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Micro-arcsecond Celestial Reference Frames: definition and realization — Impact of the recent IAU Resolutions

Nicole Capitaine

SYRTE, Observatoire de Paris, CNRS, UPMC, 61, avenue de l'Observatoire, 75014, Paris, France; *nicole.capitaine@obspm.fr*

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Abstract The adoption of the International Celestial Reference System (ICRS), based on Very Long Baseline Interferometry (VLBI) observations of extragalactic radiosources by the International Astronomical Union (IAU) since 1998 January 1, opened a new era for astronomy. The ICRS and the corresponding frame, the International Celestial Reference Frame (ICRF), replaced the Fundamental Catalog (FK5) based on positions and proper motions of bright stars, with the Hipparcos catalog being adopted as the primary realization of the ICRS in optical wavelengths. According to its definition, the ICRS is such that the barycentric directions of distant extragalactic objects show no global rotation with respect to these objects; this provides a quasi-inertial reference for measuring the positions and angular motions of the celestial objects. Other resolutions on reference systems were passed by the IAU in 2000 and 2006 and endorsed by the International Union of Geodesy and Geophysics (IUGG) in 2003 and 2007, respectively. These especially concern the definition and realization of the astronomical reference systems in the framework of general relativity and transformations between them. First, the IAU 2000 resolutions refined the concepts and definition of the astronomical reference systems and parameters for Earth's rotation, and adopted the IAU 2000 precession-nutation. Then, the IAU 2006 resolutions adopted a new precession model that is consistent with dynamical theories; they also addressed 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. An additional IUGG 2007 resolution defined the International Terrestrial Reference System (ITRS) so that it strictly complies with the IAU recommendations. Finally, the IAU 2009 resolutions adopted a new system of astronomical constants and an improved realization of the ICRF. These fundamental changes have led to significant improvements in the fields of astrometry, celestial mechanics, geodynamics, geodesy, etc. Of special interest are the improvements in the model for variations in Earth's rotation, which, in turn, can provide better knowledge of the dynamics of the Earth's interior. These have also contributed to a significant improvement in the accuracy of the ephemerides of the solar system bodies as determined from modern measurements, with a large number of scientific applications. This paper recalls the main aspects of the recent IAU resolutions on reference systems as well as their consequences on the concepts, definitions, nomenclature and models that are suitable for the definition, realization and transformation of reference frames at a microarcsecond level.

Key words: astrometry and celestial mechanics: astrometry — reference systems — Earth — techniques: interferometric

1 INTRODUCTION

A new era in astronomy started on 1998 January 1, when the International Astronomical Union (IAU) adopted the International Celestial Reference System (ICRS) based on Very Long Baseline Interferometry (VLBI) observations of extragalactic radiosources and the corresponding frame, the International Celestial Reference Frame (ICRF). This adoption was followed by a series of important resolutions on reference systems adopted by the IAU in 2000 and 2006 and endorsed by the International Union of Geodesy and Geophysics (IUGG) in 2003 and 2007, respectively. In addition, there was a specific IUGG 2007 resolution giving a definition of the International Terrestrial Reference System (ITRS), which strictly complies with the IAU Resolutions. In 2009, the IAU completed this set of international agreements with two other resolutions on astronomical references, with one of them being the adoption of the Second Realization, ICRF2, of the ICRF, which benefited from the improved concepts and models adopted by the previous resolutions. The purpose of the series of resolutions that has been passed between 2000 and 2009, has been to comply with the accuracy and improved properties of the ICRS, as well as with the precision of modern astro-geodetic observations. These included resolutions on astronomical reference systems and frames, models for Earth's rotation, concepts and nomenclature, and time scales. Refined definitions regarding the celestial reference systems were adopted as well as a new paradigm and high accuracy models to be used in the transformation from terrestrial to celestial systems. These fundamental changes have led to significant improvements in astrometry, as well as studies of Earth's rotation and solar system dynamics.

It is important to note that international coordination in this field, especially due to the existence of international scientific services, such as the International Service for Earth Rotation and Reference systems (IERS), or IVS (VLBI International Service for geodesy and astrometry), and international working groups (within the IAU, IERS and IVS) played a key role in the preparation of the IAU/IUGG resolutions and their implementation. The IERS is in charge of measuring and providing values for Earth's orientation, with the IERS products, i.e. the ITRS, ICRS and the Earth Orientation Parameters (EOP), being based on data provided by international services (IVS, ILRS, IGS, IDS). Those data are derived from observations by various modern techniques, namely VLBI on extragalactic radio sources for the IVS, laser ranging on artificial satellites and the Moon for the ILRS, observations with the GNSS systems for the IGS, and observations with the DORIS system for the IDS.

The following sections present the main aspects of the recent IAU resolutions on reference systems as well as their consequences on the concepts, definitions, nomenclature and models that are suitable for the definition, realization and transformation of microarcsecond celestial reference frames.

2 BACKGROUND

The determination of positions and motions of celestial objects requires definition and realization of reference systems, maintenance of the reference frames which realize the systems, improvement of the models for the observables, and determination of Earth's orientation on a regular basis. The availability of an inertial reference system is required for celestial dynamics. A catalog of stars, even if it is compiled for the goal of constructing a dynamical reference system, like the Fifth Fundamental Catalog, FK5 (Fricke et al. 1988), cannot be realized without rotation, due to the inaccuracies in the estimation of proper motions of stars. This is a critical problem. Only extragalactic objects, which are not influenced by the rotation of the Galaxy, can provide convenient fiducial points. This had already been discussed by Hershel as well as by Laplace in the 18th century, but extragalactic objects have only been discovered in the 20th century and compact radio sources identified as quasars in the 1960s. The hypothesis that the Universe as a whole does not rotate is necessary and seems to be confirmed by observations. The modern solution of this problem appeared in the 1970s with the astrometric application of VLBI. This technique allows measurement of the angular position of the most distant bodies we know, quasars, with uncertainties well below $0.001''$ (about one hundred times smaller than uncertainties of the corresponding ground-based measurements in the visible domain). As far as we know, the angular proper motions of these bodies are negligible in comparison with the accuracy of observations, although some of them show a variable structure. At first, catalogs of positions of quasars appeared as a by-product of VLBI measurement of the rotation of the Earth by groups in the USA. These individual catalogs were combined experimentally by the Bureau International de l'Heure (BIH) and by the IERS, the successor of the BIH in this area of activity, in a unique frame which became increasingly used. Then, the IAU prepared for the adoption of an official International Celestial Reference Frame (ICRF), aligned with the IERS frame. The increasing accuracy of astrometric observations (expected to be at a microarcsecond level in the near future) called for more precise definitions of space-time transformations, which required that they be considered in the framework of general relativity (GR). Therefore, the aim of IAU resolutions on reference systems that were passed at successive General Assemblies (GAs) from 1988 to 1997 was twofold. First, to adopt a celestial reference system based on directions of extragalactic radio sources in order to replace the FK5, which was based on directions of stars. Second, to progressively introduce GR into the space-time reference systems, in order to extend previous resolutions (1976) adopted for time scales. The resolutions that have been passed at IAU GAs to achieve the reform described above are as follows:

- the IAU GA in 1988 called for the use of extragalactic objects to define the celestial reference frame;
- the IAU GA in 1991 adopted GR as the fundamental theory, confirmed the 1988 resolution and specified the continuity with existing stellar and dynamic implementations;
- the IAU GA in 1994 adopted a list of some 600 extragalactic radio sources and formed a working group to define their positions.

These preliminary steps were successful and the IAU working group (WG) in charge of the preparation of an accurate catalog of extragalactic radio sources succeeded in providing that catalog at the IAU GA in 1997. It is important to note that such a development would not have been possible if the optical counterpart of the ICRF would not have existed: the Hipparcos catalog. The success of the astrometric mission Hipparcos provided very accurate relative positions and proper motions of stars (uncertainties of about $0.001''$ in 1992 and $0.001''\ \mathrm{yr}^{-1}$, for more than 100 000 stars). Observation programs of objects emitting both in the radio and optical frequencies were successfully organized in order to express the Hipparcos positions and proper motions in the ICRF.

