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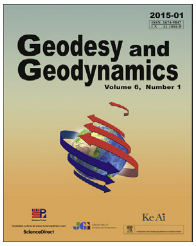

Earth rotation parameter and variation during 2005–2010 solved with LAGEOS SLR data[☆]

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ABSTRACT

Time series of Earth rotation parameters were estimated from range data measured by the satellite laser ranging technique to the Laser Geodynamics Satellites (LAGEOS)-1/2 through 2005 to 2010 using the dynamic method. Compared with Earth orientation parameter (EOP) C04, released by the International Earth Rotation and Reference Systems Service, the root mean square errors for the measured X and Y of polar motion (PM) and length of day (LOD) were 0.24 and 0.25 milliarcseconds (mas), and 0.068 milliseconds (ms), respectively. Compared with ILRSA EOP, the X and Y of PM and LOD were 0.27 and 0.30 mas, and 0.054 ms, respectively. The time series were analyzed using the wavelet transformation and least squares methods. Wavelet analysis showed obvious seasonal and interannual variations of LOD, and both annual and Chandler variations of PM; however, the annual variation could not be distinguished from the Chandler variation because the two frequencies were very close. The trends and periodic variations of LOD and PM were obtained in the least squares sense, and PM showed semi-annual, annual, and Chandler periods. Semi-annual, annual, and quasi-biennial cycles for LOD were also detected. The trend rates of PM in the X and Y directions were 3.17 and −1.60 mas per year, respectively, and the North Pole moved to 26.8°E relative to the crust during 2005–2010. The trend rate of the LOD change was 0.028 ms per year.

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1. Introduction

The Polar Motion (PM) and Length Of Day (LOD) as Earth Rotation Parameters (ERPs) are used to describe the Earth's rotation. In the terrestrial reference frame, PM is the movement of the polar point where the Earth's rotational axis intersects its surface, and LOD variations reflect the change of the Earth's rotation rate. ERPs are important for establishing and maintaining the terrestrial reference frame and they are necessary to realize the transformation between the celestial and earth reference frames. Navigation and orbit determination of artificial satellites and spacecraft require ERPs of high precision [1,2]. In addition, ERPs contain abundant geophysical information. Accurate long-term high-resolution ERPs are necessary for studying the physical factors of Earth's interior and spheres in stimulating and maintaining pole motion and the change of Earth's rotation speed [3]. Using modern space geodetic techniques to determinate ERPs has important astronomical meaning in geodynamics [4].

Laser Geodynamics Satellites (LAGEOS-1/2) are a series of scientific research satellites designed to provide orbiting laser ranging benchmarks for geodynamical studies. Using long-term satellite laser ranging data, the high stability of the orbits of LAGEOS-1/2 make it possible to monitor Earth's plate motion, measure Earth's gravitational field, and detect the motion of the Earth's axis of spin and Earth orientation parameters (EOPs). Since 1993, the number of satellite laser ranging (SLR) stations tracking LAGEOS-1/2 has increased and their observational accuracy can reach 1 cm or even millimeter precision [5]. Thus, LAGEOS-1/2-based SLR data can be processed to achieve more accurate EOPs.

This paper presents the estimation of time series of ERPs based on SLR tracking of LAGEOS-1/2 through 2005–2010. EOP (IERS) C04 and EOP International Laser Ranging Service (ILRS) ILRSA are used to check the reliability and precision of the calculated results, respectively. In addition, the seasonal and interannual variations of PM and LOD are examined using the wavelet transform and least squares fitting techniques.

2. Time series of ERPs measured using SLR

LAGEOS-1/2 are virtually identical except for their different spatial coverage. The orbital inclinations of LAGEOS-1 and LAGEOS-2 are 110° and 53°, respectively. The spatially complementary nature of these two satellites reduces the disturbance of the spatial distribution of observational data. Thus, ERPs with greater accuracy can be estimated using LAGEOS SLR data [6].

