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Seasonal and inter-annual variations of length of day and polar motion observed by SLR in 1993－2006

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A time series of length of the day (LOD) and polar motion (PM) were estimated from the range data measured by the satellite laser ranging technique (SLR) to LAGEOS 1/2 through 1993 to 2006. Compared with EOPC04 released by the International Earth Rotation and Reference Systems Service (IERS), the root mean squares errors for LOD, *X* and *Y* of PM are 0.0067 milliseconds (ms), 0.18 milli-arc-seconds (mas) and 0.20 mas, respectively. Then the time series are analyzed with the wavelet transformation and least squares method. Wavelet analysis shows that there are the obvious seasonal and inter-annual variations of LOD and PM, but the annual variation cannot be distinguished from the Chandler variation because these two frequencies are very close. The trends and periodic variations of LOD and PM are given in the least squares sense. LOD changes with the annual and semiannual periods. The annual and Chandler variations for PM are also detected, but the semiannual motion for PM is not found. The trend rate of the LOD change in 1993－2006 is –0.18 ms per year, and the difference from the well-known 1.7 ms per century showed that the trend rate is diverse in different periods possibly. The trend rates of PM in the *X* and *Y* directions are 2.25 and 1.67 mas per year respectively, and the North Pole moves to 36.5°E relative to the crust, which is different from the direction of Greenland.

satellite laser ranging (SLR), length of day, polar motion, Earth rotation, wavelet transformation

The Earth rotation is not stable, and its changes have the intra-seasonal, seasonal, inter-annual, inter-decadal periodic fluctuations and long-term trend, which are caused by different geophysical mechanisms inside and outside the Earth and influences of some celestial bodies[1]. In a rotating terrestrial reference frame, the changes of the Earth rotation include the variation of length of the day (LOD), which is the change of the rotation rate, and the fluctuation of polar motion (PM), which is the motion of the rotation axis relative to the crust. PM is commonly presented as two time series, one giving the temporal variation of the rotation pole along the Greenwich meridian (referred to as *X* component) and the corresponding east-west component variation (referred to as *Y* component)[2].

The difference between the astronomical duration of the day and standard length of the day, which is denoted by 86400 s of the International Atomic Time (TAI), is called LOD. LOD can be obtained from the data of (UT1-UTC) and (UT1-TAI) expediently. In general, it is very difficult to precisely estimate UT1 with the satellite geodetic technique because the Earth rotation is aliasing with the changes of the satellite orbit node. But LOD, as an element of the satellite orbit, can be determined with the space geodetic technique. The un-modeled force models in the satellite dynamics affect the change of a node which couples with LOD[3].

Since the 1970s, the changes of the Earth rotation have been precisely monitored with space geodetic

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techniques, including the very long baseline interferometry (VLBI), the satellite laser ranging (SLR), the lunar laser ranging (LLR), the global positioning system (GPS), the Doppler orbitography and radiopositioning integrated by satellites (DORIS). Reported by IERS, the uncertainty of PM is up to 0.1 mas, and that of LOD up to 0.005 ms, which are more precise by two orders of magnitude than those using the traditional optical technique in the middle of the 20th century[3]. SLR more precisely estimates the Earth rotation at a higher time resolution. GPS provides the parameters of the Earth rotation on the sub-daily scale. VLBI shows the standard products. DORIS is also used to calculate the parameters of the Earth rotation, but its precision is lowest. Therefore IERS provides the combined products of the Earth rotation with the integrated geodetic techniques[4–6].

Now many researchers mainly study the excitations of changes of LOD and PM. The exciting mechanisms are very complex, which include the gravitational torques of celestial bodies, and the mass redistribution of all layers inside the Earth[1,7]. The decadal fluctuation for LOD reflects the coupling effect between the mantle and the core[8], and partially the change of atmospheric currents. For the inter-annual periods, the oceans excitate some of variations of LOD[9,10]. For the seasonal periods, the atmosphere can explain about 90% of the variations in LOD[8,11–14], and the oceans and the continental water can also partially excitate the variations of LOD[8,15–17].

