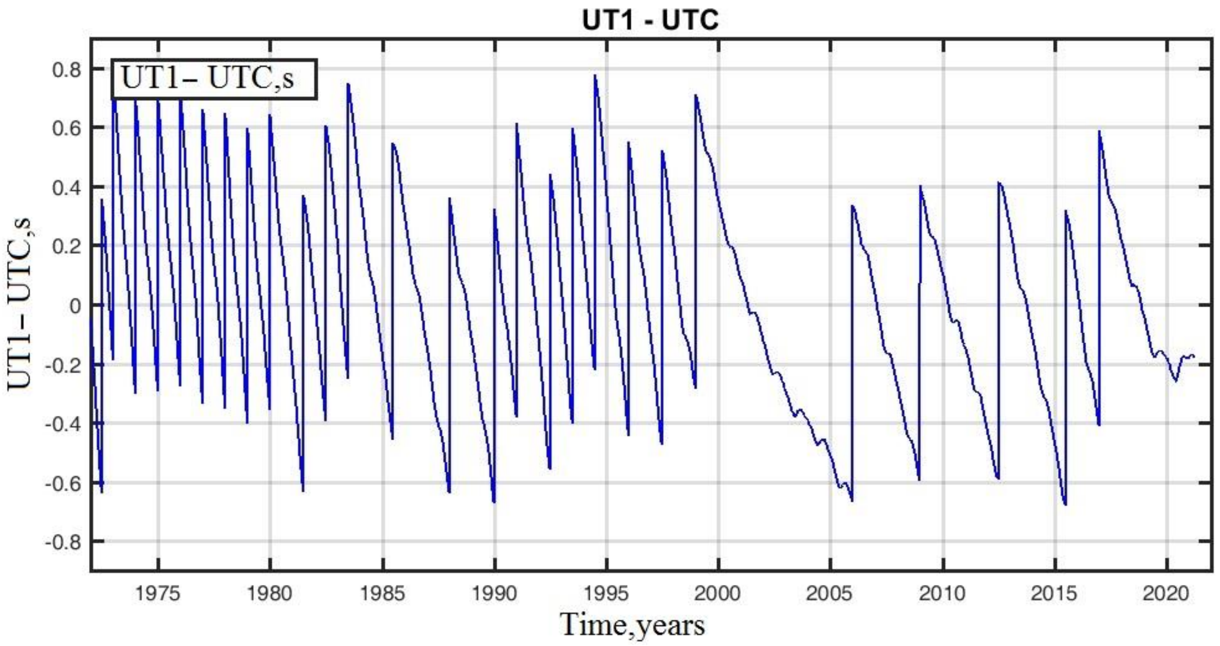
Earth's orientation parameters

Nowdays Earth's orientation parameters *(EOP)* include: *UT1-UTC*, variation in length of day (*LOD*), terrestrial pole coordinates and celestial pole coordinates offsets from theoretical values (it are expressed through nutation offsets from precession/nutation theory). The rapid Bulletines Q SSTF include the values *UT1-UTC* and terrestrial pole coordinates x_p and y_p only.

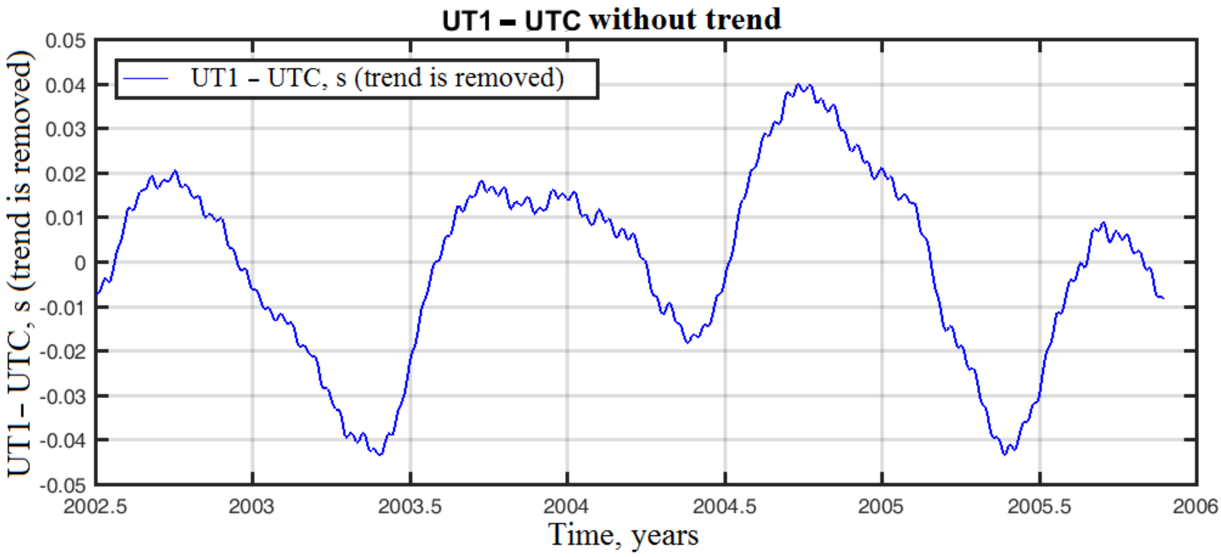
UT1-UTC, (s) – the difference between the time scales of Universal Time *UT1* and coordinated universal time *UTC*. This parameter of the Earth's orientation characterizes the difference value of the axial rotation of the Earth (between two consecutive lower culminations of the average Sun) from the value of the rotation carried out by the Earth rotating with a frequency of one revolution in one atomic day (86400 seconds *SI*). At the moment of the inserting of an coordinating second into the *UTC*, *UT1-UTC* changes abruptly, so the *UT1-UTC* graph has a characteristic sawtooth appearance for long periods of time:



