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The Interaction Between Earth's Rotation and Geophysical Processes

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Contents

Preface

The book addresses the nature of the Earth's rotation instabilities and associated geophysical processes. The spectrum of the Earth's rotation instabilities that comprise variations in the length of the day, polar motion, and precession and nutation of the rotation axis in inertial space, includes periods of several hours to thousands of years. Instabilities of the Earth's rotation are related to various geophysical processes such as terrestrial, oceanic and atmospheric gravitational and thermal tides; redistribution of air and water masses; variations in the angular momentum of the atmosphere and ocean; air mass exchange between the summer and winter hemispheres; mechanical interaction between the atmosphere, the ocean and the solid Earth; the quasibiennial wind oscillation in the equatorial stratosphere; the El Niño–Southern Oscillation, multiyear atmospheric and oceanic waves, atmospheric circulation epoch change, climate variations, evolution of ice sheets, and so forth.

All these processes are discussed in the book, their nature and the mechanism of their influence on the rotation of the Earth described as far as possible.

There are several books on the Earth's rotation published. The publications mainly address either the celestial-mechanical or astrometry and geodetic problems of determination of the Earth's rotation instabilities or the observation data processing methods. In contrast to these, our monograph covers the physical aspects of the nonuniformity of the Earth's rotation and polar motion and nutation. In terms of the research area, our book is closest to the book by Munk and MacDonald (1960), but this was issued about 50 years ago. Since then the study of all aspects of the Earth's rotation and adjacent areas has phenomenally progressed, so a new book seems long overdue.

The author has studied the Earth's rotation instabilities and related geophysical problems for about 45 years and has received a number of fundamental scientific results. Among them are a concept of translational–rotational motion of continua, theories of zonal atmospheric circulation and seasonal variations in the Earth's rotation rate, excitation mechanisms of the Chandler wobble and annual polar motion, methods of calculation of global water exchange and hydrometeorological forecasting based on the Earth's rotation parameters, a concept of multiyear and decadal fluctuations in the Earth's rotation rate, and others. The author has discovered: diurnal nutation of the atmospheric angular momentum vector with a wide spectrum of oscillations; an interhemispheric thermal engine in the atmosphere; interannual oscillations of the Earth–ocean–atmosphere system; multiyear waves in the ocean and atmosphere; superharmonics of the Chandler period in phenomena of the El Niño–Southern Oscillation and quasibiennial atmospheric oscillations; correlations between the decadal fluctuations in the Earth's rotation, on the one hand, and the changes in the ice mass in Antarctica, variations of atmospheric circulation epochs and global air temperature variations, and so forth, on the other.

The results made it possible to understand the nature of many peculiarities of the Earth's rotation. When interpreting the Earth's rotation instabilities, the author frequently faced situations when observation data were radically contrary to generally accepted concepts. In those cases, a criterion of true was the concordance of a model with observation data rather than with abstract mathematical theorems, theories and conclusions. That is why some of the author's models and estimations conflict with the fixed notions and have not been recognized yet (a concept of translational–rotational motion of continua, a theory of zonal atmospheric circulation, models of macroturbulent transport of the angular momentum, the El Niño–Southern Oscillation, tidal impacts on atmospheric processes, and so forth.).

The problems addressed in the book lie at the interface between astronomy, physics of the Earth, physics of atmosphere and ocean, climatology, glaciology, and so forth. The subject of the research is dealt with all the areas of geosciences. All materials in the book are presented in detail, so that the book could be accessible even to nonspecialists and some specialists may probably find this approach elementary. We had great difficulties in mathematical notations because of a variety of geophysical parameters under study. So, different parameters are sometimes denoted by identical symbols. The author apologizes in advance for such inconveniences.

