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Study of the Interannual Variations of the Earth's Rotation

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Abstract—In this work we investigate the variations of the Earth's rotation in the interval of periods from 2 to 8 years using the longest available observational series obtained both by means of astrometry and space geodesy. We found an abrupt change of the variation pattern in the middle of the 1980s, when classical ground-based astrometric facilities for studying the Earth Rotation Parameters (ERP) were replaced with space geodesy methods. Variations with a 6-year periodicity and ~0.2-ms amplitude practically disappeared (space geodesy instruments did not detect these variations right from the start), but the 2- to 4-year periodicities increased in amplitude and began to dominate in this frequency range under consideration. In this study, we analyze some possible excitation sources and possible causes of the change in the variability pattern.

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INTRODUCTION

Variations of the Earth's rotational speed range between intraday fluctuations obtainable with contemporary Earth Rotation Parameters (ERP) monitoring facilities and decade-timescale variations limited at the low-frequency end by the time span of the observational data. Low-frequency components have a complex irregular structure that further complicates the identification and investigation of the factors responsible for the excitation of the corresponding modes. Studying the response of the structural features to variations of the external factors is of special importance because it allows for an understanding of the nature of their interaction.

The longest timescale of the variations of the Earth's rotational period are the so-called decade variations with periods of tens of years and longer and with amplitudes reaching several milliseconds (ms). These aperiodic oscillations contain most of the energy of the Earth's rotational irregularities. These length-of-day variations are generally ascribed to various interaction mechanisms between the Earth's mantle and core. The length-of-day, or length of the day (LOD), is hereafter defined as the difference between the real and nominal (86 400 s) durations of the day, which usually does not exceed several milliseconds (ms).

The seasonal interaction of the Earth's atmosphere and hydrosphere with its solid layers produces annual and semiannual length-of-day variations with a total amplitude of slightly less than 1 ms.

Besides this, intermediate-scale 6- to 7-year-long LOD variations with an amplitude of about 0.2 ms were detected. These variations of the Earth's rotation speed were first detected by A. and N. Stojko in the universal timescale data obtained with a pendulum clock. After the atomic time scale was introduced in 1956, these variations in the Earth's rotational spectrum were reported by Korsun and Sidorenkov (1974) and were investigated in more detail by Vondrak (1977).

After the new astrometric universal time series *eopAO* based on observations by 30 instruments at 24 observatories around the world (see Fig. 1) between 1956 and 1992 was published by Vondrak et al. (1998), the causes for these six-year variations were investigated in a large number of works. Some of these explain the variations by the angular momentum exchange between the solid Earth and its fluid shells and the atmosphere and the ocean (Gross et al., 1996; Sidorenkov, 2002; Dickey et al., 2003). Other papers, primarily theoretical, apply electromagnetic and gravitational interactions between the core and the mantle of the Earth, as well as the influence of the core–mantle boundary topography (Pais and Hulot, 2000; Mound and Buffett, 2003; 2006). In a number of works, the statistical connection between the 5- to 6-year variations and solar activity cycles was researched for (Djurovi$\hat{c}$, Pâquet, 1996; Abarca del Rio et al., 2003).

In the works of Djurovi$\hat{c}$, and Pâquet (1996), Liao and Greiner-Mai (1999), and Abarca del Rio et al. (2000), atmospheric angular momentum variations were shown to have no modes corresponding to the 6-year cycle. There is also no appropriate model for the solar activity effect on the Earth's rotation, except for its influence on the atmosphere and the ocean. Hence, the hypotheses applying the mantle and core interaction are most frequently discussed in published data. The modeling of this interaction is based on the

Fig. 1. Astrometric observatories (shown by asterisks), where the data used for the *eopAO* time series were obtained, and gage level stations (circles) used in the present study.

existence of gravitational and torsional oscillation modes in the system of the mantle and the inner core in dependence on some parameters of the system. However, the estimates of the parameters (like the conductivity of the lower mantle, density distribution in the mantle, viscosity in the core, etc.) are sufficiently wide in the developed models (Mount and Buffett, 2006; Dumberry, 2007; Dumberry and Mound, 2008) in order to reliably ensure the excitation of the LOD variations in the quasi-six-year period.

There are a large number of geophysical processes that have similar time variability timescales. First is seismic activity (Kondorskaya et al., 2004) that produces, in particular, tsunamis (Levin and Sasorova, 2002; Gamburtsev et al., 2004). Seismic activity variations are often explained by the roughly six-year wobbles in the oscillations of the Earth's pole. Secondly, regional meteorological and hydrological processes with recurrence times close to 5–6 years should be mentioned. In particular, in the work by Sidorenkov (2002), variations of the amplitude of the annual oscillations of the angular momentum of the atmosphere are reported together with meteorological and hydrological processes with periodicities of close to six years.

Besides this, the regional gravimetric network in China detected gravitational perturbations of a nontidal nature (Li et al., 2001; 2005) manifesting themselves as vertical deviations on the order of 0.02″. Gravitational effects of this kind detected with other gravimeters and similar phenomena in astronomical data were thoroughly studied in the paper by Chapanov et al. (2005). In Gorshkov and Shcherbakova (2002), it was shown that not all of the classical ERP determination subsystem stations of the former Soviet Union detect similar variations in the universal time series. While for stations near the coast, the amplitudes of these variations often exceeded the corresponding values from the composite solution of the International Earth Rotation Service (IERS), continental stations usually did not detect them at all.

