Features of the axial rotation of the Earth

according S.L. Pasynok's paper «Osobennosti osevogo vrashheniya Zemli» // Almanax sovremennoj metrologii №2 (34), 2023, PP. 151 – 166 (*on Russia*).

Introduction

Axial Earth's rotation is represented in very wide frequency range, so the answer is even to such a seemingly simple question is accelerating or slowing down now the axial Earth's rotation is not so simple. If one calculate global trend of the axial Earth's rotation over the age of Earth-Moon system existing, he can find that axial Earth's rotation is slowing down and Length Of Day (*LOD*) increases, obviously. But, if one consider the local trend at other time intervals, one can find out positive trend for some time intervals or negative trend for other time intervals.

Another feature of fact that axial Earth's rotation is represented in very wide frequency range, is that it is possible to find high it's correlation with almost any geophysical factor. This makes the presence of correlation a necessary but insufficient indication that some axial Earth's rotation parameter and given geophysical factor are connected by direct causal relationships. This, of course, makes it much more difficult to find such relationships.

The purpose of this material is to consider features of the axial Earth's rotation and to answer to the questions of what measurements are exist, what is accuracy of these measurements and what conclusion about features of the axial Earth's rotation one can be made, leaving out the answer to the question of what physical causes are responsible for these features.

1. Axial Earth's rotation parameters

Earth's orientation parameters (*EOP*) are defined as the parameters of the relationship between the international terrestrial and celestial coordinate systems (*ITRS* and *ICRS*). They include: *UT1-UTC* – difference of the Universal Time scale (*UT1*) and Universal Time Coordinated (*UTC*) and terrestrial and celestial pole coordinates. Earth's rotation parameters (*ERP*) is more wide concept – any parameters which characterized of the Earth's rotation.

Pole coordinates are characterized the motion of Celestial Intermediate Pole (*CIP*) in *ITRF* and *ICRF* respectively. The axial Earth's rotation are characterized by following Earth's rotation parameters: *UT1-UTC*, variation of the axial Eath's rotation angular velocity and variation of *LOD* (*Length Of Day*). Time derivative of *UT1-UTC* is proportional to variation of the axial Eath's rotation angular velocity $\delta\Omega$ and can be expressed in radians per second. Last connected with variation of *LOD* (*DLOD*) as following:

$$\frac{DLOD}{LOD_0} = -\frac{\delta\Omega}{\Omega_0} \tag{1}$$

where Ω_0 = 7,2921151467064·10^{-5} radians per second – averaged Earth's rotation angular velocity nominal value, stated by International Earth's Rotation and Reference Systems Service (*IERS*) and LOD_0 = 86400 s – duration of atomic day in seconds of *SI*.

2. EOP Services

EOP are evaluated based on data from various measurement technics, with the help of various instruments, by various researchers and their groups and for different time periods. Every measure technic for *EOP* evaluation has its own random and systematic errors. But even if measurements are processed within the same method by different data processing and analysis centers, their results vary slightly due to the different sets of data of the initial measurements and the methods of the data processing and analysis used. So, combining data processing (combination) is necessary for ensuring the uniformity of *EOP* measurements.

The State Service for Time, Frequency and Earth orientation parameters is charged for *EOP* evaluation in Russia by governmental decree №225 which approved the provision "About State Service for Time, Frequency and Earth rotation parameters".

The dimensionless mean value of axial Eath's rotation angular velocity as such as mean value of axial Eath's rotation angular acceleration are calculated in Main metrological center (*MMC*) of the *SSTF* and published in *SSTF* annual report (see Fig. 1 and Fig. 2).

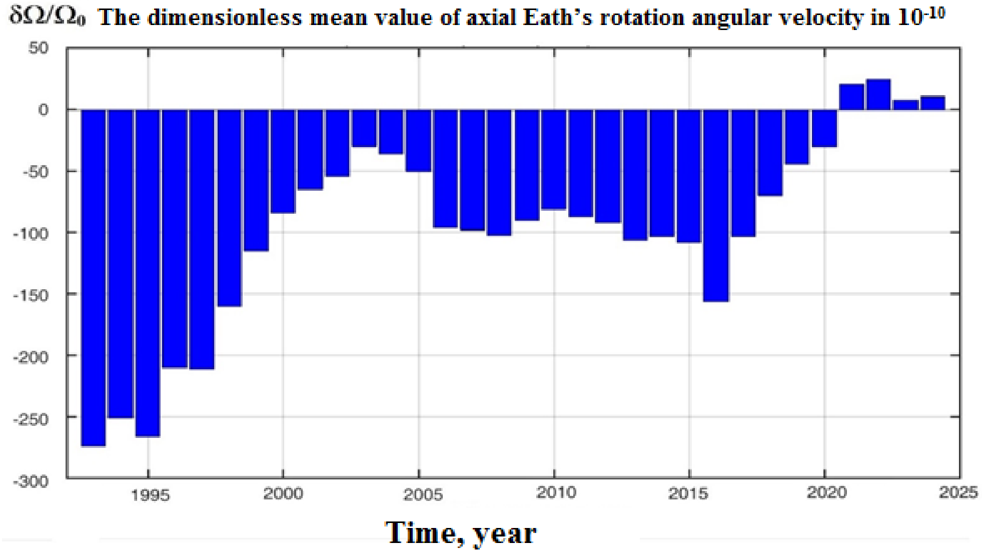

Fig. 1. The dimensionless annual mean value of axial Eath's rotation angular velocity in 10^{-10} .