Study of any natural phenomenon is confined, as a rule, to its observation, analysis, interpretation, and use in solving scientific and practical problems. In accordance with this approach, the book logically expounds the following: the results of calculation of parameters of the Earth's rotation instabilities (Chapter 3), the lunisolar tides and their effects on the Earth's rotation (Chapter 5), the influence of atmospheric and hydrospheric processes on the Earth's rotation, more focus being given to the nature of these phenomena (Chapters 6–11). The studies described in Chapters 5–11 could be difficult to understand without a general knowledge about the Earth's motion and the theory of estimation of the Earth's rotation instabilities. Hence, a brief account of these subjects is given in the first three chapters. The closing chapter (12) addresses the use of the geodynamic laws revealed by the author in hydrometeorological forecasting. Tables of data on the rotation and some global processes are given in the Appendix. A list of the abbreviations used is given in the Appendix as well.

The Earth's rotation instabilities are correlated with many characteristics of natural processes in all frequency ranges. It can be argued from the author's multiyear experience that the Earth's rotation variations can be used as a good validation test for various geophysical models because these variations are a unique index to many processes in all spheres of the Earth, including the biosphere. Various problems can be solved using the Earth's rotation parameters. The reader will find some methods in this book and can derive others from studying how some particular characteristics available to him/her are related to the parameters of the Earth's rotation given in the Appendix.

The author is deeply obliged to Michael Efroimsky for his assistance in the publication of the book, L.P. Kuznetsova, I.V. Ruzanova and B.M. Shubik for their help in translation of the text into English, and to G.L. Averina for her help in the manuscript preparation. Many results were obtained thanks to the support of the Russian Foundation for Basic Research (Projects 02-02-16178a, 06-02-16665a).

We would be grateful if readers would send us their remarks or point out any mistakes or slips. Our address is: Hydrometcentre of Russian Federation, B. Predtechensky pereulok, 11–13, Moscow, 123242 Russia. E-mail: sidorenkov@mecom.ru

1
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 (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:

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

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.

2
Motions of the Earth

2.1
Earth's Revolution

2.1.1
Introduction

The Sun is the main body of the Solar System. The Sun's diameter is 1 390 600 km, which corresponds to 109.1 diameters of the Earth. Its volume is equal to 1 301 200 volumes of the Earth, and the mass is 333 434 times greater than Earth's mass. Since the ratio between the Sun's and the Earth's volumes is much higher than their mass ratio, the Sun's average density is only 0.256 of the Earth's density. The Sun rotates with respect to one of its diameters with various velocities in different points rather than as a rigid body, all points of which have the same angular velocity. Thus, the points on the surface of the Sun's equatorial zone make one revolution with respect to the stars during 25.38 days, and the points laying further from the equator rotate more slowly. The further a point is from the equator the longer is the period of its rotation, and, consequently, the lower is its velocity. For example, the period of rotation of the near-pole points is 30 days or longer.

Eight planets, many minor planets, comets, meteoric streams, and meteoritic bodies move around the Sun. The Earth is the third planet distant from the Sun (after Mercury and the Venus). The Moon, its satellite, moves around the Earth at an average distance of 384 400 km from it. The diameter of the Moon is approximately 3.1 times smaller than the Earth's diameter. During one Earth revolution around the Sun the Moon makes about 13.5 revolutions, moving almost in the orbital plane of the Earth's motion around the Sun. Hence, the Moon is either ahead of the Earth (the last quarter) or behind it (the first quarter), between the Earth and Sun (the new moon) and further from the Earth (the full moon). Therefore, the lunisolar attraction forces acting on the Earth from the Moon and the Sun continuously change, thereby strongly complicating the Earth's motion.

The Earth makes two apparent motions with respect to the Sun: the daily motion (from east to west) as a result of the Earth's rotation around its axis and the annual motion (from west to east with a rate of about 1°/day) as a result of the Earth's orbital motion around the Sun. The trajectory of the apparent annual motion of the Sun among the stars, as seen by an observer on the Earth, passes near the ecliptic and among the constellations: Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpio, Sagittarius, Capricornus, Aquarius, and Pisces. A more accurate determination of the ecliptic needed for our discussion is given below.

