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WILEY-VCH Verlag GmbH & Co. KGaA

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Cover
Grafik Design Schulz, Fußgönheim

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

Printed in the Federal Republic of Germany
Printed on acid-free paper

Printing and Binding: betz-Druck GmbH, Darmstadt

ISBN: 978-3-527-40875-7

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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

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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

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ISBN: 978-3-527-40875-7

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

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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