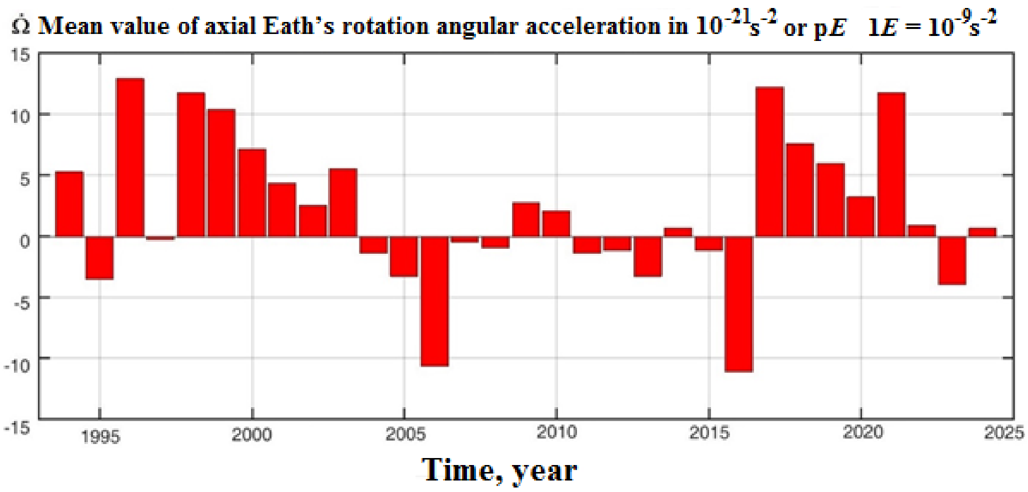

Fig. 2. The annual mean value of axial Eath's rotation angular acceleration, corresponding to dimensionless mean value of axial Eath's rotation angular velocity (see Fig. 1), picoeotvos.

The international recommended combined *EOP* values are evaluated and disseminated by International Earth Rotation and Reference Systems Service (*IERS*) which was established as the International Earth Rotation Service in 1987 by the International Astronomical Union (*IAU*) and the International Union of Geodesy and Geophysics (*IUGG*) and it began operation on 1 January 1988. It was renamed to International Earth Rotation and Reference Systems Service in 2003. In the past, this role was played by the International Latitude Service (*ILS*), Bureau International de l'Heure (*BIH*), and even earlier – the Greenwich Royal Astronomical Observatory, the Paris and Washington Astronomical Observatories. The *IERS EOP* values are used as the metrological reference *EOP* values.

Paleorotation of the Earth (before the era of the beginning of regular astronomical definitions of Universal time) is investigated by individual researchers or groups of astronomers, paleontologists and paleogeologists. Therefore, their works results accumulated in the monograph [1] as such as papers [2, 3] results were used for the assessments carried out in this paper.

3. Data of measurements and accuracy

The measurements data which used for conclusions about axial Earth's rotation can be roughly separated into 4 main groups:

1) results of variation of *LOD* evaluations from paleorotation investigations on the age of Earth-Moon system existing, before the appearance of chronicles;
2) results of variation of *LOD* evaluations from ancient chronicles data before the start of astro-optical measurements;
3) results astro-optical measurements using classical astronomical instruments before the start of measurements using modern methods of space geodesy;
4) results of variation of *LOD* evaluations from data of measurements of modern space geodesy technics.

It should be noted right away that the more distant moments in the past the variation of *LOD* is estimated for, the greater the error and the more averaged the results can be and the more slowly changing components can be estimated over time.

3.1. Data of results of *LOD* variation evaluations from paleorotation investigations on the age of Earth-Moon system existing

The first group data is results of *LOD* variation evaluations from paleorotation investigations on the age of Earth-Moon system existing, from Earth-Moon system formation time (about 4.6 billions of years ago) to the appearance of ancient chronicles. Accumulated results of *LOD* evaluation for this period and error estimates are mainly taken from [1, Table 1.5], as well as from [1, Chapter 5]. There are no error estimates for pre-Phanerozoic data in [1], however, based on the variation of data from different models under different assumptions, the error of these data on the length of the day can be estimated at ± 2 hours. As for the definitions for the Phanerozoic, the allowed deviations of the error limits range from ± 13 minutes (for dates not too far from the current moment) to ± 30 minutes. The amplitude of the variation discussed in this paper is milliseconds, so a significant conclusion for this paper purpose is possible only in terms of trend analysis.

3.2 Data of results of *LOD* variation evaluations, which used at duration of few last thousands of years

The second group data is results of *LOD* variation evaluations based on result detection of moments and places of Solar and Lunar eclipses as such as Moon coverage of stars and planets. Morrison and Stephenson [2] provided this work by analyzing ancient chronicles dating back to 700 BC and obtained 1.7 milliseconds per century for linear trend (for analyzed data time range) and found out the presumably harmonic variation with 1500 period and amplitude about 4 milliseconds. Subsequently, they [3] reprocessed this data and clarified the value of the linear trend. According to [3], it was 1.8 milliseconds per century, the margin of error was estimated at 0.05 milliseconds per century. It has been shown that the actual trend is significantly different from the 2.3 milliseconds per century obtained for the tidal friction effect, and there must be other significant factors influencing to trend.

3.3 Data of results of *LOD* variation evaluations from astro-optical measurements using classical astronomical instruments

The third group data is results of *LOD* variation evaluations from astro-optical measurements using classical astronomical instruments which were provided in Greenwich Royal Astronomical Observatory, the Paris and Washington Astronomical Observatories. Since the second half of the 19-th century the permanent astro-optical observations were started in Russian Pulkovo Imperial (Nikolay's First) Astronomical Observatory (now The Central Astronomical Observatory of the Russian Academy of Sciences at Pulkovo). The observation results of leading astronomical observatories from 1899 are began to accumulate and combine for ensuring the uniformity of *EOP* measurements in the International Latitude Service (*ILS*) and from 1912 in Bureau International de l'Heure (*BIH*) operating on the base Paris Astronomical Observatory.

The about 16 astronomical observatories are operated in Russia and its observations accounted for more than half of all measurements in the world in the sixties of the XX century. Errors of daily values of *LOD* variation evaluated astro-optical observations results were about one millisecond. Thus, it is possible to study the behavior of the *LOD* variation based on these measurements only for sufficiently large components of variations, such as the seasonal variation, decadal structures, etc.

