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Models and nomenclature in Earth rotation

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Abstract. The celestial Earth's orientation is required for many applications in fundamental astronomy and geodesy; it is currently determined with sub-milliarcsecond accuracy by astro-geodetic observations. Models for that orientation rely on solutions for the rotation of a rigid Earth model and on the geophysical representation of non-rigid Earth effects. Important IAU 2000/2006 resolutions on reference systems have been passed (and endorsed by the IUGG) that recommend a new paradigm and high accuracy models to be used in the transformation from terrestrial to celestial systems. This paper reviews the consequences of these resolutions on the adopted Earth orientation parameters, IAU precession-nutation models and associated nomenclature. It summarizes the fundamental aspects of the current IAU precession-nutation models and reports on the consideration of General Relativity (GR) in the solutions. This shows that the current definitions and nomenclature for Earth's rotation are compliant with GR and that the IAU precession-nutation is compliant with the IAU 2000 definition of the geocentric celestial reference system in the GR framework; however, the underlying Earth's rotation models basically are Newtonian.

Keywords. standards; astrometry; ephemerides; reference systems; time; Earth

1. Introduction

Earth's rotation is a diurnal rotation that exhibits fluctuations with time, about an axis that is moving both in space due to precession-nutation and within the Earth due to polar motion. The knowledge of that motion is essential for representing the coordinate transformation between the celestial and terrestrial systems that is required for many applications in fundamental astronomy and geodesy. Models for representing this motion are based on IAU and IUGG standards, on IAU models for precession-nutation and geophysical models for the part of polar motion and fluctuations in speed that are predictable. Earth Orientation parameters (EOP) can be estimated from observations by Very Long Baseline Interferometry (VLBI) of extragalactic radio sources, laser ranging of artificial satellites (SLR) and the Moon (LLR), observations of the GNSS systems, and observations with the DORIS system; each of these techniques has a specific potential for Earth orientation and reference systems determination.

Observing and modeling Earth rotation with a submilliarcsecond accuracy rely on a huge international effort. Observations and their analyses are coordinated at an international level by the International Earth Rotation and Reference systems Service (IERS). The IERS products, i.e. the realizations of the International Terrestrial and Celestial Reference Systems (ITRS and ICRS) and the EOP, are based on data provided by the international services (IVS for VLBI observations, ILRS for SLR and LLR observations, IGS for GNSS observations and IDS for DORIS observations). There also has been a continuing scientific effort for improving the models and the geophysical interpretation.

Several IAU resolutions on reference systems have been passed in 2000 and 2006, and endorsed by the IUGG in 2003 and 2007, respectively. This paper reviews the current status of the parameters for Earth's rotation, the IAU/IUGG adopted models and the associated nomenclature. It also summarizes the fundamental aspects of the IAU precession-nutation models and reports on the consideration of General Relativity in the current solutions.

2. The observed Earth orientation parameters

Three angles would be sufficient to specify the Earth's orientation in the celestial reference system. However, for practical reasons, five parameters are traditionally used in order to describe and observe the various fluctuations in Earth's rotation. The observed EOP consist of polar motion, celestial pole offsets and Universal Time, UT1. Polar motion represents variations in the terrestrial direction of the pole (see Fig. 1); it is quasi-periodic and essentially unpredictable. It includes a free, nearly circular motion of period of about 435 d (Chandler term) with a variable amplitude, an annual elliptical motion forced by the seasonal displacement of air and water masses, a small drift, and diurnal and semi-diurnal variations with amplitudes of a fraction of milliarcsecond (mas) that are due to the oceanic tides. Celestial pole offsets are corrections to the predicted celestial direction of the pole (see Fig. 3 and Sect. 4.2); they include corrections to the IAU precession-nutation (see Sect. 5) and the motion in space with a period of about 430 d (see Fig. 1) corresponding to the free retrograde diurnal motion of the Earths' axis with respect to the Earth (i.e. free core nutation, or FCN).

