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# Proceedings of the IERS Workshop on the Implementation of the New IAU Resolutions

*Observatoire de Paris, Paris, France,*
*18 – 19 April 2002*

Edited by

Nicole Capitaine,
Daniel Gambis, Dennis D. McCarthy, Gérard Petit,
Jim Ray, Bernd Richter,
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# Preface

These Proceedings contain the oral and poster presentations at the IERS Workshop on the "Implementation of the New IAU Resolutions" which was held at Observatoire de Paris on 18 and 19 April 2002. This Workshop was organized in order to discuss and explain all possible aspects of the implementation of the new Resolutions adopted by the IAU at its XXIV General Assembly in August 2000, which will become effective on 1 January 2003. The scope of the IAU actions is very broad, affecting nearly the entire spectrum of IERS services. The new IAU Resolutions provide: extended general relativistic specifications for well-defined solar system barycentric and the geocentric celestial reference systems and for time transformations of sufficient accuracy to satisfy emerging observational requirements; a new definition of terrestrial time TT; a new nutation-precession model; and a new formulation for the transformation between the celestial and terrestrial reference systems using a new Celestial Intermediate Pole and Celestial and Terrestrial Ephemeris Origins rather than the conventional ecliptic/equinox system.

Only invited position papers were presented, which were made available in advance and displayed on the website of the Workshop (www.iers.org/workshop_2002). Additionally, a questionnaire was widely distributed to the participants and other IERS users beforehand to identify key problems and questions to be considered in the presentations. About 80 participants from 20 countries attended the meeting.

The Workshop was divided into two parts. The first part included detailed presentations and explanations of the Resolutions, their background reasons (Session 2), contents and practical consequences (Session 3), comparison between "old" and "new" concepts (Session 4), procedures and software (Session 5), as well as answers to specific questions. These were followed by a summary of the responses to the questionnaire and then by the poster session. The first part also included a presentation of the future IERS products (Session 6) to comply with the IAU Resolutions and finally a presentation of the compatibility with past observations (Session 7). The second part was devoted to an extended discussion based on the responses to the questionnaire and other questions that were raised during the Workshop.

These Proceedings include all the position papers, revised to account for the Workshop discussions and reviewed by the SOC, and also include extended abstracts of all the posters that have been presented and discussed during the poster session.

During the Workshop, there were fruitful exchanges between participants and presenters on the reasons for the adoption of the Resolutions, their consequences, as well as on the details concerning their implementation in astronomy, Earth rotation, ephemerides, etc. Some specific actions were identified which will require further efforts by the IERS, the presenters, or others to facilitate the practical use of the Conventions, to provide detailed explanations, and to develop certified software routines to convert between the old and new systems. (See the website at maia.usno.navy.mil/conv2000 for further information.)

The future IERS Products are outlined in the paper of Session 6, with emphasis on possible modifications and additions that will be necessary to implement the IAU Resolutions. According to the IAU Resolutions, the IERS is obliged to start publishing EOP values in the new transformational system at the start of 2003, a goal that the IERS Directing Board has endorsed. It is important for users to note that the IERS is also committed to continuing to provide EOP time series consistent with the conventional transformations.

We hope that these Proceedings fulfil user requirements and provide to the scientific community theoretical and practical bases for the best implementation of the IAU Resolutions.

*SOC of the IERS Workshop*

*Nicole Capitaine (Chair), Daniel Gambis, Dennis D. McCarthy, Gérard Petit, Jim Ray, Bernd Richter, Markus Rothacher, Myles Standish, and Jan Vondrak*

# Background Reasons for the IAU 2000 Resolutions Requiring Actions from the IERS

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## 1 INTRODUCTION

The resolutions adopted at the IAU 24th General Assembly in 2000 have been in fact prepared during a decade. They reflect the increasing accuracy of astrometric observations (expected to be at a microarcsecond level in near future), and hence the urgent need for more precise definitions of time-space transformations. The resolutions are closely related to past IAU decisions, namely those taken at its preceding General Assemblies:

- in 1991, when the conceptual definitions of celestial reference system and time scales in the framework of general relativity were adopted,
- in 1994, when the list of extragalactic sources defining the conventional reference frame was adopted and a Joint Working Group of IAU and IUGG on the non-rigid Earth nutation was formed, and
- in 1997, when the new International Celestial Reference System (ICRS) and Frame (ICRF) were adopted.