3.4 Data of results of LOD variation evaluations from data of measurements of modern space geodesy technics

The most accurate axial rotation data is provided by 4 following modern space geodesy technics:

– very long radio interferometry (*VLBI*);
– satellite and Lunar laser ranging (*SLR* and *LLR*);
– global space navigation systems (*GNSS*);
– Doppler Orbitography and Radiopositioning Integrated by Satellite (*DORIS*).

The task of ensuring the uniformity of *EOP* measurements based on observation of modern space geodesy technics is solved by International Earth Rotation and Reference Systems Service (*IERS*) which was established in 1987. The final *IERS EOP* values have status of the metrological reference *EOP* values and have to be used for all metrological evaluation on international level. Errors of results of *LOD* variation evaluations from data of measurements of modern space geodesy technics are really very high (a few microseconds now). Unfortunately, this series covers a rather small time period (from the point of view of predicting for at least a century) time range (from 1962 till now).

Therefore, although the analysis of these values allowed to identify the stationary part of the seasonal variation and build a model of zonal tidal variations of the Earth, there is still quite a lot of uncertainty in long-period variations and trends. In addition, as will be shown below, the *LOD* contains non-stationary variations also which make long-term prediction very difficult.

4. The behavior of *LOD* variation at different time intervals

4.1. The behavior of *LOD* variation at geological time intervals

The *LOD* variation on the age of Earth-Moon system existing is presented in Fig. 3 on the base measured data (for the Phanerozoic) and semi-analytical estimates (before the Phanerozoic) with the boundaries of the above-mentioned errors (section 3.1) marked with a dashed line. The scale on the left is graded in hours, and the scale on the right is in milliseconds. The solid line is the result of approximation of measurements in the sense of the least squares method (LSM) by a fourth-order polynomial. The part of which for the last 2000 years almost coincides with the linear trend 1.5 millisecond per century. Let us to name this trend as ***main***.

It is it which describes ***the main trend in the evolution of the angular velocity of the Earth's rotation*** and its period of rotation: the main trend in the evolution of the axial rotation of the Earth is that the ***angular velocity decreases with time, the period increases, and the axial rotation of the Earth slows down***.

4.2. The behavior of *LOD* variation at duration of few last thousands of years

The data for the time interval for the last 2500 years (from 500 BC to 2000 AD) are presented in Fig. 4. The global trend is shown in gray-blue, and the observed local trend finding in [3] from ancient chronicles data is shown in green in this figure. The total effect of local trend and 1500-year period harmonic [3] is shown in red.

It should be noted that the measurement data based on the results of eclipses have the character of quasi-periodic variations.

Therefore, there are other estimates of the period of this component, depending on what weights the researchers assign to individual measurements.

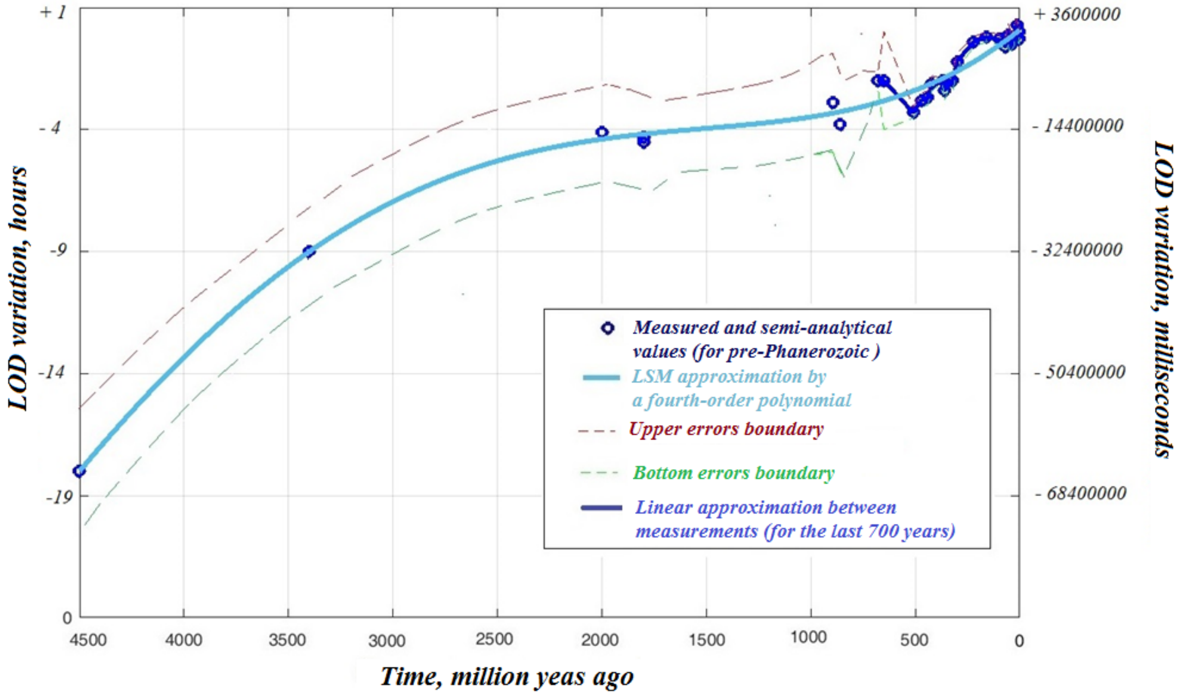

Fig. 3. LOD variation on the age of Earth-Moon system existing

For example, the period of one and half millennial variation according [1] is 1200 years, not 1500. The blue dashed line represents the results of processing astro-optical measurements. Irregular multi-decade structures are clearly noticeable in them. The red curve is smooth, because of the measurement accuracy does not allow us to detect long-term quasi-periodic variations, much less even faster variations from the noise component.