In the present work, we study the quasi-six-year cycle using all available ERP data from before 2009, while previous studies were based on data up to 1995. The variations were found to significantly decrease during the 1980s, when classical astrometric methods for ERP determination (standard astrometric ERP determination methods included transit instruments, photographic zenith tubes, astrolabes, and circumzenithals) were changed to space geodesy methods (VLBI and global positioning facilities such as GPS and laser location systems). On one hand, modern ERP determination facilities practically do not detect the 6-year periodicity. Two- to four-year LOD variations, on the other hand, start dominating the frequency range under consideration, whereas they were practically never revealed earlier. In this study, we analyze the possible causes for these changes.

DATA AND ANALYSIS TECHNIQUE

Interannual LOD variations with periods between 2 and 8 years were searched for in the data stored at the IERS site (http://hpiers.obspm.fr/eop-pc/product/). We used both the classical astrometric ERP service series (*eopAO* series incorporating data between 1956 and 1992) and the longest space geodesic series (VLBI *IVS_r* series starting in 1981, laser location *CSR_r* series starting in 1981, GPS *CODE_p* starting in 1993, and a combined ERP series *Finals2000A.all* based on all of the space geodesy data since 1981). The *eopC04* time series is manufactured and uses data obtained by different methods: it was entirely based on astrometry data before the beginning of 1980s, and the space geodesy data contribution increased and became the only data source starting from the late 1980s.

The uniform astrometric ERP series *eopAO* was extended beyond 1992 by the joint reduction of the data from the remaining five classical astrometric LOD determination stations in Irkutsk, Novosibirsk, Moscow, Pulkovo, and Kharkov kindly provided by the VNIIFTRI metrological institute. The series were merged using the common interval in 1991. The joint series is denoted as *combAO*. All of the series were cleaned from tidal LOD variations in the period range between 5 days and 18.6 years (*LODS*, in international notation) and reduced to a uniformly spaced form with a 0.02-year time step.

In addition to this, we used a preatomic time (before 1956) LOD time series based on the lunar occultations of stars (*LUNAR-97*, http://hpiers.obspm.fr/cop-pc/). The precision and density of this series are significantly smaller than others are, especially before the 1920s, but long-timescale variations are still detectable. In Fig. 2, we show the uncertainties of the series under consideration reduced to a uniform interval of 5 days.

For a comparison with the possible geophysical factors responsible for the excitation of LOD variations, we used mean sea level data provided by the Permanent Service for Mean Sea Level (PSMSL, http://www.nbi.ac.uk/psmsl/). We used sea level values measured by level gages closest to the astrometric stations where the data used for the joint *eopAO* series were obtained (Fig. 1). In addition, data on the effective angular momenta (sums of mass χ^{pib} and wind χ^{w} terms) were used: Atmospheric Angular Momentum function (AAMf) for 1948–2008 (Zhou et al., 2006, ftp://ftp.cdc.noaa.gov/dataset/ncep.reanalysis/) and the Oceanic Angular Momentum function (OAMf) for 1949–2002 (Gross et al., 2005, ftp://euler.jpl.nasa.gov/sbo/oam_global/ECCO_50yr.chi). For the *LUNAR-97* series, the Southern El Niño Oscillation index (SOI) was used instead (Stahle et al., 1998).

In our study, we primarily used the Singular Spectrum Analysis (SSA) technique and its multidimensional version (MSSA) implemented as the *Gusenitsa* (caterpillar) St. Petersburg University software (http:// www.gistatgroup.com/gus/; Golyandina et al., 2001). The method is best fitted for identification informative components, not necessarily harmonic, in a nonstationary series. It allows for the recovery of important information on the amplitude and phase variations of individual components with time and the estimation of the contributions of individual components to the energy budget of variability.

For analyzing a uniform one-dimensional array of a length N, it is transformed into a multidimensional one. For the given $M < N/2$ (window or caterpillar size), a matrix $\boldsymbol{X}$ is filled with data values from the initial array. The first row contains the first M elements of the initial array and the second row is filled with elements from the second number $M + 1$ and so on until

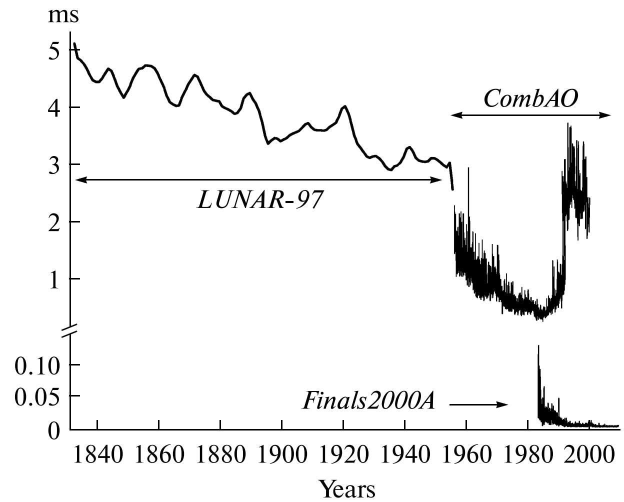

Fig. 2. Root-mean-square uncertainties of the data reduced to a uniform 5-day interval.