The resolutions, before being put on a vote at the IAU 24th General Assembly, had been discussed and pre-prepared at many scientific meetings, the most important ones being

- the Journées Systèmes de Référence Spatio-temporels - *Conceptual, Conventional and Practical Studies Related to Earth Rotation* (Paris, September 1998), where the theoretical aspects were discussed;
- the IAU Colloquium 180 *Towards Models and Constants for Sub-Microarcsecond Astrometry* (Washington, DC, March 2000), where the draft resolutions were prepared;
- the Joint Discussion 2 – *Models and Constants for Sub-Microarcsecond Astrometry* at the IAU 24th General Assembly, (Manchester, August 2000), where the final wording of the resolutions was formulated.

The International Earth Rotation Service as well as interested components of IUGG/IAG (e.g., IAU/IUGG Joint Working Group on non-rigid Earth nutation, IAG Special Commission 3 – Fundamental Parameters) have been involved, either directly or indirectly, in preparing these new concepts from the very beginning. A number of these resolutions have direct impact on the work of the IERS.

## 2 THE RESOLUTIONS AND REASONS LEADING TO THEIR ADOPTION

The IAU resolutions, relevant to the IERS, are given in a form of a 'packet' of nine closely related resolutions (B1.1-B1.9) plus an additional resolution (B2). Full text of all these resolutions is given in the Annex, here follows a shortly commented contents of each of them.

*Resolutions B1.1 and B1.2 concern the celestial reference systems and frames; they reflect the increasing need for more accurate and dense frames (in different wavelengths) with respect to which the motions and rotations of celestial bodies are observed. They were prepared by the IAU Working Group on International Celestial Reference System.*

**Resolution B1.1 Maintenance and Establishment of Reference Frames and Systems**

The International Celestial Reference System (ICRS) and Frame (ICRF) are defined by means of directions to and adopted positions of extragalactic objects in radio wavelength. At present, there are 212 defining, 294 candidate and 102 other radio objects. In spite of so far negligible proper motions of these objects, their structures have different shapes that are often time-changing. Therefore, these systems and frames need to be regularly maintained, densified and extended to other wavelengths (optical, infrared…). The resolution stresses the importance of VLBI observations, extends the activity of the IAU Working Group on Celestial Reference Systems, and asks its members to consult with the IERS regarding the maintenance of the ICRS. Very important role plays the International VLBI Service, through which the IERS cooperates with the IAU WG.

**Resolution B1.2 Hipparcos Celestial Reference Frame**

The Hipparcos Catalogue is the primary realisation of the ICRS at optical wavelengths. However, some of the Hipparcos stars belong to binary or multiple systems and exhibit complicated orbital motions. The immediate values of proper motions, determined during less than four years of Hipparcos mission, thus differ substantially from their mean values. The resolution establishes the Hipparcos Celestial Reference Frame (HCRF) that excludes these stars from the realisation. Since the IERS does not use stars as reference points, this resolution has importance only for pre-IERS Earth rotation studies and does not require any action for the present and future IERS work.

*Resolutions B1.3, B1.4 and B1.5 concern the use of general relativity in astrometry and celestial mechanics that is more and more important in view of increasing observational accuracy. These resolutions were prepared by the BIPM/IAU Joint Committee on Relativity for Space-Time Reference Systems and Metrology and the IAU Working Group 'Relativity for Celestial Mechanics and Astrometry'.*

**Resolution B1.3 Definition of Barycentric Celestial Reference System and Geocentric Celestial Reference System**

The increase of observational accuracy makes the use of general relativity approach more and more important. This resolution further extends the definition of the two basic reference systems for the solar system (BCRS) and the Earth (GCRS) in the frame of general relativity, recommends the choice of harmonic coordinates for both of them, writes the metric tensors and proposes the full post-Newtonian coordinate transformation between the BCRS and GCRS.

**Resolution B1.4 Post-Newtonian Potential Coefficients**

The motion of satellites and space probes around and amongst massive bodies of the solar system is dominantly influenced by their potential. On the present level of observational accuracy the potential is now desirable to be defined in the frame of general relativity. The resolution gives the expansion of the post-Newtonian potential of the Earth in the Geocentric Celestial Reference Frame.

**Resolution B1.5 Extended relativistic framework for time transformations and realisation of coordinate times in the solar system**

The increasing performance of time and frequency measurements provided by atomic clocks require a more accurate conventional model of time transformations and realisation of coordinate times in the solar system. The resolution defines (more completely than the IAU resolutions of 1991) the metric tensor in the BCRS and the relation between Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG).