PM has also the seasonal, inter-annual and secular motions[1]. The seasonal variation of PM is a forced wobble driven by the seasonal redistribution of mass within and between the atmosphere, oceans, and continental water[18]. The decadal fluctuation of PM is also found. The pole is drifting in a direction towards Greenland on one century scale, which is possibly related to an exchange of mass between the world's oceans and ice caps, and to the post-glacial rebound. On the geological time scale, the paleomagnetic evidence shows that the rotational pole has ever wandered over the Earth's surface relative to the continent. The principal component of the Earth rotation with respect to the Earth-fixed frame is the well-known Chandler wobble whose period is about 433 days[19]. This is a free mode of the Earth, i.e. it would still be present in the absence of external gravitational forces. It is very difficult to separate the annual and Chandler components in the polar motion data, because the frequencies of two components are so close[2].

In this paper, we use the wavelet transformation and least squares method to study the Earth rotation data measured with SLR to LAGEOS 1/2 through 1993 to 2006 to detect seasonal and inter-annual variations of LOD and PM.

1 Time series of the Earth rotation observed with SLR to LAGEOS

LAGEOS, laser geodynamics satellites, are a series of scientific research satellites designed to provide an orbiting laser ranging benchmark for geodynamical studies of the Earth. LAGEOS satellites can be used to determine the positions of stations fixed on the crust with extremely high accuracy due to the stability of their orbits by SLR technique. Long-term data sets can be used to monitor the motion of the Earth's tectonic plates, measure the Earth's gravitational field, detect the wobble in the Earth's axis of rotation, and better determine the Earth rotation. LAGEOS 1 was developed by the National Aeronautics and Space Administration (NASA), USA, and was launched into a high inclination orbit to permit viewing by ground stations located around the world in May, 1976. LAGEOS 2 was a joint mission between NASA and the Italian Space Agency (ASI), Italy, and was launched in Oct. 1992. The precision of SLR observations was only up to the decimeter or centimeter level, and the global distribution of SLR stations was asymmetrical in the 1980s. Since 1993, more SLR stations can meantime track LAGEOS 1/2 and the observing precision is up to 1 centimeter or millimeters[20].

Based on the satellite dynamics, a time series of the Earth rotation including LOD and PM was daily estimated using the SLR tracking data to LAGEOS 1/2 in 1993—2006 from 86 stations around the world with the software of GINS/MATLO by Dr. Coulot et al.[20] in Observatorie de la Côte d'Azur, France. The Earth rotation time series called SLR's data in the paper are shown in Figure 1.

There are many errors in different bands for SLR's data under effects of LAGEOS orbits, distribution of SLR stations, observing errors and solving strategy. Feissel-Vernier et al.[21] ever analyzed the systemic errors for SLR tracking data. The effects of a satellite orbit on SLR stations' positions mainly have the periods of one cycle per revolution, right ascension, semi-annual and annual variations[22]. There are 17.5- and 35-day systemic errors, and 14-day periodic errors for the

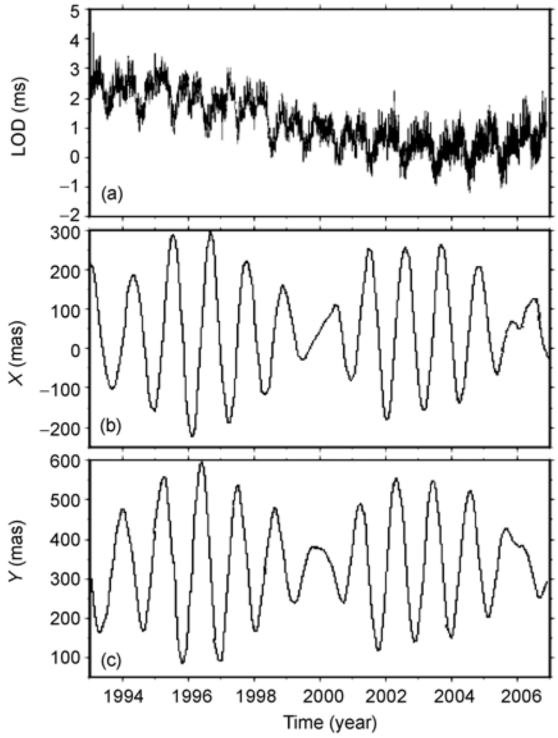

Figure 1 Time series of the Earth rotation observed by SLR in 1993—2006. (a) LOD; (b) *X* of PM; (c) *Y* of PM.