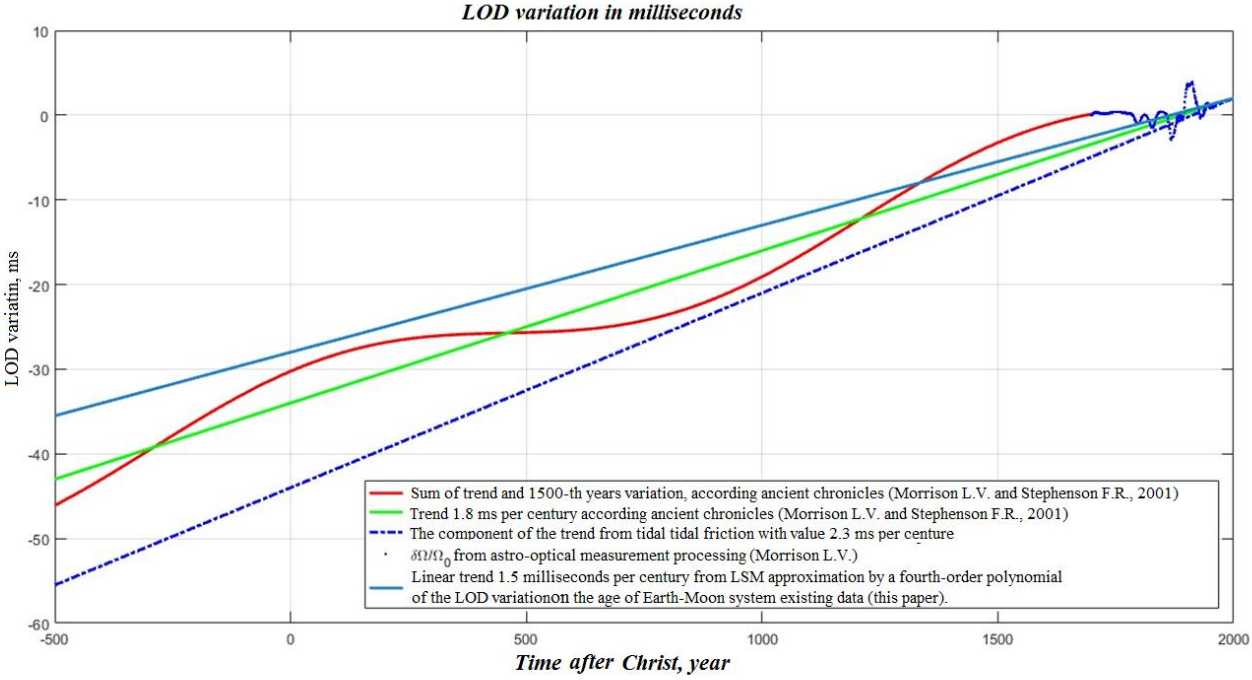

Fig. 4. *LOD* variation for last 2500 years, starting from 500 BC

4.3. The behavior of *LOD* variation at duration of few hundred years

The dimensionless variations in the *LOD* with according to astro-optical measurements (before 1962, on the left) and according to methods of modern space geodesy technics (since 1962, on the right) are shown in Fig. 5.

4.4. The behavior of *LOD* variation on time intervals shorter than century

4.4.1. The behavior of *LOD* variation at duration of modern space geodesy technics age

The accuracy of measurements using space geodesy methods is so high that near-daily and near-half-daily variations (*NNV*) become noticeable, due to the ocean tidal and librations. However, they are not included in the published official *EOP* bulletins of the *IERS* and the *SSTF* according current conventions. These variations interfere only, when analyzing the behavior of the Earth's axial rotation at time intervals of more than a day.

Therefore, before section 4.4.3 will be used the those *LOD* variation values which were obtained from modern geodesy technics data that not include *NNV* and published in official *EOP* bulletins of the *IERS* (see Fig. 6).

Due to the high accuracy of these measurements, as well as the development of theory in [4, 5] and others, it was possible to construct two models that significantly facilitate the analysis of these measurements:

– model of tidal zonal variations (recommended by *IERS*, more detailed information see in [6]);

– average seasonal variation model (other words, stationary part of seasonal variation).

If we subtract these models from the data shown in Fig. 6, we get the curve shown in Fig. 7 in red. The blue color shows the variation in the length of the day before the subtraction of these models.