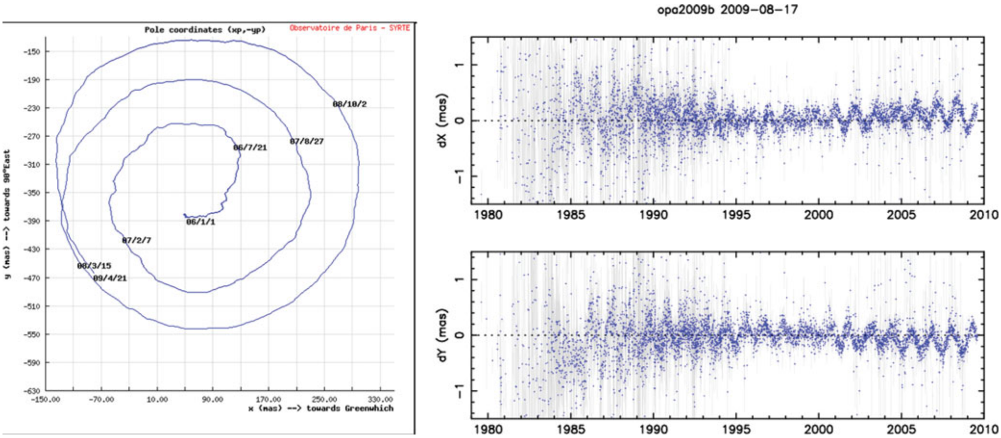

Figure 1. Spiral motion of the pole as seen from the Earth (left graph) and VLBI estimated corrections to the IAU 2006/2000 precession-nutation of the pole (right graph); unit: milliarcsecond; credit: IERS EOP Product Center and IVS OPA Analysis Center, Observatoire de Paris.

Variations in UT1, which reflects the fluctuations in the Earth's speed, are generally represented by variations in the length of day (LOD). They amount to several parts in 10^{-8}, including a secular variation, decadal variations, as well as tidal and seasonal variations (see Fig. 2).

IERS determination of polar motion mainly results from GPS observations that rely on a very dense network on the Earth, while celestial pole offsets and UT1 result mainly from VLBI that provides an accurate realization of the ICRS. The current uncertainty in the IERS determination of the EOP is a few tens of microarcseconds (μas) in the terrestrial and celestial pole directions, and a few μs for UT1.

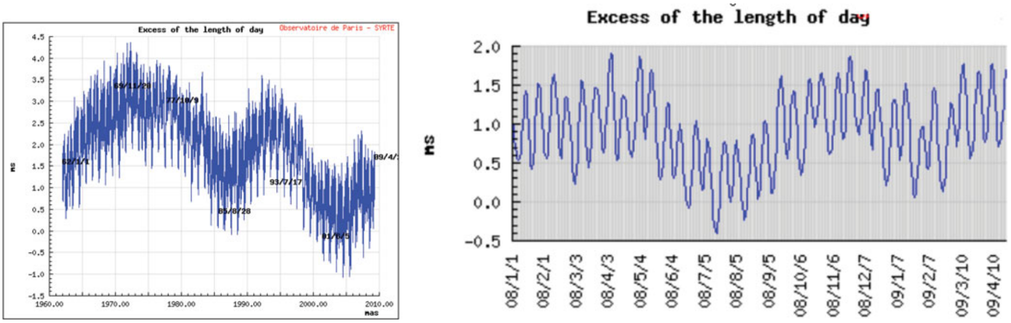

Figure 2. The variation in the length of day (unit: ms): variations over five years (left graph) and seasonal variations (right graph); credit: IERS EOP Product Center, Observatoire de Paris.

3. The IAU 2000/2006 Resolutions on reference systems

The IAU 2000 resolutions adopted by the XXIVth IAU General Assembly (August 2000) and endorsed by the XXIIIrd IUGG General Assembly (July 2003), have important consequences on the reference systems, the concepts, the parameters, and the models for Earth's rotation. IAU 2000 Resolution B1.3 specifies the systems of space-time coordinates for the solar system and the Earth within the framework of General Relativity and provides clear procedures for theoretical and computational developments of those space-time coordinates, and especially the transformation between the barycentric and geocentric coordinates (see Soffel *et al.* 2003). IAU 2000 Resolution B1.6 recommends the adoption of the IAU 2000 precession-nutation. IAU 2000 Resolution B1.7 defines the pole of the nominal rotation axis, while IAU 2000 Resolution B1.8 defines new origins on the equator, the Earth Rotation Angle (ERA) and UT1. The latter resolution also recommends a new paradigm for the terrestrial-to-celestial coordinate transformation. IAU 2000 Resolution B1.9 provides a re-definition of Terrestrial time (TT).