the end of the input array is reached. After the rows are aligned and normalized, the correlation matrix $\boldsymbol{R} = \boldsymbol{X}\boldsymbol{X}^T$ is computed that allows for a singular decomposition as $\boldsymbol{R} = \boldsymbol{P}\boldsymbol{L}\boldsymbol{P}^T$, where $\boldsymbol{L}$ is eigenvalue diagonal matrix and $\boldsymbol{P}$ is eigenvector orthogonal matrix of matrix $\boldsymbol{R}$. In this implementation of SSA (*Caterpillar*) the principal components of the matrix, $\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{P}$, may be considered, visualized, and sorted by their contribution to the initial data array. This allows for the interactive direct search for harmonic components, the filtering and smoothing of the series, and the identification of significant harmonic components $\boldsymbol{Y}_i$. The orthogonality of the eigenvector matrix $\boldsymbol{P}$ allows for the recovery of the initial matrix $\boldsymbol{X} = \boldsymbol{Y}\boldsymbol{P}^T$ using the selected principal components $\boldsymbol{Y}_i$.

Eigenvectors of the correlation matrix play the role of transfer functions of the corresponding filters. The band pass width is determined by the transfer function shape and depends on the eigenvector and the window size M. A greater M implies a narrower filter band pass. Taking the sum of several components is equivalent to a parallel filter connection. Combining the principal components allows for the creation of filters of an arbitrary spectral shape. Choosing M much smaller than the proper periodicity of series (M may be as small as 2) is equivalent to smoothing the original data set. Periodic but anharmonic oscillations in the original data set are distinguishable by a pair of adjacent eigenvectors $\boldsymbol{Y}_i$.

The most important advantages of the method and its implementation are the following:

1. The functional basis of the decomposition is generated by the data set itself. The decomposition basis is optimal because the basis functions are eigenvectors of the correlation matrix $\boldsymbol{R}$. In contrast, the Fourier analysis applies harmonic basis functions, and the wavelet analysis uses locally symmetric basis functions of some

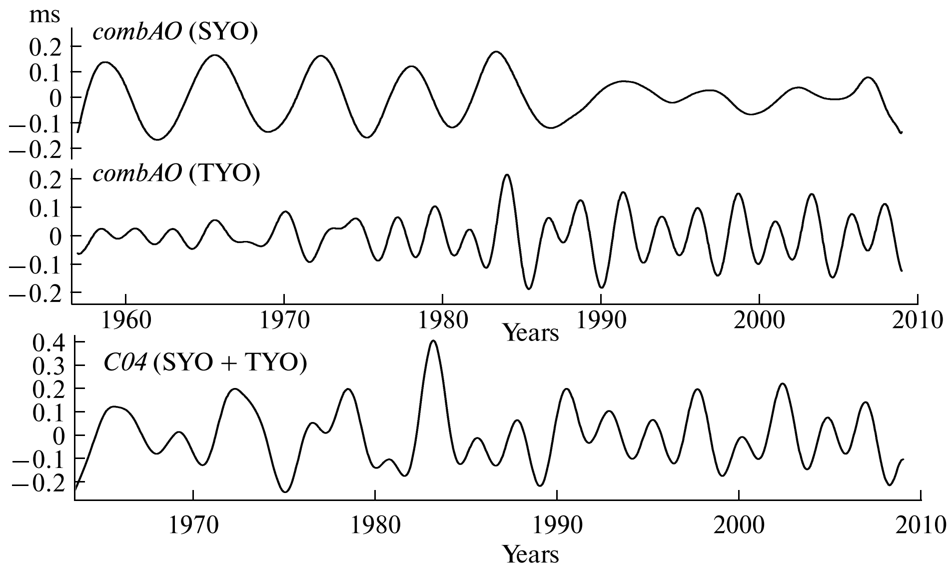

Fig. 3. SSA decomposition of the *combAO* and *eopC04* series in the period range between 2 and 8 years.

family that is best fitted for the process under consideration.

2. Any harmonic or quasi-harmonic oscillation modes in the original data set are characterized by a pair of eigenvalues, a pair of eigenvectors, and a pair of principal components that allows for the reconstruction of the series using individual components; the study of the structure of the initial time series; and the identification of individual trends, periodic, quasi-periodic, and stochastic variability components.

3. Even weak and nonlinear statistically significant trends may be identified.

Studying the time series with SSA is, however, not a completely automated procedure. Several important details should be taken into account. The window size M depends on the problem under consideration, the initial series structure, and on the relation between the data set length N and the expected period T. The maximal possible $M = N/2$ is recommended when studying the overall variability structure of the series and for a period search. The identification of the periodic components is sensitive to the possible comparability between the period T and the array length N. If adjacent eigenvalues are clearly separable, the comparability is less important, but a shorter series and noisy data are sensitive to the possible integrity of the ratio N/T. For shorter datasets, the M parameter should be chosen close to T whenever possible, sometimes at the expense of the array length. Applying SSA to different types of time series shows that every dataset has its own optimal comparability relation between M, N, and periodicity T.

LENGTH-OF-DAY VARIATION ANALYSIS

Using SSA, in the *combAO* and *eopC04* series we identified the variability components in 2- to 4- and 4- to 8-year period ranges (Fig. 3). Following Abarca del Rio et al. (2003), we will denote them as TYO (2- to 3-year oscillation) and SYO (6- to 7-year oscillation), respectively. While the large timescale trend and seasonal component contain nearly 99% of the power, the SYO and TYO contributions are only 0.3 and 0.2%, respectively. The TYO component contains a more regular periodicity with a ~2.4-year period, gradually increasing its amplitude during the 1970–1980s, and a less stable 3- to 4-year component. The SYO constituent, in turn, includes a prominent 6.3-year component practically disappearing since the late 1980s, and a less stable 4- to 5-year component.