The SLR data to LAGEOS-1/2 used in this study were provided by the ILRS (ftp://cddis.gsfc.nasa.gov). Based on the satellite dynamics, ERPs were estimated accurately 7-day arcs using the SLR tracking data from 2005 to 2010 with GEODYN II. The astronomical constants, reference frame, force models, and measurement models were consistent with IERS Conventions 2003 [7].

There are detailed calculation models and strategies in the Precision Orbit Determination (POD) processing on LAGEOS-1/2. 1) The force model adopted in this paper includes the GGM02C Earth's gravitational field, and DEHANT solid tidal and GOT00 ocean tidal loadings. In addition, the perturbation of N-body, Earth's rotational deformation, solar radiation pressure, Earth's albedo radiation pressure, drag perturbation, and empirical RTN are also applied. The position of the Sun and Moon are obtained from the DE403/LE403 planetary table. 2) The measurement model is used to make the measurements and station coordinates correct. The Marini Murray model is used for Atmospheric refraction correction. The influences of the Earth's rotational deformation, ocean loading, and solid tidal loading are considered in the displacement corrections of the SLR stations. Station coordinates are calculated using the coordinate and velocity field in International Terrestrial Reference Frame (ITRF) 2000. The correction of eccentricity of the stations adopts the results from the Texas data center. The standard center-of-mass correction for the LAGEOS satellites is 251 mm. 3) The adopted reference system in our POD procedure comprises the J2000.0 geocentric inertial system, IAU76 precession model, and IAU1980 nutation model.

The LAGEOS-1/2 orbit determination is performed using the multi-step COWELL II numerical integration [8] and the step size for the orbit integration is 60 s. The a priori values of EOPs are from EOP 05 C04. ERPs are estimated at noon of each day. In the process of ERP estimation, all parameters are solved together, such as atmospheric drag coefficients, solar radiation coefficients, and empirical acceleration coefficients. Pressure coefficient CR and drag coefficient CD are to be estimated. The initial state vectors and empirical acceleration coefficients in the along-track and cross-track directions are estimated every orbital arc. The least squares estimation method is applied to solve the initial parameters, and the calculated values are considered as the initial parameters of the next iteration until the residual between the results of two adjacent iterations is less than the tolerance.

During 2005–2010, there were 41 SLR stations tracking LAGEOS-1/2, whose spatial distribution is shown in Fig. 1. There are about 2200 LAGEOS-1/2 SLR observational data from about 20 stations around the world in each 7-day arc. The orbit determination residual root mean square (RMS) of each 7-day arc is less than 2 cm; ERPs of repeat arcs are calculated by averaging. The time series of ERPs measured with LAGEOS-1/2 SLR data are shown in Fig. 2.

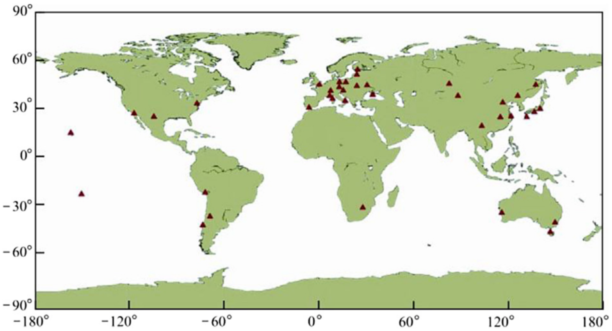

Fig. 1 – Distribution of SLR stations tracking LAGEOS during 2005–2010.