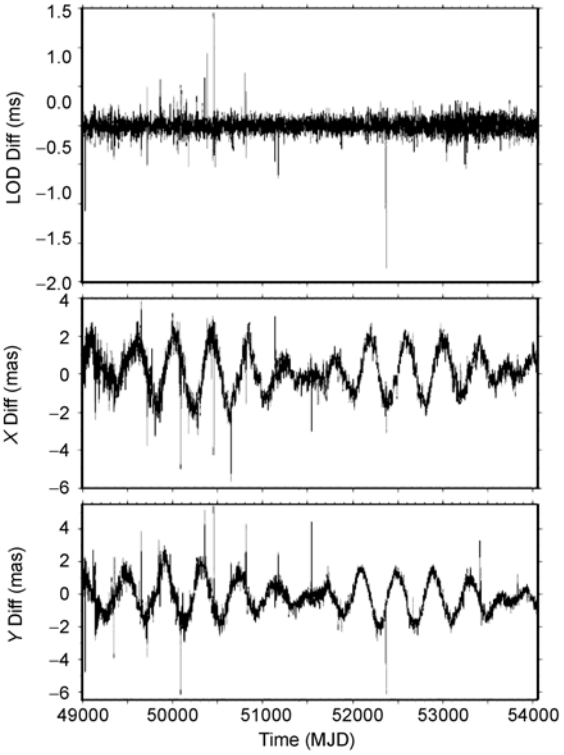

Figure 2 Comparison of the Earth rotation observed by SLR with EOPC04 in 1993—2006.

Table 1 Statistical results of comparison with EOPC04

	Maximum	Minimum	Mean	RMS
X (mas)	3.87	–5.73	0.14	0.18
Y (mas)	5.42	–6.22	–0.17	0.20
LOD (ms)	1.4519	–1.8308	–0.0029	0.0067

LAGEOS orbits. Meantime, there is a 140-day bias in the SLR tracking data. An inter-annual systemic error with 1 mm of amplitude for SLR tracking data is caused by the atmospheric loading[23].

EOPC04 is a time series of the Earth rotation regularly recomputed to take advantage of the improvement of various individual contributions and of the refinement of analyses procedures by IERS[5,6,24]. EOPC04 is smoothed on 1-day intervals with Vondrak algorithm in order to remove the high-frequency noise. EOPC04 is free from the diurnal/subdiurnal terms due to the oceanic effects and can be interpolated linearly. As the IERS combined series is often used as a reference for comparison, the comparison of SLR's data with EOPC04 is made, shown in Figure 2. The statistical results of differences are listed in Table 1. There are periodic variations with small amplitudes in differences of *X* and *Y* of PM, which may be caused by the different solving strategies of SLR's data and EOPC04, and the different reference scales.

2 Analysis of LOD variations

The wavelet transformation is a signal-analyzing method in time and frequency domains with the variable resolutions, whose mathematical principle is to use a family of functions to approach a signal or a function[25]. A mother wavelet is translated and scaled to make the transformation. Because the Morlet wavelet is a combination of trigonometric and Gaussian functions, it is widely used in the space geodetic and geophysical data analysis. Signals can be separated from noises in a time series by a wavelet filtering in time and frequency domains, which can efficiently wipe off the effect of noises. Then a clean signal can be reconstructed and an ideal fitting function can be gotten. Therefore the time series of the Earth rotation measured with SLR in 1993—2006 are analyzed with the wavelet transformation.