Let us consider now the plane passing through the Sun's center S, the mass center of the Earth–Moon system (the barycenter) T, and the velocity vector $\boldsymbol{V}$ of the barycenter moving around the Sun. It will be an instantaneous orbit plane of the center of mass of the Earth–Moon system. This plane does not keep its position unchanged in space (relative to the stars) but rotates around the center of the Sun S, due to the attraction of the Earth and the Moon (and, consequently, the barycenter) by planets.

The motion of the orbital plane of the mass center of the Earth–Moon system, which occurs due to the planets perturbation, can be divided into two motions: a slow displacement of the plane with a low velocity and a series of its very small periodical fluctuations.

The plane passing through the center of the Sun and possessing only the secular motion of the instantaneous orbital plane of the Earth–Moon system center of gravity is called the heliocentric ecliptic plane. The plane parallel to it and passing through the Earth's center is called the geocentric ecliptic plane. The intersection of the celestial sphere by the geocentric ecliptic plane is called *the ecliptic*.

Because the ecliptic is displaced as a result of the secular motion, it is accepted to refer it to a certain time or epoch to fix the position of the vernal equinox point. For example, one talks about the ecliptic of the adopted epoch J1950.0, J2000.0, and so forth. The movable ecliptic position for any instant can be given with respect to one of the motionless ecliptics.

Let us recall that the points of intersection of the celestial sphere with an imaginary axis of the Earth's rotation are called the celestial poles. The celestial pole found in the area of the Ursa Minor constellation is the North celestial pole, opposite to it is the South celestial pole. The great circle of the celestial sphere, which is perpendicular to the Earth's rotation axis and whose plane passes through the celestial sphere center, is called the celestial equator. The ecliptic is intersected with the celestial equator in two diametrically opposite points. One of these points, where the Sun moves along the ecliptic passes from the southern hemisphere of the celestial sphere to the northern one, is called the vernal equinox point. At present, it is in the Pisces constellation. The opposite point of intersection of the equator and the ecliptic is the autumnal equinox point. It is situated in the Virgo constellation. The ecliptic points that are equidistant from the vernal and autumnal equinox points are called the solstice points. In the Northern hemisphere of the celestial sphere (in the Taurus constellation) the point of the summer solstice is situated, and in the Southern hemisphere (in the Sagittarius constellation) is the point of the winter solstice. The Sun passes through the vernal equinox point approximately on March 21, the summer solstice – June 22, the autumnal equinox point – September, 23, and the winter solstice – December 22.

Two diametrically opposite points of the celestial sphere, equidistant from all ecliptic points, are called the poles of the ecliptic. The north ecliptic pole is situated in the Dragon constellation, the southern one – in the Dorado constellation.

According to the universal gravitation law, two mass points (or bodies) with masses M and m are mutually attracted with the force directly proportional to the product of their masses and inversely proportional to the square of distance R between them.

$$F = \gamma \frac{Mm}{R^2} \tag{2.1}$$

where $\gamma = 6673 \times 10^{-14}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ is the coefficient of proportionality, or the gravitational constant. M in the product $\gamma M = 39\,860\,044 \times 10^7\,\mathrm{m}^3\,\mathrm{s}^{-2}$ is the Earth's mass.

The point of mass, on which the external forces do not act, can be only at two states: at relative rest or a uniform and rectilinear motion. This is the concept of Newton's first law – the law of inertia.

The motion of a rigid body is more complicated. It can make the translation motion: translation and rotate simultaneously with respect to the center of mass. The center of inertia or the body center of mass (the material system) is the point in which the total mass of the body or the system is supposed to be concentrated and all external forces acting on the body points or system are applied to. The motion of the inertia center, or the center of mass follows the same laws as the motion of an individual point of mass.