Then, following the recommendation of the IAU WG on Reference Frames, the IAU GA in 1997 passed these resolutions:

(a) that, as from 1998 January 1, the IAU celestial reference system shall be the ICRS as specified in the 1991 IAU Resolution on reference frames and as defined by the International Earth Rotation Service (IERS);
(b) that the corresponding fundamental reference frame shall be the ICRF constructed by the IAU WG on Reference Frames;
(c) that the Hipparcos Catalog shall be the primary realization of the ICRS at optical wavelengths.

The latter recommendation was amended by the IAU 2000 Resolution B1.2 in order to exclude stars from the Hipparcos catalog with proper motions that were known, or suspected, to be affected by errors that are too large; this modified Hipparcos frame was labeled the Hipparcos Celestial Reference Frame (HCRF).

3 THE RECENT IAU RESOLUTIONS

3.1 The New Celestial Reference System and its Realization

With the adoption of the ICRS/ICRF and its optical counterpart, the HCRF, the availability of a quasi-ideal reference system for measuring the angular motion of celestial bodies became reality. This opened a new era for fundamental astronomy and for astrophysics.

The ICRF, regarded as the realization of the ICRS, is based upon an ensemble of very distant extragalactic sources, whose proper motions are assumed to be not detectable with the current precision of VLBI observations. The first version of the ICRF (also referred to as ICRF1) contains 608 compact radio sources in which 212 are selected as defining sources (Ma et al. 1998). The precision of the positions of the ICRF1 reference points and the accuracy in the orientation of its axes are 100 times better than those of the previous IAU official celestial reference system, the FK5 (see Table 1).

Table 1 Evolution of the Celestial Reference Frames

Name	Fiducial objects	Number	Magnitude limit	Mean time of observations	Technique of observation	Uncertainties in: pos.	proper motion (yr^{-1})	Status
FK5	stars	1535 3117	< 7 $< 9,5$	1940 to 1950	Optical astrometry	$0.02''$ $0.08''$	$0.0008''$ $0.002''$	Fundamental catalog from 1976 to 1997
ICRF1	Extragalactic radiosources	608 (212 defining)		1987	VLBI	$0.001''$ $(0.0004'')$		Celestial reference frame from 1998
Hipparcos catalog	stars	118 218	< 12	1991.25	Astrometric satellite Hipparcos	$0.001''$	$0.001''$	HCRF: Optical counterpart of ICRF from 2000
ICRF2	Extragalactic radiosources	3414 (295 defining)		1999	VLBI	$0.001''$ $(0.0004'')$		Celestial reference frame from 2010

An essential difference with respect to the FK5 is that the definition of the axes of the celestial reference system is no longer related to the equator or the ecliptic; it is totally independent of solar system dynamics. The ICRF was aligned with the FK5 at J2000, but no attempt was made to refer the positions of the sources to the mean pole or mean equinox at a fundamental epoch as was the case in the fundamental catalogs. As a consequence, the celestial reference frame is no longer dependent on the Earth's motion (i.e. on the Earth's rotation or its revolution around the Sun). The resolution defining the ICRS/ICRF has recommended that further improvements of the ICRF should be accomplished without introducing any global rotation; that recommendation has actually been followed for all new implementations of the ICRF, as explained in the following.

The second version ICRF2 (Fey et al. 2009) of the ICRF came into force in 2010. It represents a significant improvement over the previous version while preserving, by construction, the same directions of the reference axes. It contains 3414 radio sources, in which 295 are defining sources. The ICRF1 resulted from 1 600 000 VLBI observations performed from 1979 to 1995, while the ICRF2 resulted from 6 000 000 VLBI observations performed from 1979 to 2009. Its accuracy, about 40 microarcseconds (μas), is 5–6 times better than that of the ICRF. The axis stability of ICRF2 is 10 μas, which is nearly twice as stable as ICRF1. Figure 1 clearly shows the densification of the ICRF2 with respect to the ICRF1, as well as its better coverage of the Southern Hemisphere.

Since the HCRF is comprised of bright stars that are sparsely distributed on the sky, several densification projects have been developed that are intended for astronomical programs requiring a denser distribution of faint stars. Significant efforts have been made in both optical reference frame densification programs and the maintenance of the link between these programs and the HCRF. Other programs have also been developed to extend the celestial frame into wavelengths other than

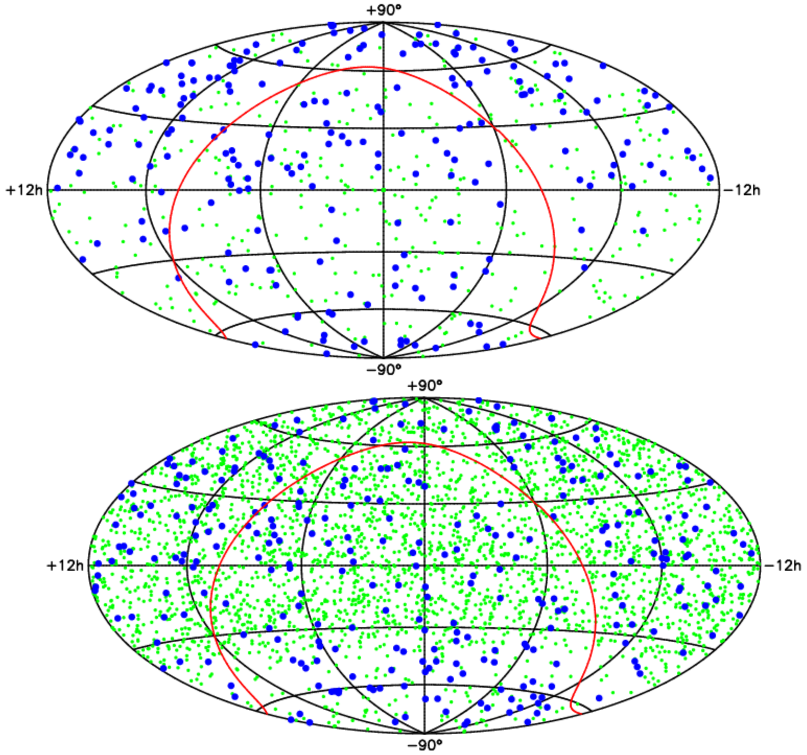

Fig. 1 The two versions (representation on the celestial sphere) of the ICRF successively adopted by the IAU: *top frame*: ICRF1 adopted in 1997 (Ma et al. 1998); *bottom frame*: ICRF2 adopted in 2009 (Fey et al. 2009). The blue dots are for the positions of the defining sources, while the green dots are for the other sources. (*Credit: International Earth Rotation and reference systems Service, IERS*)

optical or radio or at higher frequency radio-wavelength observations, where source structure is less pronounced; for more details, see e.g. Fey & Gaume (2006) or Zacharias (2006).

3.2 Main Recommendations of the IAU 2000 and IUGG 2003 Resolutions

The IAU 2000 resolutions, adopted by the XXIVth IAU General Assembly (August 2000) and endorsed by the XXIIIrd IUGG General Assembly (July 2003), have made important recommendations on space and time reference systems, the concepts, the parameters, and the models for Earth's rotation. These resolutions resulted from the recommendations of the IAU "ICRS Working Group" and the IAU/IUGG work on "Non-rigid Earth nutation theory." IAU 2000 Resolution B1.3 specifies the systems of space-time coordinates for the solar system and the Earth within the framework of GR and provides clear procedures for theoretical and computational developments of those space-time coordinates, and especially the transformation between the barycentric and geocentric coordinates. 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).

3.3 Main Recommendations of the IAU 2006 and IUGG 2007 Resolutions

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 and 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 Barycentric Celestial Reference System (BCRS) (and hence the Geocentric Celestial Reference System, GCRS) is assumed to be oriented according to the ICRS axes). IAU 2006 Resolution B3 provides a re-definition of Barycentric Dynamical Time (TDB) as a linear function of Barycentric Coordinate Time (TCB).

The adoption of a new precession model was recommended by the IAU WG on "Precession and the ecliptic" (Hilton et al. 2006), while the new terminology associated with the IAU 2000/2006 resolutions, along with some additional definitions related to them, was recommended by the IAU WG on "Nomenclature for Fundamental Astronomy" (Capitaine et al. 2007).