The IAU 2006 resolutions, adopted by the XXVIth IAU General Assembly (August 2006) and endorsed by the XXIVth IUGG General Assembly (July 2007), supplement the IAU 2000 resolutions on reference systems. IAU 2006 Resolution B1 recommends a new precession model as a replacement to the IAU 2000 precession in order to be consistent with both dynamical theory and the IAU 2000A nutation. IAU 2006 Resolution B2 addresses definition, terminology or orientation issues relative to reference systems that needed to be specified after the adoption of the IAU 2000 resolutions (e.g. that for all practical applications, unless otherwise stated, the BCRS (and hence GCRS) is assumed to be oriented according to the ICRS axes). IAU 2006 Resolution B3 provides a re-definition of Barycentric Dynamical Time (TDB).

The new terminology associated with the IAU 2000/2006 resolutions, along with some additional definitions related to them, were recommended by the 2003–2006 IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU NFA WG) (Capitaine *et al.* 2007) and endorsed by IAU 2006 Resolutions B2 and B3.

4. The parameters and nomenclature for Earth's rotation

4.1. *The IAU 2000/2006 space-time coordinates for Earth's rotation*

As specified by IAU 2000 Resolution B1.3, the Barycentric Celestial Reference System (BCRS), as a global coordinate system for the solar system, should be used with Barycentric Coordinate Time (TCB) for planetary ephemerides. In contrast, the Geocentric Celestial Reference System (GCRS), as a local coordinate system for the Earth, should be used with Geocentric Coordinate Time (TCG) for the Earth's rotation and precession-nutation of the equator. The spatial orientation of the GCRS is derived from that of the BCRS. Consequently, the GCRS is "kinematically non-rotating" so that Coriolis terms (that come mainly from geodesic precession) have to be considered when dealing with equations of motion in that system.

The IUGG 2003/2007 resolutions have endorsed the IAU 2000/2006 resolutions on reference systems and have additionally defined (IUGG 2007 Resolution 2) a Geocentric Terrestrial Reference System (GTRS) in agreement with IAU 2000 Resolution B1.3, and the International Terrestrial Reference System (ITRS) as the specific GTRS for which the orientation is operationally maintained in continuity with past international agreements.

The IAU 2000/2006 resolutions have clarified the definitions of both the Terrestrial Time (TT) and Barycentric Dynamical Time (TDB). The new definitions are such that TT is a time scale differing from TCG by a constant rate, which is a defining constant. In a very similar way, the new TDB is a linear transformation of TCB, the coefficients of which are defining constants. The consequence is that TT (or TDB), which may be for some practical applications of more convenient use than TCG (or TCB), can be used with the same rigorous approach. This applies in particular to the solutions of the Earth's rotational equations expressed in TT and the solar system ephemerides (necessary for computing the luni-solar and planetary torque acting on Earth's rotation) expressed in TDB.

4.2. *The IAU 2000/2006 definition and use of the Earth orientation parameters*

IAU 2000 Resolution B1.7, specifies that the pole of the nominal rotation axis is the *Celestial Intermediate Pole* (CIP), which is defined as being the intermediate pole, in the ITRS to GCRS transformation, separating nutation from polar motion by a specific convention in the frequency domain. The convention defining the CIP is such that (i) the GCRS CIP motion includes all the terms with periods greater than 2 days in the GCRS (i.e. frequencies between −0.5 cycles per sidereal day (cpsd) and +0.5 cpsd); (ii) the ITRS CIP motion, includes all the terms outside the retrograde diurnal band in the ITRS (i.e. frequencies less than −1.5 cpsd or greater than −0.5 cpsd).

IAU 2000 Resolution B1.8 recommends using the "non-rotating origins" (Guinot 1979) as origins on the CIP equator in the GCRS and ITRS; they were re-named *Celestial and Terrestrial Intermediate Origins* (CIO and TIO), respectively by IAU 2006 Resolution B2. Their kinematical property provides a very straightforward definition of the Earth's diurnal rotation based on the *Earth Rotation Angle* (ERA) between those two origins. The definition of UT1 has been refined as being linearly proportional to the ERA through the following conventional transformation (Capitaine *et al.* 2000):

$$\begin{aligned}\mathrm{ERA(UT1)} = 2\pi[&0.7790572732640\\ &+ 1.00273781191135448\ (\mathrm{Julian\,UT1\,date} - 2451545.0)].\end{aligned} \tag{4.1}$$