The Earth makes a variety of motions of both the periodic and secular types. It rotates around its axis, doing a complete circuit in $23^{\mathrm{h}}\,56^{\mathrm{m}}\,04^{\mathrm{s}}$ (86 164.09 s) and revolves (that is, describes the translational motion) around the Sun with a period of 365.2422 days. Simultaneously with the motion around the Sun, the Earth's center of gravity rotates around the center of mass of the Earth–Moon system with a period of 27.3217 days. The Earth rotation axis makes the long-periodical motion (systematically divided into precession and nutation) with a period of 25 784 years, being the generating line of the almost circular cone. The Earth's body, in its turn, wobbles with respect to the axis of rotation, owing to which the Earth's geographic poles are displaced over its surface, describing complicated helical curves.

The Sun, in addition to the rotation around its axis (which does not influence the Earth's motion), rotates around the center of mass of the entire Solar System, the position of which depends on the planet's position for the given time. The orbital motion of the Sun basically consists of two almost circular motions with a radius of about 0.003 astronomical unit and the periods close to the Jupiter and the Saturn periods of revolution. Like many stars, the Sun also has its proper motion and displaces in the direction of the Hercules constellation with a velocity of 19.5 km/s, or 6×10^8 km/year. And, finally, the Solar System moves around the Galaxy center with a velocity of 250 km/s, doing the full circuit each 200 million years. The Earth, being the Sun's satellite, also participates in all these motions.

2.1.2
Orbit of the Earth's Center

All the bodies of the Solar System, the Earth including, move around the Sun along their own orbits. The mean distance between the Earth and the Sun is

149 600 000 km. It is called the astronomical unit and used as a standard for all astronomical and astronomy–geodetic calculations.

Let us consider at first a simplified problem of the Earth's motion. We will assume that the Solar System consists only of two bodies: the Sun and the Earth (without the Moon). The Sun center of gravity will be away from the mass center of the Sun–Earth system at a distance of $X = \frac{M_E}{M_S + M_E} \cdot A = 0.00003$ astronomical unit, ($1{:}332\,480 = 0.000\,030\,077$), where M_S is the mass of the Sun, M_E is the mass of the Earth. The distance X is small in comparison with the astronomical unit; therefore we suppose also that the Earth moves around the motionless Sun. If we assume that the Sun and the Earth are spheres with a density decreasing to the periphery and the dimensions of the Earth and the Sun are small in comparison with the distance between them, then this problem can be solved as a problem of motion of two mass points mutually attracted by the universal gravitation law.

In this case, the Earth's translation motion around the Sun is described by two of Kepler's laws. The first law states that the orbit of each planet (the Earth) is an ellipse with the Sun at one focus of the ellipse. The second law defines that the line connecting the planet to the Sun (the Earth's radius-vector) sweeps equal areas in equal time intervals.

Like any ellipse, the orbit of the Earth's center of gravity in its motion around the Sun has two axes of symmetry – the major and the minor axes (Figure 2.1). The major axis passes through the ellipse focuses, that is, through the Sun S. Its intersection points with the orbit are called the apses.

The rate of change in the distance between the Earth and the Sun in apses is equal to zero; therefore, the Earth is closest to the Sun in one of the apses and as far as possible removed from the Sun in another apse. The point Π, where the Earth is the closest to the Sun, is called the perihelion; the most remote point A is the aphelion.

The Earth's position in the orbit is determined by the angle ΠSE reckoned from the perihelion towards in the direction of the Earth's motion up to its radius-vector SE. This angle is called the true anomaly and is designated as ϑ.

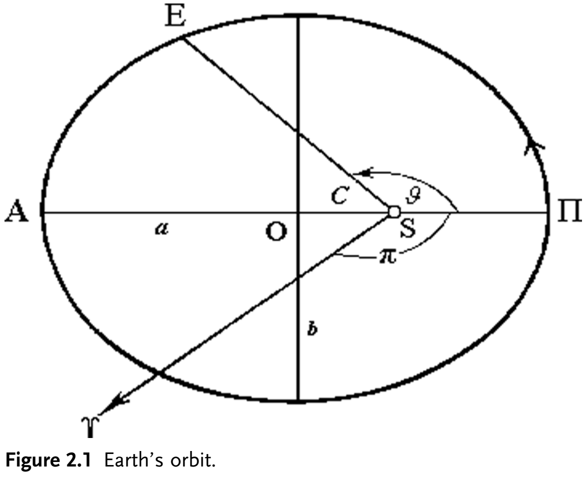

Figure 2.1 Earth's orbit.