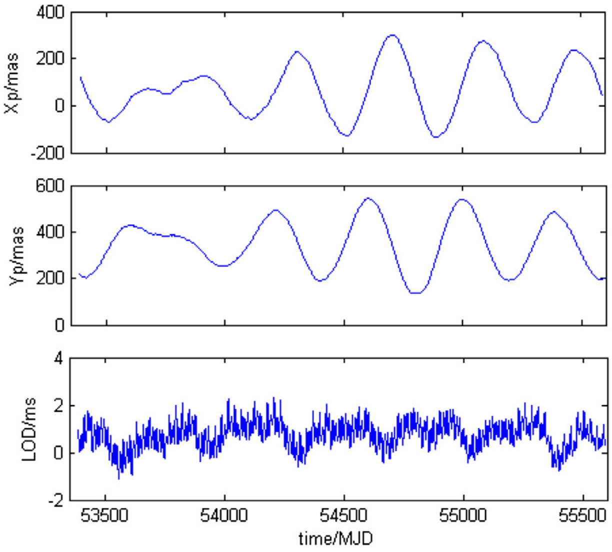

Fig. 2 – Time series of ERPs measured with LAGEOS SLR data during 2005–2010.

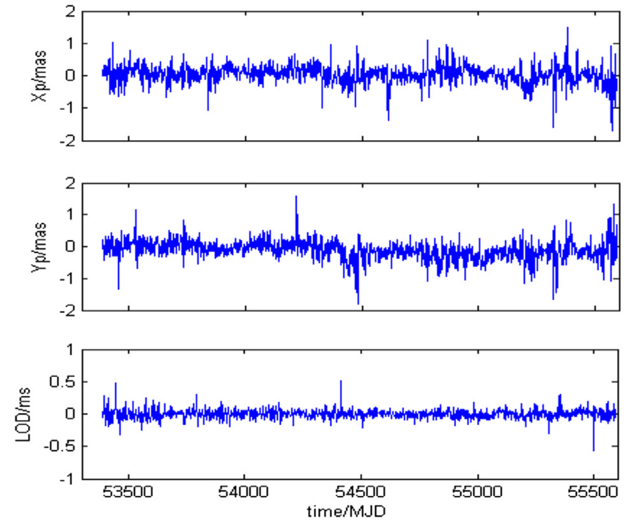

Fig. 4 – Comparison between the ERP series solved with the LAGEOS data during 2005–2010 with the corresponding (ILRS) ILRSA EOP series.

Six ILRS analysis centers release weekly station coordinates and daily EOPs estimated from 7-day arcs (Sunday 00:00 UTC to Saturday 24:00 UTC) every week [9]. Two types of generated products are a loosely constrained estimation of coordinates and EOP, and an EOP solution constrained to an ITRF. The ILRS analysis centers generate the individual EOPs and station positions with SLR observations of LAGEOS-1, LAGEOS-2, Etalon-1, and Etalon-2 in 7-day arcs. Analysis contributors are free to follow their own computational models or analysis strategies, but they must follow IERS conventions as closely as possible.

EOP C04, released by IERS, is a standard product of the Earth's rotation, which combined with a variety of space geodetic results, has higher accuracy and greater system stability. In this paper, the time series are compared with EOP (IERS) C04 and EOP (ILRS) ILRSA, as shown in Figs. 3 and 4, respectively. The statistical results of the differences are presented in Table 1. Overall, the results show that the solution precision is reliable. There is a slight difference between the time series and ILRSA, mainly because ILRS adopted SLR observational data of Etalon-1/2 at the same time. The number, intensity, and spatial distribution of the observations are better than the observational data of LAGEOS-1/2 used in this paper. In addition, their solution strategy is also different.

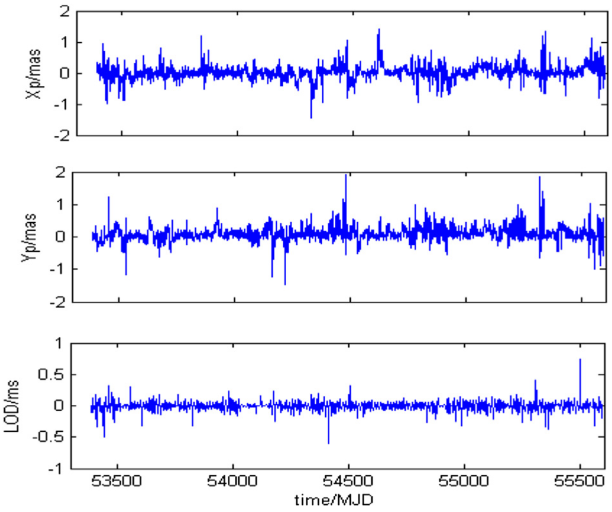

Fig. 3 – Comparison between the ERP series solved with the LAGEOS data during 2005–2010 with the corresponding (IERS) EOP C04 series.