It can be seen that the main component of *UT1-UTC* between two consecutive introductions of coordinating second is a descending "slope" due to the difference between the average solar days for this period and the ephemeris average days for the epoch of 1900. If they were equal, the "slope" would be replaced by a "plain", and if the Earth began to rotate on average faster than in 1900, then there would not be a "slope", but an "climbing".

The next most important component is seasonal. It is a superposition of annual and semi-annual harmonic waves. Mainly, it is because of it that the "slope" has a "bumpy" appearance.

To notice a seasonal wave, you need to subtract the trend in the area between the introduction of coordinating second in the *UTC* scale. The result is shown in the following figure. The main tidal harmonics in the form of "scallops" on a seasonal wave are also visible there.

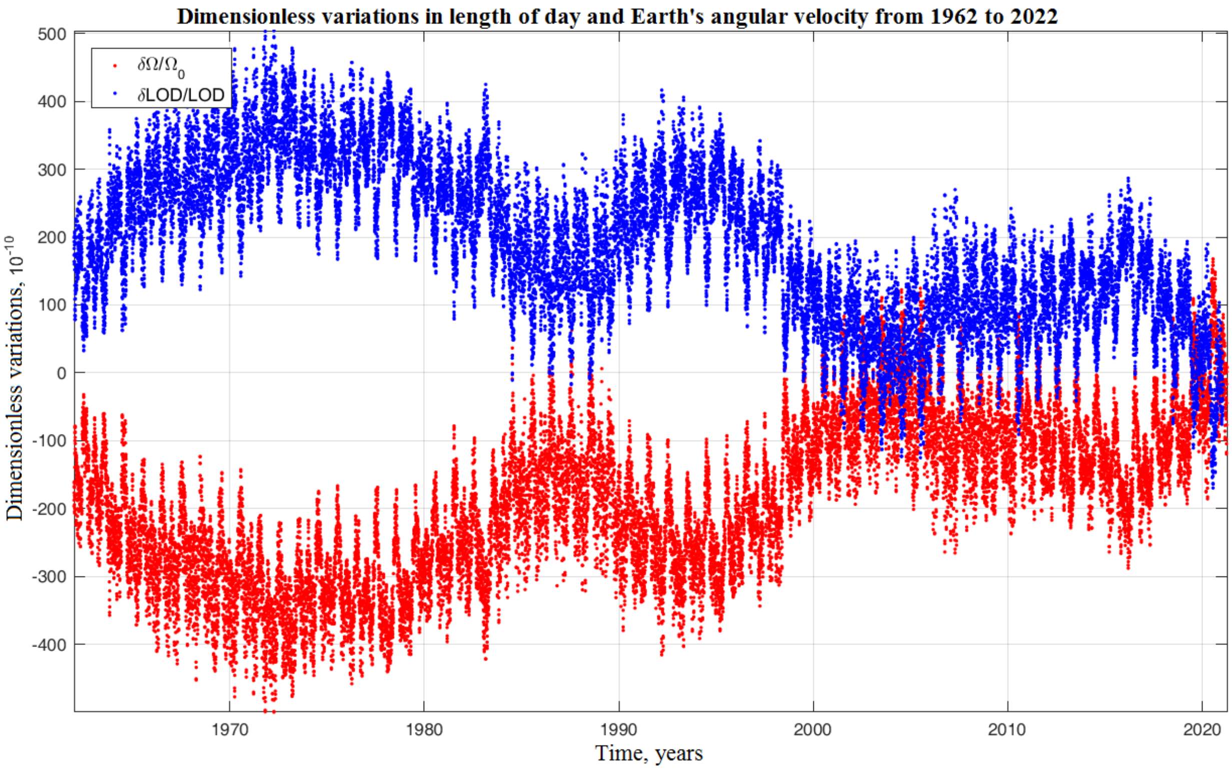


<u>Variation in length of day</u>, (s) – is the difference between length of day of *UT1* time scale and length of day with duration of 86400 (atomic) seconds of *SI*. If the Earth rotates slower than one revolution per day SI, then the variation in length of day is positive, if faster, it is negative, and if they coincide, it is zero.

