RECENT PROGRESS IN CONCEPTS, NOMENCLATURE AND MODELS IN FUNDAMENTAL ASTRONOMY

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ABSTRACT. The IAU 2006 resolutions B1, B2 and B3, 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. The aim of IAU 2006 Resolution B1 is to adopt a precession model as a replacement to the IAU 2000 precession in order to be consistent both with both dynamical theory and the IAU 2000 nutation. The aim of IAU 2006 Resolutions B2 and B3 is to address definition, terminology or orientation issues relative to reference systems and time scales that needed to be specified after the adoption of the IAU 2000 resolutions. This paper explains the changes resulting from the joint IAU 2000 and 2006 resolutions with respect to the previous position and reviews the progress in the concepts, nomenclature, models and conventions for fundamental astronomy. The paper also reports on practical aspects related to the Earth orientation parameters and describes the characteristics of the IAU high precision model for the celestial motion of the Earths pole.

1. THE IAU 2000/2006 RESOLUTIONS ON REFERENCE SYSTEMS

The IAU 1997 adoption of the International Celestial Reference System (ICRS) based on extragalactic radio-sources, and of the International Celestial Reference Frame (ICRF) (Ma et al. 1998) that realizes the ICRS, made it possible to refer to celestial reference systems at a sub-milliarcsecond accuracy. Then, several IAU resolutions on reference systems have been passed in 2000 and 2006 (and endorsed by the IUGG in 2003 and 2007, respectively), which have important consequences on the concepts, the nomenclature and the models for fundamental astronomy.

IAU 2000 Resolution B1.3 specifies that the systems of space-time coordinates for the solar system and the Earth within the framework of General Relativity are named the *Barycentric Celestial Reference System* (BCRS) and the *Geocentric Celestial Reference System* (GCRS), respectively and the time-coordinates, the *Barycentric Coordinate Time* (TCB) and the *Geocentric Coordinate Time* (TCG), respectively. It also provides a general framework for the metric tensor and coordinate transformations at the first post-Newtonian level(see Soffel et al. 2003) between the BCRS and the GCRS.

IAU 2000 Resolution B1.6 recommends the adoption of the IAU 2000 precession-nutation (version A corresponding to the model of Mathews et al. (2002), of 0.2 mas accuracy, and its shorter version B (McCarthy and Luzum 2002) with an accuracy of 1 mas).

IAU 2000 Resolution B1.7 specifies that the pole of the nominal rotation axis is the *Celestial Intermediate Pole* (CIP), defined as being the intermediate pole in the transformation between the International Terrestrial Reference System (ITRS) and GCRS, separating nutation from polar motion by a specific convention in the frequency domain.

IAU 2000 Resolution B1.8 recommends using the "non-rotating origins" (Guinot, 1979) as origins on the CIP equator in the celestial and the terrestrial reference systems. They were designated *Celestial and Terrestrial Ephemeris Origins*, but re-named *Celestial and Terrestrial Ephemeris Origins*, respectively by IAU 2006 Resolution B2; it also defines UT1 as linearly proportional to the *Earth Rotation Angle* (ERA) between those origins (Capitaine et al. 2000). It recommends that the ITRS to GCRS transformation be specified by the positions of the CIP in the GCRS and the ITRS, and the ERA. It finally recommends that the IERS continue to provide data and algorithms for the transformations referred to the equinox.

IAU 2000 Resolutions B1.6, B1.7 and B1.8 came into force on 1 January 2003. The models, procedures, data and software to implement these resolutions operationally had been made available by the IERS Conventions 2003 and the *Standards Of Fundamental Astronomy* (SOFA) activities (Wallace 1998). These

include the procedure based on non-rotating origins, but also the equinox based procedure, both being delivered with equal precisions.

As the precession part of the IAU 2000A model consists only in corrections to the precession rates of the IAU 1976 precession, which does not correspond to a dynamical theory, IAU 2000 Resolution B1.7 recommends the development of new expressions for precession consistent with dynamical theories and with IAU 2000A nutation. The 2003-2006 IAU Working Group on "Precession and the Ecliptic" (P&E WG) has looked at several solutions and recommended (Hilton et al. 2006) the adoption of the P03 precession theory (Capitaine et al. 2003), which was endorsed by IAU 2006 Resolution B1.