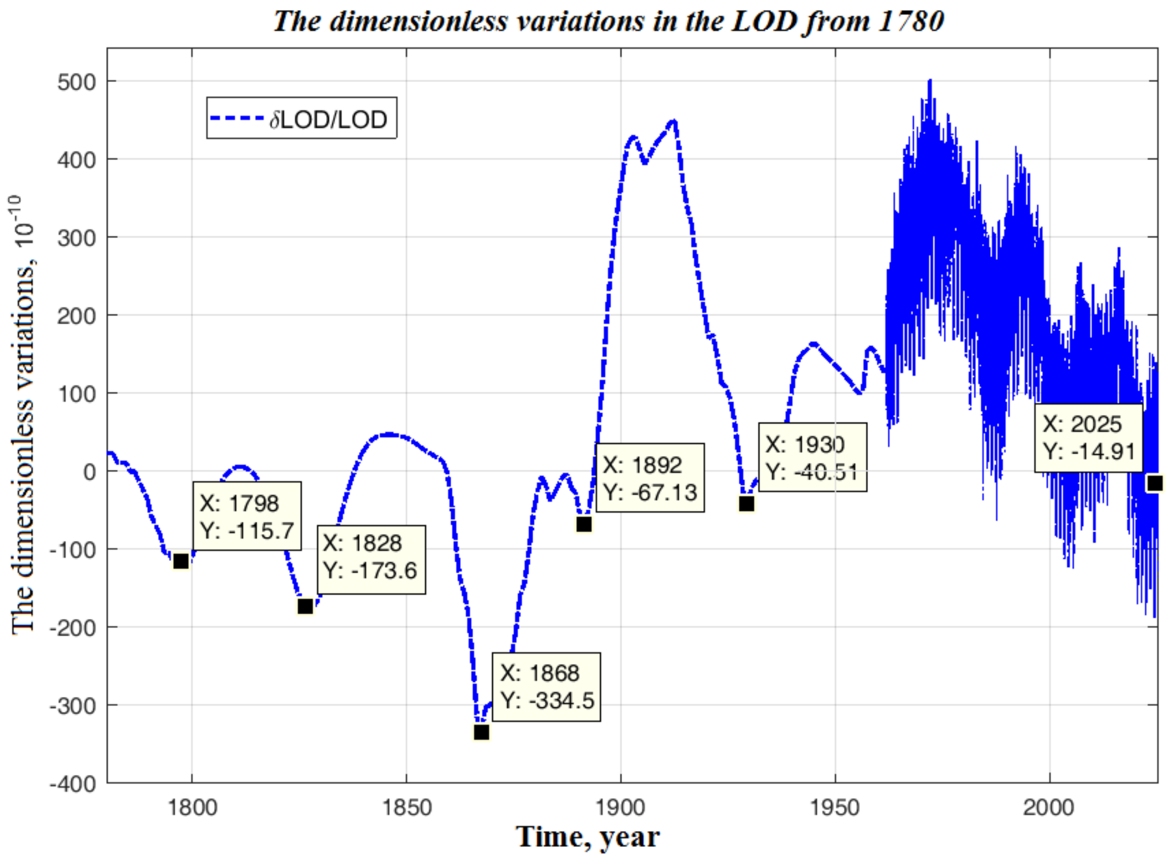

Fig. 5. The dimensionless variations in the LOD from 1780 in millisecond according to astro-optical measurements (before 1962, on the left) and according to methods of modern space geodesy technics (since 1962, on the right)

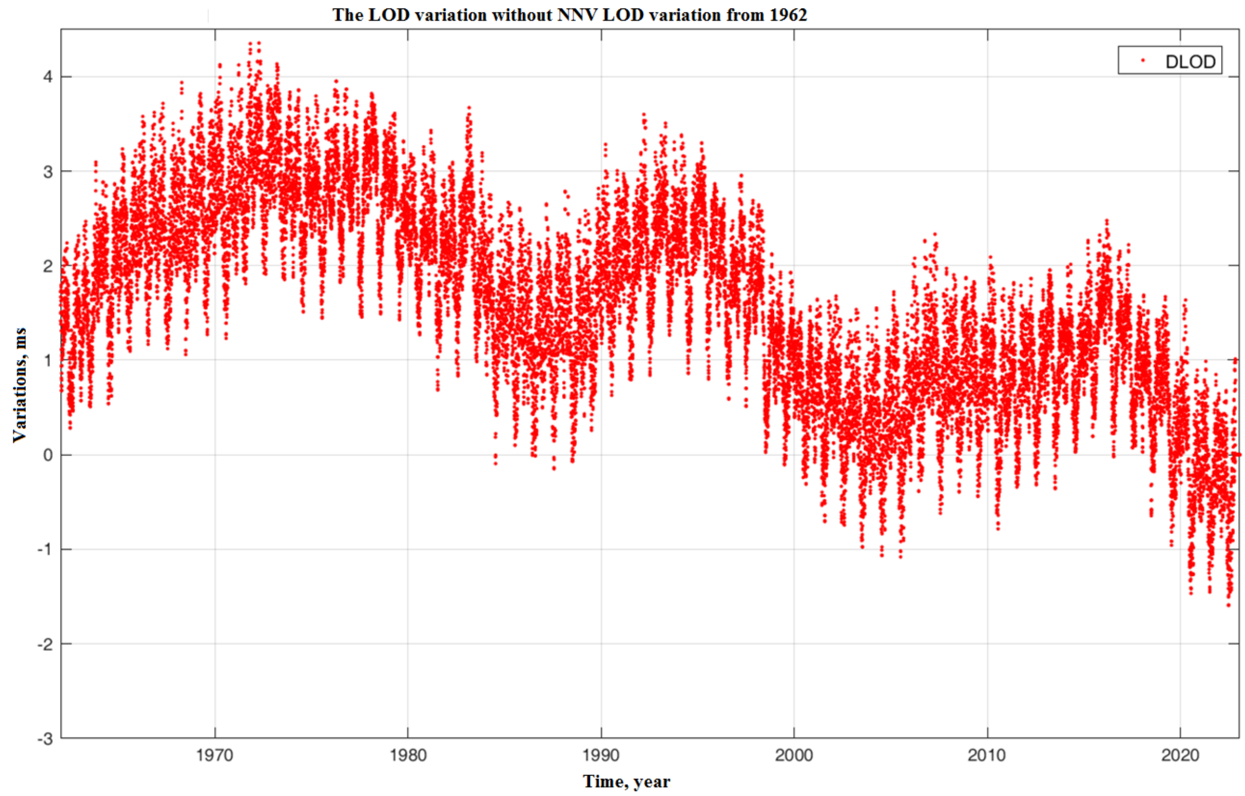

Fig. 6. *LOD* variations over the past 60 years based on the results of measurements using methods of modern space geodesy technics according to data published in official *EOP* bulletins of *IERS*

