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Introduction

The Earth's rotation accounts for the alternation of day and night, the daily cycle of solar radiation influx, formation of diurnal and semidiurnal tidal waves and finally causes diurnal variations in all characteristics of the atmosphere, hydrosphere and biosphere. The revolution of the Earth around the barycenter of the Earth–Moon system and the revolution of the Earth–Moon system around the Sun modulate the amplitudes of the diurnal oscillations of the solar radiation influx and atmospheric tides, and in the end define the variability of terrestrial processes over periods of up to several years.

The Sun revolves around the barycenter of the Solar System along compound curves of the fourth order (conchoids of a circle), so-called "Pascal's limacons". The curvature of the Sun's trajectory constantly changes and the Sun moves with varying acceleration. Being a satellite of the Sun, the Earth revolves around it and also moves with the Sun around the Solar System's barycenter. Like the Sun, the Earth undergoes all varying accelerations. Similar to the lunisolar tides, the accelerations disturb processes in the Earth's shells, producing decadal fluctuations in the latter.

Movements in the Earth's shells are observed mainly from the earth surface. Reference systems for description of the movements are tied to the Earth as well. Different points of the earth surface move with different velocities and varying accelerations. For this reason any movement looks rather complicated in a reference system tied to the Earth. Newton's laws are valid in such a reference system provided that so-called inertial forces, the Coriolis force and centrifugal force, are taken into account. The Coriolis force and centrifugal force are caused by the movement of the terrestrial reference system in an inertial system rather than by the interaction of bodies. Terrestrial processes are formed under the action of many forces. Among them the inertial forces connected with the Earth's rotation play a key role. Their contribution to atmosphere dynamics is especially significant. As a result of the Earth's rotation, the direction of movement of air masses deflects to the right in the Northern hemisphere and to the left in the Southern hemisphere; the cyclonic and anticyclonic vortices arise; systems of western winds and east winds (trade winds) are formed in the middle latitudes and in the equatorial latitudes, respectively; zones of higher pressure are formed in the subtropical latitudes and zones of lower pressure, near to the polar circles. The centrifugal force makes level surfaces

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(equigeopotential surfaces) stretch out along the equatorial axis and compress along the polar axis, as a result, these surfaces tend to form ellipsoids of rotation. Owing to the fact that the reference system is noninertial, atmospheric transfer processes seem so complicated that for the sake of their interpretation geophysical hydrodynamics has accepted the concept of negative viscosity, which contradicts to physical laws.

Bodies and particles in continua move along elliptic gravity potential surfaces and everywhere gravity is vertically directed to the center of the Earth. Gravity force tends to adjust moving bodies and particles in continua to a direction of the local gravity vertical. As a result, all bodies and particles of geophysical continua move in a translational–rotational manner. An exact description of their motion requires not only momentum conservation equations but also angular momentum conservation equations.

The Earth's rotation around its axis gives a basis for celestial and terrestrial reference systems in astronomy, serves as a natural standard of time and allows the universal time scale to be defined. The Earth's rotation is characterized by the vector of instantaneous angular velocity, which can be decomposed into three components: one component along the mean axis of rotation and two others, in the perpendicular plane. The first component defines the instantaneous velocity of the Earth's rotation around its mean axis, or the length of day, and the other two the coordinates of the instantaneous pole. The vector of the angular velocity of the Earth's rotation does not remain constant. Change in the vector's first component is manifested in nonuniformity of the Earth's rotation, and the two other in the motion of the poles.

Polar motion is the movement of the rotation axis in the body of the Earth measured relative to the Earth's crust. But the Earth's rotation axis also moves relative to the inertial celestial reference system and undergoes precession and numerous nutations.

Instabilities of the Earth's rotation (nonuniformity of rotation, polar motion, precession and nutation) distort the coordinates of celestial objects and complicate the universal time scale. The distortions can be taken into account only if peculiarities of the Earth's rotation are known and there is a theory of the Earth's rotation nonuniformity, polar motion, and precession and nutations. Nowadays, astronomical measurement accuracy requirements are becoming increasingly stringent in connection with the necessity of solving a number of scientific and applied problems in astronomy, geodesy, space research and so forth. Therefore, the study of the Earth's rotation is of great importance to modern astrometry, geodesy and geophysics.