3.4 Main Recommendations of the IAU 2009 Resolutions

The IAU 2009 resolutions adopted by the XXVIIth IAU General Assembly (August 2009) have completed the 2000–2006 set of international agreements: (i) IAU 2009 Resolution B1 recommends adopting the IAU 2009 System of astronomical constants, consistent with the current measurement accuracy, as recommended by the IAU WG "Numerical Standards in Fundamental Astronomy," and (ii) IAU 2009 Resolution B2 recommends adopting a new version, called ICRF2, of the ICRF, which was constructed by the IERS/IVS working group on the ICRF.

4 CONSEQUENCES OF THE 2000–2009 RESOLUTIONS ON THE CONCEPTS, DEFINITIONS AND MODELS

4.1 Improved Definitions of Reference Systems for Astronomy and Geodesy

Relativistic modeling of astronomical observations is based on a relativistic four-dimensional reference system, which is a purely mathematical construction (a chart or a coordinate system) giving names to space-time events. Space-time coordinates have no direct physical meaning; it is therefore essential to construct the observables as coordinate-independent quantities. First, a coordinate picture of the measurement procedure should be formulated. Then the observables should be derived from that procedure, which requires defining useful and adequate coordinate systems for astronomy. A preliminary definition of systems of space-time for the solar system and the Earth was given by the IAU 1991 Resolution A4, but further developments were needed to ensure an accuracy in agreement with that of the modern measurements.

As specified by IAU 2000 Resolution B1.3, the BCRS should be used, with TCB, as a global coordinate system for the solar system. In contrast, the GCRS should be used, with Geocentric Coordinate Time (TCG), as a local coordinate system for the Earth, e.g. 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 BCRS-to-GCRS transformation was specified as an extension of the Lorentz transformation for the space and time coordinates that also contain acceleration terms and gravitational potentials (see Soffel et al. 2003). The recommended form of the metric tensor can be used to describe the barycentric reference system of the whole solar system, and also to define the geocentric reference system centered at the center of mass of the Earth with a suitable function depending upon geocentric coordinates. Thus the BCRS and GCRS are theoretically defined, but without any constraint on the orientation of the BCRS axes. Their default orientation was specified by IAU 2006 Resolution B2 that recommends the BCRS orientation be such that for all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes.

The IAU 2000/2006 resolutions on reference systems have been endorsed by IUGG (IUGG 2003 Resolution 4 and 2007 Resolution 2). In addition, IUGG recommended a terrestrial counterpart (IUGG 2007 Resolution 2), which stipulates that the Geocentric Terrestrial Reference System (GTRS) is defined in agreement with IAU 2000 Resolution B1.3, and the ITRS as "the specific GTRS for which the orientation is operationally maintained in continuity with past international agreements."

Thanks to these IAU/IUGG resolutions, the theoretical definition, as well as the orientation of the BCRS, GCRS, GTRS and ITRS, is specified in a clear and consistent way, which is essential for realizing both the ICRF and the ITRF, as well as for determining the Earth orientation parameters.

4.2 Improved Definitions of Time Coordinates for Astronomy and Geodesy

The IAU 2000 Resolution B1.3 has defined TCB and TCG as the time coordinates of the BCRS and GCRS, respectively. It has also defined the origin of the time scales in terms of International Atomic Time (TAI) and specified that the unit of all these time scales should be the SI second.

The IAU 2000/2006 resolutions have clarified the definitions of both the Terrestrial Time (TT) and Barycentric Dynamical Time (TDB). The re-definition of TT by IAU 2000 Resolution B1.9 is such that TT is a time scale differing from TCG by a constant rate, which is a defining constant

$$\mathrm{TCG} - \mathrm{TT} = L_G \times (\mathrm{JD} - 2443144.50) \times 86400\,\mathrm{s}, \tag{1}$$

with $L_G = 6.969290134 \times 10^{-10}$.

In a very similar way, the re-definition of TDB by IAU 2006 Resolution B3 is a linear transformation of TCB, the coefficients of which are defining constants

$$\mathrm{TCB} - \mathrm{TDB} = L_B \times (\mathrm{JD} - 2443144.5003725) \times 86400\,\mathrm{s} + TDB_0 \tag{2}$$

with $L_B = 1.550519768 \times 10^{-8}$ and $TDB_0 = 6.55 \times 10^{-5}\,\mathrm{s}$.

The consequence is that TT and TDB, which, for some practical applications, may be of a more convenient use than TCG and TCB, respectively, can be used with the same rigorous approach. This applies in particular to the solutions of the Earth's rotational equations that are usually expressed in TT and the solar system ephemerides (necessary for computing the lunisolar and planetary torque acting on Earth's rotation) that are usually expressed in TDB. This also applies to the realization of the ICRF, using TT-compatible VLBI space-coordinates and to the realization of the ITRF for which the use of TT was eventually applied, instead of TCG, due to historical reasons. The use of the SI second for TT as well as TDB has been further emphasized by Klioner et al. (2010).

It is important to note that, although TT and TDB have rigorous IAU definitions, the time coordinates recommended by IAU/IUGG for the solar system and the Earth are TCB and TCG, respectively. Note also that there is currently a significant effort at using TCB instead of TDB for solar system ephemerides and pulsar timing.

4.3 Improved Concepts, Definitions and Expressions for Earth Rotation

4.3.1 The Earth Orientation parameters

The transformation between the celestial and terrestrial systems is based on IAU and IUGG standards and models, plus IERS EOP. According to IAU 2000 Resolution B1.8, the ITRS to GCRS

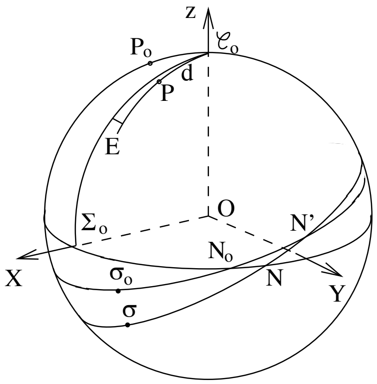

Fig. 2 The position of the Celestial Intermediate Pole (P) in the GCRS $(OX_0Y_0Z_0)$ (with pole $\mathcal{C}_0$ and origin Σ_0 on the GCRS equator) and the celestial intermediate origin, CIO (σ), on the CIP equator (with P_0 and σ_0 being the CIP and CIO at epoch t_0). E and d are the GCRS polar coordinates of P.

transformation should be specified by the position of the Celestial Intermediate Pole (CIP) in the GCRS (see Sect. 4.3.2 and Fig. 2), the position of the CIP in the ITRS, and the Earth Rotation Angle (ERA; see Sect. 4.3.3 and Fig. 3).

The position of the CIP in the ITRS (i.e. the ITRS direction of the CIP unit vector) is currently expressed in the form of the pole coordinates, i.e. x and y coordinates, in arcseconds, the values of which represent the corresponding angles with respect to the polar axis of the ITRS. The sign convention is such that x is positive towards the x-origin of the ITRS and y is in the direction 90° to the west of x. This can also be expressed in the form of the polar coordinates g and F, such that: $(x = \sin g \cos F; y = -\sin g \sin F)$. The motion of the Earth's pole with respect to the ITRS is called polar motion; it is quasi-periodic and essentially unpredictable. Its main components are the Chandlerian free motion with a period of approximately 430 days, and an annual motion. It also includes sub-daily variations caused by ocean tides and periodic motions driven by gravitational torques with periods less than two days.

The position of the CIP in the GCRS is currently represented by the x and y coordinates of the CIP unit vector in the GCRS, denoted X and Y $(X = \sin d \cos E; Y = \sin d \sin E)$; these quantities are often multiplied by $1\,296\,000''/2\pi$ in order to represent the approximate values in arcseconds of the corresponding angles with respect to the polar axis of the GCRS. This can also be expressed in the form of polar coordinates d and E (see Fig. 2), which are the celestial counterpart of the g and F angles in the ITRS. The quantities X and Y, which mainly include precession, nutation and frame bias, thus replace the classical precession and nutation quantities ψ_A, $\Delta\psi_A$, ω_A, $\Delta\omega_A$, etc. (see Fig. 3). The triaxiality of the Earth is responsible for nutations with a 0.5 day period that are not part of the IAU model but, according to the conventional definition of the CIP (see Sect. 4.3.2), are considered through the corresponding terms in polar motion. The celestial direction of the pole is predicted by the a priori IAU precession-nutation model; small adjustments (denoted $\mathrm{d}X$ and $\mathrm{d}Y$), which include the inaccuracies of the model and the observations, are derived from VLBI observations.