The orbit of the Earth is determined by a and b semiaxes. But, as a rule, instead of the minor semiaxis b the orbit eccentricity is used, equal to

$$e = \frac{c}{a} = \frac{a - \Pi S}{a} = 0.01675 \tag{2.2}$$

where a is the orbit semimajor axis, c is the distance from the focus to the center of the ellipse, ΠS is the perihelion distance of the Earth from the Sun.

The distance between the Earth and the Sun continuously changes owing to the ellipticity of the Earth's orbit. The velocity of the Earth's motion along the orbit also changes: the further the Earth is from the Sun the lower is its velocity. In the most distant point of the orbit, Earth's velocity is $V_{\min} = 29.27\,\mathrm{km/s}$; in the nearest point (that is, in the perihelion) $V_{\max} = 30.27\,\mathrm{km/s}$. The product of the radius-vector $\boldsymbol{r}$ of the Earth's inertia center by its velocity is a constant value ($\boldsymbol{r}\boldsymbol{V}_{\mathrm{C}} = \mathrm{const}$). It is impossible to observe directly the Earth's motion around the Sun. But the Earth's motion among the stars, which is observed from the Sun, will be the same as the Sun's motion among the stars, which is observed from the Earth. Therefore, in order to study the Earth's motion around the Sun it is necessary to observe the Sun's motion among the stars and other distant objects.

When the distance between the Earth and the Sun is the shortest (the Earth is in the perihelion) the velocity of the Sun's motion among the stars is the highest. It is possible to conditionally say that the Sun is in the perigee.

At the maximum distance between the Earth and the Sun, the speed of the Sun's motion among the stars is the lowest. An apparent deceleration caused by the motion of more remote objects (which is less visible than the motion of closer objects) perpendicular to the beam of sight is also added to the true slow displacement of the Sun. Therefore, the velocity of the Sun's motion among the stars changes during the year. To obtain the velocity of motion for some time during the year, the average velocity is taken (for example, the average arithmetic of the velocities in the perihelion and the aphelion). This average velocity is considered constant during the year; then one searches the correction for the given moment of the year. Since the true velocity within one half of the orbit is higher than the mean velocity and within another half of the orbit it is lower than the mean velocity (in the opposite points of the orbit, the corrections to the mean velocity are equal but of different sign), then it is easy to understand that the above correction changes during the year according to the sine law.

2.1.3
Motion of the Barycenter of the Earth–Moon System Around the Sun

Let us consider now the joint motion of the Earth and the Moon around the Sun. Unlike the case where the Earth's motion around the Sun alone was considered, here the Earth's orbit will not be an ellipse but a complicated curve whose points do not lie in one plane. The full solution of the problem of motion of the Earth–Moon system around the Sun is very difficult. Despite the efforts of the greatest mathematicians of the nineteenth and twentieth centuries, it was only possible to obtain solutions for some special cases rather than the general solution.

Let us assume that the Moon's motion is connected with the Earth's motion in such a way that their general center of mass moves around the Sun along an ellipse. This assumption does not quite correspond to the truth. However, since the distance to the Sun exceeds by many times the distance from the Moon to the Earth and the mass of the Sun is very large, the errors can be neglected in this case.

The position of the Earth–Moon system center of mass (further on – the barycenter) is given as usual

$$M_{\mathrm{E}}x = M_{\mathrm{M}}(a_{\mathrm{M}}-x) \tag{2.3}$$

whence

$$x = \frac{M_{\mathrm{M}}}{M_{\mathrm{E}}+M_{\mathrm{M}}}a_{\mathrm{M}} \tag{2.4}$$

where M_{M} is the mass of the Moon, a_{M} is the distance between the Earth and the Moon.