Figure 3 shows the wavelet analysis of LOD variations through 1993 to 2006. Periodic variations LOD are obviously detected from the wavelet power spectrum and the global wavelet spectrum. These periods include half-year, one-year, twenty-six-month, fifty-two-month and eighty-five-month. The eighty-five-monthly period

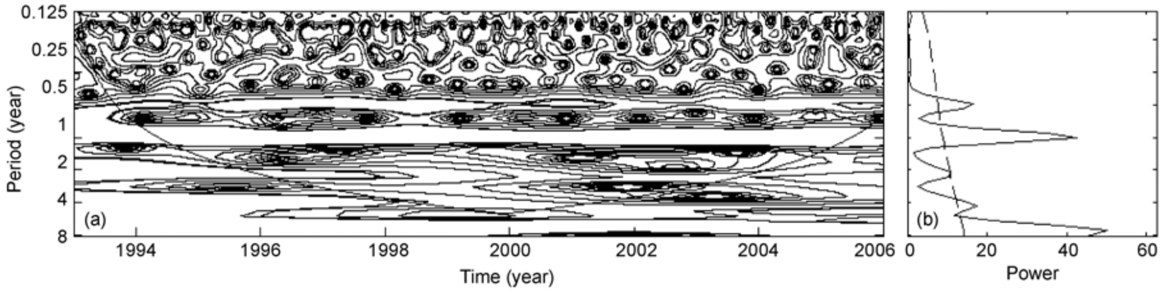

Figure 3 Wavelet analysis of LOD series. (a) Wavelet power spectrum; (b) global wavelet spectrum.

is of low reliability because the time span of LOD data is only 14 years.

To determine the detailed periods and amplitudes of LOD variations, LOD series is also analyzed in the least squares sense. Supposing there is a time series (t_i, y_i)(i = 1, 2, $\cdots n$) of LOD which has the secular and periodic fluctuations. The long-term variation can be fitted with a polynomial, and the periodic term can also be fitted with a trigonometric function. Suppose there are m periodic terms. Then

$$y_i = a + bt_i + \sum_{j=1}^{m}[c_j \cos(2\pi f_j t_i) + s_j \sin(2\pi f_j t_i)], \quad i = 1, 2, \cdots n, \qquad (1)$$

where a is a constant, b is the trend rate, and f_j is the frequency for the j-periodic term. The estimated results are listed in Table 2. The trend rate of the LOD change is (−0.178±0.002) ms per year. These periods of 182.5-, 364.7-, 823.5- and 1352.9-days in the least squares sense are corresponding to half-year, one-year, twenty-six-month and fifty-two-month in the wavelet spectrum. But the eighty-five monthly period is not found with the least squares method because of the short time span (only 14 years).

3 Analysis of PM variations

The time series of PM measured with SLR technique to LAGEOS 1/2 in 1993—2006 are shown in Figure 4. PM series in the X and Y directions are also analyzed with the wavelet transformation. Figures 5 and 6 show the wavelet analysis on X and Y variations, respectively. 14-month-periodic fluctuations in the X and Y directions are obviously found to express the Chandler wobble. The annual change is not present, whose frequency is very close to that of the Chandler wobble. The decadal fluctuation is not explored because of the short time span (only 14 years) of PM data.

The time series of PM are also analyzed with the least squares method. The trend rates in the X and Y directions

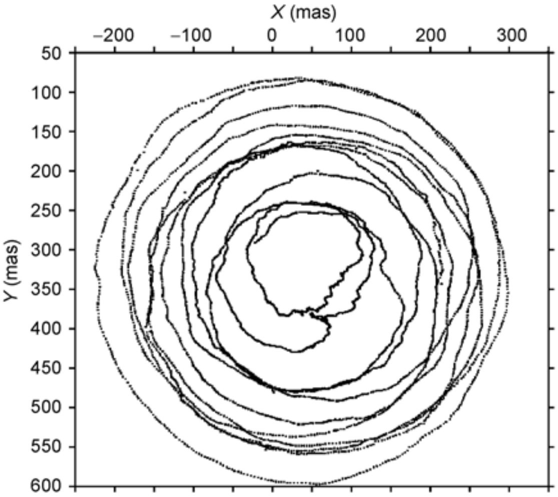

Figure 4 Polar motion measured with SLR in 1993—2006.