The dimensionless variation of the length of the day is almost equal to the dimensionless variation of the angular velocity of the Earth's rotation with a minus sign. It follows from this that if the Earth rotates slower than one revolution per day *SI*, then the variation in the angular velocity of the Earth's rotation is less than zero, if faster, it is greater than zero, and if they coincide, it is equal to zero. At the same time, the maximum variation in the length of the day corresponds to the minimum variation in the angular velocity of the Earth's rotation and vice versa. If these relative variations are depicted on the same graph, they will be a mirror image of each other (see the following figure).

Since it is the variation in the angular velocity of the Earth's rotation that is associated with the derivative of *UT1-UTC*, and also because the behavior of the variation in the duration of the day is often considered in publications, let us consider here the behavior not of the variation in the length of the day, but of the variations in the angular velocity of the Earth's rotation.

The magnitude of the variations in angular velocity is at the level of the eighth decimal place or, in other words, is tens of billionths of an absolute value. Despite such a small amount, the change in the kinetic energy of the Earth corresponding to variations in the angular velocity of rotation is significant due to the huge size of the planet. For example, a relative change in the angular velocity of the Earth's rotation by one billionth leads to a change in the kinetic energy of rotation by about 0.4 sextillion ($4 \cdot 10^{20}$) J, which is comparable to the energy released annually as a result of earthquakes.



The dimensionless variations in the angular velocity of the Earth's rotation have a complex structure.

They contain:

- long-term quasi-periodic variations (including decade variations) with a deviation from the average value of about $4 \cdot 10^{-8}$, clearly visible over time intervals of a hundred years;

- seasonal variations in the angular velocity of the Earth's rotation, fully fitting into the band ± 15 billionths relative to the average annual value;

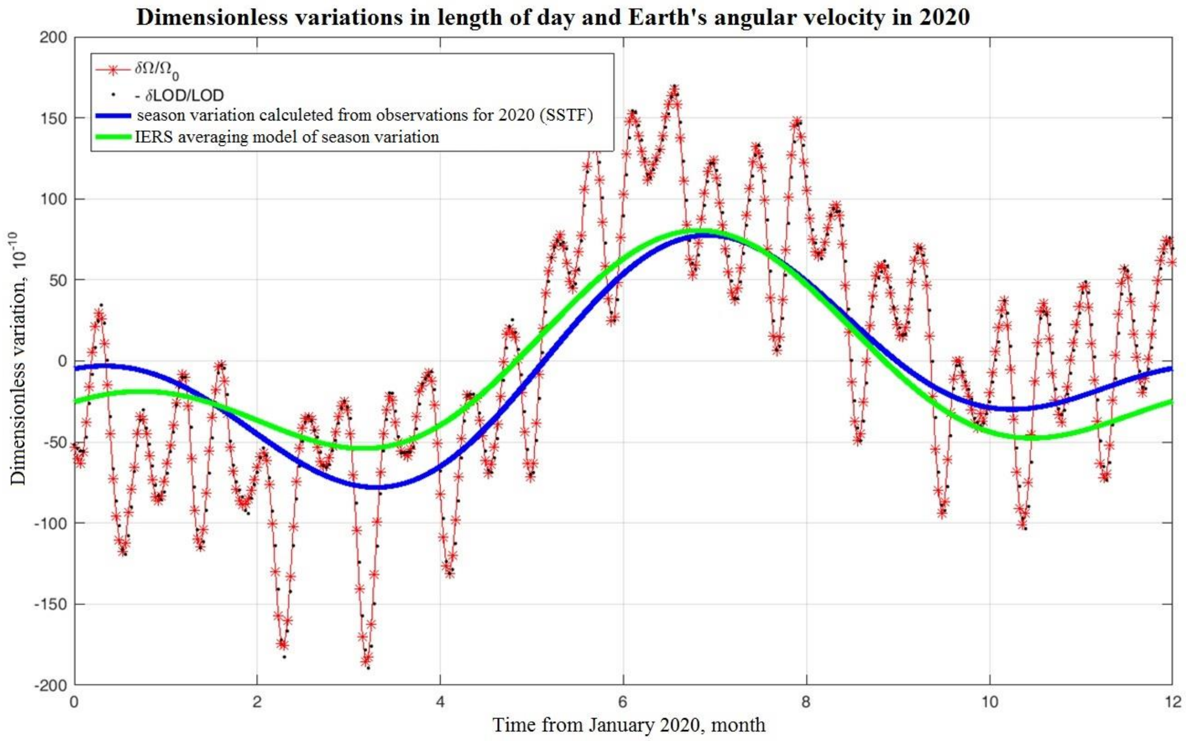
- short-period variations with periods within a quarter (where the maximum harmonic has a period of slightly less than two weeks) and an amplitude of about $5 \cdot 10^{-9}$;

