Detection of different-time-scale signals in the length of day variation based on EEMD analysis technique

Wenbin Shen\textsuperscript{a,b,*}, Cunchao Peng\textsuperscript{a}

\textsuperscript{a}Department of Geophysics, School of Geodesy and Geomatics/Key Laboratory of Geospace Environment and Geodesy of Ministry of Education, Wuhan University, Wuhan 430079, China
\textsuperscript{b}State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China

\textbf{Abstract}

Scientists pay great attention to different-time-scale signals in the length of day (LOD) variations $\Delta$LOD, which provide signatures of the Earth’s interior structure, couplings among different layers, and potential excitations of ocean and atmosphere. In this study, based on the ensemble empirical mode decomposition (EEMD), we analyzed the latest time series of $\Delta$LOD data spanning from January 1962 to March 2015. We observed the signals with periods and amplitudes of about 0.5 month and 0.19 ms, 1.0 month and 0.19 ms, 0.5 yr and 0.22 ms, 1.0 yr and 0.18 ms, 2.28 yr and 0.03 ms, 5.48 yr and 0.05 ms, respectively, in coincidence with the results of predecessors. In addition, some signals that were previously not definitely observed by predecessors were detected in this study, with periods and amplitudes of 9.13 d and 0.12 ms, 13.69 yr and 0.10 ms, respectively. The mechanisms of the LOD fluctuations of these two signals are still open.

© 2016, Institute of Seismology, China Earthquake Administration, etc. Production and hosting by Elsevier B.V. on behalf of KeAi Communications Co., Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

How to cite this article: Shen W, Peng C, Detection of different-time-scale signals in the length of day variation based on EEMD analysis technique, Geodesy and Geodynamics (2016), 7, 180–186, http://dx.doi.org/10.1016/j.geog.2016.05.002.
1. Introduction

The Earth rotation rate changes with time, which could be caused for instance by tidal friction, and the exchanges of angular momentum among the core, mantle, atmosphere, and oceans. Previous various analyses of time series of the length of day (LOD) variation (ΔLOD) data suggested quite a few of ΔLOD periodic signals \([1–6]\), most of which are correlated with changes in atmospheric and oceanic angular moment and some with tidal dissipation in the Earth–Moon and Earth–Sun systems.

As the Moon moves around the Earth, due to the tidal effects, the Earth’s inertial moment tensor changes with the lunar orbital periods of 27.7 and 13.7 days. Hence, it is clear that there are variations in the LOD at the periods, characterizing by 27.7 and 13.7 days \([6]\). Similarly, tidal deformation between the Earth and the Sun system may also cause various periods that are sensed to the Earth’s orbit perturbation. It is responsible for about 10% of the annual and about 50% of the semiannual periods, and other causes could be the seasonal exchange of angular momentum among the solid Earth, atmosphere and the ocean \([7]\). A quasi-biennial oscillation was observed by many researchers \([8–11]\). The El Niño-Southern Oscillation in the troposphere-ocean system and the Quasi-Biennial Oscillation in the equatorial stratosphere, accounts for most of the observed quasi-biennial oscillation of LOD \([8,9]\).

Mound and Buffett observed an about 6-year variation in the LOD \([12]\). They explained it as an exchange of angular momentum arising from gravitational coupling between the mantle and core. The decadal fluctuation in LOD has been long discovered, but its excitation mechanism is still open. Four different couplings between core and mantle, namely, electromagnetic, topographic, viscous and gravitational couplings, might explain the decadal LOD variation \([13–17]\).

With the development of observation technology, the ΔLOD time series with high precision is available. In this paper, we analyzed the latest time series of ΔLOD using the ensemble empirical mode decomposition (EEMD) technique \([18–20]\) to detect ΔLOD signals with various periods. EEMD is an effective analysis tool, which has successful applications in geoscience \([11,21–23]\).

2. Data

The time series of ΔLOD that we use in this study is released by International Earth Rotation Service (IERS) Earth Orientation Centre (http://datacenter.iers.org/eop/-/somos/5Rgv/latest/214). It spans from 1st of January, 1962 to 1st of March, 2015, with sampling rate at 1 d, as shown by Fig. 1. Parameters in the series are with respect to IAU 2006/2000A precession-nutation model and consistent with International Terrestrial Reference Frame 2008 \([24]\). Compared to the old version, the new version has an impressive higher precision in 2 orders \([25–27]\).