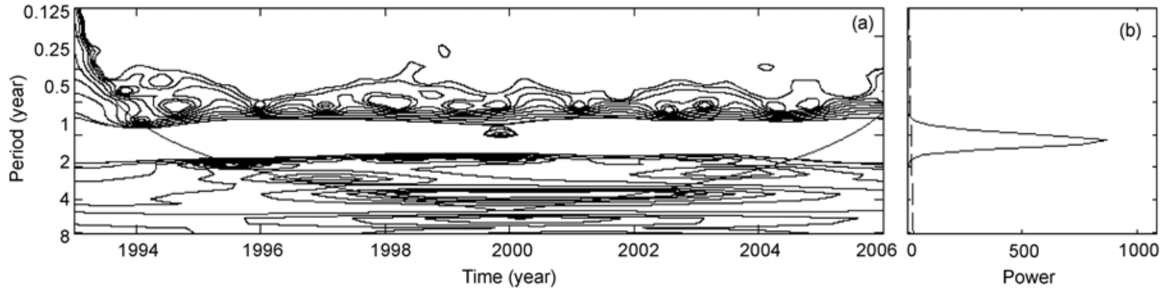

Figure 5 Wavelet analysis of X variations. (a) Wavelet power spectrum; (b) global wavelet spectrum.

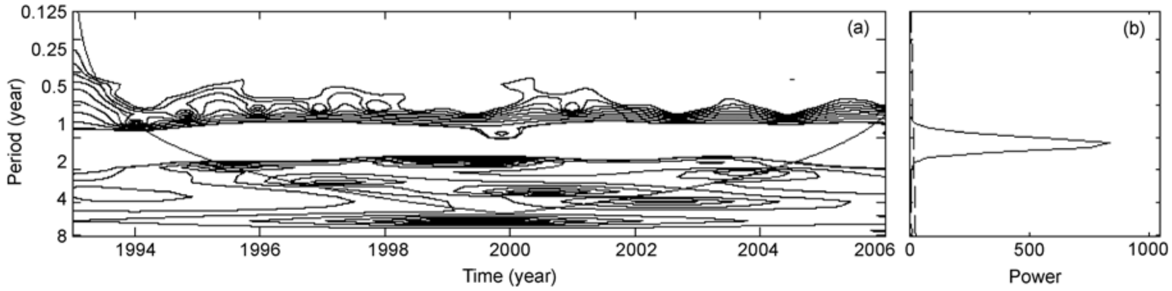

Figure 6 Wavelet analysis of *Y* variations. (a) Wavelet power spectrum; (b) global wavelet spectrum.

are (2.2553±0.2518) and (1.6695±0.2205) mas per year, respectively. The periods and amplitudes of PM variations are listed in Table 2. 14-month periodic fluctuations in the *X* and *Y* directions are detected, which is corresponding to Chandler wobble. Meantime, the changes with different periods are also found in the least squares sense.

4 Discussion and conclusions

4.1 Variation trend

The visible secular variations appear in the Earth rotation measured with SLR technique to LAGEOS 1/2. The least square analysis gives the trends of LOD, *X* and *Y* for PM through 1993 to 2006, which obviously departs away zero.

The trend rate of the LOD change is (−0.178±0.002) ms per year. The negative value narrates that the Earth rotation speeds up in the latest decade, which is different from the long-term retardment in the geologic age. The reason may be the short time span used in the paper. The rate of LOD is 1.7 ms per century for a long series in the latest century[26].

Table 3 shows the rate and direction of PM from different authors. The trend rates of PM in the *X* and *Y* directions are (2.2553±0.2518) and (1.6695±0.2205) mas per year, respectively. Therefore the north pole moves to 36.5E degrees in the longitude direction with respect to the crust. Barents Sea is fitly in this direction, which is different from the well-known direction of Greenland. The trend rate of pole motion is 2.8060 mas per year. The trend of PM may show the effect of temperature rise all over the world. Effects of changes of glacial ice, Antarctic ice, and Greenland ice on PM[27–29] were ever analyzed (Table 3).

Table 2 Variations of the Earth rotation in the least squares sense

LOD			*X*			*Y*		
Period (day)	Amplitude (ms)	Phase (degree)	Period (day)	Amplitude (mas)	Phase (degree)	Period (day)	Amplitude (mas)	Phase (degree)
182.5±0.1	0.3184±0.0144	232.2±2.7	433.2±0.1	157.30±0.91	59.0±0.4	433.6±0.1	157.65±0.77	151.5±0.4
364.7±0.4	0.3608±0.0138	56.1±2.5	363.8±0.1	87.13±0.90	208.6±0.7	363.7±0.1	80.02±0.77	296.3±0.8
823.5±4.9	0.1506±0.0141	63.0±6.3	328.9±0.6	16.34±1.13	320.5±4.2	325.8±0.5	11.79±0.91	45.9±4.6
1352.9±14.6	0.1646±0.0153	313.6±5.2	1309.6±10.3	5.40±1.16	234.8±4.3	1310.1±9.3	10.96±0.75	241.6±4.8