Traditionally, the Earth's rotation instabilities are studied by astrometry. Astronomical methods register rotation instabilities. By their nature, the Earth's rotation instabilities are purely geophysical phenomena. They are related to processes in geospheres and depend on the structure and physical properties of the Earth's shells. The Earth's rotation instabilities reflect geophysical processes and give irreplaceable information on the latter, serving as natural integral characteristics of them and associated phenomena. Studying instabilities of the Earth's rotation broadens our knowledge in various areas of Earth sciences. Data on the Earth's rotation instabilities serve as criteria that can be used to verify some theories and models in geophysics, geology, space science, and so forth.

Doubts concerning constancy of the Earth's rotation rate arose after E. Halley discovered the secular acceleration of the Moon in 1695. The idea of secular slowing down of the Earth's rotation under the effect of tidal friction was first proposed by I. Kant in 1755. Nowadays, it is universally recognized that the secular slowing down of the Earth's rotation really exists and is caused by the tidal friction. The value of the secular slowing down is only discussed (Yatskiv *et al.*, 1976).

Simon Newcomb first suggested irregular fluctuations in the Earth's rotation rate in 1875. Their existence was ultimately proved at the beginning of the twentieth century. During the last hundred years, deviations in the length of day from the average value reached $\pm 45 \times 10^{-4}$ s.

Evidence of polar motion was also obtained then. Seth C. Chandler discovered a 14-month period of the latitude variations in 1891. The International Latitude Service (ILS) was established in 1899 for the purpose of monitoring the North Pole's motion. The main components of the polar motion are the Chandler motion whose amplitude is about 160 ms of arc, the annual motion, whose amplitude is about 90 ms of arc, and the secular motion toward North America with a velocity of about 10 cm/year.

In the 1930s, quartz clocks allowed seasonal variations of the Earth's rotation rate to be discovered. A more uniform scale of the Atomic Time was created in 1955 and parameters of seasonal variations began to be determined quite confidently. The length of day was established to have annual and semiannual variations with amplitudes of 37×10^{-5} s and 34×10^{-5} s, respectively.

Until the 1980s, estimations of polar motion and nonuniformity of the Earth's rotation were based on optical astrometric observations of latitude variations and the universal time variations. The observations were nonuniform and had various systematic errors. Reanalysis of the optical astrometric data in the Hipparch system, performed under the direction of J. Vondrak (Vondrak, 1999), partly eliminated these shortcomings and the data could be used in studying long-period instabilities of the Earth's rotation.

In the late 1970s, new engineering complexes were introduced: very long baseline interferometer (VLBI), global positioning system (GPS), satellite laser ranging (SLR), lunar laser ranging (LLR), Doppler orbitography and radio navigation (DORIS service) and new methods of monitoring the Earth's rotation instabilities with unprecedented accuracy. Instead of traditional astrooptical time and latitude estimations, scientists began to observe extragalactic radio sources and satellites of the Earth and process the results of the measurements (time and geometrical delays) to produce corrections to the universal time, the coordinates of the Earth's pole, and corrections to precession and nutation. Thanks to these methods, the resolution and accuracy of the estimation of rotation instabilities has increased 100-fold and are now $0''.0001$ of arc for the pole coordinates and nutation, and 0.000 005 s for corrections to Universal time UT1; which corresponds to several millimeters on the Earth surface. The time resolution of measurements reached several hours.

Regular rawinsounding of atmosphere by means of aerological station network started in the postwar years. The estimations based on these first, very limited data on the winds in atmosphere showed that seasonal variations in the Earth's rotation were mostly caused by redistribution of the angular momentum between the Earth and atmosphere (Pariiski, 1954; Munk and MacDonald, 1960).

The decadal fluctuations in the Earth's rotation rate, which are changes in the rotation rate with characteristic times of 2 to 100 years, are many times the seasonal variations. The fluctuations can be explained by extremely large increments of either the angular momentum of the atmosphere or the moment of inertia of the Earth. Therefore, it is believed that the decadal fluctuations in the Earth's rotation rate cannot be caused by geophysical processes on the Earth's surface (Pariiski, 1954; Munk and MacDonald, 1960). The fluctuations are usually considered to be related to the processes of interaction of the Earth's core and mantle (Hide, 1989).

Practically all variations in the Earth's rotation rate with periods of several days to two-three years (this range includes seasonal, quasibiennial and 55-day variations) are caused by changes in the atmospheric angular momentum (Munk and MacDonald, 1960; Lambeck, 1980; Sidorenkov, 2002a). Polar motion with a one-year period is mainly caused by seasonal redistribution of air masses between Eurasia and oceans. In the case of the Chandler wobble and nutation of the Earth's axis, the role of the atmosphere is still unclear and requires further study.

