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Earth Rotation

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Definition

Earth	Solid Earth including oceans and atmosphere.
Earth rotation	Temporal variation of the orientation and the rotation speed of the Earth.

Introduction

The rotation of the Earth or Earth rotation, respectively, specifies the spatiotemporal change of the Earth rotation vector. The direction of the Earth rotation vector corresponds to the instantaneous rotation axis of the Earth and its absolute value equals the rotation speed. The Earth's rotation is not uniform and is given in terms of Earth orientation parameters (EOP): *precession* and *nutation* are long-term and periodic changes of the direction of the Earth rotation vector with respect to a space-fixed reference system. *Polar motion* is the variation of the direction of the Earth rotation vector with respect to an Earth-fixed reference system (qv "▶ Geodesy, Networks and Reference Systems"). Changes in the Earth rotation speed are expressed as deviations of *Universal Time 1* (UT1) from the uniform atomic time (*Universal Time Coordinated*, UTC) *dUT1* = UT1–UTC or as variations in the *length of day* (LOD). The subgroup of *polar motion* and *dUT1* or LOD is called Earth rotation parameters (ERP). Fundamental information on Earth rotation theory and observation and about the relations of Earth rotation variations with geophysical processes is given in the seminal works of Munk and MacDonald (1960), Lambeck (1980), and Moritz and Mueller (1987).

While the existence of *precession* was already known to the Greek astronomer Hipparchus in the second century before Christ, *nutation* was not discovered before the eighteenth century by James Bradley. Observations of *polar motion* were taken for the first time by the Bonn astronomer Friedrich Küstner at the end of the nineteenth century by measuring latitude variations. From the 1970s to the twentieth century onward, space geodetic techniques like *Very Long Baseline Interferometry* (VLBI) (qv "▶ Very Long Baseline Interferometry"), *Satellite Laser Ranging* (SLR) (qv "▶ Satellite Laser Ranging"), *Lunar Laser Ranging* (LLR), *Doppler Orbitography and Radiopositioning Integrated by Satellite* (DORIS), and the *Global Navigation Satellite Systems* (GNSS) like the *Global Positioning System* (GPS) (qv "▶ GPS, Data Acquisition and Analysis") have been employed in addition to astronomical methods. Approximately since the year 2000, the latter are no longer routinely applied. Nowadays, the achievable accuracies of the measurements are better than 2×10^{-4} arcsec or less than 0.6 cm, if projected to the Earth's surface. EOP can be determined from space geodetic observations within the respective parameter estimation process. The transformation between Earth-fixed and space-fixed system and thus the EOP are thereby components of the technique's observation equation and can be solved for as unknowns. The most precise technique to observe *polar motion* is GNSS, whereas precession/*nutation* and *dUT1* can be measured directly only by VLBI. Due to the correlation of *nutation* and *dUT1* with the orbital elements of the satellites, satellite techniques are only sensitive to the time derivation of those parameters, i.e., *nutation rates* and LOD. Promising new devices for the observation of high-frequency variations of the instantaneous Earth rotation vector are large ring laser gyroscopes. These instruments can access absolute rotation by measuring the beat frequency of two laser beams rotating in opposite direction, the *Sagnac frequency* (Schreiber et al. 2004). Information about the

H. K. Gupta (ed.), *Encyclopedia of Solid Earth Geophysics*, Encyclopedia of Earth Sciences Series,
https://doi.org/10.1007/978-3-030-10475-7_177-1

long-term behavior of the EOP is obtained from historical records of lunar and solar eclipses and from the analysis of sedimentary deposition. Evidence for a secular increase in LOD can be found for instance in paleontological studies of coral growth rate.

The observed EOP show a wide spectrum of variations. Its interpretation allows for drawing valuable conclusions about the structure of the Earth and the dynamical features of the Earth's interior, the atmosphere, hydrosphere, and cryosphere. Even anthropogenic influences on Earth rotation such as the impact of mass transfer due to an increased CO_2 emission are subject of scientific investigations (de Viron et al. 2002).