Table 3 Trend of polar motion

Ref	Time span	Rate (mas per year)	Direction (degree)
[30]	1900—1966	3.2	–60
[31]	1900—1966	3.5	–65
[32]	1899—1966	2.2	–77.7
[33]	1900—1977	3.4	–66
[34]	1900—1990	3.31	–78.1
[35]	1899—1994	3.33	–75
[36]	1899—1992	3.31	–76.1
This paper	1993—2006	2.806	36.5
	Predicted		
[27]	changes in glacial ice	0.439	63
[29]	changes in Antarctic ice	3.6	–85
[28]	changes in Greenland ice	2.0	141.2

Table 4 Periodic variation of the Earth rotation

LOD					
Ref	Time span	Annual		Semiannual	
		Amplitude (ms)	Period	Amplitude (ms)	Period
[14]	1992—2000, predicted from atmospheric and oceanic data	0.3630±5.2	1 year	0.2381±5.2	0.5 year
[38]	1983—1993	0.3564—0.4089	361.1—372.4 days	0.2885—0.3864	176.6—187.5 days
[39]	1997—2000	0.3664	365.2 days	0.3310	182.6 days
[40]	1956—1992	0.3371	364.6 days	–	–
This paper	1993—2006	0.3622±0.0131	364.9±0.4 days	0.3351±0.0134	(182.5±0.1) days

X of PM					
Ref	Time span	Annual		Chandler	
		Amplitude (mas)	Period	Amplitude (mas)	Period
This paper	1993—2006	87.1286±0.8972	363.8±0.1 days	157.3036±0.9136	433.2±0.1 days
[33]	1960—1977	92.4	1 year		
[32]	1962—1971	95	1 year	130	14 months

Y of PM					
Ref	Time span	Annual		Chandler	
		Amplitude (mas)	Period	Amplitude (mas)	Period
This paper	1993—2006	80.0240±0.7742	363.7±0.1	157.6521±0.7729	(433.6±0.1) days
[33]	1960—1977	76.2	1 year		
[32]	1962—1971	90	1 year	135	14 months

4.2 Seasonal variations

The seasonal variation of the Earth rotation that includes the semiannual and annual fluctuations is the main part, which may be principally derived from the mass redistribution of atmosphere, oceans and continental water[1,7,37]. Seasonal variations of LOD and PM are obviously shown in the wavelet and least squares analysis in the paper.

There are obviously semiannual and annual variations in LOD detected with the wavelet transformation. The least squares analysis shows that the semiannual and annual periods are 182.5 and 362.7 days respectively, which is basically consistent with those of wavelet analysis. The amplitude of the annual change is in some sort greater than that of the semiannual change. The seasonal amplitudes of LOD variation basically accord with the predicted results by Gross et al.[14] with the atmospheric and oceanic models, which means that the atmospheric and oceanic mass redistributions are the principal reason to excitate the seasonal fluctuation of LOD.

There is also seasonal variation in PM. But the variation with the period of 14-month is only detected with the wavelet analysis, and the annual change is not found. This is because the annual motion is very close to the Chandler wobble, and the Chandler wobble is much stronger. 11-, 12- and 14-month variations are estimated in the least squares sense. The amplitude with the period of 14 months is about double that of annual variation.

Variation phases of PM in the *X* and *Y* directions are different, which indicates that there are different astrophysical and geophysical mechanisms to excitate periodic variations of *X* and *Y*.

4.3 Interannual variations

Table 4 shows the periodic variation of the Earth rotation given by different authors. The fluctuations with the periods of twenty-six-month, fifty-two-month and eighty-five-month for LOD are explored with the wavelet spectrum. The periods of 523.5 and 1352.9 days are found in the least squares sense. The change with the period of about 1310 days is found for PM in the least squares sense. These are the inter-annual variations for the Earth rotation.

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