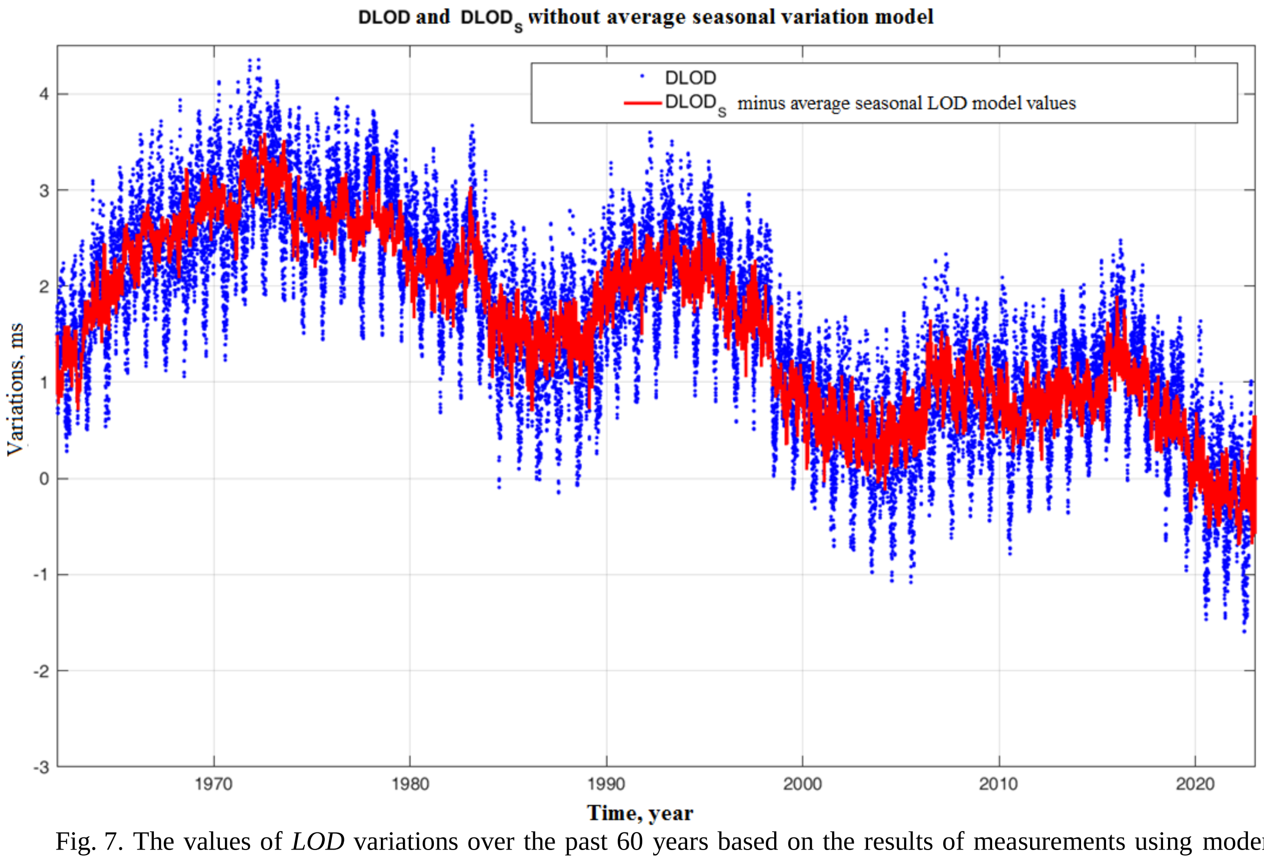

Fig. 7. The values of *LOD* variations over the past 60 years based on the results of measurements using modern space geodesy technics (in blue), published in *IERS* official *EOP* bulletins and that what is obtained after excluding models of zonal tides and seasonal variations (in red).

It can be seen that the main part of the short-period "fringe" is excluded. *DLOD*$_S$ means a *LOD* variations values from which the complete zonal tidal model is excluded. If only zonal harmonics with periods up to 35 days are excluded, then the corresponding variation is designated as *DLOD*$_R$.

There are also three fairly large "arches" with a span of about 3 ms and a time span of 20 to 30 years. These details are called "decadal" *LOD* variations. It can be seen that these do not repeat exactly, therefore, here these are referred to as the "structures" of corresponding *LOD* variations to the average period of time during which such a structure develops. For example, from this point of view, "decadal" variations should be called "decadal structures" of the axial Earth's rotation variations.

Residual variations on characteristic time scales of several years are called as interannual structures of *LOD* variations.

Of course, there is a temptation to carry out further Fourier analysis and use the astrooptical measurement results, and, of course, all this has been done. But then the researchers got an unexpected result: the results strongly depend on which area is subjected to Fourier analysis, and the main periods change by almost one and a half times. If we try to identify periods using correlation analysis, it turns out that these periods not only do not coincide with the results of Fourier analysis, but are generally far from expected. The reason is that, in fact, these residual variations are unsteady and irregular. Therefore, the result of Fourier analysis depends on the time interval over which the decomposition is performed, and based on correlation analysis, it is possible to construct a stationary harmonic function that maximally covers most of the deviations in a single interval, but with the slightest shift or change in the analyzed interval, this agreement is immediately destructed.

A wavelet analysis is used to illustrate this situation. To illustrate, energy wavelet spectra were constructed, shown in Fig. 8. On the left, the energy wavelet spectrum of the model of tides in a solid body of the Earth is shown, as an example of a function close to periodic and stationary. The energy wavelet spectrum of the residual deviations shown in Fig. 7 in red.

The offset is set on the horizontal axis, and the scale is set on the vertical axis. If we ignore the edge effects that exist on both energy wavelet spectra, then the difference is obvious: a process close to periodic looks like horizontal straight lines or periodically almost exactly repeating "teeth", while a non-stationary process has the appearance of spots that repeat somewhere, disappear somewhere, where-they arise, "sink" somewhere, and "float" somewhere, which illustrates the violation of the periodicity and nonlinearity of the process, which is responsible for the "pumping" of energy from one frequency domain to another.

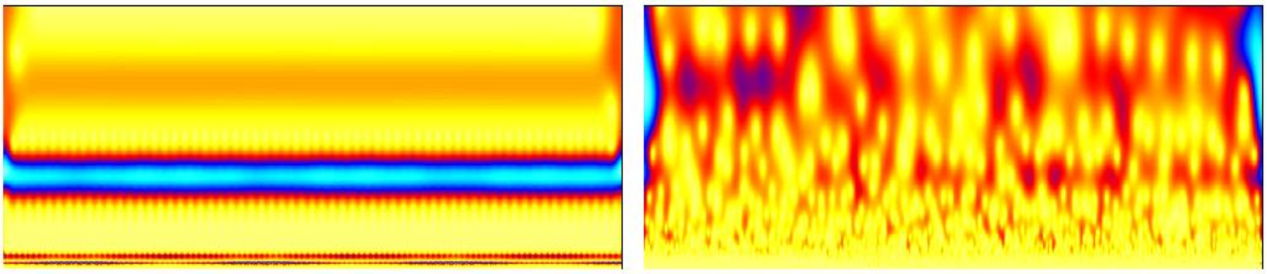

Fig. 8. Wavelet spectra for the model of zonal tides in the solid body of the Earth (left) and for the residual deviations shown in Fig. 7 in red (right).