Medium and long-period as well as long-term mass displacements affect Earth rotation (cf. e.g., Gross (2007) or Seitz and Schuh (2010) for a comprehensive compilation and further references). According to the conservation of total angular momentum of the Earth in short terms, the rotation of the solid Earth undergoes variations, which are mirror image to changes in atmosphere and oceans. Any mass variation in one or more components of the system Earth that changes the Earth inertia tensor leads to a corresponding variation in the Earth rotation. One can also think of a mass movement which does not change the inertia tensor, because once a mass element moved away it is replaced by another, like in a circular ocean current. Such a mass transport causes a motion relative to the considered reference frame, which affects Earth rotation as well. In which way changes of the inertia tensor and relative motions can be related to variations in Earth rotation is shown in the successive section.

Mathematical Formulation of Earth Rotation

The dynamical equation of motion of a rotating body with respect to a space-fixed system is given by

$$\boldsymbol{L} = \frac{\mathrm{d}\boldsymbol{H}}{\mathrm{d}t} \tag{1}$$

relating the torque $\boldsymbol{L}$ acting on the body to the temporal change of its angular momentum $\boldsymbol{H}$. This is the basic relation for the development of (Newtonian) *precession/nutation* theories, since it describes the motion of the rotating body in a space-fixed reference system. To characterize *polar motion* and changes of the rotation rate of a rotating body, Eq. 1 has to be referred to body-fixed axes, rotating with the angular velocity $\boldsymbol{\omega}$:

$$\boldsymbol{L} = \frac{\mathrm{d}\boldsymbol{H}}{\mathrm{d}t} + \boldsymbol{\omega} \times \boldsymbol{H} \tag{2}$$

This is one form of *Euler's dynamical equations* for rigid body rotation referred to a body-fixed coordinate system. The angular momentum $\boldsymbol{H}$ can be expressed as the product of the tensor of inertia $\boldsymbol{I}$ and the angular velocity vector $\boldsymbol{\omega}$. The inertia tensor is a symmetric matrix containing the moments of inertia and the products of inertia of a rotating body and thus characterizing the mass distribution in the body. Since single particles do not move with respect to the body-fixed system, this tensor is invariant in the case of a rigid body. For a nonrigid (deformable) body, the inertia tensor becomes time variable, and the particles can move with respect to the body frame, thus allowing for relative motions which introduce relative angular momentum. The angular momentum $\boldsymbol{H}$ of a rotating deformable body is then written as

$$\boldsymbol{H} = \boldsymbol{I}\boldsymbol{\omega} + \boldsymbol{h} \tag{3}$$

with $\boldsymbol{h}$ denoting relative angular momentum. The first summand is often referred to as *mass* or *matter term*, and the second is called *motion term*. As the Earth is a nonrigid body, the equation of rotational motion 2 has to be extended considering the above stated differences to the motion of a rigid body, leading to

$$\boldsymbol{L} = \frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{I}\boldsymbol{\omega} + \boldsymbol{h}) + \boldsymbol{\omega} \times (\boldsymbol{I}\boldsymbol{\omega} + \boldsymbol{h}) \tag{4}$$

These are the *Euler-Liouville equations* or simply *Liouville equations*. The deviations from uniform, rigid rotation are formulated as follows for the rotation vector $\boldsymbol{\omega}$:

$$\omega_1 = \Omega m_1, \omega_2 = \Omega m_2, \omega_3 = \Omega(1 + m_3) \tag{5}$$

where Ω is the mean angular velocity of the Earth. The m_i are small dimensionless quantities describing the excursions of the rotation vector from its uniform rotation due to time-variable changes in the mass distribution of the Earth system and relative particle motion. Assuming the body-fixed axes to be principal axes of inertia and the body to be rotationally symmetric, these mass changes can be taken into consideration by composing the tensor of inertia from constant and time-variable parts:

$$\begin{aligned} &I_{11} = A + \Delta I_{11} \quad I_{22} = A + \Delta I_{22} \quad I_{33} = C + \Delta I_{33} \\ &I_{ij} = \Delta I_{ij}, \qquad\quad i \neq j \end{aligned} \tag{6}$$

where the constant parts are the polar moment of inertia C, and the equatorial moment of inertia A of the undeformed Earth and the time-variable components are the quantities ΔI_{ij}. If second-order terms are neglected and the relations 5 and 6 are introduced, the linearized equations of motion can be rewritten as

$$m_1 - \frac{1}{\sigma_E}\dot{m}_2 = \psi_1,$$
$$m_2 + \frac{1}{\sigma_E}\dot{m}_1 = \psi_2, \quad (7)$$
$$m_3 = \psi_3 + \text{const.}$$

with $\sigma_E = \left(\frac{C-A}{A}\right)\Omega$ being the *Euler frequency*, which would be the frequency of the resonance of a rigid Earth, corresponding to a circular motion of the rotation axis with a period of approximately 305 days. If the Earth is considered to be an elastic or at least deformable body, the *Euler frequency* is replaced by the complex *Chandler frequency* $\sigma_C = \frac{2\pi}{T_C}\left(1 + \frac{i}{2Q}\right)$, with $T_C \sim 433$ days denoting the observed period of the *Chandler wobble* and $Q = 30...200$ being a dimensionless dissipation factor (see next section for a brief discussion of the *Chandler wobble*). The ψ_i are called *excitation functions*. They contain the changes of the tensor of inertia and the relative angular momenta:

$$\psi_1 = \frac{1}{\Omega^2(C-A)}\left[\Omega^2\Delta I_{13} + \Omega\Delta\dot{I}_{23} + \Omega h_1 + \dot{h}_2 - L_2\right]$$
$$\psi_2 = \frac{1}{\Omega^2(C-A)}\left[\Omega^2\Delta I_{23} - \Omega\Delta\dot{I}_{13} + \Omega h_2 - \dot{h}_1 + L_1\right] \quad (8)$$
$$\psi_3 = \frac{-1}{\Omega^2 C}\left[\Omega^2\Delta I_{33} + \Omega h_3 - \Omega\int_0^t L_3 \mathrm{d}t\right]$$

The first two equations of 7 for m_1 and m_2 express *polar motion*, while the third equation for m_3 describes the magnitude of the rotation speed and hence LOD variations. Provided that all the time-variable parts of the *excitation functions* (changes of the inertia tensor ΔI_{ij}, relative angular momenta h_i, and external torques L_i) are introduced as known quantities from models or observations, the *Euler-Liouville equations* can be solved for $\boldsymbol{\omega}$. Earth rotation variations can be thus calculated or predicted, respectively, from observed or modeled changes in the components of the system Earth, such as atmosphere or oceans. In general, relative motions (relative angular momenta) contribute more to LOD variations while the major effect on *polar motion* comes from alterations of the inertia tensor. The *excitation functions* are in practice mostly replaced by so-called angular momentum functions, introduced by Barnes et al. (1983). Elaborate explications of the basic Earth rotation formalism can be found in the fundamental books mentioned in the introduction.

Definition and Observation of Earth Orientation Parameters

The elements which are used to perform the transformation between a space-fixed and an Earth-fixed reference system are commonly referred to as EOP. The realizations of such reference systems by assigning coordinates to selected celestial objects or terrestrial sites, respectively, are called reference frames. The definition and maintenance of the reference frames is one major task of the *International Earth Rotation and Reference Systems Service* (IERS). Conventional reference frames are the space-fixed *International Celestial Reference Frame* (ICRF) and the Earth-fixed *International Terrestrial Reference Frame* (ITRF). The current version of the ICRF is its third realization, the ICRF3 (Charlot 2018). The ITRF2014 (Altamimi et al. 2016) has been adopted as the official terrestrial reference frame and will be followed by the ITRF2020 which is currently under construction. The definition of the EOP actually depends on the kind of the applied transformation method. The IERS recommends the transformation according to the IAU (*International Astronomical Union*) 2000 and 2006 Resolutions (Petit and Luzum 2010). The transformation procedure is defined from the *Geocentric Celestial Reference System* (GCRS) to the *International Terrestrial Reference System* (ITRS) or vice versa. The ICRS is not a geocentric system – its origin is located in the barycenter of the solar system. To transfer from a barycentric system to a geocentric system, effects, which are not directly related to Earth rotation, like aberration and parallaxes have to be taken into account. The orientation of the ICRS however corresponds to the orientation of the GCRS. The transition from the GCRS to the ITRS is described as a sequence of time-dependent rotation matrices:

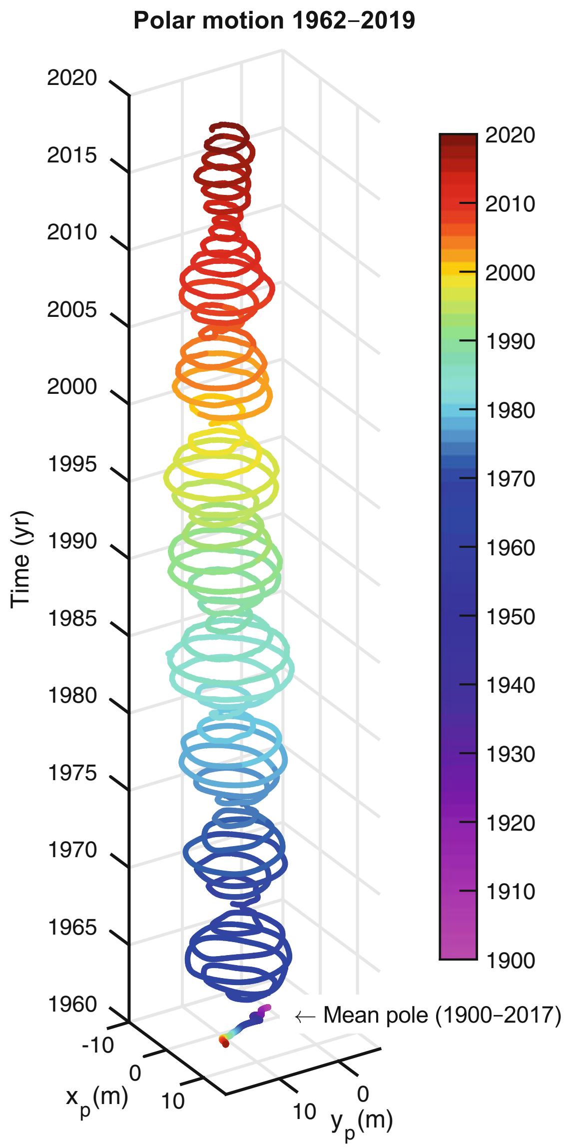
$$[\mathbf{ITRS}] = \boldsymbol{W}(t)\cdot\boldsymbol{R}(t)\cdot\boldsymbol{Q}(t)\cdot[\mathbf{GCRS}] \quad (9)$$