The third parameter to be used for the ITRS to GCRS transformation provides the variations in the Earth's diurnal angle of rotation through the ERA or UT1 (see Sect. 4.3.3).

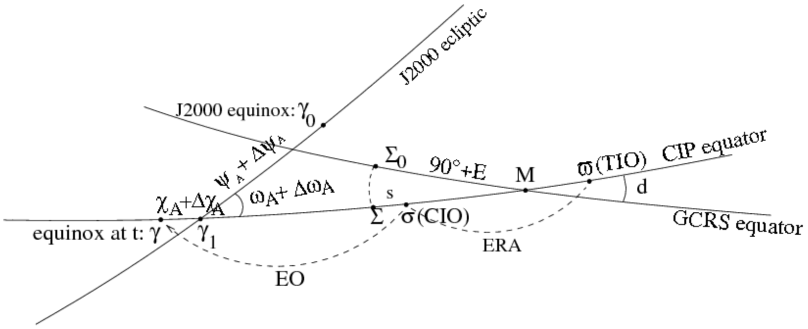

Fig. 3 The CIO based parameters for Earth rotation; E and d are the polar coordinates of the CIP (P) in the GCRS and the ERA is from the TIO to the CIO. EO is the equation of the origins that links the CIO and equinox based parameters; EO is the difference ERA−GST between ERA and Greenwich sidereal time, GST.

4.3.2 The conventional definition of the Celestial Intermediate Pole

IAU 2000 Resolution B1.7 specifies that the pole of the nominal Earth's rotation axis is the CIP. It is defined as the intermediate pole in the ITRS to GCRS transformation, separating nutation from polar motion by a specific convention in the frequency domain. The CIP definition in fact is an extension of the IAU 1980 definition of the Celestial Ephemeris Pole (CEP) in order to best define the pole in the high frequency domain.

The convention defining the CIP is such that (see Table 2): (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).

Table 2 Frequency Convention (in cycles per sidereal day) for the Definition of the CIP (note that, due to Earth's rotation: $\sigma_{\mathrm{ITRS}} = \sigma_{\mathrm{GCRS}} - 1$).

Frequency in TRS	−3.5	−2.5	−1.5	−0.5	+0.5	+1.5	+2.5 (cpsd)
	polar motion	polar motion		polar motion	polar motion		
Frequency in CRS	−2.5	−1.5	−0.5	+0.5	+1.5	+2.5	+3.5 (cpsd)
			nutation				

According to Resolution B1.7, the CIP is an intermediate pole separating, by convention, the motion of the pole of the TRS in the CRS into two parts:

- the celestial motion of the CIP (precession/nutation), including all the terms with periods greater than 2 days in the CRS (i.e. frequencies between -0.5 counts per sidereal day (cpsd) and $+0.5$ cpsd);

- the terrestrial motion of the CIP (polar motion), including all the terms outside the retrograde diurnal band in the TRS (i.e. frequencies lower than -1.5 cpsd or greater than -0.5 cpsd).

This allows us to clarify the models to be used for high frequency polar motion versus those to be used for the GCRS motion of the pole. With that convention, the celestial motion includes precession, nutations with periods greater than 2 days, the free core nutation (FCN), plus the offsets; in contrast, nutations with periods lower than 2 days should be included in the model for the polar motion in the ITRS.

4.3.3 The Earth Rotation Angle

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 (see Fig. 4) 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)

$$\begin{aligned}\mathrm{ERA(UT1)} &= 2\pi[0.7790572732640 \\ &+1.00273781191135448\,(\mathrm{JulianUT1date} - 2451545.0)]\,. \end{aligned} \tag{3}$$

The linear relationship between ERA and UT1 is a consequence of the kinematically non-rotating nature of the origins to which the ERA refers.

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 combined with Earth's rotation in the equinox based expression for Greenwich sidereal time, GST, which includes the accumulated precession and nutation in right ascension.

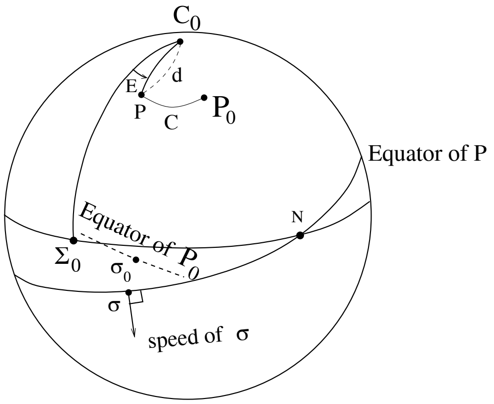

Fig. 4 The kinematical definition of the non-rotating origin, σ, on the intermediate equator of pole P moving with respect to the GCRS (P_0, Σ_0): the instantaneous displacement of σ is always perpendicular to the CIP equator. (P_0 and σ_0 are the CIP and CIO at epoch t_0).

4.3.4 Position of the CIP and the CIO in the GCRS

The x and y coordinates of the CIP unit vector in the GCRS, denoted X and Y, include (see e.g. Capitaine et al. 2003) (i) precession and nutation that are referring to a fixed conventional ecliptic, (ii) coupling between precession and nutation giving rise to Poisson terms, (iii) celestial offsets ξ_0, η_0 of the CIP at J2000.0 with respect to the GCRS and (iv) the coupling between the frame biases and precession-nutation. The offsets ξ_0, η_0 are the values, associated with the IAU 2000 nutation, as derived from VLBI observations and the equinox offset is the GCRS right ascension of the mean dynamical equinox at J2000 (-14.6 ± 0.5 mas) as provided by Chapront et al. (2002) from a fit to LLR observations based jointly on the use of a dynamical theory for the Moon and of VLBI EOP.

The IAU 2006/2000 expressions for X and Y (Capitaine & Wallace 2006) have the following form:

$$\begin{aligned} X \;=\; & -0.016617'' + 2004.191898''t - 0.4297829''t^2 - 0.19861834''t^3 \\ & -0.000007578''t^4 + 0.0000059285''t^5 \\ & +\textstyle\sum_i[(a_{\mathrm{s},0})_i \sin(\mathrm{ARG}) + (a_{\mathrm{c},0})_i \cos(\mathrm{ARG})] + \sum_i[(a_{\mathrm{s},1})_i t \sin(\mathrm{ARG}) + (a_{\mathrm{c},1})_i t \cos(\mathrm{ARG})] \\ & +\textstyle\sum_i[(a_{\mathrm{s},2})_i t^2 \sin(\mathrm{ARG}) + (a_{\mathrm{c},2})_i t^2 \cos(\mathrm{ARG})] + \cdots \end{aligned} \tag{4}$$

$$\begin{aligned} Y \;=\; & -0.006951'' - 0.025896''t - 22.4072747''t^2 + 0.00190059''t^3 \\ & +0.001112526''t^4 + 0.0000001358''t^5 \\ & +\textstyle\sum_i[(b_{\mathrm{c},0})_i \cos(\mathrm{ARG}) + (b_{\mathrm{s},0})_i \sin(\mathrm{ARG})] + \sum_i[(b_{\mathrm{c},1})_i t \cos(\mathrm{ARG}) + (b_{\mathrm{s},1})_i\, t \sin(\mathrm{ARG})] \\ & +\textstyle\sum_i[(b_{\mathrm{c},2})_i t^2 \cos(\mathrm{ARG}) + (b_{\mathrm{s},2})_i t^2 \sin(\mathrm{ARG})] + \cdots \end{aligned} \tag{5}$$

where $t = (\mathrm{TT} - 2000$ January 1d 12h TT$)$ in days/36525 and ARG stands for various combinations of the fundamental arguments of the nutation theory, including both lunisolar and planetary terms.