- a secular trend associated with a secular slowdown in the rotation of the Earth (angular velocity decreases by about 20 billionths over a hundred years).

The secular trend is very small and it becomes clearly visible only over long periods of time, comparable to several hundred or even thousands of years.

The causes of variations in the angular velocity of the Earth's rotation are weather and climatic phenomena, the tidal influence of the Moon, Sun and planets, as well as global geodynamic processes occurring inside the Earth.

If we consider the behavior of the angular velocity of the Earth's rotation during the year, we can see that the annual time interval covers too short parts of the secular trend line and the curve of long-term quasi-periodic variations. Therefore, their contribution to it is small in the annual period. The main components in the annual interval are seasonal and short-period components (see the following figure. In this figure, the dimensionless variation in *LOD* is shown with the reverse sign).



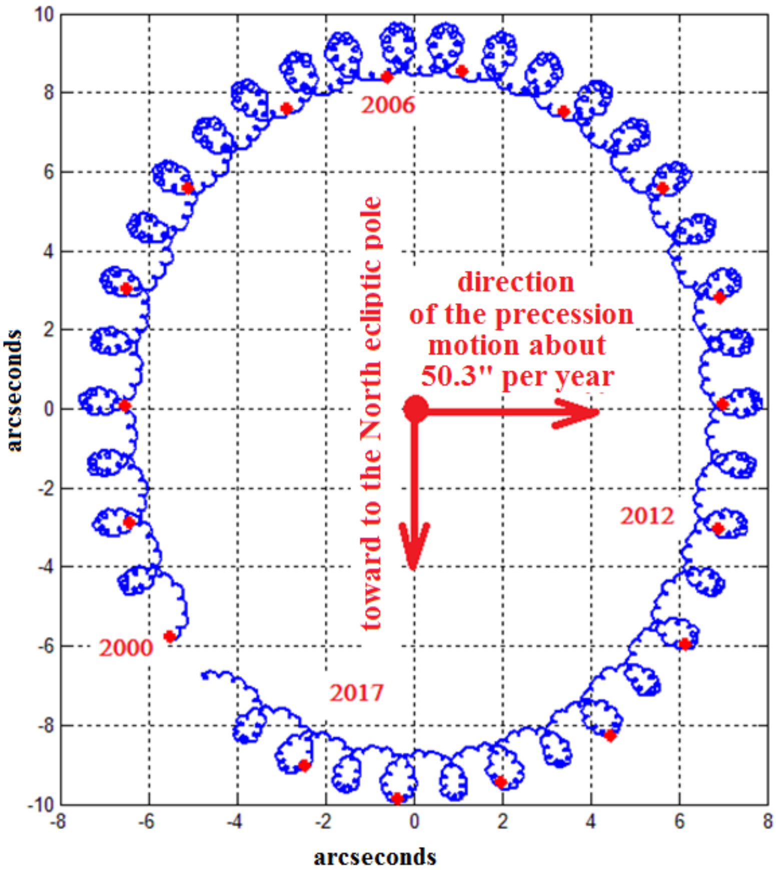
The seasonal variations consist of two harmonics: annual and semi-annual. The International Earth Rotation and Reference Systems Service (*IERS*) has built an empirical model of seasonal variations by averaging the amplitudes and phases of seasonal variations over long-term measurements. However, as can be seen in the figure, the seasonal component determined from the measurements for a single year slightly differs from this averaged model.

Usually, the angular velocity of the Earth's rotation reaches the minimum value for the year in March-April, and the maximum value for the year in July-August.

Such a time spread is due to the fact that the seasonal variations (the main ones in the annual interval) are superimposed with short-period components of variations in the angular velocity of the Earth's rotation, as well as a small trend. Thus, the date of the maximum or minimum of the angular velocity of the Earth's rotation in the annual interval depends on the result of their superposition.

So far, we have been talking about axial rotation, but the axis of rotation of the Earth, in addition, changes its direction in space. From a practical point of view, it is convenient to divide the general change in the direction of the Earth's axis of rotation in space into two parts: slow (with periods of more than two days) in the celestial coordinate system and fast (with periods of less than two days). This is achieved by introducing a special intermediate celestial coordinate system. Its pole is called the celestial intermediate pole (*CIP*).