$\boldsymbol{W}(t)$ (with "W" for wobble) designates the *polar motion* matrix. It contains the coordinates x_p and y_p of the reference pole CIP (*Celestial Intermediate Pole*) in the Earth-fixed system and the angle s', which provides the position of the TIO (*Terrestrial Intermediate Origin*) on the equator of the CIP. The TIO and the *Celestial Intermediate Origin* (CIO) realize an instantaneous prime meridian in the respective system. These terms are part of the transformation concept using the *non-rotating origin* (NRO), which replaced the older transformation scheme with ecliptic (plane of the Earth's orbit) and equator. The rotation between TIO and CIO is performed with $\boldsymbol{R}(t)$ using a quantity named *Earth Rotation Angle* (*ERA*). The *ERA* is directly related to UT1, which is relevant for Earth rotation research. *Precession* and *nutation* are represented by the matrix $\boldsymbol{Q}(t)$. It comprises rotations around the angles X and Y, the coordinates of the CIP in the celestial system and around the angle s, which locates the CIO on the equator of the CIP. In case of using the transformation according to IAU 2000 resolutions, the five quantities $\{x_p, y_p, dUT1, X, Y\}$ therefore represent the EOP. If the older transformation concept based on ecliptic and equator is applied, X and Y are replaced by $\Delta\varepsilon$ and $\Delta\psi$, *nutation* in obliquity and longitude. The before cited *Celestial Intermediate Pole* is the reference pole measurements of space geodetic techniques are related to. The CIP thus defines the observed axis. This is a pure convention, realized by an accordingly adapted *precession-nutation* theory. The direction toward the CIP does not correspond to any physically defined axis, like the rotation axis, the figure axis, or the angular momentum axis; nevertheless, it is possible to mathematically connect it to each of those axes. Casually, it is often said that Earth rotation observations represent the motion of the Earth rotation axis. Regarding the measurements of space geodetic techniques, this is actually not entirely correct, since they are not sensitive to the instantaneous Earth rotation vector but to the complete rotation matrix only. The CIP defines an intermediate pole, separating the motion of the pole of the ITRS in the GCRS into a celestial part and a terrestrial part. The celestial part (*precession* and *nutation*, $\{X, Y\}$) comprises all motions with periods greater than 2 days, as seen from space. This is equivalent to frequencies between -0.5 and $+0.5$ cycles per sidereal day (cpsd). With the minus sign labeling retrograde motions (opposite to the sense of Earth rotation) and the plus sign labeling prograde motions (in the sense of Earth rotation), all motions outside of the retrograde diurnal band in the Earth-fixed system, i.e., frequencies below -1.5 and above -0.5 cpsd, are allocated to the terrestrial part (*polar motion*, $\{x_p, y_p\}$).

The celestial motions, *precession* and *nutation*, are long-term and periodic changes of the direction of the Earth rotation axis or actually of the CIP axis, with respect to a space-fixed reference system, which is realized, for example, by the positions of extragalactic radio sources observed by VLBI. Due to *precession*, the Earth axis moves with respect to the space-fixed system on a cone with an aperture of 23.5°, corresponding to the angle between the Earth's equator plane and the ecliptic. The revolution period amounts to approximately 25,800 years. This time interval is also called Platonic year. The tidal forces of moon and sun are responsible for this steady motion. Since the Earth is not a sphere but can be characterized as an oblate spheroid (qv "► Geodesy, Figure of the Earth") and its rotation axis is inclined by 23.5° with respect to the ecliptic normal, the gravitational torques force the equatorial plane into the ecliptic. Because of its rotation, the Earth acts like a gyroscope and swerves by moving on the abovementioned cone, whose surface can be calculated very precisely.

The smaller periodic change in the direction of the Earth rotation axis that is superimposed to *precession* is called *nutation*. This comprises motions of the Earth rotation axis with respect to the space-fixed system with periods from a few days to 18.6 years, caused by gravitational influences of sun, moon, and the planets of our solar system. *Precession* and *nutation* can be modeled and predicted precisely using time-dependent harmonic series expansions. The arguments of the individual harmonic terms are thereby calculated from combinations of five fundamental astronomical arguments. The currently most precise *precession-nutation* model adopted by IAU Resolutions (2000, 2006) is IAU 2006/2000A. In this model, effects of planets, ocean tides, mantle anelasticity, and electromagnetic coupling mechanisms between core and mantle as well as between inner and outer core are considered (Mathews et al. 2002). As for the planets, their direct effect on Earth as well as the indirect effect of the sun acting on a planet, which also causes subtle *nutation* terms, is taken into account. Remaining parts of the axis motion with respect to the space-fixed system that are not covered by the *precession-nutation* model can be measured by means of VLBI and are provided by the IERS as so-called celestial pole offsets. These residuals originate from still deficiently modeled and unpredictable effects, like the *free core nutation* (FCN). The FCN is a proper mode of the Earth, caused by a misalignment of the rotation axes of mantle and core. Whereas first theoretical estimations indicated a period of about 460 days for this mode, VLBI measurements show that the FCN period is more likely to be around 430 days with highly variable amplitude.