The IAU 2006/2000 expression for the quantity s (Capitaine et al. 2003), providing the GCRS position of the CIO, limited to the terms with amplitudes greater than 10 µas, is as follows (unit µas)

$$\begin{aligned} s(t) \;=\; & -XY/2 + 94 + 3809t - 123t^2 - 72574t^3 + 28t^4 + 16t^5 \\ & -2641 \sin\Omega - 64 \sin 2\Omega - 12 \sin(2F - 2D + 3\Omega) - 11 \sin(2F - 2D + \Omega) \\ & +744t^2 \sin\Omega + 57t^2 \sin(2F - 2D + 2\Omega) + 10t^2 \sin(2F + 2\Omega) - 24t^3 \cos\Omega\,. \end{aligned} \tag{6}$$

The above expressions for X, Y and s are provided in the IERS Conventions 2010 together with the corresponding software to implement them.

4.4 Improved Nomenclature for Fundamental Astronomy

The IAU WG on "Nomenclature for Fundamental Astronomy" (IAU WG NFA) 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; it also contains new definitions proposed by the WG, including those formally endorsed by the IAU in 2006 and the IUGG in 2007. This concerns terminology for the pole, the Earth's angle of rotation, the longitude origins and the related reference systems.

A change with respect to the usual equinox based nomenclature concerns in particular the equatorial coordinates, the nomenclature of which has been associated, in addition to the equinox, to the CIO or with the ICRS (see Fig. 5 and Table 3). With that terminology, right ascension and declination are considered as being generic terms which can refer to any equator and any origin on that equator.

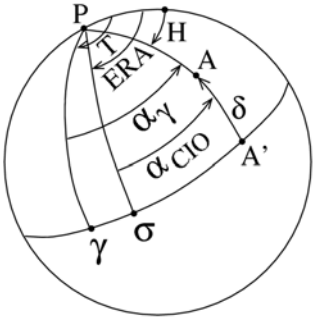

Fig. 5 The equinox right ascension, α_γ (or α_e), and the CIO right ascension, $\alpha_{\rm CIO}$ (or α_i) of a celestial object, A. α_γ and $\alpha_{\rm CIO}$ should be associated with Greenwich sidereal time, T and Earth Rotation Angle (ERA), respectively. The hour angle of A is H=T$-\alpha_\gamma$ =ERA$-\alpha_{\rm CIO}$.

Table 3 Equatorial Coordinates Referring to Various Origins According to the IAU WG on Nomenclature for Fundamental Astronomy (Capitaine et al. 2007).

Notation	Nomenclature
α	right ascension (generic term)
α_i or $\alpha_{\rm CIO}$	intermediate right ascension CIO right ascension
α_e or α_γ	equinox right ascension right ascension with respect to the equinox
$\alpha_{\rm ICRS}$	ICRS right ascension
δ	declination (generic term)
$\delta_{\rm ICRS}$	declination measured from the ICRS equator

The IAU WG NFA has also provided a chart explaining the reduction process from ICRS to ITRS coordinates of the directions of stars specifying in what order to apply the usual corrections as well as the successive celestial reference systems to which the coordinates are referred and the time scale to use (see Fig. 6).

The NFA Glossary includes in particular definitions for the celestial and terrestrial reference systems ICRS, BCRS, GCRS, ITRS and the Celestial and Terrestrial Intermediate Reference Systems. Definitions are given for the intermediate equator as the equator of the CIP, the CIO and TIO origins, 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. A few examples of refined definitions provided in the IAU 2006 NFA Glossary for terms related to the ICRF definition and realization are given below.

- **ICRS**: the idealized barycentric coordinate system to which celestial positions are referred. It is kinematically non-rotating with respect to the ensemble of distant extragalactic objects. It has no

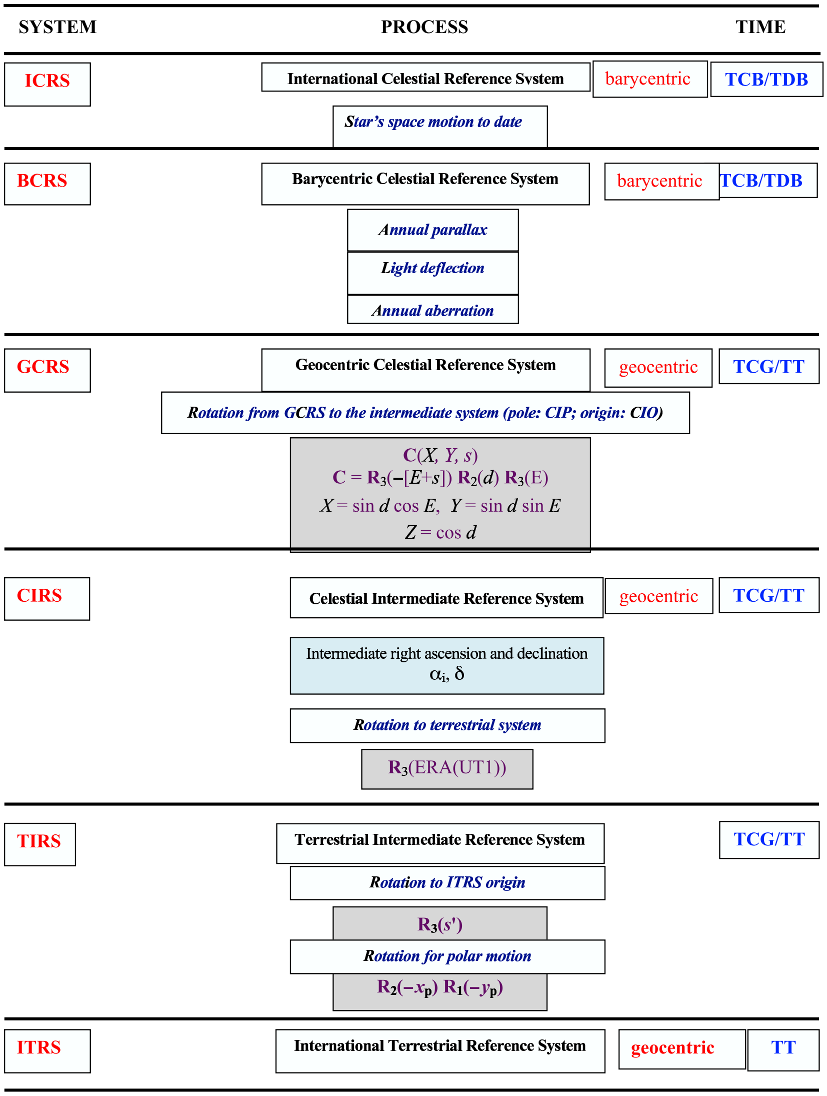

Fig. 6 The reduction process from ICRS to ITRS coordinates of the directions of stars specifying in what order to apply the usual corrections as well as the successive celestial reference systems to which the coordinates are referred and the time scale to use. The process refers to the CIO based parameters for Earth's rotation; E and d are the polar coordinates of the CIP in the GCRS and ERA is the Earth Rotation Angle.

intrinsic orientation but was aligned close to the mean equator and dynamical equinox of J2000.0 for continuity with previous fundamental reference systems. Its orientation is independent of epoch, ecliptic or equator and is realized by a list of adopted coordinates of extragalactic sources.

- **ICRF**: a set of extragalactic objects whose adopted positions and uncertainties realize the ICRS axes and give the uncertainties of the axes. It is also the name of the radio catalog, with 212 defining sources, that is currently the most accurate realization of the ICRS. Note that the orientation of the ICRF catalog was carried over from earlier IERS radio catalogs and was within the errors of the standard stellar and dynamic frames at the time of adoption. Successive revisions of the ICRF are intended to minimize rotation from its original orientation. Other realizations of the ICRS have specific names (e.g. the HCRF).