4.4.2. The behavior of *LOD* variation at duration of year

Interannual variations, as well as trend and long-term quasi-periodic variations, make a small contribution to the change in the *LOD* during the year. The behavior of LOD variations at duration of 2021 year are shown in Fig. 9 (in blue).

The main details of the curve over an annual time interval are set by harmonics describing zonal tides in the solid Earth and seasonal variations. The residual part of the LOD variations which is obtained from the total *LOD* variation after subtracting the model of zonal tides in the solid body of the Earth and the model of the stationary part of seasonal variations, is shown in Fig. 9 in red.

The largest residual changes lasting about 60 days are the so-called intra-seasonal variations or intra-seasonal structures of these variations.

4.4.3. The behavior of *LOD* variation at duration of day

As noted above, those (observed) *EOP* values which should be inserted into the rotation matrix are actually different from those *EOP*, which are published by national and international *EOP* services. According to the recommendations (standards) *IERS Conventions 2010* to obtain the *EOP* observed at a given time, it is necessary to interpolate the values published by the *IERS* at a given date (using the Lagrange interpolation polynomial), and then add corrections to them for the short-period part of the influence of ocean tides and librations. Since these corrections contain near-diurnal and near-half-diurnal harmonics for given value of the universal time, we will call them near-diurnal and near-half-diurnal variations (*NNV*). They are shown in Fig. 10.

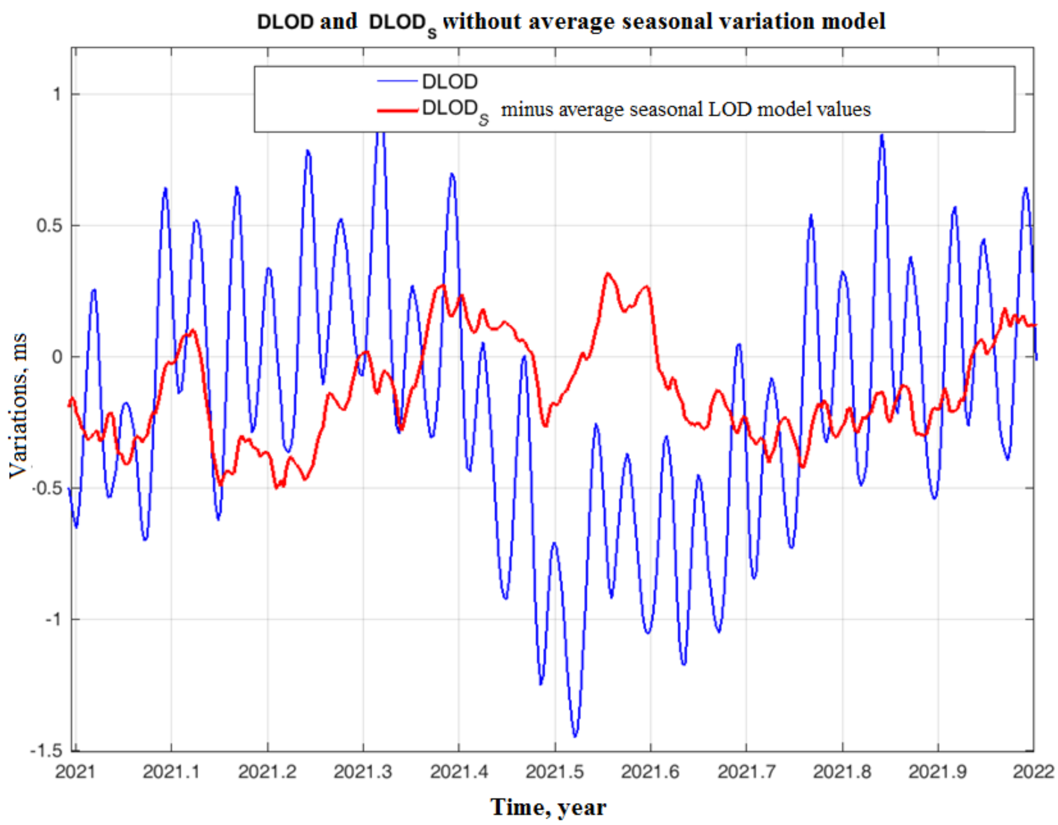

Fig. 9. *LOD* variation over the annual interval and its residual part

5. LOD variation variability discussion

In section 4, the general patterns of *LOD* variation over time were considered, which can easily be recalculated to variations in the Earth's rotation angular velocity, using (1).

Let's return to the discussion of Fig. 3. It allows you not only to judge the magnitude and sign of a global trend. If you look closely at the upper right part of Fig. 3, you can see that in certain geological periods, the value of the local trend within intervals of even several tens of millions of years may differ significantly from the main trend and even, at certain time intervals, have a negative slope, which contradicts the main trend in the evolution of the axial rotation of the Earth.