The terrestrial part of the change of the direction of the Earth axis or rather the CIP axis is designated *polar motion* (Fig. 1). *Polar motion* has an order of magnitude of several meters and is expressed in a two-dimensional coordinate system by the *pole coordinates* x_p and y_p. According to the definition of the IERS and its precedent organizations, the x-axis is oriented in the direction of the Greenwich meridian, and the y-axis is oriented positively toward 90° west longitude. Already in 1765, the Swiss mathematician Leonhard Euler calculated a circular motion of the pole (of an Earth at that time assumed to be rigid) with a period of around 304 days. Today, we know that *polar motion* is mainly composed from an annual variation and the *Chandler oscillation* or *Chandler wobble*, named after Seth Carlo Chandler who first detected a period of approximately 14 months when analyzing *polar motion* observations at the end of the nineteenth century. The *Chandler wobble* is another proper motion of the Earth with strongly varying amplitude. More precisely, this nearly circular motion is a damped oscillation, which would have vanished due to friction in the Earth's interior after a few decades if there was not a constantly revolving excitation. Although the *Chandler oscillation* is known for more than 100 years, its underlying excitation mechanism is still under investigation. Today, there is broad consensus that the necessary excitation energy emerges from irregular processes in the atmosphere-ocean system (Gross 2000). A radical change in the phase of the *Chandler wobble* around 1925 could also not yet fully be explained. Variations of the Earth's magnetic field are nowadays quoted as potential causes for the phase variations. The interference of the *Chandler wobble* and the annual motion leads to a beat-like rising and ebbing of the *polar motion* amplitude to a