3. Analysis of the Earth's rotational variations

Wavelet transform is a signal-analyzed method in the time and frequency domains with variable resolution [10]. In this paper, ERP series measured with SLR to LAGEOS-1/2 in 2005–2010 are analyzed using wavelet transform.

PM and LOD have long-term and multi-periodic variations. The least squares method is used to fit the time series to determine the long-term trend and specific periods with its amplitudes [11]. Supposing there is a time series (t_i, y_i) ($i = 1, 2, \ldots, n$) of ERP, which has secular and periodic fluctuations. The

Table 1 – EOP daily residuals with respect to EOP C04 and ILRSA.

	EOP C04		ILRSA	
	Mean	RMS	Mean	RMS
X_p (mas)	0.08	0.24	0.04	0.27
Y_p (mas)	0.10	0.25	−0.09	0.30
LOD (ms)	0.001	0.068	0.0002	0.054

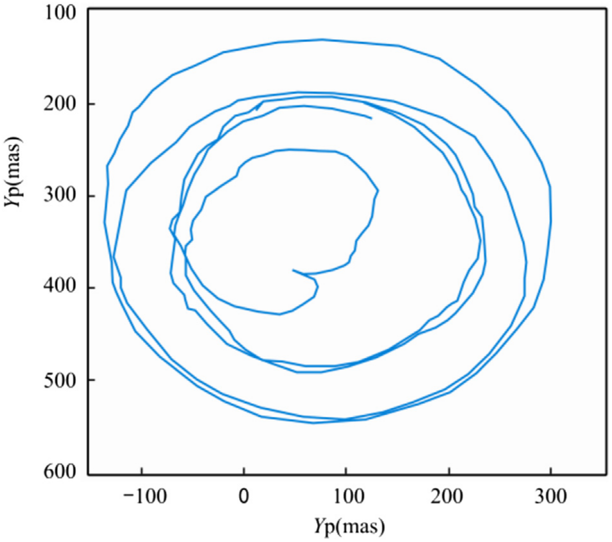

Fig. 5 – Time series of PM measured with SLR of LAGEOS during 2005–2010.

long-term variation can be fitted with a polynomial, and the periodic term can be fitted with a trigonometric function. Suppose there are *m* periodic terms, then

$$y_i = a + bt_i + \sum_{j=1}^{m}\left(s_j \sin\left(2\pi f_j t_i + \varphi_j\right)\right) \tag{1}$$

where *a* is a constant, *b* is the secular rate, and f_j is the frequency for the *j*-th periodic term. The amplitude and phase of the *j*-th periodic term are s_j and φ_j, respectively.

3.1. *Analysis of PM variations*

The time series of PM measured by SLR of LAGEOS-1/2 during 2005–2010 are shown in Fig. 5. The wavelet analyses of the PM series in the *X* and *Y* directions are shown in Figs. 6 and 7, respectively. A 14-month periodic fluctuation in both the *X* and Y directions is an obvious expression of the effect of the Chandler wobble; however, the annual change is not obvious because its frequency is close to that of the Chandler wobble. The semi-annual, annual, and Chandler periods in the *X* and *Y* directions are given in the least squares sense. The specific periods and amplitudes of PM are listed in Table 2.