The variations evidently change their structure. The SYO amplitude abruptly drops after 1986, while the TYO oscillation amplitude increases. For the *eopC04* series, the decomposition is similar, but since 1990 it has been composed of only space geodesy data. As was already mentioned, the astrometric ERP determination network was reorganized in 1986 when the number of astrometry stations was reduced to only five mostly continental stations existing in the early 1990s.

The longer time series *LUNAR-97* shows LOD variations in a broad period range (Fig. 4). After subtracting the trend and decade constituents, the LOD power spectrum has two relatively broad maxima at 4.5–7 years and one significantly fainter peak at about 2.5 years. The basic variability pattern holds in the past for SYO, but individual oscillation amplitudes change significantly and the periods themselves change slightly. It should be noted that the uncertainties are

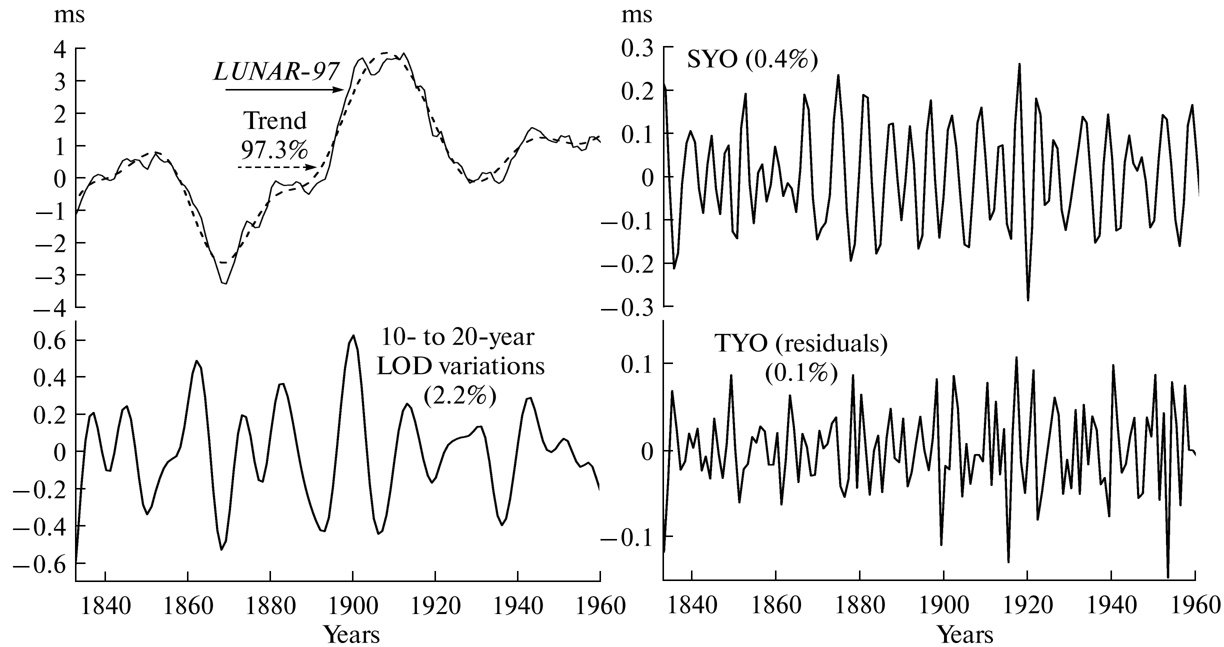

Fig. 4. Complete SSA decomposition of the *LUNAR-97* data series.

relatively high before 1925 (see Fig. 2), and the phase uncertainties may be approximately a year and even longer if the data points are as scarce as one per year.

Unfortunately, although lunar occultation data exist for recent years, the information on the length-of-day was not extracted from these data. These observations could provide an independent LOD series in the Earth's center of mass frame rather than for the local vertical, as in the case of astrometric ERP determination facilities. The absence of reduced data and the termination of the global astrometric ERP determination network significantly complicate the process of period search for this period range. With the existing data, the observational bias (change in observational technique) is difficult to separate from a real change in the variability pattern.

In Fig. 5 (upper panel), we show the *IVS_r* series decomposition. As in other shorter space geodesy ERP series (Fig. 5, lower panel), SYO oscillations are completely absent.

In the TYO range, on one hand, length-of-day variations exist in all of the astrometric and space-based data. According to space geodesy measurements, during the 1980s their amplitude grew from 0.1 to 0.2 ms. On the other hand, the length-of-day variations in the SYO range practically disappear from the astrometric ERP series after the number of ERP determination stations was reduced (by a factor of several tens) and their coverage area was restricted. This does not, however, exclude real variability pattern changes in the period range of 2–7 years. From the beginning of their observations, cosmic ERP determination facilities have not detected any length-of-day variations in the SYO period range. This should be taken into account when studying the possible variation excitation mechanisms.