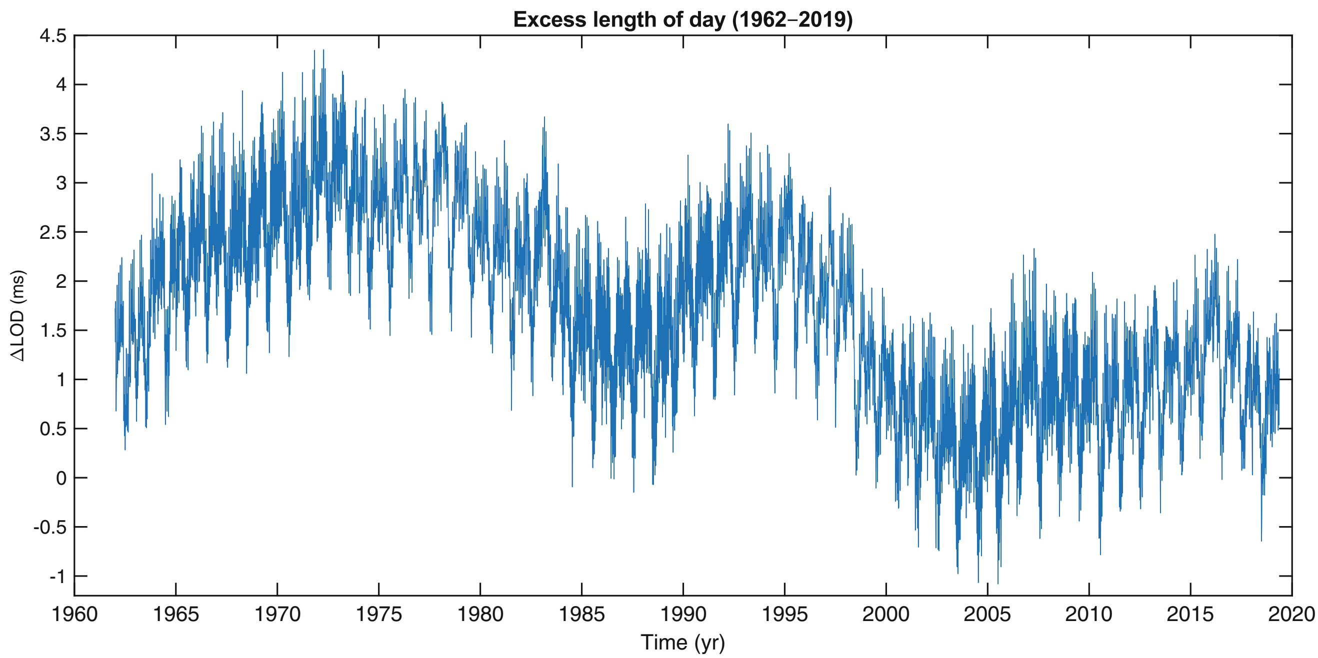


Earth Rotation, Fig. 1 *Polar motion* from the combined EOP series C04 14 of the IERS (1962–2019, daily resolution) and position of the mean pole from 1900 to 2017

maximum of 9 m with a beat period of about 6.3 years. The *polar motion* spectrum below 1 year is dominated by irregular variations appearing in 3 and 5 months intervals. The most important short-period variations are due to the ocean tides caused by sun and moon with essentially diurnal and semidiurnal periods (Karbon et al. 2019), albeit the total effect is only about 1/100 of the *Chandler wobble*. Analysis of long-term *polar motion* shows a distinct variation of approximately 11 years. It is usually associated with processes in the Earth's interior but could also be connected to a corresponding cycle of the solar activity. In addition there are other, decadal variations with periods around 30 years and between 70 and 80 years. These are assumed to be caused by geodynamic couplings between Earth's core and mantle. Recently, Adhikari and Ivins (2016) identified terrestrial water storage variability as the source of decadal-like changes in observed *polar motion* during their study period 2003–2015. Secular *polar motion*, i.e., the long-term linear trend in the position of the pole, amounts to about 10.5 cm/year toward Labrador, Canada (e.g., Schuh et al. 2001 or Adhikari et al. 2018). This effect is supposed to be predominantly due to melting of the polar ice masses and postglacial rebound, but also long-term mass movement due to mantle convection is suspected to play a role.

For an extensive review on precession, nutation, and wobble of the Earth, refer to Dehant and Mathews (2015).

LOD is used to express the speed of Earth rotation alternatively to the difference *dUT1* between UT1, which is



Earth Rotation, Fig. 2 Excess length of day from the combined EOP series C04 14 of the IERS (1962–2019, daily resolution)

directly connected to the Earth rotation speed, and the regular atomic time UTC. The parameter, which is usually quoted to characterize changes in LOD, is actually ΔLOD, the so-called excess LOD which represents the deviation of the effective LOD from the nominal value of 86,400 s (Fig. 2). Variations of LOD can be assigned to different period ranges. In the short-period range with periods from around 1 day and half a day, the strongest influence emerges from the ocean tides caused by sun and moon (Karbon et al. 2018). Hydrodynamic models or altimetry (qv "► Geoid Determination, Theory and Principles") provide variations of ocean heights and velocities of the water masses, from which global changes of angular momentum of the world oceans are calculated. These are subsequently used to estimate the oceanic influence on the Earth rotation parameters. In this way high-frequency ERP variations can be predicted from tide and circulation models, and they can already be observed by the high-precision space geodetic techniques mentioned above. In the range of a few weeks to months, periods of ~14 and ~28 days, due to solid Earth tides (qv "► Earth Tides"), are dominant. In addition, there are other strong variations between 40 and 90 days basically excited by zonal winds. Seasonal variations due to changes in the angular momentum of the atmosphere show semiannual and annual periods. The variation of LOD with a period of approximately 1 year is predominantly due to annually changing wind patterns. A definite amplification of the annual variation every 4–6 years is associated with large-scale climate signals related to the El Niño phenomenon by which an ocean circulation with a very characteristic pattern in the Southern Pacific is connected to variations of the meteorological parameters. The existence of decadal fluctuations of LOD at the ms level suggests an internal coupling between the Earth's core and mantle exhibiting torques on the order of 10^{18} Nm. Four coupling mechanisms and associated torques are commonly identified, the viscous, topographic, gravitational, and electromagnetic torques. Except for the viscous torque which seems too weak, any of the other torques, would be capable of explaining these LOD variations (qv "► Core-Mantle Coupling"). Because of tidal friction and long-term mass variations, a secular prolongation of the day by about 1.8 ms in 100 years is observed as well (Stephenson et al. 2016). This is, of course, an average long-term trend deduced from eclipse data over the last 2,700 years. Besides the secular trend, there is also evidence of LOD fluctuations on a timescale of centuries and some indication of an around 1500 years oscillation.