IAU 2006 Resolution B1 recommends the adoption (from 2009) of the P03 Precession as a replacement to the precession part of the IAU 2000A precession-nutation in order to be consistent with both dynamical theories and the IAU 2000 nutation. It also clarifies the definitions of the precession and of the ecliptic.

In parallel, the new terminology associated with the IAU 2000 resolutions, along with some additional definitions related to them, have been recommended by the 2003-2006 IAU Working Group on "Nomenclature for Fundamental Astronomy" (NFA WG) (Capitaine et al. 2007). This was endorsed by IAU 2006 Resolutions B2 and B3.

IAU 2006 Resolution B2, which is a supplement to the IAU 2000 Resolutions on reference systems, consists of two recommendations: 1) harmonizing "intermediate" to the pole and the origin (i.e. *Celestial and Terrestrial Intermediate Origins*, CIO and TIO instead of CEO and TEO, respectively) and defining the celestial and terrestrial "intermediate" systems; 2) fixing the default orientation of the BCRS and GCRS, which is, is unless otherwise stated, assumed to be oriented according to the ICRS axes.

IAU 2006 Resolution B3 recommends a re-definition of the Barycentric Dynamical Time (TDB) through a conventional linear relation between TDB and TCB.

2. PROGRESS IN THE CONCEPTS FOR FUNDAMENTAL ASTRONOMY

The space-time coordinates to be used in the framework of General Relativity

The IAU 2000/2006 Resolutions have provided clear procedures for theoretical and computational developments of the space-time coordinates to be used in the framework of General Relativity. The BCRS, which can be considered to be a global coordinate system for the solar System, has to be used (with TCB) for planetary ephemerides. In contrast, the GCRS should be considered as a local coordinate system for the Earth to be used (with TCG) for Earth rotation, precession-nutation of the equator, motion of Earth's satellite, etc. 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. For all practical applications, unless otherwise stated, the BCRS (and hence GCRS) is assumed to be oriented according to the ICRS axes. The expression of the transformation between the barycentric and geocentric coordinates (i.e. an extension of the Lorentz transformation) is defined at the first post-Newtonian level for space coordinates and at an extended level for the time coordinates.

The Terrestrial Time and Barycentric Dynamical Time

The IAU 2000/2006 Resolutions have clarified the definitions of TT and TDB. The new TT definition 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 satellite orbit computations for TT and solar system ephemerides, or analysis of pulsars timings, for TDB.

The Celestial Intermediate Pole

The IAU 2000 definition of the CIP is such that (i) its GCRS 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) its ITRS 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). This corresponds to an extension of the IAU 1980 definition of the *Celestial Ephemeris pole* to the high frequency domain.

According to IAU 2000 resolutions, the GCRS position of the CIP replaces the classical precession and nutation quantities. It can be provided by expressions as function of time of the rectangular coordinates, X and Y of the GCRS direction of the CIP unit vector, which include precession and nutation and the frame bias between the pole of the GCRS and the CIP at J2000.0.

The Celestial and Terrestrial Intermediate Origins and Earth Rotation Angle

The IAU 2000/2006 Resolutions have provided a very straightforward definition of the Earth's diurnal rotation based on the angle (ERA) between the non-rotating origins, CIO and the TIO. The conventional linear transformation that defines UT1 from the ERA is (Capitaine et al. 2000):

$$\mathrm{ERA}(\mathrm{UT1}) = 2\pi[0.7790572732640 + 1.00273781191135448\ (\mathrm{JulianUT1date} - 2451545.0)] \qquad (1)$$

Note that the CIO is at present very close to GCRS longitude zero and almost stationary in longitude, while the equinox to which Greenwich sidereal time, GST, refers is moving at about 50 arcsec per year in GCRS longitude. Moreover, the CIO based procedure allows a clear separation between (i) the GCRS motion of the CIP (i.e. mainly precession-nutation) and (ii) the ERA, which is not model-dependent. In contrast, precession and nutation are mixed up with Earth's rotation into the expression of GST as function of UT1: GST(UT1, TT) = ERA − EO, where EO, represents the accumulated precession and nutation in right ascension and is therefore directly dependent on the precession-nutation models.