GEOPHYSICAL CAUSES FOR LENGTH-OF-DAY VARIATIONS

What may be the cause for the LOD oscillations and the variability pattern change in the middle of the 1980s? Of the three processes mentioned above (mantle–core interaction, angular momentum exchange between the solid Earth and its fluid envelopes, and the solar activity influence), only the interaction with the atmosphere and ocean may be directly checked using *real* geophysical data. The connection with solar activity may be checked by statistical methods searching for correlations between the solar activity indices and LOD variations. In this work, we do not aim to investigate this link, because the period of the main solar activity cycle is not related to any of the LOD variation periods, and the existence of a 5-year solar activity cycle is debatable (Djurovič, Pâquet, 1996; Kocharov et al., 1999).

Information on the effective angular momentum functions (AAMf and OAMf) has existed since the middle of the past century; therefore, it cannot be applied to the *LUNAR-97* series. It is known (Chao, 1989; Levitsky et al., 1995) that a larger part of the geophysical excitation of LOD variations was attributed to the South El-Niño Oscillation. Length-of-day variations from the *LUNAR-97* series were compared to one of the numerous SOI index reconstructions (Stahle et al., 1998). Our analysis is qualitative, but

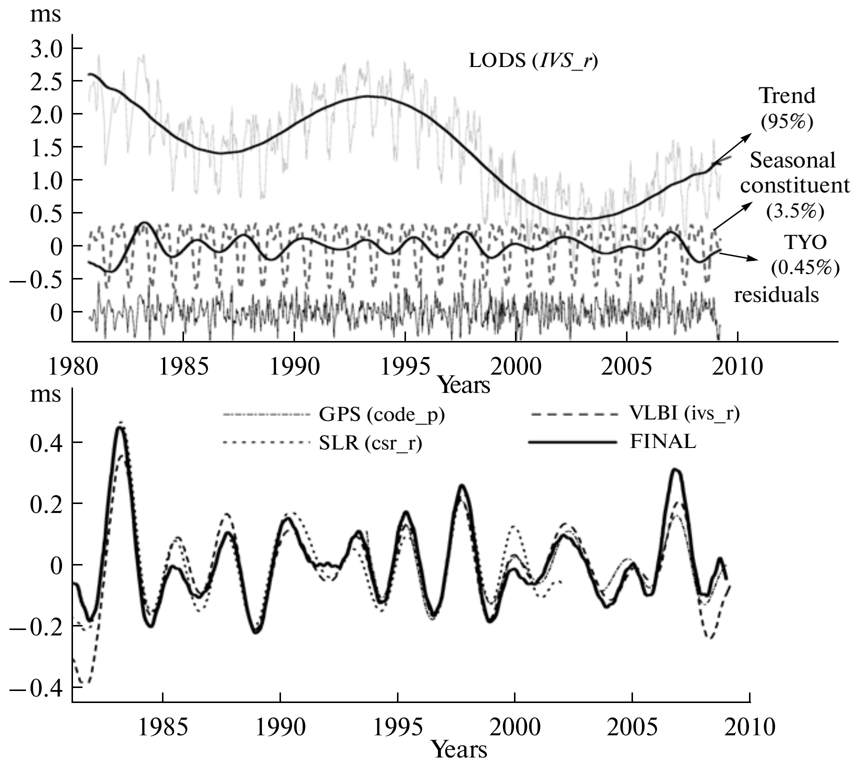

Fig. 5. Upper panel: complete SSA decomposition of the *IVS_r* data series. Lower panel: SSA decomposition in the period range between 2 and 8 years of the longest space geodesy series.

allows only for the determination of the phases of two oscillations.

After normalizing the two series (the mean value was subtracted and the residuals divided by the root-mean-square deviation), we jointly reconstructed the oscillations in the period range of 4–8 years (Fig. 6, upper panel) using our implementation of multidimensional SSA. SOI cannot be entirely responsible for the SYO-range length-of-day variations in the *LUNAR-97* time series, but strong El-Niño outbreaks like that in the 1920s are characterized by the synchronization of the two variations. The reconstruction of individual oscillations results in even higher phase shifts. Using the LOD variation series by Jordi et al. (1994) instead does not improve the consistency between the two series as well. As we already mentioned, the uncertainties of lunar occultation data, as well as the uncertainties of the SOI indices reconstructed by indirect (dendrochronological) data, are very high, which definitely affects the resulting joint decomposition of the two series.

Other LOD series were compared to the components χ_3 of atmospheric (AAMf) and oceanic (OAMf) angular momentum functions. As was found by Djurovič, and Pâquet (1996), Liao and Greiner-Mai (1999), and Abarca del Rio et al. (2000) and confirmed by us, the axial AAMf component χ_3 has no significant variability in the SYO range. However, χ_3 contains a component with a period of about 5 years (not shown in the figures) and an amplitude increasing from ~0.03 ms in the late 1970s towards 0.1 ms with signatures of a slight turnover near 2004. The two- to three-year variations of the χ_3 momentum function have increased in amplitude starting from the 1970s from ~0.08 ms to ~0.15 ms. These variations show clear a correlation with quasi-biennial wind circulation variations in the tropical stratosphere (Sidorenkov, 2002).

The middle panel of Fig. 6 shows the results of the joint (multidimensional, using MSSA) decomposition of the axial AAMf component and *combAO* series after the subtraction of the seasonal and decadal (with periods greater than 10 years) variations. Evidently, before 1983, the LOD variations in *combAO* (as well as in *eopC04*) contain only a SYO mode and are not connected to any variations in the atmospheric angular momentum. Starting from the 1980s, LOD variations have been almost solely determined by the momentum exchange with the atmosphere, but only in the TYO range. In *IVS_r*, the TYO variability is also almost entirely determined by the atmosphere dynamics (see Fig. 6, lower panel).