According to IAU 2000 Resolution B1.8, the ITRS to GCRS transformation should be specified by the position of the CIP in the GCRS, the position of the CIP in the ITRS, and the ERA. The GCRS direction of the CIP unit vector (which includes precession, nutation and the frame bias) thus replaces the classical precession and nutation quantities (see Fig. 3). The CIO (σ) is at present very close to the GCRS x-origin, Σ_0, and almost stationary in longitude, while the equinox (γ) to which Greenwich sidereal time, GST, refers is moving at about $50''$/year in longitude. The CIO based procedure allows a clear separation between precession-nutation and the ERA, which is not model-dependent. In contrast, precession and nutation are mixed up with Earth's rotation into the expression

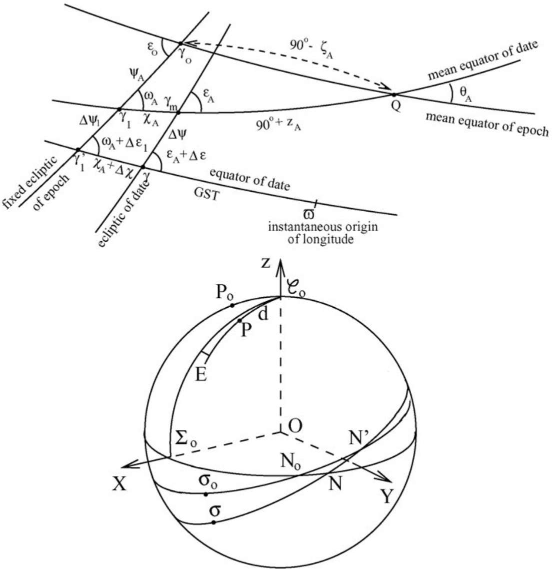

Figure 3. Precession-nutation of the equator in the GCRS: the classical precession-nutation angles (upper part) versus the CIP coordinates, d and E, and the CIO, σ (lower part).

for GST = ERA(UT1) − EO(TT), where EO, represents the accumulated precession and nutation in right ascension.

4.3. *The IAU 2000/2006 Nomenclature for Earth's rotation*

The IAU NFA WG made a number of recommendations on terminology (see Capitaine *et al.* 2007). It also produced the "IAU 2006 Glossary" including a set of detailed definitions (compliant with GR) that best explain all the terms required for implementing the IAU 2000 resolutions, as well as new definitions proposed by the WG, including those formally endorsed by the IAU in 2006 and the IUGG in 2007. The IAU 2000/2006 resolutions have provided the appropriate terminology for the pole, the Earth's angle of rotation, the longitude origins and the related reference systems. The IAU 2006 NFA Glossary (2006) includes in particular definitions for the celestial and terrestrial reference systems ICRS, BCRS, GCRS, ITRS and the *Celestial and Terrestrial Intermediate Reference Systems*, the *intermediate equator*, as the equator of the CIP, the origins CIO and TIO, the *CIO and TIO locators*, s and s', for positioning those origins in the GCRS, the *equation of the origins* (EO), as the distance between the CIO and the equinox along the intermediate equator, and the time scales TCB, TDB, TCG and TT.

5. The IAU 2006/2000 precession-nutation

5.1. *The adoption of the current IAU model*

IAU 2000 Resolution B1.6 recommends the adoption of the new precession-nutation model that is designated IAU 2000 (version A corresponding to the model of Mathews *et al.* (2002), denoted MHB2000, of 0.2 mas accuracy, and version B corresponding to its shorter version (McCarthy & Luzum 2002) with an accuracy of 1 mas). The precession part of the IAU 2000A model consists only in corrections $\delta\psi_A = -0\overset{''}{.}29965$/century and $\delta\omega_A = -0\overset{''}{.}02524$/century to the precession rates (in longitude and obliquity referred to the J2000.0 ecliptic), of the IAU 1976 precession and hence does not correspond to a dynamical theory. The second step in improving the IAU precession model was the endorsement by IAU 2006 Resolution B1 of the recommendation of the 2003–2006 IAU Working Group on “Precession and the Ecliptic” (Hilton *et al.* 2006) to adopt the P03 Precession (Capitaine *et al.* 2003) as a replacement for the precession part of the IAU 2000A precession-nutation, beginning on 1 January 2009.