$d\psi$, $d\varepsilon$ – nutation offset from theoretical ones (″) The precession/nutation angles ψ and ε – characterize the position of the celestial intermediate pole (*CIP*) in geocentric celestial reference system (*GCRF*). They describe that part of the variations in the direction of the Earth's axis of rotation in space, which is mainly due to cosmic space factors (the tidal influence of the Moon, the Sun and the large planets of the Solar system). The angles of precession/nutation are distinguished from the full variation of the direction of the Earth's axis of rotation in space by limiting the periods (or corresponding frequencies) of their harmonics: they have periods of more than 2 days (dimensionless frequencies less than 0.5 units per sidereal day in absolute magnitude) in the celestial coordinate system. The following figure shows the movement of the celestial intermediate pole as it looks from the outside when viewed from space in the direction of the Earth’s north pole.



In the first approximation, the nutation motion of the axis of rotation is an ellipse and a complete revolution along it takes 18.6 years. The semi-axes of the nutation "ellipse" are about 10" and 8". A more precise examination shows that the complete nutation motion consists of more than a thousand harmonic components, which look like loops in the figure. The main one is an elliptical motion with a period of 18.6 years and semi–axes of about 9" and 7", which gives the full nutation motion the elliptical shape. The second largest is the semi–annual harmonic, responsible for the formation of large loops. It is also elliptical with semi-axes of about 0.6" and 0.5". And the main component of the next largest whorls is formed by an almost circular elliptical motion with a period of slightly less than two weeks (13.6 days) and semi-axes of about 0.01". The semi-annual and two-week components correspond to displacements with amplitudes of 15 m and 30 cm on the Earth's surface, respectively. Three largest harmonics 19-year-old, annual and almost two-week responsible for the approximate form of precession/nutation motion.

Since there are highly accurate theories of the motion of the large planets of the Solar system and the Moon, there are nutation models that allow us to calculate precession/nutation angles with high accuracy, and their main part changes slowly. Therefore, although the precession/nutation angles are large, their evaluation is less of a problem for the *EOP* rapid service than evaluation the Earth's terrestrial pole coordinates.

The angles of nutation offsets $d\psi$, $d\varepsilon$ are corrections, which one has to add to the theoretic angles ψ_{1980}, ε_{1980}, calculated according precession/nutation theory *IAU1980*, for obtaining the observables angles ψ, ε. It should be noted that the use of the old *IAU1980* model does not affect on the accuracy of the resulting values, since the inaccuracies of the model are compensated by the corresponding correction values and in total they give the observed values ψ and ε with the accuracy with which they can be determined from measurements. The first of the following pair of figures shows these corrections calculated by subtracting the theoretical angles ψ_{1980} and ε_{1980} of the *IAU1980* model from the angles ψ and ε determined from the measurements.

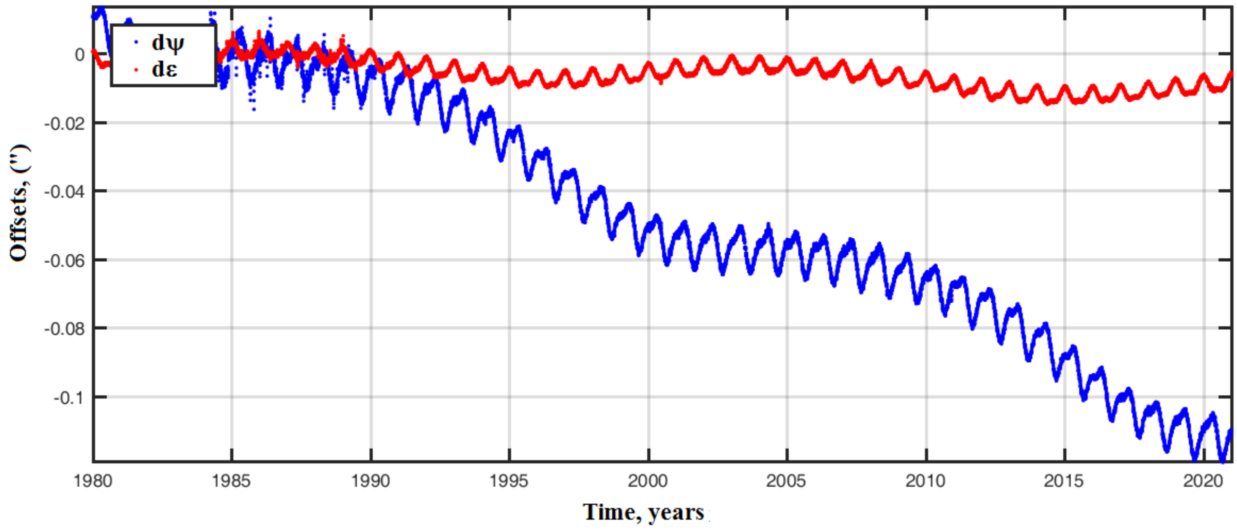
The main part of the corrections is the linear part and harmonics with the main periods of nutation (18.6 years, six months, two weeks, etc.) which necessary to compensate the difference between the values of precession and the main nutation harmonics in the *IAU1980* model from the observed ones.