Although the mass and moment of inertia of the atmosphere is almost a million times less than those of the Earth and a hundred times less than those of the ocean, it appears that its contribution to the Earth's rotation instabilities with periods of several days to several years is prevailing. This paradoxical fact is explained by the high mobility of air. Whereas the characteristic velocity of movement within the Earth's mantle is 1 mm/year and the velocity of ocean currents is 10 cm/s, the velocity of wind in jet streams may exceed 100 m/s.

As a result of strong winds, changes in the atmospheric angular momentum considerably surpass variations in the angular momentum of the ocean and the liquid core. Energy estimations confirm the reliability of that conclusion as well. In fact, the Earth's rotation instabilities, on account of the law of angular momentum conservation, may be a consequence of movements with reversed sign in the shells surrounding the solid Earth: the atmosphere, hydrosphere, cryosphere, liquid core or the space. It is clear that the power of the energy sources exiting those movements should be not less than that of instabilities of the Earth's rotation. For the within-year and interannual nonuniformities of the Earth's rotation, the power is as follows:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = C\omega\frac{\mathrm{d}\omega}{\mathrm{d}t} \approx 10^{14}\text{–}10^{15}\ \mathrm{W} \tag{1.1}$$

where E is the kinetic energy of the Earth's rotation, C is the polar moment of inertia, ω is the angular velocity and $\mathrm{d}\omega/\mathrm{d}t$ is the angular acceleration equal to 10^{-19}–$10^{-20}\,\mathrm{s}^{-2}$. The average powers of the energy sources are approximately as follows: atmospheric air movements – 2×10^{15} W, oceanic currents – about 10^{14} W, geomagnetic storms – 10^{12} W, auroras polaris – 10^{11} W, earthquakes – 3×10^{11} W, volcanoes – 10^{11} W, heat flows from the Earth's deep interior – 10^{13} W, interplanetary magnetic field and solar wind interacting with magnetosphere – less than 10^{12} W (Magnitskiy, 1965; Kulikov and Sidorenkov, 1977; Zharkov, 1983). The presented values indicate that only atmospheric air movements, and possibly currents in the ocean as well, are likely to cause the Earth's rotation instabilities. The power of other geophysical processes is small compared with the power of variations of the Earth's rotation. Note that such important, in terms of the Earth's rotation, effects as transport of water from the ocean to the continent (including the ice sheets of Antarctica and Greenland) and global redistribution of air masses would be impossible in the absence of atmospheric air movements. Bearing all the above in mind, as well as the fact that currents in the ocean are mostly generated by winds, we come to the conclusion of the paramount importance of atmospheric processes as far as the nature of the Earth's rotation instabilities is concerned.

Changes in the Earth's rotation rate are partly caused by changes in the moment of inertia of the Earth, which in turn results from tidal deformations. A theory of these oscillations is well developed (Woolard, 1959; Yoder, Williams and Parke, 1981; Wahr, Sasao and Smith, 1981). Therefore, the tidal oscillations are usually excluded from evaluation of the influence of various geophysical processes on the Earth's rotation.

The diurnal and semidiurnal atmospheric tides cause small changes in polar motion, nutation and the Earth's rotation rate. The most important effect is the direct annual nutation whose amplitude is about 0.1 ms of arc and excitation of free nutation of the core with amplitude ranging between 0.1 and 0.4 ms of arc. However, the excitation of the Earth's rotation instabilities by the diurnal and semidiurnal oceanic tides is approximately by two orders of magnitude greater than the corresponding influence of the atmospheric tides (Brzezinski *et al.*, 2002).

The book consists of thirteen chapters.

Chapter 1 describes the role of the Earth's rotation in dynamics of terrestrial processes, and gives a history of discovery and interpretation of the Earth's rotation instabilities. Also, the structure of the book is given here.

Chapter 2 acquaints the reader with motions of the Earth around the Sun and the barycenter of the Earth–Moon system. Compound motions of the Earth's rotation axis are described, and their geometrical interpretation given.

Chapter 3 addresses the motion of the geographical poles and variations of the angular rate of the diurnal Earth's rotation. A history of discovery of the motion of the Geographical North Pole and nonuniformity of the Earth's rotation rate is given in this chapter. Time series of instrumental observations of the North Pole's coordinates and the Earth's rotation rate are given. The results of mathematical analysis of the time series are presented, and the seasonal, multiyear and secular components are separated.