The procedures, data and software for implementing the IAU 2000/2006 space-time coordinates, parameters and paradigm, nomenclature and models for Earth’s rotation have been made available by Chapter 5 of the IERS Conventions 2003 that was updated in 2009 (see at: `http://tai.bipm.org/iers/convupdt/convupdt.html`) and the Standards Of Fundamental Astronomy (SOFA) (Wallace 1998).

5.2. *Main features of the IAU 2000A Nutation*

The IAU 2000A nutation is based on the REN2000 rigid Earth nutation of Souchay *et al.* (1999) for the axis of figure. The latter is expressed as a series of luni-solar and planetary nutations in longitude $\Delta\psi$ and obliquity $\Delta\epsilon$ referred to the ecliptic of date, composed of “in-phase” and “out-of-phase” components with their time variations, as follows:

$$\begin{aligned}\Delta\psi &= \textstyle\sum_{i=1}^{N} (A_i + A_i' t)\sin(\textsc{argument}) + (A_i'' + A_i''' t)\cos(\textsc{argument}),\\ \Delta\epsilon &= \textstyle\sum_{i=1}^{N} (B_i + B_i' t)\cos(\textsc{argument}) + (B_i'' + B_i''' t)\sin(\textsc{argument}),\end{aligned} \tag{5.1}$$

where t is measured in Julian centuries of TT from epoch J2000.0 and ARGUMENT is a function of the fundamental arguments of the nutation theory.

The rigid Earth nutation was transformed to the non-rigid Earth nutation by applying the MHB2000 “transfer function” to the REN2000 series of the corresponding prograde and retrograde nutations. The sub-diurnal terms due to the imperfect axial symmetry of the Earth are not part of the solution, so that the axis of reference of the nutation model is compliant with the definition of the CIP. The MHB “transfer function” is based on the solution of the linearized dynamical equation of the wobble-nutation problem. Seven “Basic Earth Parameters” (BEP) were treated as adjustable for fitting the theoretical outputs to the VLBI. This improves the IAU 1980 theory of nutation by taking into account the effect of mantle anelasticity, ocean tides, electromagnetic couplings produced between the fluid outer core and the mantle as well as between the solid inner core and fluid outer core, and the consideration of nonlinear terms. The axis of reference is the axis of maximum moment of inertia of the Earth ignoring time-dependent deformations.

The IAU 2000A nutation series that is expressed in the form of Eq (5.1), includes, as the REN2000 series, 678 lunisolar terms and 687 planetary terms. The resulting nutation is expected to have an accuracy of about 10 μas for most of its terms. On the other hand, the FCN (see Sect. 2), being a free motion which cannot be predicted rigorously, is not considered a part of the IAU 2000A model, which limits the accuracy in the computed direction of the celestial pole in the GCRS to about 0.3 mas.

The IAU 2000A nutation includes the geodesic nutation contributions to the annual, semiannual and 18.6-year terms from Fukushima (1991); these contributions to the nutations in longitude and obliquity are in μas:

$$\begin{aligned}\Delta\psi_g &= -153\ \sin l' - 2\ \sin 2l' + 3\ \sin\Omega,\\ \Delta\epsilon_g &= 1\ \cos\Omega,\end{aligned} \tag{5.2}$$

where l' is the Sun’s mean anomaly and Ω the Moon’s longitude of the ascending node.

5.3. *Main features of the IAU 2006 precession*

The IAU 2006 precession (Capitaine *et al.* 2003) provides improved polynomial expressions up to the 5th degree in time t, both for the precession of the ecliptic and the precession of the equator.

The precession of the equator was derived from the dynamical equations expressing the motion of the mean pole about the ecliptic pole. Consequently, the IAU 2006 precession is consistent with a dynamical theory. The convention for separating precession from nutation, as well as the integration constants used in solving the equations, has been chosen in order to be consistent with the IAU 2000A nutation. This includes corrections for the perturbing effects in the observed quantities.

In particular, the IAU 2006 value for the precession rate in longitude is such that the the corresponding Earth's dynamical flattening is consistent with the MHB value for that parameter. This required applying a multiplying factor to the IAU 2000 precession rate of $\sin\epsilon_{\mathrm{IAU2000}}/\sin\epsilon_{\mathrm{IAU2006}} = 1.000000470$ in order to compensate for the change (by 42 mas) of the J2000 mean obliquity of the IAU 2006 model with respect to the IAU 2000 value (i.e. the IAU 1976 value). Moreover, the IAU 2006 precession includes the Earth's J_2 rate effect ($i.e.\ \dot{J}_2 = -3 \times 10^{-9}$/century), mostly due to the post-glacial rebound, which was not taken into account in the IAU precession models previously.