*Resolution B1.6, concerning the new model of precession-nutation was prepared by the Joint IAU/IUGG Working Group on Non-rigid Earth Nutation Theory.*

**Resolution B1.6 IAU 2000 Precession-Nutation Model**

The last precession-nutation model adopted by the IAU in 1980 is the model based on Lieske's algorithm for precession, Kinoshita's rigid Earth solution (with external torque only due to the Moon and the Sun), Wahr's transfer function computed for an oceanless elastic stratified model of the Earth and optical astrometric observations. The VLBI observations made afterwards proved that this model is not adequate any more, on the present level of observational accuracy. Therefore, a new model is defined that is based on a more accurate rigid Earth solution (by Souchay et al.) taking into consideration additional torques by the planets and a more sophisticated transfer function (worked out by Mathews, Herring and Buffet) considering also the anelasticity and ocean tide effects, electromagnetic couplings of the mantle and the solid inner core to the fluid outer core, annual atmospheric tide and geodesic nutation. A few basic Earth parameters are estimated by a fit to VLBI observations of precession-nutation. Two versions of the model exist – IAU 2000A with full precision (of about 0.2mas) and a shorter version IAU 2000B (precise to only 1 mas). The model is constructed so that it describes the motion of the Celestial Intermediate Pole (see below).

*Resolutions B1.7 and B1.8 deal with the transformation between the terrestrial and celestial reference systems. The resolutions, proposed by the IAU Working Group on International Celestial Reference System, define the new pole and origins that replace the so far used definitions of the Celestial Ephemeris Pole, equinox and zero meridian. These resolutions imply a different formulation of the transformation algorithm.*

**Resolution B1.7 Definition of Celestial Intermediate Pole**

Although in principle only three parameters (e.g., Euler angles) are necessary to describe the mutual orientation between terrestrial and celestial reference system, there is an obvious need to have two more parameters, describing the motion of a conventionally chosen intermediate axis with respect both to the terrestrial and celestial reference system. This axis should be chosen, quite naturally, close to the instantaneous axis of rotation and its terrestrial and celestial motion has to be observationally separable. This role has been played so far by the Celestial Ephemeris Pole (CEP), whose definition was based on the requirement that it exhibits no near-diurnal motion in either of the two reference systems. However, in view of the present accuracy and sub-diurnal resolution of the observations, the existence of small high-frequency (diurnal and sub-diurnal) nutation and polar motion makes this definition obsolete. Therefore, a new Celestial Intermediate Pole (CIP) is defined so that its periodic celestial motion (nutation) contains only the terms with periods longer than two days; all other motions are interpreted as polar motion.

**Resolution B1.8 Definition and use of Celestial and Terrestrial Ephemeris Origins**

So far, equinox and zero meridian have been used as origins to define the Earth's angle of rotation (sidereal time). However, the instantaneous equinox, being the intersection of the Earth equator and the ecliptic, is dependent both on the theory of Earth's orbital motion around the Sun and the model of precession-nutation. Consequently, it exhibits both secular and periodic (equation of equinoxes) motions with respect to the celestial system. The ecliptic, being a plane fitted to the Earth's orbit that is a three-dimensional curve, cannot be defined uniquely, and in addition it is in fact redundant and not needed for the transformation between the terrestrial and celestial reference system. The system based on equinox has a principal disadvantage – each time when the model of precession-nutation and/or definition of the ecliptic is changed, it must be necessarily accompanied by a change of the definition of the relation between Universal and Greenwich Sidereal Times. It should also be noted that the official conventional celestial system, the ICRS, is not based on ecliptic/equinox any more, since 1997 when it was adopted.

Therefore, it is advisable to select an origin that is independent both of the orbital motion of the Earth and the adopted model of precession-nutation. It is also advantageous to define a stellar angle (different from sidereal time), with a relatively simple relation to Universal time UT1. This is achieved by adopting Guinot's concept of 'non-rotating origin' on the moving equator of CIP – the Celestial Ephemeris Origin (CEO). It is accompanied by a similar concept in the terrestrial system – the Terrestrial Ephemeris Origin (TEO); the rigorous definition of the origin of longitudes on terrestrial equator (in the presence of polar motion) has not been given so far. Both origins satisfy the condition that they exhibit no motion along the moving equator of CIP. The angle between the CEO and TEO, the Earth Rotation Angle (or Stellar Angle), is related to UT1 by a simple linear relationship. The transformation between the ITRS and GCRS is then given by the position of the CIP in the GCRS, the position of the CIP in the ITRS and the Earth Rotation Angle.