- **BCRS**: a system of barycentric space-time coordinates for the solar system within the framework of GR with metric tensor specified by the IAU 2000 Resolution B1.3. Formally, the metric tensor of the BCRS does not fix the coordinates completely, leaving the final orientation of the spatial axes undefined. However, according to IAU 2006 Resolution B2, for all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes.
- **GCRS**: a system of geocentric space-time coordinates within the framework of GR with metric tensor specified by the IAU 2000 Resolution B1.3. The GCRS is defined such that the transformation between BCRS and GCRS spatial coordinates contains no rotation component, so that GCRS is kinematically non-rotating with respect to BCRS. The equations of motion of, for example, an Earth satellite, with respect to the GCRS will contain relativistic Coriolis forces that come mainly from geodesic precession. The spatial orientation of the GCRS is derived from that of the BCRS, that is (c.f. IAU 2006 Resolution B2), unless otherwise stated, by the orientation of the ICRS.
- **CIO**: origin for right ascension on the intermediate equator in the Celestial Intermediate Reference System. It is the non-rotating origin in the GCRS that is recommended by the IAU 2000 Resolution B 1.8, where it was designated the Celestial Ephemeris Origin. The name CIO was adopted by IAU 2006 Resolution B2. The CIO was originally set close to the GCRS meridian and throughout 1900–2100 stays within $0.1''$ of this alignment.

4.5 Improved Precession-Nutation

VLBI observations, which allow an accurate determination of the direction of the celestial pole with respect to the GCRS direction, have provided, on a regular basis since 1985, the difference between the observed direction and that predicted with the IAU precession-nutation model at that time, which was the 1976/1980 model. The time series of these so-called "celestial pole offsets" observed by VLBI showed a linear variation in longitude × sin (obliquity) of the order of $-0.1''$ century^{-1}, as well as periodic terms in both components due to errors in the amplitudes of nutation (see Fig. 7).

4.5.1 The improvement of the IAU model

IAU 2000 Resolution B1.6 recommends the adoption of the new precession-nutation model that is designated IAU 2000A corresponding to the model of Mathews et al. (2002), denoted MHB2000. The precession part of the IAU 2000A model consists only of corrections, $\delta\psi_A = -0.29965''$ century^{-1} and $\delta\omega_A = -0.02524''$ century^{-1} to the precession rates (in longitude and obliquity referring 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 recommendation of IAU 2006 Resolution B2 to adopt the P03 Precession (Capitaine et al. 2003) as a replacement for the precession part of the IAU 2000A precession-nutation, beginning on 2009 January 1. Details for implementing the IAU 2006/2000 precession-nutation have been given by Capitaine & Wallace (2006) and Wallace & Capitaine (2006). All 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 in Chapter 5 of the IERS Conventions 2003, in its final form in the 2010 version (IERS Conventions 2010) and the Standards Of Fundamental Astronomy (SOFA) (Wallace

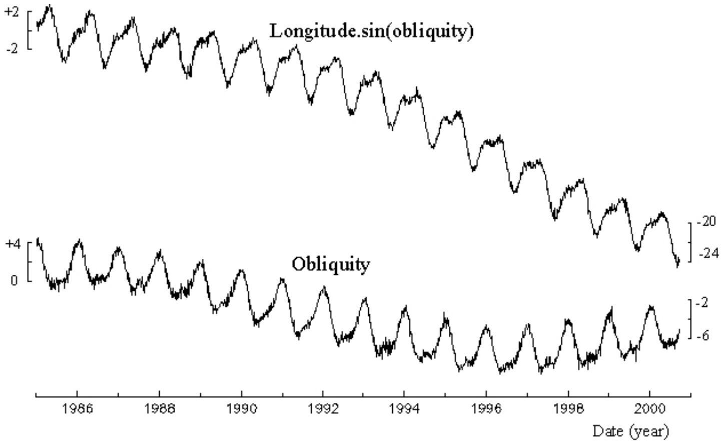

Fig. 7 Differences observed in $0.001''$ (mas) between the direction of the celestial pole in the ICRS, determined from VLBI observations of extragalactic radio sources and the direction of that pole computed with the IAU 1976/1980 precession-nutation model, between 1985 and 2001. The differences are mainly due to the discrepancy of the model: a linear term in the first component due to an error in precession rate and periodic terms in both components due to errors in the amplitudes of nutation (the largest ones being on the 18.6-yr and semi-annual terms). (*Credit: International Earth Rotation and Reference System Service*)

1998). A detailed comparison of that model with other models and with VLBI observations has been provided by Capitaine et al. (2009).

4.5.2 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 lunisolar and planetary nutations, $\Delta\psi$ in longitude and $\Delta\epsilon$ in obliquity, referring to the ecliptic of date, composed of "in-phase" and "out-of-phase" components with their time variations, with arguments that are functions 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 geodesic nutation contributions to the annual, semi-annual and 18.6-year terms from Fukushima (1991) are part of the model.

The IAU 2000A nutation includes, from 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, there is a free core nutation (FCN) that is due to the existence of a fluid core, which being a free motion, cannot be predicted rigorously. It is not considered a part of the IAU 2000A model; this limits the accuracy in the computed direction of the celestial pole in the GCRS to about 0.3 mas. However, once corrected using an empirical model, the accuracy is reduced to better than 0.15 mas (see Fig. 8). The MHB2000 Basic Earth Parameters fitted to VLBI data (c.f. Table 4) are:

- the Earth's dynamical flattening $H_d = e/(1+e)$, which is a scale factor for the precession rate and nutation amplitudes;
- the deformability parameters of the whole Earth and the core under tidal forcing;
- three real and imaginary parts of the complex coupling constants of the electromagnetic couplings, core/mantle and fluid core/inner core;
- the dynamical flattening of the core, e_{f}, which is a resonance factor for the nutation amplitudes.

The determination of the above parameters is essential for improving the knowledge of the dynamics of the Earth in a way that is complementary to geophysical means, such as seismologic observations.

Table 4 Estimates of BEP from a Least Squares Fit to VLBI by Mathews et al. (2002)

Basic Earth Parameters	Estimate
Dynamical flattening of the Earth or fluid core	
e	0.0032845479 ± 12
e_{f}	0.0026456 ± 20
Elasticity parameters	
κ	0.0010340 ± 92
γ	0.0019662 ± 14
Electromagnetic coupling factors	
Im $K^{(\mathrm{CMB})}$	–0.0000185 ± 14
Re $K^{(\mathrm{ICB})}$	0.00111 ± 10
Im $K^{(\mathrm{ICB})}$	–0.00078 ± 13
rms residuals (in mas)	0.0132

4.5.3 Main features of the IAU 2006 precession

The IAU 2006 precession (Capitaine et al. 2003) provides improved polynomial expressions up to the fifth 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 corresponding Earth's dynamical flattening is consistent with the MHB value for that parameter (by taking into account the change by 42 mas of the J2000 mean obliquity with respect to the IAU 2000 value). Moreover, the IAU 2006 precession includes the Earth's J_2 rate effect ($dJ_2/dt = -3 \times 10^{-9}$ century^{-1}), 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 second order effects, the J_3 and J_4 effects of the lunisolar torque, the J_2 and planetary tilt effects, as well as the tidal effects are from Williams (1994), and the non-linear terms are

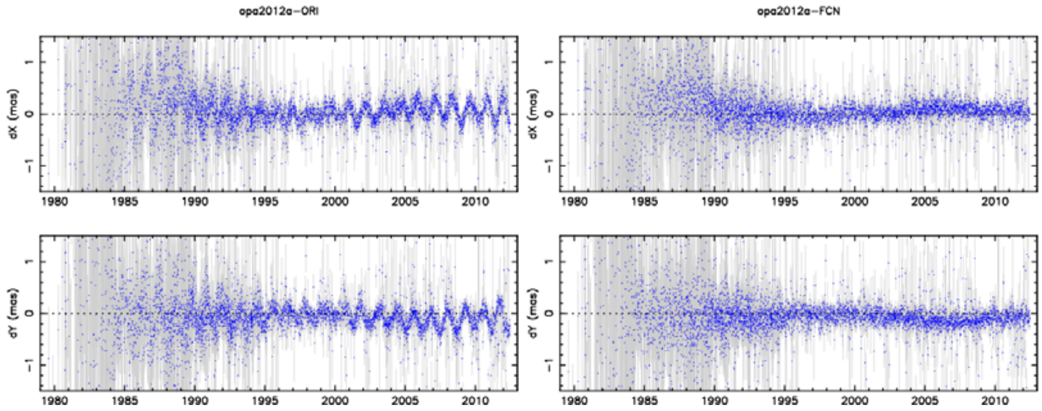

Fig. 8 Differences observed in $0.001''$ (mas) between the direction of the celestial pole in the ICRS, determined from VLBI observations of extragalactic radio sources and the direction or that pole computed with the IAU 2006/2000 precession-nutation model, between 1985 and 2012. The differences are mainly due to a periodic free motion of the pole (called "free core nutation"), of period about 430 days in the ICRS and amplitude between 0 and 0.4 mas, which cannot be perfectly modeled. Once this term is corrected for, the (weighted mean square) difference between model and observations is less than 0.15 mas. (*Credit: Paris Observatory (SYRTE) IVS analysis center*)

from MHB2000. The geodesic precession (i.e. $p_{\rm g} = 1.9198830''$ century^{-1}) is from Brumberg et al. (1992).