The contributions to the IAU 2006 precession rates for the 2nd order effects, the J_3 and J_4 effects of the luni-solar torque, the J_2 and planetary tilt effects, as well as the tidal effects are from Williams (1994), and the non-linear terms are from MHB2000.

The geodesic precession is from Brumberg *et al.* (1992), i.e. $p_g = 1\overset{''}{.}919883$/century. It is important to note that including the geodesic precession and geodesic nutation in the precession-nutation model ensure that the GCRS is without any time-dependent rotation with respect to the BCRS.

5.4. *IAU 2006 adjustments to the IAU 2000A nutation*

The difference between IAU 2006 and IAU 2000 lies essentially in the precession part, though very small changes are needed in a few of the IAU 2000A nutation amplitudes in order to ensure compatibility with the IAU 2006 values for ϵ_0 and the J_2 rate:

- the amplitudes of the nutation in longitude have to be adjusted in order to compensate for the change from the IAU 2000 to the IAU 2006 value for ϵ_0, the largest term being of the order of 10 μas for the 18.6-yr nutation (note that no such adjustment is needed in the case of the coordinate $X \approx \psi \sin\epsilon_0$);
- introducing the IAU 2006 J_2 rate value gives rise to additional Poisson terms in nutation, the coefficients of which are proportional to $\dot{J}_2/J_2$ ($i.e.\ -2.7774 \times 10^{-6}$/century); the largest effects for the corresponding changes in the X, Y series are of the order of a few tens of μas after a century (Capitaine & Wallace 2006).

Whenever these small adjustments are included in the periodic terms, the notation "IAU 2000A$_{\mathrm{R06}}$" can be used to indicate that the nutation has been revised for use with the IAU 2006 precession. These adjustments are taken into account in the SOFA implementation of the IAU 2006/2000A precession-nutation.

5.5. *The IAU 2000/2006 expressions for the GCRS coordinates of the CIP*

Expressions for the coordinates X and Y of the CIP in the GCRS have been derived from the IAU 2006/2000A$_{\mathrm{R06}}$ expressions for the precession and nutation quantities referred to the J2000 ecliptic and the relationships between the X and Y coordinates and those quantities. The developments for X and Y include polynomial expressions up to the 5th degree in time t that are mainly due to precession plus the frame biases, and a periodic part, with a form similar to Eq. (5.1), but with Poisson terms up to the 4th degree.

Those expressions for X, Y, as well as the procedures for implementing the IAU 2006/2000 precession-nutation, have been provided by Capitaine & Wallace (2006) and Wallace & Capitaine (2006); they have been implemented in SOFA.

5.6. *Comparisons between models and observations*

Comparisons of the IAU 2006/2000 precession-nutation model with VLBI observations, once corrected for an empirical model for the FCN (see Fig. 1 and Sect. 5.2), show residuals with a w.r.m.s of about 130 μas. Those residuals can be empirically modeled in a variety of ways (see Capitaine *et al.* (2009) for more details). The fit of a combination of linear and 18.6-yr terms to the residuals show that the residuals would be compatible with corrections of a few tens of μas to the 18.6-yr nutation. Note that this would correspond to small corrections to the estimates for a couple of the BEP of the MHB model. This result is consistent with independent fits to the LLR celestial pole offsets with respect to the same IAU precession-nutation model (Zerhouni *et al.* 2008).

A comparison over 400 years has also been made between the INPOP06 (Fienga *et al.* 2008) numerical integration of the GCRS motion of the axis of angular momentum and the IAU 2006 precession plus the IAU 2000A nutation for the axis of angular momentum (i.e. the REN 2000 solution for that axis). The INPOP06 solution corresponds to an external torque modified by the non-rigid Earth; it uses the J_2 rate value of IAU 2006 and has been fitted to the IAU 2006 linear term in longitude. The only differences appearing in the comparison are one Fourier and Poisson term at the 18.6-yr period in X with a coefficient of about 50 μas/century and a linear term in Y of about 200 μas/century, which is less than the expected accuracy in that term. This provides another external check of the precision of the IAU 2006/2000A precession-nutation.