*Resolution B1.9 concerns the new definition of Terrestrial Time in the frame of general relativity, and was initiated by the BIPM/IAU Joint Committee on Relativity for Space-Time Reference Systems and Metrology.*

**Resolution B1.9 Re-definition of Terrestrial Time TT**

The Terrestrial Time (TT) was defined by the IAU already in 1991 as a time scale for all practical matters on Earth. It has been defined as the time scale differing from the Geocentric Coordinate Time (TCG) by a constant rate, the unit of measurement of TT has been chosen so that it agrees with the SI second on the geoid. This constant rate is therefore dependent on the adopted value of the potential on the geoid, and should be changed each time when the IUGG adopts a new value. In order to avoid this, the new definition fixes the value of the rate, based on the present value of geopotential at the geoid as a defining constant.

**Resolution B2 Coordinated Universal Time**

Because of the variable speed of rotation of the Earth, universal time UT1 and International Atomic Time TAI diverge. Therefore the Coordinated Universal Time (UTC) was introduced, based on the SI unit of time, with irregular insertions of leap seconds, in order to keep it within certain 'reasonable' limit in accordance with UT1 (at present, this limit is 0.9s). Since the definition of UTC relies on the astronomical observation of UT1, the decision of inserting leap seconds is in the responsibility of the IERS. The unpredictability of leap seconds affects modern communication and navigation systems, therefore a working group of the IAU is established to reconsider the necessity of leap seconds and propose a possible redefinition of UTC. The working group is asked to cooperate with the appropriate groups of the International Union of Radio Science (URSI), the International Telecommunications Union (ITU-R), the International Bureau for Weights and Measures (BIPM), the International Earth Rotation Service (IERS), and relevant navigational agencies.

# 3 CONCLUSIONS

The new resolutions should become effective on January 1, 2003. Evidently, only some of them require an immediate action by the IERS. The task of the IERS Workshop is to explain the real meaning of the resolutions to a general community of users and to discuss the necessary changes in the IERS products and analyses in order to comply with the IAU recommendations. The IERS Directing Board will then decide which steps should be taken and which products of the IERS will be affected.

Since the implementation of the resolutions will affect a broader community than just the IERS, the impact on astrometry, ephemerides and astronomical almanacs are also to be discussed. This concerns namely the questions of a clear explanation of the concepts of the new celestial transformation and the relation to the conventional transformation, usage of the precession-nutation model IAU 2000A/B and developing software for the actual implementation of the new systems by users.

# Practical Consequences of Resolutions B1.3, B1.4, B1.5 and B1.9 Concerning "Relativity in Astrometry, Celestial Mechanics and Metrology"

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## 1 Resolutions

Many arguments can be given why the old IAU 1991 Resolutions concerning relativity are not sufficient for present and future applications, both because of conceptual reasons and considerations of accuracy. The new IAU framework is given by 4 Resolutions that were adopted at the GA 2000.

### 1.1 Resolution B1.3

Resolution B1.3 defines the barycentric celestial reference system BCRS and the geocentric celestial reference system GCRS. The BCRS might be associated with a celestial sphere of remote astronomical objects (quasars etc.) and represents the ICRS. It should be used as basic reference system for astrometry and solar system ephemerides. On the other hand the GCRS is only a local system moving with the geocenter. Dynamical processes occuring in the Earth's system and its immediate vicinity such as the dynamics of the Earth and its constituents should be referred to the GCRS. The GCRS replaces classical concepts used for the definition of classical Earth orientation parameters (such as 'ecliptic and equinox at a certain epoch etc.). Note, that the coordinates of the BCRS and of the GCRS are related by a complex 4-dimensional space-time transformation.

### 1.2 Resolution B1.4

Resolution B1.4 defines post-Newtonian potential coefficients for the Earth. They generalize the classical potential coefficients $C_{lm}$ and $S_{lm}$ in the expansion of the Newtonian potential that is now replaced by $W_E(T, \mathbf{X})$. They are chosen to keep deviations from the Newtonian framework at a minimum. Note, that in the old IAU framework not even the mass of the Earth was defined with post-Newtonian accuracy. The gravito-magnetic potential $W_E^a$ is expressed in terms of the spin vector $\mathbf{S}_E$ of the Earth. The recommended expansions of $W_E^\alpha$ lead to the post-Newtonian accelerations of Earth's satellites including the usual Schwarzschild and Lense-Thirring terms.