3. PROGRESS IN NOMENCLATURE FOR FUNDAMENTAL ASTRONOMY

The IAU NFA WG made a number of recommendations on terminology. It also produced the "IAU 2006 Glossary" providing definitions corresponding to 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 (e.g. the ITRS). 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.

Terminology choices related to the intermediate pole and origins

Terminology choices endorsed by the IAU 2006 Recommendations include harmonizing the name of the pole and the origin to "intermediate" and therefore using "Celestial Intermediate Origin" (CIO) and "Terrestrial Intermediate Origin" (TIO), respectively instead of CEO/TEO. The new nomenclature related to the newly defined pole and origins is using "intermediate" to describe the moving geocentric celestial reference system containing the CIP and the CIO (with its terrestrial counterpart containing the TIO); or giving the name "equation of the origins" (EO) to the distance between the CIO and the equinox along the intermediate equator, the sign of this quantity being such that it represents the CIO right ascension of the equinox, or equivalently, the difference between the Earth Rotation Angle and Greenwich sidereal time.

The "celestial intermediate reference system" (CIRS), based on the CIP and the CIO, replaces the classical celestial system based on the true equator and equinox of date. The CIRS can be derived from the GCRS with using the GCRS CIP coordinates X, Y and the quantity s positioning the CIO, which has been called the "CIO locator".

Terminology choices related to the procedural framework and equatorial coordinates

The new nomenclature associated with the procedural framework, is using"equinox based" and "CIO based" for referring to the classical and new paradigms, respectively; or choosing "equinox right ascension" (or "RA with respect to the equinox") and "intermediate right ascension" (or "CIO right ascension", or "RA with respect to the CIO"), for the azimuthal coordinate along the equator in the classical and new paradigms, respectively.

The IAU NFA WG recommendations include using the equatorial coordinates in an extended way, such that right ascension and declination be generic terms that can be referred to any equator (e.g. GCRS equator, CIRS equator, etc.) or to any origin on those equators (i.e. GCRS origin, CIO, equinox, etc.).

4. PROGRESS IN MODELS FOR FUNDAMENTAL ASTRONOMY

The IAU 2000/2006 Resolutions have adopted a high precision model for precession and nutation with two successive steps.

The first step was the adoption of the IAU 2000 precession-nutation model (MHB) of Mathews et al. (2002), which has been implemented in the IERS Conventions 2003. This model is composed of a nutation part and a precession part. In addition to the IAU 2000A model are frame bias values between the J2000 mean pole and equinox and the GCRS. The IAU 2000A nutation includes 1365 luni-solar and planetary terms, which are based on rigid Earth nutation transformed with the MHB transfer function based on basic Earth parameters (BEP) that have been fitted to VLBI data. That model is expected to have an accuracy of about 10 μas for most of its terms. In contrast, the so-called free core nutation

(FCN), which is due to geophysical effects and is largely unpredictable, is not part of the model. The precession part, which consists only in corrections to the precession rates of the IAU 1976 precession, was known to do not correspond to a dynamical theory.

The second step in the improvement of the IAU precession-nutation was the adoption (IAU 2006 Resolution B1) of the P03 Precession as a replacement to the precession part of the IAU 2000A precession-nutation in order to be consistent with both dynamical theory and the IAU 2000 nutation. The P03 model include improved expressions for both the precession of the ecliptic and the precession of the equator. The latter has taken into account the Earth's J_2 rate effect, mostly due to the post-glacial rebound. The P03 precession polynomial developments provide separately the developments for the basic quantities for the ecliptic and the equator that are directly solutions of the dynamical equations, and derived quantities, such as those for the GCRS coordinates of the CIP. These also include expressions for the P03 sidereal time that can been derived from the expression of the Earth Rotation Angle (itself independent of precession-nutation) and the expression for the equation of the origin, which is directly dependent on the precession-nutation.

The various ways of forming the precession-nutation matrix in the new IAU framework have been discussed in Capitaine & Wallace (2006) and the precession-nutation procedures consistent with IAU 2006 resolutions have been provided in Wallace & Capitaine (2006).

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