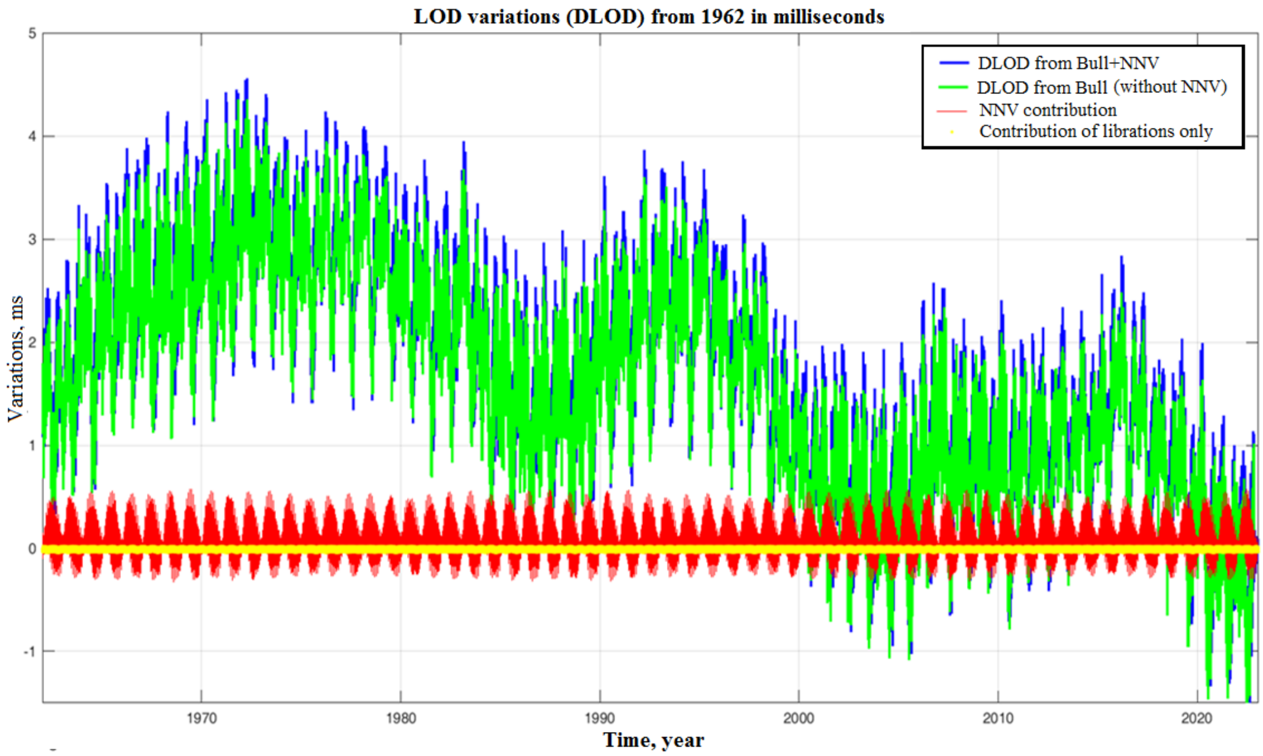

Fig. 10 – The *NNV* contribution into the *LOD* variations (in red), the total variation of the *LOD* taking into account the *NNV* (in blue), *LOD* variations published in the *IERS EOP* bulletins (in green). The contribution from librations alone is shown in yellow

However, the range of these deviations does not exceed an hour and, on average, they compensate for each other over long periods of time. This indicates that there may be variations on time scales of even tens of millions of years, and they may lead to a difference between the trend observed over the past millennia and the main one. The following Fig. 4 clearly shows that the observed local (defined over the last 2500 years) trend (green line) differs significantly from the global (gray-blue line), which also confirms this conclusion.

The following Fig. 5 shows the contours of the so-called "multi-decade" structures of variations in the axial rotation of the Earth, which make up the bulk of the irregularities in the rotation of the Earth on a 60 - 70-year time scale, and, of course, the decade structures are clearly visible, the characteristic time scale of which is about 20-30 years. In addition, Fig. 5 shows that *LOD* variations have repeatedly reached quite large in absolute negative values in the past (for example, in 1930 and earlier, in 1892) and even very large in absolute negative values (in 1798, 1828 and 1868), which cannot be explained within the framework of local a trend of 1.8 millisecond per century in the *LOD* variation (which, translated into dimensionless variations, corresponds to about $21 \cdot 10^{-10}$ per century). The results of the Fourier analysis of the data shown in Fig. 7 (without zonal tides and the average seasonal component) give the largest components for periods from 2 to 3 years, from 6 to 8, from 10 to 15 years, from 20 to 30 years, and from 50 to 70 years, which correspond to scales or multiples of the scales of the structural details of variations in the axial rotation of the Earth mentioned above. The specific values of the periods depend on the time interval at which the analysis is performed.

6. Global Geophysical Fluids Center

Since only a part of the *LOD* variation can be taken into account using models, in order to predict the non-stationary component of the variations, it is necessary to develop methods in which it would be possible to calculate the change in the total effective angular momentum based on external signs (the state of the atmosphere, data on the Earth's magnetic field, etc.). Ultimately, all these changes can be expressed in terms of corresponding variations in the total angular momentum of the Earth's mobile fractions (oceans, atmosphere, hydrology, currents in the Earth's liquid core, etc.).

To account for these factors, the Center for accounting for the global impact of mobile geophysical fractions of the Earth, the Global Geophysical Fluids Center (*GGFC*) has been established by IERS. This center for accounting for the global impact of the Earth's mobile geophysical fractions includes:

– Special Bureau for the Oceans (*SBO*);
– Special Bureau for Hydrology (*SBH*);
– Special Bureau for the Atmosphere (*SBA*);
– Special Bureau for the Core (*SBC*);
– Special Bureau for Combination Products (*SBCP*).

As a result, angular moments of the Earth's mobile geophysical fractions (oceans, atmosphere, and hydrology) as such as Effective Angular Momentum Functions are formed, which are used mainly for predicting.

7. Resume

This article discusses the general patterns of variation in the variation of the length of the day (the angular velocity of the Earth's rotation) over time. In part, variations in the average length of the day can be predicted using *IERS* models, and, in part, these represent a complex non-stationary process (the wavelet spectrum of this part is presented). To account for this part the *GGFC* Center has been established by *IERS* to account for the global impact of the Earth's mobile geophysical fractions (oceans, atmosphere, and hydrology).

Since even a simple discussion of the physical interpretation of each of the mentioned *LOD* variations features is very voluminous in itself, and entire books may even be devoted to some issues, the physical interpretation of these features of the axial rotation of the Earth is not considered in this paper.

It follows from the above results that the local trend of increasing the angular velocity of the Earth's rotation (decreasing *LOD*) has persisted over the past 64 years. The numerical value of the current average annual variation in the angular velocity of the Earth's rotation is not unique: it has been repeatedly achieved in the past and has even been significantly exceeded (taking into account the trend in the angular velocity of the Earth's rotation over the past 2500 years).

When constructing the drawings, the materials of the *SSTF* annual report, the original papers, as well as data of the *EOPC* series from the International Earth Rotation and Reference Systems Service (*IERS*) were used.

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