The trend rates in the X and Y directions are (3.1705 ± 0.1059) and (−1.6013 ± 0.1544) mas per year, respectively. Therefore, the trend rate of PM is 3.5519 mas per year. The North Pole moves to 26.8°E in the longitude direction with respect to the crust. This direction points to Greenland, which is slightly different to the direction on a century time scale. In the last century, the trend rate of PM was about 3.3–3.4 mas per year, and its direction about 75–78°W [12–14]. From 1993 to 2006, the trend rate and direction of PM is 2.8060 mas per year and 36.5°W, respectively [15], which shows that PM measured by SLR of LAGEOS might contain an unexplained long-period interannual variation.

Seasonal variation is the principal component of Earth's rotational variations, including the semi-annual and annual periods, which are caused mainly by the atmospheric, oceanic, and terrestrial water distribution [16,17]. The study of the physical mechanism of the seasonal variation of PM has been an important aspect of analysis. The Chandler wobble is a major component of PM. In investigating the Chandler wobble, researchers have conducted a number of studies with consideration of many factors, e.g., the atmosphere,

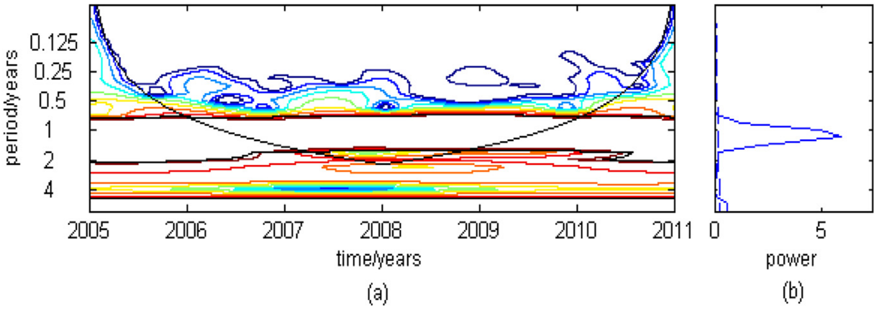

Fig. 6 – Wavelet analysis of *Xp* variation. (a) wavelet power spectrum, (b) global wavelet spectrum.

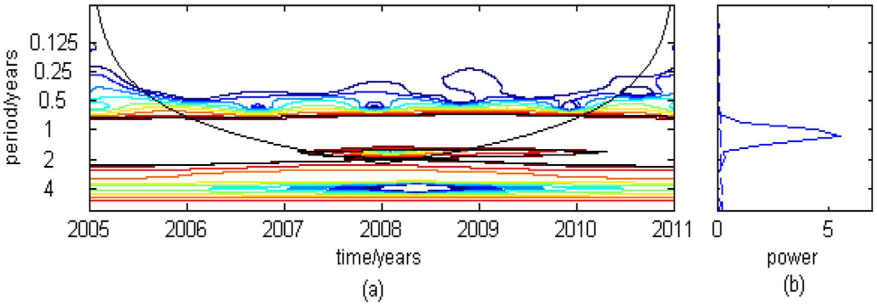

Fig. 7 – Wavelet analysis of *Yp* variation. (a) wavelet power spectrum, (b) global wavelet spectrum.

Table 2 – Earth's rotational variations in the least squares sense.

LOD			X_p			Y_p		
Period (d)	Amplitude (ms)	Phase (°)	Period (d)	Amplitude (ms)	Phase (°)	Period (d)	Amplitude (ms)	Phase (°)
50.4 ± 0.3	0.0527 ± 0.0126	153.4 ± 8.5	184.7 ± 1.4	4.73 ± 0.75	232.8 ± 9.2	179.8 ± 2.6	3.49 ± 1.06	169.3 ± 3.4
182.8 ± 0.6	0.3375 ± 0.0150	268.0 ± 2.6	360.6 ± 0.2	105 ± 0.80	208.5 ± 1.1	358.8 ± 0.5	97.15 ± 1.18	289.3 ± 1.8
367.9 ± 2.4	0.3673 ± 0.0255	79.1 ± 4.1	435.5 ± 0.4	116.7 ± 0.80	93.3 ± 0.9	433.7 ± 0.5	116.8 ± 1.2	179.9 ± 1.5
913.2 ± 18.2	0.1724 ± 0.0254	184.6 ± 8.8						