The maximum discrepancy of VLBI celestial pole offsets with respect to IAU 2006/2000, expressed as GCRS direction of the CIP, are currently of the order of 0.1 mas century^{-1} in the coefficients of the secular terms, a few tens of μas in the amplitude of the 18.6-yr nutation (see Fig. 8) and lower than 20 μas for the other nutation terms.

Comparing Figures 7 and 8 illustrates (i) the significant improvement of the accuracy of the VLBI observations from the period 1985–1995 to the period 1995–2012, (ii) the significant improvement of the accuracy of the IAU precession-nutation model used for predicting the GCRS CIP position and (iii) the change from the equinox based parameters (dψ, dϵ) to the CIO ones (dX, dY).

4.5.4 The improved Earth model

Improvement in the model for precession-nutation corresponds to a better knowledge of the dynamics of the Earth's interior. One illustration is the period of the Free Core Nutation (FCN) (Mathews et al. 2002), which is closely linked to the dynamical flattening of the outer core, $e_{\rm f}$ (see Table 4). The geophysical model PREM gives a period of 458 days, whereas the VLBI estimate is (430.20 ± 0.28) d, which corresponds to a difference of 350 m in the equatorial bulge (see Fig. 9) resulting from the non-hydrostatic effect plus electromagnetic coupling. Another illustration is the precession rate in the X CIP coordinates that is closely related to the dynamical flattening of the Earth, e, which corresponds to a change of about 0.1 mas century^{-1} in the previous (1976) precession rate.

4.6 Improved Astronomical Constants

A system of "astronomical constants" is a conventional set of numerical values adopted for some constants involved in the representation of astronomical and geodetic observations and in the nu-

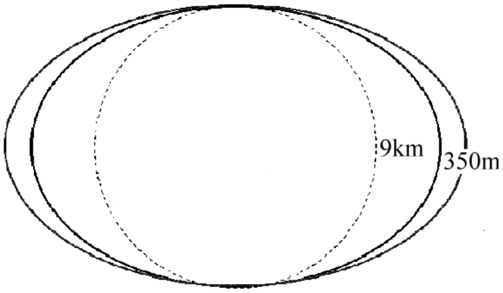

Fig. 9 Correction to the dynamical flattening of the core derived from VLBI observations through the determination of the effect of that parameter on the amplitudes of nutation.

merical developments of the theory of motions of celestial objects. These numerical values are the basis of all astronomical calculations, and they set the dynamic representation of the solar system and its possible connection with galactic and extragalactic objects. The consistency and accuracy of that system of constants are of great importance for any reduction of astronomical observation and theoretical calculation for any position or motion of a body in the solar system or a star. Only the use of the same constants in all astronomical works allows a valid comparison of the results. It is essential e.g. for the computation of astronomical ephemerides, or for modeling the motion of Earth around its axis (precession-nutation), or computing the direction of a star relative to an observer on Earth. The quality of that system of constants must be regularly adapted to the measurement accuracy, as has been done for over a hundred years. The first system of astronomical constants was adopted in 1896 during the "International Conference of fundamental stars," held in Paris, and took effect from 1901. Then, the IAU has successively adopted the systems named "IAU 1964," which

Table 5 Extract of the Table of Numerical Values of the IAU 2009 System of Astronomical Constants (from Luzum et al. 2011)

Constant	Description	Value	
		Auxiliary Defining Constants	
k	Gaussian gravitational constant	1.720209895 $\times 10^{-2}$	
Constant	Description	Value	Uncertainty
		Other Constants	
au	Astronomical unit	1.49597870700 $\times 10^{11}$ m (TDB compatible)	3 m (TDB compatible)
		Body Constants	
$\mathrm{GM_S}$	Heliocentric gravitational constant	1.32712442099 $\times 10^{20}$ m^3 s^{-2} (TCB-compatible) 1.32712440041 $\times 10^{20}$ m^3 s^{-2} (TDB-compatible)	1.0 $\times 10^{10}$ m^3 s^{-2} (TCB-compatible) 1.0 $\times 10^{10}$ m^3 s^{-2} (TDB-compatible)
a_E	Equatorial radius of the Earth	6.3781366 $\times 10^6$ m (TT compatible)	1 $\times 10^{-1}$ m (TT compatible)
J_2	Dynamical form factor	1.0826359 $\times 10^{-3}$	1 $\times 10^{-10}$
$\dot{J}_2$	Time rate of change in J_2	-3.0×10^{-9} century^{-1}	6 $\times 10^{-10}$ century^{-1}

was applied from 1968, "IAU 1976," implemented from 1984 and "IAU 2009," implemented from 2010.

The improvement of the IAU 2009 system of astronomical constants on the previous system consists of a more rigorous classification of the constants according to their nature, a very significant improvement in the accuracy of numerical values, the addition of new constants and the expression of the numerical values in agreement with the different relativistic time scales used in the solar system. Note that the list of constants includes conventional values adopted by the IAU in 2000 and 2006 for the definition of the Earth rotation angle (ERA) and time scales TT and TDB. The numerical values benefit from the precision of the determination of physical parameters of the Earth, Moon, planets and small bodies in the solar system by radar and Doppler measurements, or laser ranging, as well as by recent determinations of the gravity field on Earth by space geodesy. Note for instance that the relative uncertainty in the measurements of the Earth-Sun distance, which was of the order of 10^{-4} in 1960, has been reduced to 10^{-11}.

Table 5 is an extract of the table of numerical values of the IAU 2009 system of astronomical constants published by Luzum et al. (2011).

5 MICROARCSECOND DEFINITION AND REALIZATION OF CELESTIAL REFERENCE FRAMES

The significant improvement of the astronomical references provided by the recent resolutions on reference systems that have been adopted by the IAU, as described in the previous sections, allows obtaining a better accuracy of the positions and motions of the celestial objects (i.e. the Earth, bodies in the solar system, stars, extragalactic objects, etc.). This opens new perspectives for a better understanding of physical processes, such as those affecting the Earth's orientation in space, or those being sensitive to possible variations of constants in physics, such as the gravitational constant, G, or of the mass of the Sun. Note that the role of astronomical reference systems is also essential for a number of practical applications, e.g. the launch of artificial satellites and spacecraft navigation.

5.1 The Astronomical Space-time Coordinates

Recent IAU resolutions on the astronomical space-time coordinates aim at achieving microarcsecond accuracy. The BCRS can be considered as being inertial (if neglecting the external Galactic and extragalactic matter). It is used for solar system ephemerides, concepts such as an ecliptic, interplanetary spacecraft navigation, etc. The positions of remote objects can be defined in that system. The BCRS is the fundamental astrometric system, in which concepts such as proper motion and radial velocity can be defined. The GCRS can be considered as being quasi-inertial, since the spatial axes are not rotating in the Newtonian absolute sense, whereas the geocenter is accelerated. It is used for the description of physical processes in the vicinity of Earth, for satellite theory, the dynamics of Earth (including Earth's rotation), etc. It is also used for the introduction of concepts such as the equator and the ITRS. This requires using the IAU recommended four-dimensional space-time transformation (generalized Lorentz transformation) between BCRS and GCRS coordinates.