6. Theoretical basis for the models

The basic dynamical equation for Earth's rotation is the equation of angular momentum balance with the luni-solar and planetary torques acting on the oblate Earth. This can be developed in various forms. The classical Euler equations in the terrestrial system have an appropriate form for best considering the non-rigid Earth effects. Such equations have been developed by Sasao *et al.* (1980) for a non-rigid Earth with fluid core (designated SOS equations). The MHB transfer function on which the IAU 2000A nutation is based results from a generalization of the SOS equations to an Earth model including an inner core, with dissipative phenomena and BEP parameters fitted to VLBI (see Sect. 5.2). That transfer function should be applied to a rigid Earth solution.

The rotational equations for a rigid Earth can be written in the celestial reference system using various formalisms. The REN2000 analytical solution is based on an Hamiltonian formalism; it is the sum of solutions corresponding to each part of the second member for successive orders of approximation and different contributions (luni-solar effects, planetary effects, etc.). Other forms of equations and resolutions have been used.

The equations as functions of the two first Euler angles, ψ and ω, (e.g. Woolard 1953, Bretagnon *et al.* 1997) can be expressed as:

$$\begin{cases} -\ddot{\omega} + \sigma\,\dot{\psi}\sin\omega + \dot{\psi}^2\sin\omega\cos\omega = L_1/A \\ \sin\omega\,\ddot{\psi} + \sigma\,\dot{\omega} + 2\,\dot{\psi}\,\dot{\omega}\cos\omega = M_1/A, \end{cases} \tag{6.1}$$

where A and C are the Earth's principal moments of inertia, $\sigma = (C/A)\,\Omega$, is the frequency of the Euler free motion in the GCRS, Ω being the mean angular velocity of the Earth. L_1 and M_1 are the components of the external torque in the equatorial reference system defined by the CIP and the intersection of the CIP equator with the J2000 ecliptic.

The equations as functions of the GCRS CIP coordinates, X, Y can be written with similar notations as (Capitaine *et al.* 2005):

$$\begin{cases} -\ddot{Y} + \sigma\dot{X} = L/A + F'' \\ \ddot{X} + \sigma\dot{Y} = M/A + G'', \end{cases} \tag{6.2}$$

where L and M are the components of the torque in the equatorial reference system defined by the CIP and the point of the CIP equator that is distant from the CIO by the quantity s (see Sect. 4.3). F'' and G'' are functions, of the second order, of the X and Y variables and their first and second time derivatives. This form is best appropriate for expressing all the quantities, including the nutation arguments, in the GCRS.

Eq. (6.1) and (6.2), applied to a semi-analytical expression for the external torque, provide a semi-analytical solution for the parameters (i.e. Euler angles, or X, Y) using the method of variations of parameters (see Woolard 1953) and successive iterations. Non-rigid effects expressed in space can also be introduced in the second member.

7. Summary

The consequences of IAU 2000/2006 resolutions for Earth's rotation are the following:

– the definition of the celestial and terrestrial reference systems that are essential for Earth rotation theory and observations are compliant with General Relativity (GR),

– the definition of the Earth orientation parameters (EOP) have been clarified thanks to the use of the Celestial intermediate pole and origin that is compliant with GR,

– the nomenclature associated with the new concepts and quantities has been specified,

– the IAU precession-nutation model, including the geodesic precession-nutation, is compliant with the "kinematically non-rotating" definition of the GCRS.

The current definitions and nomenclature for Earth's rotation are thus compliant with General Relativity and the current IAU precession-nutation is compliant with the GCRS definition in the GR framework. However, it should be noted that the IAU precession-nutation does not result from a rigorous GR treatment. Firstly, both the development of the equations and the transformation between BCRS and GCRS coordinates of the Moon, Sun and planets used for computing the torque, were considered in a Newtonian framework. Secondly, the relativistic rotation of the dynamical geocentric celestial reference system with respect to the GCRS, was taken into account by adding the geodesic precession-nutation to the dynamical solution, while the rigorous way would be to consider an additional torque in the second member of the angular momentum equation. Thirdly, TT has been used instead of TDB in the semi-analytical expressions of the solutions. The latter effect can be shown to be less than $10^{-8}{}''$ in the CIP location. In contrast, according to Brumberg & Simon (2004), the effect of the relativistic part of the BCRS-to-GCRS transformation can reach 150 μas on the precession-nutation solution after one century. A complete GR treatment is, therefore, required in order that the precession-nutation models can achieve a microarcsecond accuracy (see Klioner *et al.* 2009).

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