The mean distance between the Moon and the Earth is 384 400 km, and the Earth's mass is larger by 81.30 times than that of the Moon. Proceeding from this, $x = 4670$ km, that is, the mass center of the Earth–Moon system is situated inside the Earth and is closer to its surface than to the center.

Over one month, the Earth's center of mass E describes an elliptic orbit around the barycenter O_I, this orbit being similar to the orbit of the Moon mass center M around the same barycenter; however, the first orbit is smaller in the ratio $M_{\mathrm{M}}/M_{\mathrm{E}}$ and is turned in its plane by 180° (Figure 2.2). The terrestrial ellipse dimensions are smaller than the lunar ellipse dimensions by as many times as the Moon's mass M_{M} is

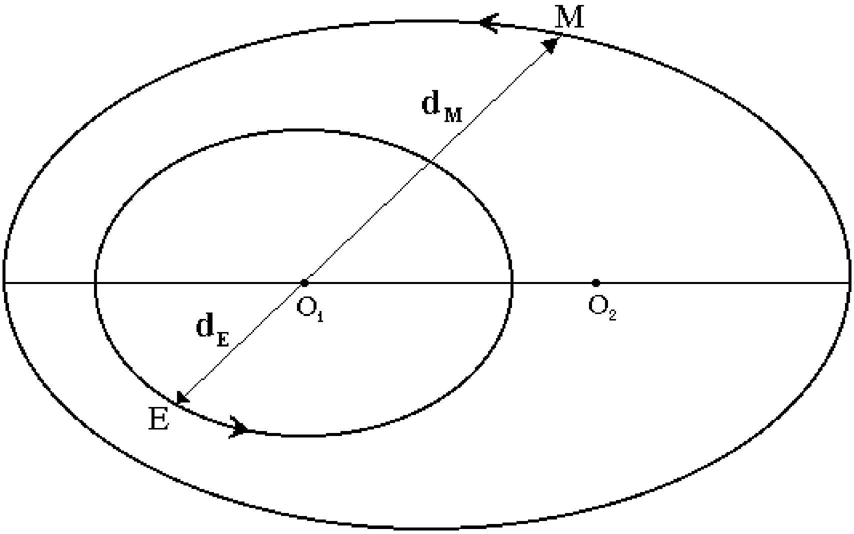

Figure 2.2 Revolution of the Moon and Earth around the center of inertia O_1 of the Earth–Moon system.

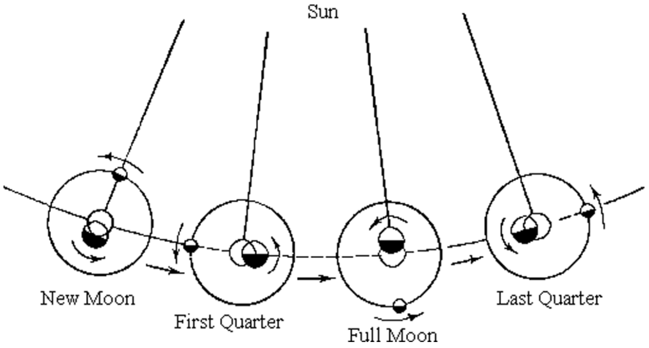

Figure 2.3 Earth's and Moon's motion around the barycentere. Phase of the Moon.

smaller than the Earth's mass M_E. Due to the motion of the Earth and the Moon around the barycenter, the observer from the Sun will see the Earth in front of the barycenter at the Moon first quarter and behind the barycenter at the Moon last quarter (half the synodic month, or 14.76 mean solar days later) (Figure 2.3). This is the so-called lunar inequality in the Earth's motion. The period of this inequality is the synodic month and its value $L = 6''.44$. The same pattern, that is, the same inequality, is observed from the Earth in the motion of the Sun among the stars. But the plane of the lunar orbit in its motion around the Earth does not coincide with the barycenter orbital plane and is inclined to it at an angle of $5°09'$. Hence, the Earth's center occurs above the barycenter orbital plane or below it. The observer from the Earth's center will see the reverse picture: the center of the Sun is situated below the barycenter orbital plane or above it. Due to this inequality (its value is approximately $0''.6$), the Sun's geocentric latitude is not always equal to zero.