IERS International Earth Rotation and Reference Systems Service

The IERS is an international service for the determination of EOP and their dissemination to interested users. The definition and realization of reference systems for geodesy and astronomy can be regarded as its superior task. According to the terms of reference (Dick and Thaller 2018), the primary objectives of the IERS are to serve the astronomical, geodetic, and geophysical communities by providing the following:

- The International Celestial Reference System (ICRS) and its realization, the International Celestial Reference Frame (ICRF).
- The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).
- EOP required to study Earth orientation variations and to transform between the ICRF and the ITRF.
- Geophysical data to interpret time/space variations in the ICRF, ITRF, or EOP, and to model such variations.
- Standards, constants, and models (i.e., conventions) encouraging international adherence.

In addition, the IERS collects, archives, and distributes several products such as reference frames, monthly Earth orientation data, daily rapid service estimates of near real-time Earth orientation data, and their predictions. The IERS also announces the differences between astronomical and civil time for time distribution by radio stations and leap seconds which – if necessary to keep the differences *dUT1* smaller than 0.9 s – are added at midnight of July 31 or December 31. Further products are related to global geophysical fluids such as mass and angular momentum distribution, annual reports and technical notes on conventions and other topics, and long-term Earth orientation information. The IERS began operation on January 1, 1988, as common institution of the IAU and the *International Union of Geodesy and Geophysics* (IUGG) and replaced thereby the former *International Polar Motion Service* (IPMS) and the Earth rotation section of the *Bureau International de l'Heure* (BIH). The service consists, among other parts of a Central Bureau, combination centers of the space geodetic techniques and several product centers, for example, for the collection of data about geophysical influences on Earth rotation (*Global Geophysical Fluids Center*, GGFC). These are atmospheric and oceanic variations, hydrodynamic effects like groundwater variations, and processes in the Earth's interior which lead to changes in the rotational behavior of the Earth. The Central Bureau is located at the BKG (*Bundesamt für Kartographie und Geodäsie*) in Frankfurt am Main, Germany. Apart from regular publication of EOP, the IERS also issues guidelines (IERS Conventions, Petit and Luzum (2010)), which contain models and standards recommended for the data processing of space geodetic techniques.

Summary

Earth rotation is conventionally described by the EOP, which represent the link between a space-fixed (celestial) and an Earth-fixed (terrestrial) coordinate system. Those EOP expressing the temporal variations of the orientation of the Earth correspond to *precession/nutation* (changes of the direction of Earth rotation axis with respect to a space-fixed reference frame) and *polar motion* (wobbling of the Earth with respect to its axis). Small variations of the speed of Earth rotation are expressed by UT1 minus the uniform atomic time (UTC) or as variations in the LOD. A precise knowledge of the Earth's attitude is needed for all positioning and navigation tasks on Earth and in space. It also gives fundamental information about the interactions between the various geophysical components of system Earth and allows deriving conclusions about phenomena of celestial mechanics. The EOP are nowadays monitored by space geodetic techniques and assembled and published by the IERS.

Cross-References

► Core-Mantle Coupling
► Earth Tides
► Geodesy, Figure of the Earth
► Geodesy, Networks and Reference Systems
► Geoid Determination, Theory and Principles
► GPS, Data Acquisition and Analysis
► Satellite Laser Ranging
► Very Long Baseline Interferometry

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