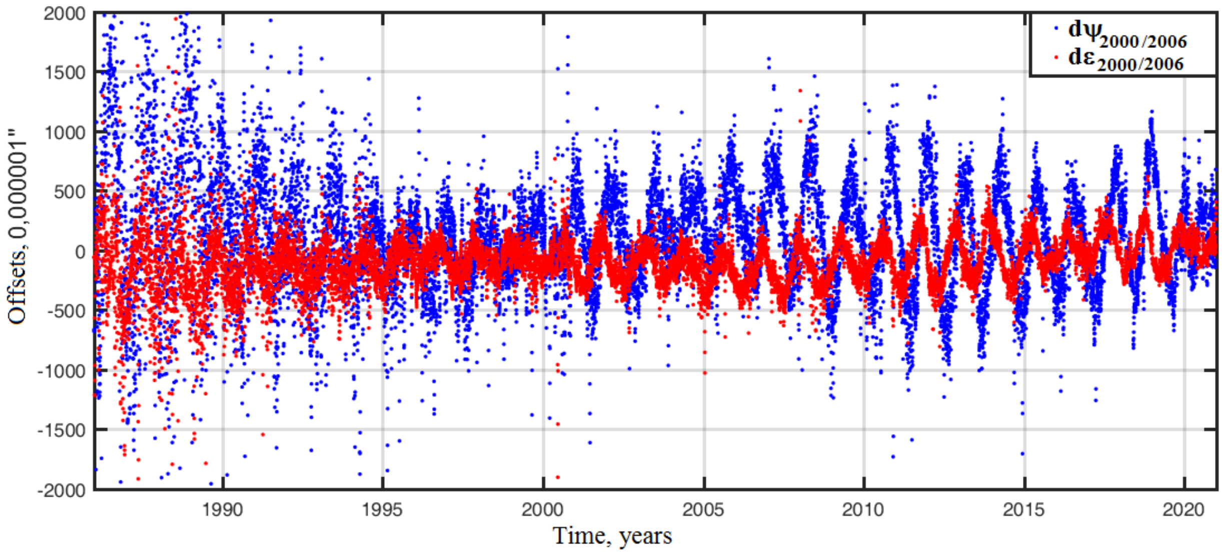
These model inaccuracies (and a number of others) are excluded from the new *IAU2000/2006* model. The corrections to its precession-nutation angles ($d\psi_{2000/2006}$ and $d\varepsilon_{2000/2006}$) are shown at the second of the following pair of figures.

The main part of the remaining deviations are fluctuations at the so-called free core nutation frequency (*FCN*) with a period of about 430 days relative to the celestial coordinate system. Since the corresponding rotation is not stable in time, it is not included in the modern theory of precession-nutation *IAU2000/2006*.

The corrections $d\psi$, $d\varepsilon$ are related by a known dependence with the celestial pole coordinates offsets dX_C, dY_C.

dX_C, dY_C – celestial pole offset from theoretical values, (″)[1] Celestial pole coordinates X_C, Y_C – are the coordinates of the celestial intermediate pole in geocentric celestial coordinate system (*GCRS*). These expressed through the nutation angles ψ and ε by the well-knowing formulas.





Celestial pole coordinates as such as nutation angles ψ and ε describe that part of the variations in the direction of the Earth's axis of rotation in space, which is mainly due to cosmic space factors (the tidal influence of the Moon, the Sun and the large planets of the Solar system).