IERS provides rapid, monthly and long term Earth orientation data in the form of bulletins or data files. The time series of ΔLOD used in this study are contained in a long term Earth orientation data file. It has been recorded since 1846. However, the data collected in the period before 1962 have relatively poor precision, because at that period precise atomic clocks were not yet applied. Hence, in this study we use time series after 1962.

3. Method

Empirical mode decomposition (EMD) was proposed by Huang et al. \([18,19]\). This method is to decompose the data according to their intrinsic characteristic scales into a number of intrinsic mode function (IMF) components.

The EMD can decompose time series into many IMFs whose instantaneous frequency and instantaneous amplitude

\[
\text{LOD (days)} \quad 1965 \quad 1970 \quad 1975 \quad 1980 \quad 1985 \quad 1990 \quad 1995 \quad 2000 \quad 2005 \quad 2010 \quad 2015
\]

\[
\text{Time (Year)}
\]

Fig. 1 – Length of day variation (ΔLOD) from 1st of January, 1962 to 1st of March, 2015.
are physically meaningful. It is based on the following assumption: at any given time, the data may have many coexisting simple oscillatory modes of different frequencies. Each oscillatory mode is defined as an IMF satisfying the following two critical conditions [18]: (1) in the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one; (2) at any data point, the mean value of envelopes defined by local maxima and minima is zero. The decomposing process of an IMF is stated as follows [18]:

1) Identify the local extrema of data \( x(t) \);
2) Fitting the local maxima (minima) by a cubic spline to form the upper (lower) envelop;
3) The mean value of upper and lower envelopes is designated as \( m_n \), then compute the difference between \( x(t) \) and \( m_n \), noted as \( h_n \), i.e.

\[
h_n = x(t) - m_n
\]

Then we should examine whether \( h_n \) satisfies the above mentioned two critical conditions. If it does, \( h_1 \) becomes the first IMF of the data series, noted as

\[
c_1 = h_1
\]

If it does not satisfy the two critical conditions, repeat the sifting processes (1)–(3). In the iterating process, \( h_1 \) is regarded as the new data series, thus

\[
x(t) = h_1
\]

After \( k \) times of iterations, then we will find the first IMF, thus

\[
c_1 = h_{1k}
\]

As for the stoppage criteria for the sifting process, it can be stated as follows: the normalized squared difference between two successive sifting operations \( SD_k \) must be smaller than a predetermined value:

\[
SD_k = \frac{\sum_{t=0}^{T} |h_{n-1}(t) - h_n(t)|^2}{\sum_{t=0}^{T} h_{n-1}(t)}
\]

After the first IMF is obtained, then we can extract other IMFs from the data as follows [18]:

1) Compute the residue \( r_1 \), expressed as

\[
r_1 = x(t) - c_1
\]

2) Treat the residual as a new data and make the same sifting process as described above to obtain other IMFs.
3) Repeat the procedure until the residue becomes a monotonic function or a function with only one extreme from which no more IMF can be extracted.

Finally, the data \( x(t) \) can be expressed as

\[
x(t) = \sum_{j=1}^{N} c_j + r_n
\]

EEMD is an adaptive time-frequency analysis method [20], and it has been proven to be reliable for extracting signals from data collected in noisy nonlinear and non-stationary processes. It presents a substantial improvement over the original EMD, overcoming some major drawbacks of EMD, including the mode mixing problem and end effects [20].

Since the white noise may contaminate the time series, when signal and white noise mix together, individual decomposition of the data series may produce very noisy results. However, as sufficient ensemble experiments are considered, the noises are almost canceled out in the ensemble mean of the experiments and the target signals are reserved.

Comparing with EMD, the proposed EEMD has following characteristics [20–22]:

i) Add a white noise series to the targeted data;
ii) Decompose the data with added white noise into IMFs;
iii) Repeat step i) and step ii) many times, but with different white noise series each time; and obtain the (ensemble) means of corresponding IMFs of the decompositions as the final result.

