYO, DH20 concluded that the EYO was excited by the jerks, but the jerks were not responsive to the excitations of the SYO. We repeated the similar comparisons as those performed by DH20, and our results showed that only the 2017 jerk corresponded well to the peak of the EYO, while there were 7 jerks that corresponded well to the peaks/valleys of the SYO (see Figure 7). If DH20’s conclusion that the EYO is excited by the jerks is correct, the SYO is more likely to be excited by the jerks, which is in contrast with another conclusion from DH20. In addition, considering that

Figure 9. (a) The excitation functions $\varphi_S(t)$ and $\varphi_E(t)$ for the SYO and EYO, respectively; (b) $\varphi_{E1}(t)$: the filtered $\varphi_E(t)$ after using a median filter; (c) $\varphi_{Ed}(t)$: the first derivative of the $\varphi_{E1}(t)$; (d) the NMWT spectrum of the $\varphi_{Ed}(t)$ time series in (c). The gray areas in (a)–(d) indicate the jerks and jerk bounds from De Michelis et al. (1998), Brown, et al. (2013), Soloviev et al. (2017) and Hammer (2018).
the jerk duration time may even be up to 4.7 years (Pinheiro et al., 2019), our results also indicated that the EYO could not be used to predict jerks (differ from DH20). We further compare the jerks with the sudden changes in the SYO/EYO time series (similar to Holme and de Viron, 2013) and their excitation time series (similar to Ding, 2019), the results do demonstrate that the jerks seem to be related to the excitations of the SYO/EYO (see Figures 7 and 9). Although we have suggested this possibility, considering the findings in Cox et al. (2016), further studies are still certainly needed.

Recalling the two disputes we summarized in Section 1, in this study, we obtain the following conclusions:

(1) We confirmed that the SYO and EYO have not exhibited stable damping trends since 1962. Instead, both of them have time-varying amplitudes. The NMWT + BEPME methods used in previous studies may cause a strange increasing or decreasing trend for a stable cosine signal when there are many signals contained in the used time series

(2) Although the geomagnetic jerks did not have good consistency with the peaks/valleys of the SYO and EYO, they did have some consistency with the sudden changes in the SYO/EYO time series and in their corresponding excitation sequences. Such findings mean that the jerks are possible excitation sources for the SYO and EYO.

In addition, based on a deconvolution process, we estimate that the period $P$ and $Q$ values for the SYO and EYO are, respectively, $(P = 5.85 \pm 0.06 \text{ years}, Q \geq 180)$ and $(P = 8.45 \pm 0.17 \text{ years}, Q \geq 350)$. The estimates for the SYO are very close to the values given in Ding (2019). We also added some explanations about the convolution/deconvolution in the Supplementary Information (see Figure S3), which can help other researchers understand the convolution/deconvoluted for the SYO and EYO.

Data Availability Statement

The used $\Delta$LOD data can be freely downloaded from IERS (www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html); the AAM, OAM and HAM datasets were downloaded from: www.iers.org/IERS/EN/DataProducts/GeophysicalFluidsData/geoFluids.html; The geomagnetic data set was downloaded from: http://www.wdc.bgs.ac.uk/dataportal/. If the readers have no access to the required nonstandard licensed Matlab toolboxes, please contact the first author.

Acknowledgments

The authors thank the Editors, an anonymous reviewer and Aleksand-er Brzezinski for their constructive suggestions and thank Jim Ray for his help for the English; they also thank L.T. Liu, X.Q. Su for NMWT algorithm and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes. This work is supported by NSFC (grant # 41774024, 41974022, and codes.
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