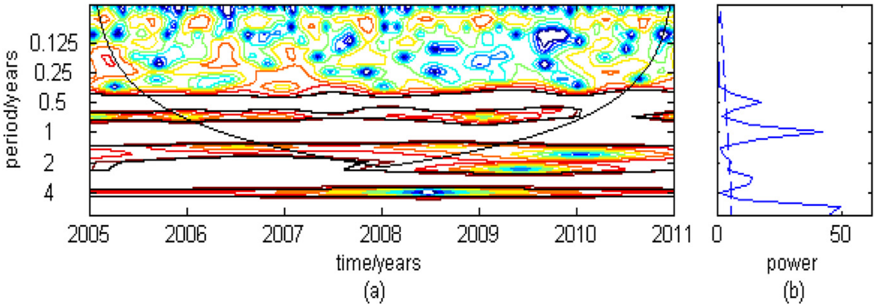

Fig. 8 – Wavelet analysis of *Yp* variation. (a) wavelet power spectrum, (b) global wavelet spectrum.

groundwater, earthquakes, undersea pressure changes, and core-mantle coupling; however, these sources of excitation do not fully explain the Chandler wobble [18].

3.2. Analysis of LOD variation

The wavelet analysis of LOD variations through 2005 to 2010 is shown in Fig. 8. It shows obvious semi-annual, annual, and 2.7-year variations of LOD. The detected period of 5.5 years is unreliable on 6-year time scales. In addition, variations of LOD in the least squares sense are listed in Table 2. The periods of 182.8, 367.9, and 913.2 days, in the least squares sense, correspond to the semi-annual, annual, and 2.7-year periods found in the wavelet spectrum. Furthermore, a period of 50.4 days is estimated in the least squares sense.

The least squares analysis provides a trend rate of LOD as 0.028 ± 0.005 ms per year, which indicates that the rotation of the Earth accelerated between 2005 and 2010. Over geological time scales, the rotation of the Earth exhibits a gradual decrease, but the Earth's rotation has accelerated in the last hundred years [19]. Using VLBI data, Wei et al. [20] determined that the rotation of Earth accelerated from January 2001 to March 2009.

The wavelet and least squares analyses detected obvious semi-annual and annual seasonal variations of LOD. The seasonal variation of LOD might be caused mainly by the atmospheric angular momentum [21,22]. By studying atmospheric angular momentum data, researchers have found that the excitation of the atmosphere to seasonal variations of LOD can exceed 85%, and the contributions of the atmosphere to the semi-annual and annual LOD changes are 95% and 88%, respectively (including the contributions of atmospheric wind g pressure) [23]. The 2.7-year period detected by the wavelet and least squares analyses is the interannual variability, and the 50.4-day period detected in the least squares analysis is the sub-seasonal variability.

4. Conclusions

Time series of ERPs were estimated accurately from SLR data tracking to LAGEOS-1/2 in 2005–2010. The results were compared with EOP (IERS) C04 and EOP (ILRS) ILRSA during the same period, respectively, which showed that the precision of the time series was reliable.

Secular and periodic variations of Earth's rotation measured with SLR were detected using wavelet transformation and the least squares method, respectively. Wavelet analysis detected both the annual variation and the Chandler wobble of PM, but the annual variation could not be distinguished from the Chandler wobble because the frequencies of both are very close. The least squares analysis detected the semi-annual and annual variation, and the Chandler wobble with the corresponding variation rates and directions of PM. The semi-annual, annual, and quasi-biennial periods of LOD were detected in the wavelet and least squares analyses. Furthermore, the least squares analysis detected a sub-seasonal period and secular rate of the LOD. The amplitudes were shown in the least squares analysis, which indicated that the semi-annual and annual variations are the principal components of the LOD, and that the annual variation and Chandler wobble are the principal components of PM.

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