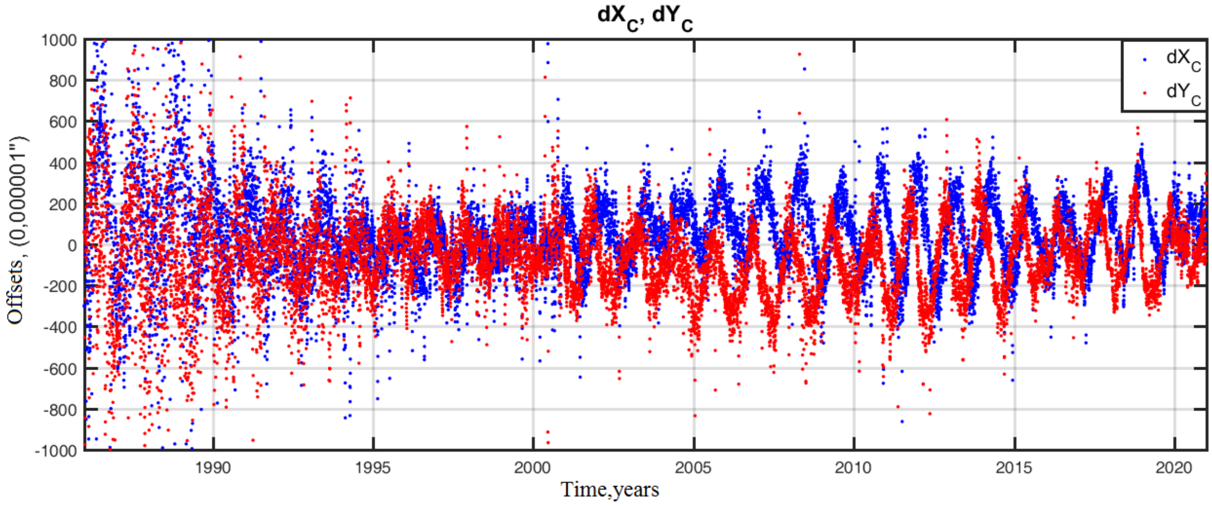
Celestial pole coordinates are distinguished from the full variation of the direction of the Earth's axis of rotation in space by limiting the periods (or corresponding frequencies) of their harmonics: they have periods of more than 2 days (dimensionless frequencies less than 0.5 units per sidereal day in absolute magnitude) in the geocentric celestial coordinate system.

The celestial pole coordinates offsets dX_C, dY_C – are values which one has to add to theoretical celestial pole coordinates $X_{C2000/2006}$, $Y_{C2000/2006}$, calculated according precession/nutation model *IAU2000/2006*, for obtaining observable values X_C, Y_C.

1 – Sometimes the coordinates of the poles are expressed in special units: in meters (or millimeters) on the Earth's surface. In these units, 1″ corresponds to approximately 30 meters on the surface of the Earth, 0,001″ – 3 cm on the surface of the Earth, 0,0001″ – 3 mm on the surface of the Earth.

The celestial pole coordinates offsets dX_C и dY_C, evaluated from observation are shown on the following figure.

The main part of the remaining deviations are fluctuations at the so-called free core nutation frequency (*FCN*) with a period of about 430 days relative to the celestial coordinate system. Since the corresponding rotation is not stable in time, it is not included in the modern theory of precession-nutation *IAU2000/2006*. Its amplitudes range from 0,0001″ to 0,0003″.



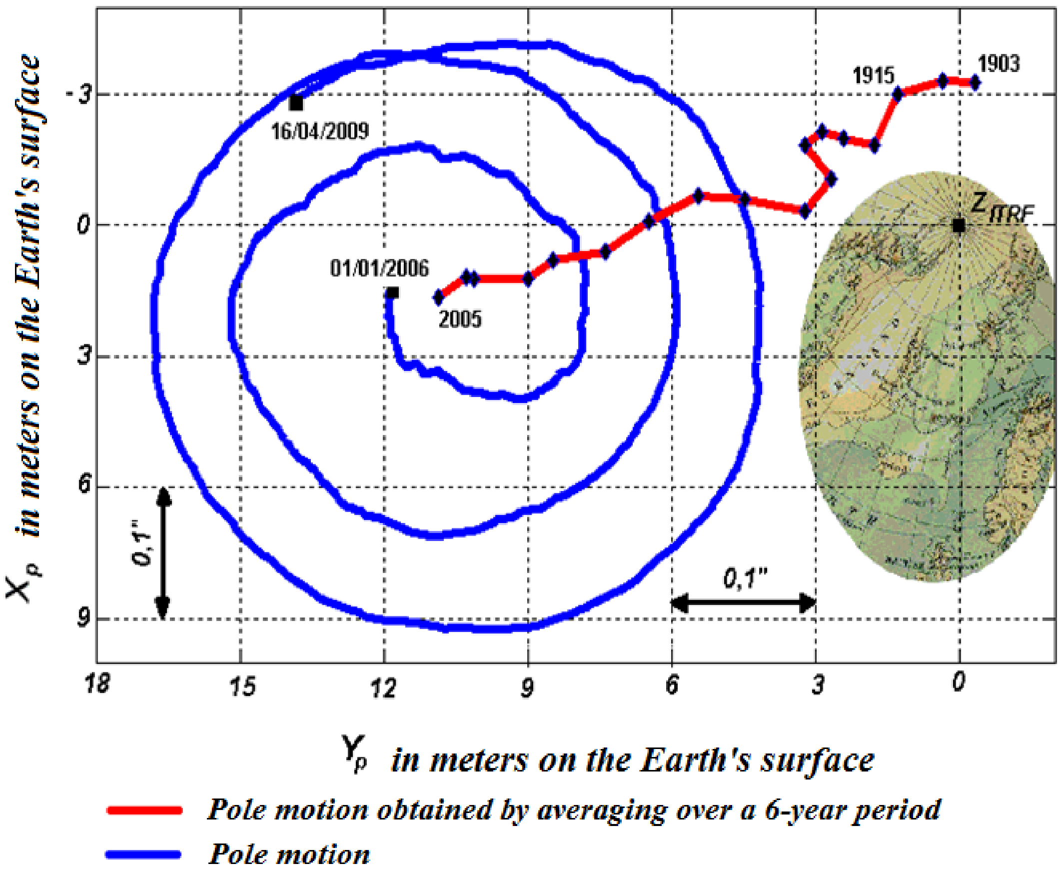
x_p, y_p – terrestrial pole coordinates, (″)[1] – celestial intermediate pole (*CIP*) coordinates in international terrestrial reference frame (*ITRF*).