The theory of estimations of the Earth's rotation instabilities is described in Chapter 4. The differential equations are deduced for instabilities of rotation of an absolutely firm and perfectly elastic Earth under the action of exciting functions empirically calculated. The advantages and disadvantages of "balance method" and "method of the moment of forces" used to estimate various effects on the Earth's rotation instabilities are presented. Polar motion under the action of a harmonious exciting function is described. Basic equations of the theory of precession and nutation are deduced.

Chapter 5 addresses the lunisolar tides and their influence on the Earth's rotation instabilities. The derivation and decomposition of tidal potential is given in this chapter. The basic harmonics of zonal, diurnal and semidiurnal tides are given. A theory of tidal oscillations of the Earth's rotation angular velocity, polar motion, precession and nutation of the Earth axis is expounded. Introductory information on atmospheric tides is given.

The effects of seasonal redistribution of air masses on the Earth's rotation are addressed in Chapter 6. Detailed calculations of seasonal redistribution of air masses in the atmosphere are given. Components of the tensor of inertia of the atmosphere and the amplitude of their annual variations are calculated. Annual variations of the Earth's rotation rate and polar motion are estimated and compared with the calculations carried out by other authors.

The results of a study into the atmospheric angular momentum are discussed in Chapter 7. Data on zonal atmospheric circulation are analyzed. Series of components of the atmospheric angular momentum calculated by David Salstein (Atmospheric and Environment Research, Inc., USA) on the basis of the NCEP/NCAR reanalysis data from 1948 to the present time are described. The results of analysis of time series of the axial and equatorial components of the angular momentum of winds in the atmosphere are given. The existence of diurnal nutation of the vector of the angular momentum of atmospheric winds is shown. Components of lunisolar tides are separated. The contribution of variations of the angular momentum of winds to seasonal variations of the Earth's rotation rate and nutation is evaluated.

The zonal atmospheric circulation is described in Chapter 8. A concept of translational–rotational motion of geophysical continua is formulated. The origin of the zonal circulation and atmosphere superrotation is shown. A special theory of zonal circulation and subtropical maxima of pressure is developed. A new mechanism of seasonal variations of the angular momentum of the atmosphere and seasonal variations of the Earth's rotation is suggested.

Chapter 9 addresses the interrelation of the Chandler motion with oceanic variations known as the El Niño and La Niña, and with atmospheric oscillations manifested as the Southern Oscillation and Quasibiennial Oscillation of winds. Proofs of the existence of multiyear waves in the ocean and atmosphere are offered. The results of analysis of oceanic and atmospheric characteristics indicating that there is a connection between the variations in the ocean and atmosphere and Chandler variations of the Earth are described. A new model of excitation of free polar motion is presented.

Chapter 10 addresses the moments of forces of friction of wind and pressure on mountains. A theory of mechanical interaction of the atmosphere with the underlying surface is expounded. The results of calculations of the Earth's rotation rate by the method of moment of forces are described. A mechanism of the movement of lithosphere plates is proposed.

Chapter 11 discusses the geophysical processes that may be responsible for the decadal components (periods of 2 to 100 years) in the Earth's rotation rate fluctuations. The contribution of interplanetary magnetic field and solar wind is estimated; as well as the influence of glaciers and variations of the sea level on changes in the Earth's rotation. Variations in the mass of ice in Antarctica, Greenland and the ocean, which are necessary for explanation of the observed decadal instabilities of the Earth's rotation, are calculated. Data on the connection of the decadal fluctuations in the Earth's rotation rate with geomagnetic variations, decadal variations in atmospheric circulation and climate change are given. The nature of these connections is discussed.

Chapter 12 discusses how laws of tidal oscillations in the Earth's rotation can be used in hydrometeorological forecasting. Lunar cycles in variations of hydrometeorological characteristics are discovered. A technique of air-temperature forecasting is described. It is revealed that there is a connection between the extremality of natural processes and long-term variability of tidal forces. It is justified that tidal forces must be introduced into motion equations for global atmospheric and oceanic models in order to radically improve weather forecasting.

Unsolved problems of the Earth's rotation instabilities and prospects of further researches are discussed in Chapter 13.

The Appendix contains descriptions of surface spherical functions; the figure of the Earth, list of acronyms, tables of the annual values of the Earth's rotation velocities and secular polar motion, and the mass of ice in Antarctica, Greenland and the mass of water in the ocean, which are calculated from the above data, and indices of quasibiennial oscillations.