In the χ_3 decomposition of OAMf, there is also a weak component with a 5-year period probably caused by atmosphere dynamics. Neither its period nor its amplitude (less than 0.01 ms) allow for this oscillation

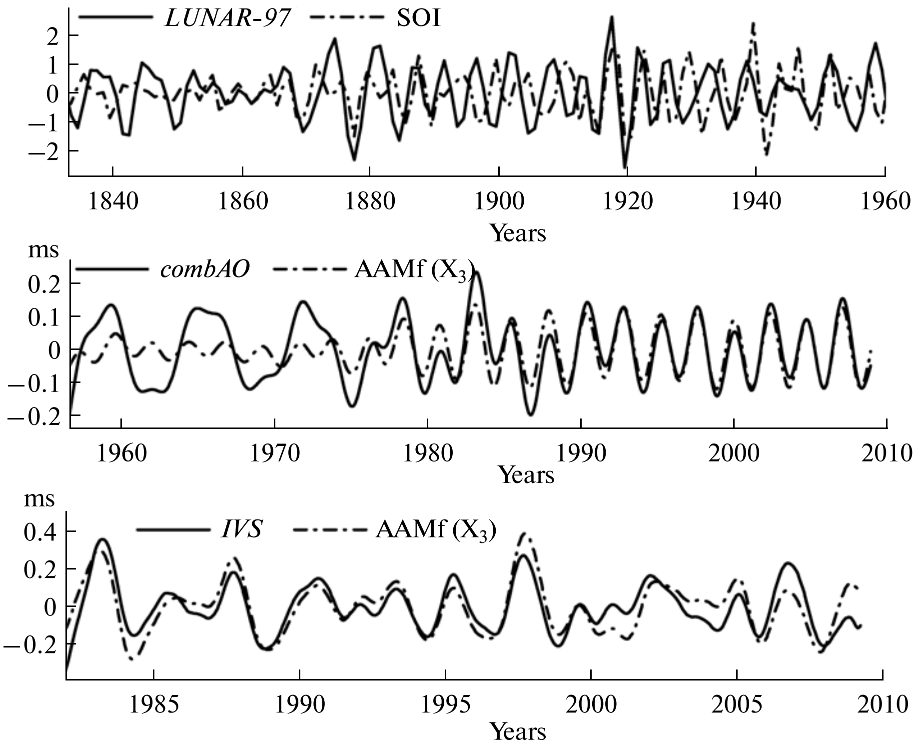

Fig. 6. Upper panel: joint (MSSA) decomposition of the *LUNAR-97* LOD series and Southern El-Niño oscillation index in the period range from 2 to 8 years. Middle panel: joint decomposition of the AAMf and *combAO* series. Lower panel: the same, but *IVS_r* LOD data were used.

mode to be responsible for the LOD variations in the SYO range.

This geophysical excitation factor has a global nature. Because many of the stations having the highest weight in the astrometric ERP determination network are situated near the coastline (Fig. 1), we checked the possibility of LOD variations in the SYO range being produced by deviations of the vertical line caused by sea level variations. We performed a regional study using monthly averaged level gage station data with the overall time of operation of not less than 50 years. Linear trends and the seasonal variations were subtracted from all of the data.

In Fig. 7, we show the sea level variations in the relevant frequency range for the regions closest to the astrometric ERP determination stations. The periods of these variations lie in the range between 3.9 (Japan) and 5.3 years (Baltic region), and the amplitudes do not exceed 15 cm. The periodicities are close to those found for the AAMf and OAMf axial components but are different from the observed SYO oscillations. More important, the sea level variations in this period range are insufficient for exciting the required vertical deviations.

According to the Vening Meinesz decomposition (Grushinsky, 1963), for annular regions encircling the observational site and having radii of not larger than 2000 km, we have the deviation in the prime vertical

$$\xi'' \approx -0.0263''dg_5 - 0.0050''dg_{100}$$
$$-0.0020''dg_{300} - 0.0015''dg_{1000} - 0.00087''dg_{2000},$$

where $dg_i = \Sigma\, \Delta g_i \cos A$, Δg_i is gravitational anomaly in mGal, A is the azimuthal coordinate of the equivalent surface area element of the annular region, and i is the annular region index (in km) measured from the observational site.

Our sea level variation estimates of ±10 cm (Fig. 7) averaged over a number of level gage stations correspond in the relevant frequency range to $\Delta g \approx 4$ μGal (Levine et al., 1986). This is a factor of several tens less than the vertical deviation required for explaining the observed 0.2-ms LOD variations even in the central (coastal) zone.