In addition to the Earth's complicated motion caused by the Moon, other changes in the Earth's motion occur, namely in the apsis (a straight line connecting the apses) and the orbital elements. The apsis rotates in its plane towards the Earth's motion, due to which the orbital perihelion longitude π, that is, the angle between the directions from the Sun to the perihelion and to the equinox point γ increases by $61''.9$ per year. At present, the perihelion longitude is about $102°8'$. The period of the longitude change π is equal to 20 900 years.

As for the orbital elements of the mass center of the Earth–Moon system moving around the Sun, they may be considered very stable, due to which the orbit is close to an ellipse (Kepler's motion). The semimajor axis a, eccentricity e, and the mean velocity change only slightly and periodically. Instead of the mean velocity astronomers use the mean motion $2\pi/P$, where P is the period of revolution. These elements (they are called the osculation elements) indicate that the orbit gradually changes in its form and dimensions. Notice that if the orbital elements of a body moving along an ellipse do not change or change periodically we may say about a stable motion: the body can move in the same position forever. If the orbital elements change progressively (this, for example, is characteristic of the satellites motion near the Earth), then the motion is unstable. In this case the elliptic orbit of the body can change its orbital elements, and the satellite will fall down onto the Earth.

Frequently, one asks how long the Earth will move around the Sun and whether it will suffer a catastrophe through descending from its orbit? In other words, whether one can say about the stable Earth's motion or, generally speaking, about the stable Solar System?

Laplace, the well-known French scientist, was the first who tried to solve the problem of the Solar System stability. He proved this stability, but not completely (only in the first and second approaches). In any case, the secular perturbations of the first and second orders are absent in the semimajor axes of the major planets of the Solar System. Lagrange, another French scientist, has also approximately proved that the secular perturbations in the eccentricities and the orbital inclinations of the major planets are of the type oscillatory and are rather small. At present, one can tell with confidence that the changes in the orbits of the major planets over a future ten thousand years will be small. In particular, the Earth's and the Moon's orbits around the Sun over the last hundred thousand years have differed little from their present-day orbits.

In the 1960s, A.N. Kolmogorov and A.I. Arnold, the soviet mathematicians, had proved the stability of the bodies system that differed considerably from the Solar System. A.I. Arnold has also obtained the examples of the systems that are unstable in individual cases. However, all these results cannot be extended to the Solar System.

The pattern of motion will change slightly, if the motion of the barycenter T around the Sun is considered taking into account the attraction of the Earth–Moon system by other planets (that is, the disturbed motion of the center of mass of the Earth–Moon system). Under the influence of the gravitational perturbations, the Earth–Moon system's center of mass moves around the Sun along an orbit close to an elliptic one but somewhat changed (perturbed) due to the Earth's and Sun's attraction by planets. Owing to these perturbations, the motion of the Earth–Moon system's center of mass deviates from the motion following by Kepler's laws. The deviations are insignificant: the change of the longitude l caused by the Moon does not exceed $\pm 7''.377$, by Mercury – $\pm 0''.050$, by Venus – $\pm 17''.57$, by Mars – $\pm 7''.02$, by Jupiter – $\pm 15''.65$, and by Saturn – $\pm 1''.04$ (in total – $\pm 48''.71$). The latitude deviation does not exceed $\pm 0''.8$.