Terrestrial pole coordinates characterize that part of the variations in the direction of the Earth's axis of rotation in space, which is mainly due to variations in the distribution of Earth masses and their velocities (oceans, atmosphere, movements in the mantle, groundwater, etc.).

They are distinguished from the full variation in the direction of the Earth's axis of rotation in space by limiting the periods (or corresponding frequencies) of their components harmonics: they have periods of less than 2 days (frequencies of more than 0.5 units per sidereal day in absolute magnitude) in the celestial coordinate system. Since the motion of the pole is considered in the Earth's coordinate system, the periods are also expressed relative to this coordinate system. In it, short periods close to days in the celestial coordinate system for part of the harmonics correspond to long periods (for example: 6.5 years; 430 days and 1 year, mentioned below).

Visually, the pole movement is a twisting, then unwinding spiral (see the following figure), the center of which is shifted by a secular way in the direction of the Baffin Sea (it lies between the northeastern part of North America and Greenland).

1 – Sometimes the coordinates of the poles are expressed in special units: in meters (or millimeters) on the Earth's surface. In these units, 1″ corresponds to approximately 30 meters on the surface of the Earth, 0,001″ – 3 cm on the surface of the Earth, 0,0001″ – 3 mm on the surface of the Earth.



The twist on – twist off period of the spiral is about 6.5 years relative to the Earth's coordinate system. The greatest distance from the center of the spiral is approximately about 0.25", which corresponds to about 7.5 meters on the Earth's surface. The center of the spiral moved away from its position in 1903 by about 13 meters.

Frequency analysis reveals two main harmonic components of the pole motion relative to the center of the twisting on – twisting off spiral: a harmonic with an annual period and a harmonic with a period of about 430 days (in the Earth's coordinate system), which is called the Chandler wobble (*CW*). Duration of the five *CW* periods are very closely to 6 years.

Although the amplitudes of the pole motion are small in comparison with precession and nutation, their high-precision evaluation (as well as *UT1–UTC*) is the main task of the Earth's orientation parameters service. The reason for this is that so-called fluids - mobile parts of the Earth (atmospheric and oceanic masses, groundwater, ice fraction, precipitation, currents in the core and mantle of the Earth, etc.) - make a significant contribution to the formation of these irregularities. Their movement is difficult for prediction (at the required level of accuracy), in particular as a result, the high-precision evaluation of these *EOP* requires permanent astronomical and geodetic measurements and their mathematical processing.

Comment. In this material, *EOP* are described in a free style, slightly deviating from the rigorous definitions for simplicity. Those who wish to familiarize themselves with strict documents and precise definitions are recommended to consult with additional sources.

During the construction of the figures, reference data on the *EOP IERS* were used – the *eopc04.62-now* series and the *eopc01.1900-now* series (for pole coordinates earlier than 1962), as well as data from the *SSTF* (the second parts of the *Bulletins A SSTF*). The text uses fragments of the message of the *CAC SSTF* dated 07/15/2016, published on our website. The Yandex translator was used for English translation of original article on Russian.

References

[1] GOST 8.567–2014, Gosudarstvennaya sistema obespecheniya edinstva izmereniy, «Izmereniya vremeni i chastoty. Terminy i opredeleniya», Moskva, Standartinform, 2019 (on Russian).

[2] Transformation between the International Terrestrial Reference System and the Geocentric Celestial Reference System. IERS Conventions 2010 .