RESULTS AND DISCUSSION

Although we lack observational data that could complement the ERP determined by space geodesy, we propose that in the middle of the 1980s there was a real structural change in the low-frequency length-of-day variation pattern, during which 6- to 7-year oscillations were replaced by a 2- to 3-year timescale variability. These 2- to 3-year variations may be completely explained by the geophysical excitation

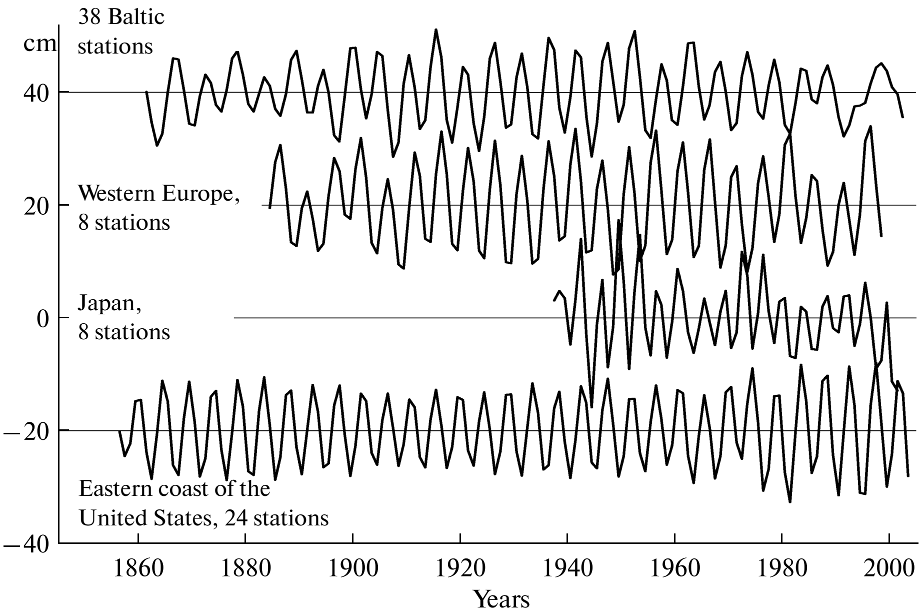

Fig. 7. MSSA reconstruction of sea-level variations using yearly averaged PSMSL data for different coastal regions and for the 2- to 8-year period interval.

through angular momentum exchange with the atmosphere. As we already mentioned, one of the possible sources of quasi-six-year variations in the length-of-day is the gravitational or electromagnetic interaction between the Earth's core and mantle. The trigger that can lead to the sudden shutdown of this excitation mechanism should be found. Alternatively, this excitation process may be assumed to be irrelevant for the oscillation modes under consideration.

An alternative explanation may be the hypothesis proposed by Sidorenkov (2002) based on the climate change in the late 1970s (termination of droughts in Russia and India, Indian monsoon change, start of Caspian Sea level growth, and other climatic changes).

There is one more Earth rotation parameter that significantly correlates with the quasi-six-year length-of-day variations. Korsun and Sidorenkov (1974) note that the SYO period is close to the Earth's polar coordinates' $P = X_p - iY_p$ beat (B) period between the two principle polar wobble components, annual (an) and Chandler (cw) modes:

$$T_B = T_{cw}T_{an}/(T_{cw} - T_{an}) \cong 6.3 \text{ yr}.$$

After taking into account the secular motion of the pole, the polhode coordinates are primarily (by 93%) determined by the sum of the annual and Chandler motion components:

$$\{X, Y\} = \{X_p - X_m, Y_p - Y_m\} \approx \{X_{cw} + X_{an}, Y_{cw} + Y_{an}\}.$$

All of these components can be easily detected by SSA (Vorotkov et al., 2002; Gorshkov, 2007) applied to the longest pole coordinate series *eopC01* provided by IERS.

To calculate the beat curve for the pole coordinates, let us introduce the conjugated pole coordinate function P. Then

$$PP^* = E_{cw}^2 + E_{an}^2 + 2B(\text{an, cw}),$$

where E are the envelopes for the annual and Chandler components, and $B = (X_{cw}X_{an} + Y_{cw}Y_{an})$ is the beat curve for the pole coordinates incorporating the phase difference between the two oscillations. This curve qualitatively reproduces the radius $R_{pol} = (X^2 + Y^2)^{1/2}$ of polhode variations with time, but is better fit for a comparison with length-of-day variations.

In Fig. 8, we compare the SYO-range variations using the *LUNAR-97* and *CombAO* data series with a scaled version of the Earth's polar coordinate beat oscillations. Before 1925, LOD variations poorly correlate with the beat curve, probably due to the low precision of the ERP determination for this period. The width of the SYO-range peak in the *LUNAR-97* data series (Fig. 4) lies between 4.5 and 7.1 years, while in the *CombAO* series there is a narrow peak with a 6.3-year period. The two processes were synchronized after the well-known Chandler period breakdown and phase jump in late 1920s. The correlation coefficient is $r = 0.37$ at the time span of 1890–1987, $r = 0.78$ in 1929–1978, and $r = 0.86$ in the global astrometric ERP determination network operation period of 1956–1986.

This practically exact correlation means that when the two polar motion modes are close in phase (i.e., when Earth's polar motion amplitude is maximal), the Earth's rotational speed decreases, and increases when the movement is minimal.