2.2
Motion of the Earth's Spin Axis in Space

2.2.1
Dynamics of the Spinning Top

The Earth can be considered as a huge celestial gyroscope. To understand the motion peculiarity of the Earth's rotation axis, let us remember the laws of dynamics of rigid bodies. Let us consider the quickly rotating top. Let its axis of rotation be deviated from the normal by angle θ (Figure 2.4). The gravity acting on the top is $\boldsymbol{P} = m\boldsymbol{g}$, where m is the top mass, $\boldsymbol{g}$ is the gravity acceleration vector. One would think that under the gravity influence the top should fall. In reality the fall is not observed. The top rotation axis is continuously shifting perpendicularly to gravity rather than in its direction.

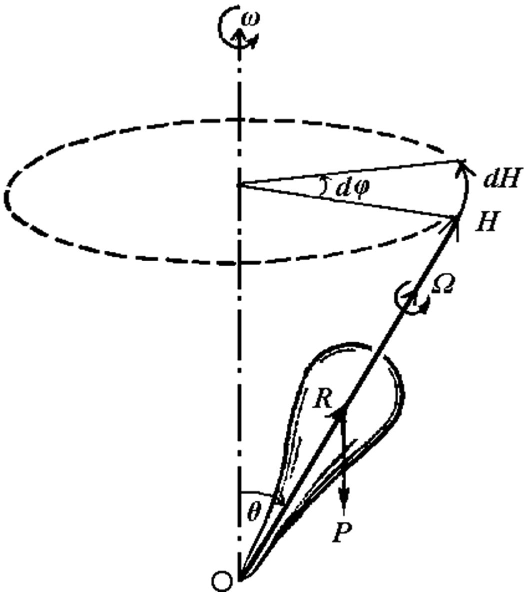

Figure 2.4 Precession of the top.

The axis describes a cone around the normal. This top axis motion is called the *precession*. Why does the top behave in such a way? Let us analyze its dynamics in order to understand this behavior.

The top's vector of angular momentum $\boldsymbol{H} = J\Omega$, where J is the top's moment of inertia with respect to its axis of rotation and Ω is the angular velocity vector. Gravity $\boldsymbol{P}$ creates the force moment $\boldsymbol{L}$ with respect to the fulcrum O: $\boldsymbol{L} = [\boldsymbol{RP}]$, where $\boldsymbol{R}$ is the radius-vector of the center of gravity. Under the effect of the force moment $\boldsymbol{L}$ the top's angular momentum will change with a speed $\frac{\mathrm{d}\boldsymbol{H}}{\mathrm{d}t} = \boldsymbol{L}$. Since the vector of $\boldsymbol{L}$ is perpendicular to $\boldsymbol{R}$ and $\boldsymbol{P}$ and the direction of vector $\boldsymbol{H}$ coincides with that of $\boldsymbol{R}$, the end of vector $\boldsymbol{H}$ and the top rotation axis shift in the direction perpendicular to the direction of gravity $\boldsymbol{P}$. When friction is absent, vector $\boldsymbol{H}$ will change only in the direction: it will rotate, describing a cone with its apex at fulcrum O.

What is the angular velocity ω of the top precession? During the time interval $\mathrm{d}t$ vector $\boldsymbol{H}$ receives increment $\mathrm{d}\boldsymbol{H} = \boldsymbol{L}\mathrm{d}t$, perpendicular to itself and lying in the plane of horizon. The ratio $\mathrm{d}H$ to the projection of vector $\boldsymbol{H}$ on the plane of horizon $H \sin\theta$ gives angle $\mathrm{d}\varphi$ through which this projection turns during time interval $\mathrm{d}t$:

$$\mathrm{d}\varphi = \frac{L}{H\sin\theta}\mathrm{d}t \tag{2.5}$$

The derivative $\mathrm{d}\varphi/\mathrm{d}t$ is the required angular velocity of precession:

$$\omega = \frac{L}{H\sin\theta} = \frac{mgR\sin\theta}{J\Omega\sin\theta} = \frac{mgR}{J\Omega} \tag{2.6}$$

The angular velocity of precession is directly proportional to the value of the gravity moment with respect to the top fulcrum and inversely proportional to the top