For a set of stationary random signal \( x(n) \), the power spectrum can be computed as [28].

\[
p_x(\omega) = \frac{1}{N} |X(k)|^2
\]

where \( N \) is the length of \( x(n) \), \( X(k) \) is Discrete Fourier Transform of \( x(n) \). Especially, based on Welch method [29–32], \( x(n) \) is divided into \( p \) sections \( (k = 1, 2, ..., p) \), each section with the number of \( M \). Then the modified periodogram of \( k \)-th section is

\[
J_k(\omega) = \frac{1}{MU(\omega)} \sum_{n=0}^{M-1} x_n(n)w(n)e^{-j\omega n}
\]

where

\[
U(\omega) = \frac{1}{M} \sum_{n=0}^{M-1} w^2(n)
\]

is an adjustable normalization factor and \( w(n) \) is window function, which is defined as a mathematical function that is zero-valued outside of some chosen interval.

The power spectrum estimation of \( x(n) \) is an average of all of the \( p \) sections, thus

\[
p(\omega) = \frac{1}{p} \sum_{k=0}^{p-1} J_k(\omega)
\]

4. Results

Based on EEMD, data series can be sifted and decomposed into certain IMFs. First, we processed the original \( \Delta LOD \) data series by EEMD. The results are presented in Fig. 2.

After obtaining the IMF components of \( \Delta LOD \), the power spectrum density (PSD) and amplitude spectrum of all of these IMF components are then obtained by Welch method and FFT method. The results are shown in Figs. 3 and 4, from which we
can find around ten periodic signals, as listed in Table 1. For the purpose of comparison, we also list relevant results observed by some previous studies [5,6,9,12,33].

When frequencies of these periodic signals are available via the PSD and amplitude spectrum, we further estimated the amplitudes of them through least square fitting.

The original data series can be written as

$$y_t = \sum_i A_i \cos(\omega_i t + \phi_i) + Kt + C + e_t$$  \hspace{1cm} (11)

$C$ is the constant term, $K$ is the slope of the linear trend term, $e_t$ is the residual, and $A_i, \omega_i, \phi_i$ are the amplitude, frequency and initial phase of the periodic terms, respectively.

Since the frequencies of periodic signals are known, the unknown parameters which are to be obtained by least square fitting are amplitudes and initial phase angles of the periodic signals. Based on the least square fitting, the solutions are the parameters which make the following equation with minimum value:

$$\sum_t e_t = \sum_t \left[ y_t - Kt - C - \sum_i A_i \cos(\omega_i t + \phi_i) \right]^2$$  \hspace{1cm} (12)
Applying least square fitting, the amplitudes corresponding to the periodic signals can be determined. The results are listed in Table 1.

For all of these signals, most of them are well-known [34]. Fluctuations at monthly and fortnightly periods are caused by lunar tides. Tidal deformation from the Sun, and the excitations caused by ocean currents and ground-water storage are responsible for fluctuations at yearly and 6-month periods [6]. The quasi-biennial signal of LOD is closely related to the El Niño-Southern Oscillation (ENSO) and quasi-biennial oscillation in stratosphere [11]. ENSO is a global-scale oscillation of the coupled atmosphere-ocean system characterized by fluctuations in atmospheric surface pressure and ocean temperatures in the tropical Pacific. And the transport of ozone by the induced meridional circulation in various latitudes and heights causes the quasi-biennial oscillation in stratosphere [35]. For the 9.13d signal, Seize and Schuh thought it was induced by solid earth tide [40], which needs further confirmation.

For the remaining signals with period 13.69 yr, in our knowledge, we did not find literatures addressing them. Our present study suggests its existence. The mechanism of this signal is still open.

5. Discussion and conclusion

The purpose of this study is to observe/detect the signals of LOD variation using the EEMD technique. Our study shows that using EEMD, the major well-known signals are detected, with similar amplitudes as predecessors. In addition, some periodic signals that have not been definitely observed by