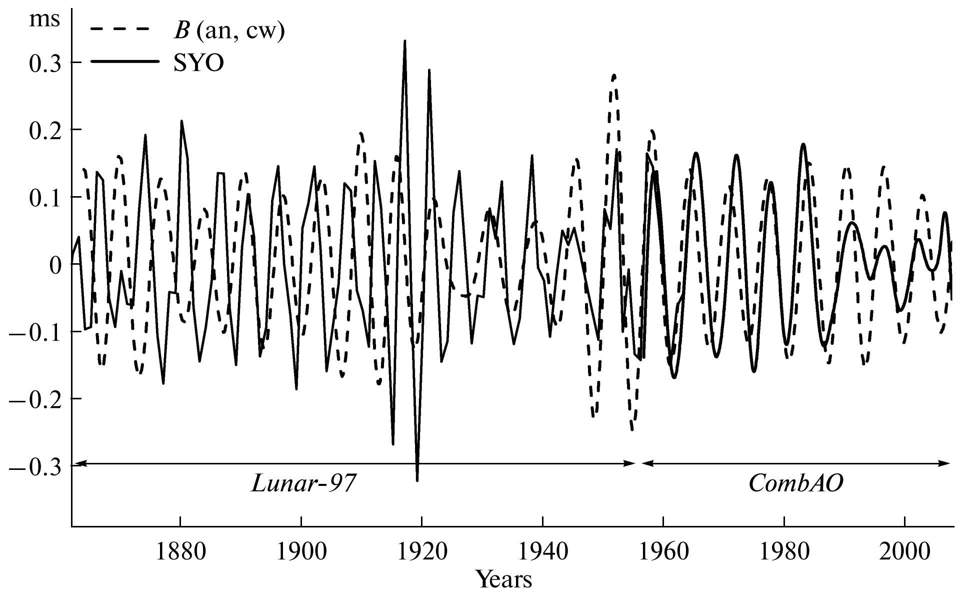

Fig. 8. SYO-range length-of-day variations coplotted with the polar coordinate beat oscillation.

What can be the cause for the energy transfer between the Earth's two rotation vector components? Polar motion is known to excite pole tides; however, the impact of the pole tide on the longitudes of the astrometric stations is negligibly small (less than 7 mm). The maximal altitude variations (at latitudes of about 45 deg) are limited to 1.5 cm, which is also much smaller than the quantity needed for the observed LOD variations. Most important, there is no appropriate mechanism for pole-tide signal demodulation that is needed for extracting the 6-year beat component. Hence, the pole-tide effect, not considered during the classical astrometry ERP determination network data reduction (in contrast with space geodesy observations), is unable to reproduce the observed length-of-day variations.

Another possible mechanism that possesses an element of nonlinearity that is necessary to account for the demodulation effect may be the interaction of the outer layers of the solid Earth (crust and upper mantle) with nonlinear friction between them (Gorshkov and Vorotkov, 2002). The existing lithosphere drift with respect to the asthenosphere at a velocity reaching ~20 cm yr^{-1} (Smith and Lewis, 1998) may oscillate at the polar motion beat frequency due to annual and Chandler mode nonlinear interaction. It is usually supposed that the exchange torque with the atmosphere and ocean make the Earth's crust the place where the annual polar motion component is generated and then elastically transferred inwards through the mantle, while the Chandler wobble is caused primarily by dynamic mantle contraction and elastically propagates outwards toward the crust.

The opposite propagation directions of the Chandler and annual modes correspond to the opposite motions of two adjacent strata of a hot viscous medium that leads to an increase in nonlinear friction. Higher (by a factor of 6–8) viscosity under the continental crust leads to a nonuniform velocity field with the strongest velocity gradients at the continental lithospheric plate boundaries where most of the astrometric ERP determination stations were situated. Stronger core-mantle coupling in global scale will spin the crust up and, vice-versa, weaker friction between them will restore the lithosphere drift-speed variations to the mean velocity of the western drift. The proposed drift-speed variations due to this process are less than 5 cm yr^{-1}. The model described above is qualitative and requires a separate investigation.

CONCLUSIONS

Using the longest available and the most precise universal time series, we found that 2- to 3-year length-of-day variations are present in all of the data obtained with both classical and space-based ERP determination facilities. According to the space geodesy data, their amplitude increased during the 1980s from 0.1 ms to 0.2 ms. At the same time (in the middle of the 1980s), quasi-six-year oscillations practically disappeared from the astrometric data, while the number of astrometric stations was significantly reduced and their spatial coverage restricted. Space-based facilities are initially free from any significant six-year oscillation modes.

Two- to three-year oscillations may be almost entirely explained by the angular momentum exchange between the solid Earth and the atmosphere. The 6- to 7-year oscillations observed up to the 1990s are not caused by the interaction with the atmosphere or ocean. We also exclude as the cause of these variations the vertical deviations at the astrometric ERP determination network stations due to sea-level variations.

Lacking any alternative to space-based ERP determination facilities, we must assume that in the middle of the 1980s there was a real change in the low-frequency variability pattern, during which the 2- to 3-year variations replaced the 6- to 7-year oscillations. The most discussed mechanism of the excitation of the latter mode (mantle-core interaction) should explain this abrupt change in variability structure in order to be consistent. There is an alternative hypothesis developed by Sidorenkov (2002), who linked the effect to the climate change in late 1970s that affected numerous hydrological, atmospheric, and oceanic processes.

We find a correlation between six-year beat variations of the Earth's polar coordinates and the quasi-six-year oscillation mode of the LOD variations. These two oscillations are correlated with $r = 0.86$ in the global astrometric ERP determination network operation period of 1956–1986. This strong correlation is characterized by the spin-down of the Earth when the two wobble motions, Chandler and annual, are in phase (and the polar motion amplitude is maximal), and by spin-up when the two motions are in antiphase and the Earth's wobble is the smallest. We have shown that pole tides cannot be responsible for the quasi-six-year length-of-day variations. We propose a qualitative explanation for the synchronization of the polar coordinate beat variations and LOD quasi-six-year oscillations.

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