5.2 The Second Realization of the International Celestial Reference Frame

The second version of the International Celestial Reference Frame, called ICRF2, was realized by the IERS/IVS WG and recommended by the IAU WG "ICRF2" (Fey et al. 2009); it was adopted by IAU 2009 Resolution B3 as the fundamental realization of the ICRS. The aim was to improve the realization with densification of the frame and a more precise definition of the axes. The ICRF2 contains precise positions of 3414 compact radio astronomical sources; it has been found to have a noise floor of 40 μas. The densification of the frame was made possible thanks to the very large number of VLBI and VLBA observations available. Improvement in the accuracy results from the improved accuracy of VLBI observations along with advances in modeling and estimation. These have benefited, in many aspects, from the improvements in the concepts, models and procedures that have been introduced by the recent IAU resolutions, and especially the 2000/2006 resolutions.

One important aspect for the accuracy of the ICRF is the use of the IAU 2000/2006 definitions and procedures for the barycentric and geocentric space-time coordinates and the transformation between them. Another important aspect is the orientation issue. ICRF2 was aligned to ICRF1 by using a set of stable sources common to both ICRF2 and ICRF1-ext2. The purpose was to minimize rotation from the original ICRF orientation. This complies with the IAU 1997 resolution recommending that further improvements of the ICRF will be accomplished without introducing any global rotation. This also complies with IAU 2006 Resolution B2 on the default orientation of the BCRS/GCRS. Moreover, it is important to note that, according to the IAU 2000/2006 resolutions, (i) the geodesic precession and geodesic nutation have been taken into account and (ii) the frame biases between the model and the GCRS have been introduced in a rigorous way. This ensures that the GCRS is defined without introducing any time-dependent rotation with respect to the BCRS and that the orientation of the ICRF is not dependent on the Earth's orientation at a given epoch.

The way the varying Earth's celestial orientation (i.e. of the ITRS in the GCRS) is also essential. The refined definition of the pole as well as the use of the new paradigm recommended by the resolutions for the terrestrial-to-celestial coordinate transformation allow an accurate estimation of the Earth's rotation and precession-nutation separately. This is important for the accuracy of the ICRF realization. Thanks to special efforts, the IAU 2000/2006 expressions have been developed in order that the equinox based paradigm can benefit from the clear separation between the Earth's angle of rotation and precession-nutation offered by the CIO based representation and consequently provide the same accuracy.

Since the adoption of ICRF2, a number of catalogs of celestial objects have been linked to that frame in order to densify it and make it accessible to astronomical observations at different wavelengths.

5.3 The Proposal for a New Definition of the Astronomical Unit of Length

Microarcsecond realization of celestial reference frames should be associated with a self consistent set of units and numerical standards compliant with GR. For this purpose, the definition and status of the astronomical unit need to be re-considered as explained in the following.

The IAU 1976 System of Astronomical Constants specifies the units for the dynamics of the solar system; this includes the day (D=86400 s), the mass of the Sun, M_S, and the astronomical unit of length (i.e. the astronomical unit), the definition of which is based on the value of the Gaussian gravitational constant, k. The aim of the above definition was to provide accurate relative distances (expressed in astronomical units) in the solar system, when BCRS distances could not be estimated with high accuracy. The value of the astronomical unit in meters was determined observationally, i.e. fitted to a planetary ephemeris with a given uncertainty; the value in SI units of the heliocentric gravitational constant (or Sun mass parameter), GM_S, had to be derived from k, along with the adopted the adopted value, A, for the astronomical unit in meters, using the formula: $GM_\mathrm{S} = A^3k^2/D^2$ (1). The IAU 2009 system of astronomical constants adopted by IAU 2009 Resolution B2 (see Table 5) retained the IAU 1976 definition of the astronomical unit. The Gaussian gravitational constant is listed as an "auxiliary defining constant" (with its IAU 1976 numerical value) that has to be used to define the astronomical unit and its relationship with GM_S. The IAU 2009 value of the astronomical unit is an average (from Pitjeva & Standish 2009) of recent estimates for the astronomical unit defined by k. The value is compatible with TDB. There was no accepted definition for the TCB-compatible value of the au at the time of the adoption of the IAU 2009 system. The IAU 2009 TDB-compatible value for GM_S was derived from the relation (1) above by using the astronomical unit (as defined by

k) fit to the DE421 ephemerides (from Folkner et al. 2008), which is consistent with the IAU 2009 value of the au to within the errors of the estimate.

Huge improvements have been achieved in solar system ephemerides during the last decade. A revision of the definition and status of the astronomical unit has been shown to be necessary in order to make the system of astronomical constants best comply with modern dynamical astronomy. This was discussed recently by Klioner (2008), Capitaine & Guinot (2009) and Capitaine et al. (2011). This is recommended in a draft resolution proposal to the IAU 2012 General Assembly that re-defines the astronomical unit as a fixed number of SI meters through a defining constant. The new definition will change the status of the astronomical unit of length, with a number of advantages as compared to the historical definition (still in use in the IAU 2009 system of astronomical constants). First, this will provide a self-consistent set of units and numerical standards for use in modern dynamical astronomy in the framework of GR. Second, the accuracy of measurements provided by modern observations in the solar system (ranging to planets, spacecraft observations, VLBI, etc.) makes the use of relative distances (which was the reason for the historical definition of the au) unnecessary so that the historical definition of the au is no longer appropriate for being used with modern solar system ephemerides. Third, modern planetary ephemerides (e.g. INPOP08, DE423, EPM2008) can now determine the solar mass parameter, $GM_{\rm S}$, directly in SI units and this quantity may vary with time. The direct estimation of $GM_{\rm S}$ was first tested in the INPOP08 ephemerides (Fienga et al. 2009). The decrease of that quantity is expected to be detectable in a near future, i.e. when the accuracy has been improved by a factor of 10. With the current definition of the au, the time dependence of $GM_{\rm S}$ leads to time-dependent astronomical units for length and mass; the use of such units to measure possible time variations of the solar mass parameters would be non sense. These make clear that the IAU 1976 definition of the au currently appears as an intermediate unit only used for historical purposes and has to be changed. It it necessary to note, that although the definition of the au has to be revised, there is still a need (especially for expressing the distances in the solar system) for a unit of length approximating the Sun-Earth distance.

The draft resolution proposal, which has been submitted to the IAU 2012 General Assembly, recommends that the astronomical unit be re-defined to be a conventional unit of length equal to 149 597 870 700 m exactly, as adopted in IAU 2009 Resolution B2 and that this definition of the astronomical unit be used with all time scales (including TCB, TDB, TCG, and TT). Note that the Bureau International des Poids et Mesures (BIPM) Consultative Committee for Units (CCU) declared its support to move to a fixed relationship to the SI meter through a defining number determined by continuity (CCU 2009). Therefore the Gaussian gravitational constant k will not be used any longer for such a use and the value of the heliocentric gravitational constant, $GM_{\rm S}$, will be determined observationally in SI units.

6 SUMMARY

The IAU resolutions on reference systems that have been adopted since 1997 have had important consequences in astronomy. The ICRF adopted since 1998 January 1, which is fixed and epoch independent, is now in general use. The IAU 2000 and IAU 2006 resolutions have adopted high accuracy definitions, models and conventions that have been progressively implemented. These improvements have contributed to the improvement of the definition and realization of the ICRF, the second version of which has been adopted by the IAU in 2009 as the fundamental realization of the ICRS. The astronomical reference systems to be used, as well as the transformation between them, are defined in the framework of GR. These are the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS) with their associated time scales, the Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG). The way the Earth orientation (i.e. the transformation between the terrestrial and celestial reference systems) is expressed, as well as the observation reduction procedure, has been modified. The recommended procedures, that have been implemented in the IERS Conventions 2003, are CIO based procedures that use the intermediate reference systems defined by the CIP, CIO and TIO and Earth Rotation Angle (ERA). The IAU 2006/2000 precession-nutation model, that has been implemented in the IERS Conventions 2010, has an accuracy of the order of tens of microarcseconds over a 20-yr period; when expressed as the GCRS coordinates of the CIP, the model combines precession and nutation and includes the frame bias with respect to the GCRS. Current ephemerides of solar system bodies refer to the ICRF and the equinox and ecliptic are only needed for the phenomena. The concepts, nomenclature, models and conventions in fundamental astronomy have been improved by these resolutions in order to be the most suitable for the most accurate realization of the reference systems. Thanks to these refinements, microarcsecond accuracies in the definition and realization of Celestial Reference Frames, are possible.

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