<table>
<thead>
<tr>
<th>Frequency (cpy)</th>
<th>Period</th>
<th>Amplitude (ms)</th>
<th>Causes/Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.99</td>
<td>9.13 d</td>
<td>0.12</td>
<td>Solid earth tide/Seize &amp; Schuh (2010) [40]</td>
</tr>
<tr>
<td>26.74</td>
<td>13.70 d</td>
<td>0.19</td>
<td>Lunar tides/This study</td>
</tr>
<tr>
<td>13.18</td>
<td>27.7 d</td>
<td></td>
<td>Lunar tides/Wahr (1988) [6]</td>
</tr>
<tr>
<td>13.26</td>
<td>27.50 d</td>
<td>0.19</td>
<td>Lunar tides/This study</td>
</tr>
<tr>
<td>About 2.00</td>
<td>About 182 d</td>
<td>About 0.3</td>
<td>Solar tides and ocean currents/Rosen (1993) [5], Hopfner (1996) [33]</td>
</tr>
<tr>
<td>2.10</td>
<td>181.80 d</td>
<td>0.22</td>
<td>Solar tides and ocean currents/This study</td>
</tr>
<tr>
<td>About 1.0</td>
<td>About 365 d</td>
<td>About 0.3</td>
<td>Solar tides and ocean currents/Rosen (1993) [5], Hopfner (1996) [33]</td>
</tr>
<tr>
<td>0.99</td>
<td>370.40 d</td>
<td>0.18</td>
<td>Solar tides and ocean currents/This study</td>
</tr>
<tr>
<td>About 0.41</td>
<td>About 2.42yr</td>
<td></td>
<td>Quasi-biennial oscillation in the stratosphere/Chao B F (1989) [9]</td>
</tr>
<tr>
<td>0.44</td>
<td>2.28yr</td>
<td>0.03</td>
<td>Unknown/This study</td>
</tr>
<tr>
<td>About 0.17</td>
<td>About 6yr</td>
<td>About 0.12</td>
<td>Exchange of angular momentum between the mantle and inner core/Mound &amp; Buffet (2003) [12]</td>
</tr>
<tr>
<td>0.18</td>
<td>5.48yr</td>
<td>0.05</td>
<td>Exchange of angular momentum between the mantle and inner core/This study</td>
</tr>
<tr>
<td>0.07</td>
<td>13.69 yr</td>
<td>0.10</td>
<td>Unknown/This study</td>
</tr>
</tbody>
</table>

“—” denote that the data is unavailable.
predecessors are clearly observed in this study, namely, the signals with periods and amplitudes of 9.13 d and 0.12 ms, 13.69 yr and 0.10 ms, respectively.

The quasi-biennial signal in the LOD has been discovered since 1980s. It seems that this signal is closely related to the quasi-biennial oscillation in stratosphere [36]. Study of Chao demonstrated that there is a relationship between them with the correlation coefficient being 0.48 [9]. A group led by WB Shen also observed this signal in GPS records at many stations [11]. They explained it as loadings of atmosphere, non-tidal and hydrology. Our present study clearly showed the existence of the quasi-biennial signal in the LOD. Its mechanism might be as suggested as Ref. [11].

Mound and Buffet observed an approximately 6-year variation [12], which correspond to our observation 5.48 yr (see Table 1). They considered that it is due to the exchange of angular momentum with the core arising from gravitational coupling between the mantle and core. Holme and Viron detected this signal later in their study [15]. They suggested that it is most likely related to fluid core motions and inner-core coupling. Results by Duan and his colleagues indicate that the amplitude of the signal has a long-term decreasing trend and the total amplitude reduction is about 0.05 ms during the past 50 years [37]. This signal has not been widely acknowledged yet. Our study further suggests that there exists a signal of approximately 6-year variation in the LOD.

Our study clearly shows a 9.13-day signal in the LOD. Dickman predicted the effects of long-period ocean tides, including the 9.13-day term, on polar motion [38]. Gross even developed an improved empirical model for the effect of long-period ocean tides, including 9.13-day term, fortnightly term and monthly term, on polar motion [39]. Seize and Schuh indicated that it was induced by solid earth tide [40]. We suppose this signal to be caused by long-term ocean tides, but the mechanism is still open.

As for the 13.69-years signal in the LOD, we did not find previous studies addressing it. Based on our results, we consider that this signal might be related to the solar cycle or solar magnetic activity cycle, within Sun–Earth system. The solar cycle or solar magnetic activity cycle is around 11 years, which may cause the corresponding periodic effects in space, in the atmosphere, and on Earth’s surface. In addition, frequency modulation is possible, which might further explain the mentioned signal.

As a summary, besides the well-known signals, we observed additional signals that were not or not definitely observed by predecessors. The physical implications behind these signals are still open.

Acknowledgments

We sincerely thank two anonymous Reviewers for their valuable comments, corrections, and suggestions on the original manuscript, which improved the manuscript. This study is supported by National 973 Project China (2013CB733305), and National Natural Science Foundation of China (NSFCs) (41174011, 41429401, 41210006, 41128003, 41021061).

REFERENCES


Wenbin Shen, Professor, Department of Geophysics, School of Geodesy and Geomatics, Wuhan University. His interests include gravity theory and application, Earth rotation, Earth’s free oscillation, relativistic geodesy.