### 1.3 Resolution B1.5

Resolution B1.5 applies the formalism recommended in Resolutions B1.3 and B1.4 to the problem of time transformations and realizations of coordinate times in the solar system.

### 1.4 Resolution B1.9

Resolution B1.9 contains a re-definition of Terrestrial Time $TT$. It is recommended that $TT$ be a time scale differing from $TCG$ by a constant rate $d(TT)/d(TCG) = 1 - L_G$, where $L_G = 6.969290134 \times 10^{-10}$ is a defining constant. This removes the reference to the geoid in the $TT$ definition.

## 2 Practical aspects

Fields of applications concern: 1. clock rates, definition and realization of time scale in the solar system, 2. astrometry and problems of reference systems and 3. celestial mechanics. A very detailed explanatory supplement concerning these new resolutions will be submitted to the Astronomical Journal in the near future.

### 2.1 Clock rates, definition and realization of time scales

Various aspects of $TCG$, $TT$, $TAI$, $TCB$ and proper time have been treated in detail in the Resolutions.

### 2.2 Astrometry and problems of reference systems

#### 2.2.1 The celestial sphere

Usually one considers the solar system to be isolated, i.e., one neglects other stars, galaxies etc. In other words one usually forgets about the cosmological problem. In that case the BCRS is a global coordinate system that contains all the 'far away regoins'. Consider some light-ray in the BCRS and follow it back in time. That region where all light-rays originate might be called the celestial sphere. Since the BCRS is a global coordinate system it contains the celestial sphere. In practice the BCRS represents a theoretical backbone of the ICRS.

The situation, however, is very different for the GCRS. The origin of the GCRS is accelerated with $g \sim GM_S/(AU)^2$ and one can show that any reasonably defined accelerated coordinates become meaningless for $d \gg c^2/g$. Accelerated coordinates are only local ones and the remote celestial spheres cannot be described in the GCRS.

For the problem of Earth's rotation and the introduction of Earth's orientation parameters the GCRS is the primary celestial system to be used. Only in a second step by means of space-time coordinate transformations the relations with the ICRS/BCRS can be obtained.

#### 2.2.2 Observables - coordinate quantities

In relativity one has to distinguish carefully observables from coordinate dependent objects. In astrometry one fundamental observable is the angle between two incident light-rays as seen by some observer. This observable can be derived in any coordinate system as a coordinate independent object. Usually, however, in the field of astrometry one talks about a large number of quantities, such as parallax, proper motion or radial velocity that are pure coordinate objects. For that reason it is essential to fix the coordinates (theoretically by the corresponding metric tensors) by convention.

Other coordinate objects have to be introduced for the description of Earth's rotation. The GCRS coordinates $\mathbf{X}$ clearly can be used for the introduction of diverse quantities, like polar angles $r, \theta, \phi$ and a corresponding directional

sphere, coordinate vectors $\mathbf{X} = (X, Y, Z)$, the equator of the GCRS etc. The EOP should be defined with respect to the GCRS and NOT with respect to the ICRS/BCRS.

#### 2.2.3 Astrometry at the $\mu$as level

The resolutions allow for the calculation of practically every astrometric effect at the $\mu$as level. Details can be found in the literature.

### 2.3 Celestial mechanics

#### 2.3.1 Ecliptic, equator, equinox etc.

For celestial mechanics the travel time of some electromagnetic signal between various points in space as measured by some observer is a fundamental observable. This observable can be derived directly from the metric tensor and the equations for photons and the observer. Obviously in celestial mechanics one talks about diverse quantities such as orbits of satellites, planets, spacecrafts etc., that are mere coordinate objects. The same applies for concepts like the ecliptic or some celestial equator. An ecliptic might be defined as $t = TCB$ =const. coordinate plane by means of $\mathbf{x}_E(t_0)$ and $\mathbf{v}_E(t_0)$ in the BCRS. I.e., one is forced to consider the ecliptic only as a BCRS coordinate object related with the Earth's ephemeris. A transformation of this object into the GCRS yields nothing reasonable. On the other hand some celestial equator might be defined in the GCRS only. The classical equinox should be considered as an obsolete quantity and should not be used in the future.

#### 2.3.2 Equations of motion

The new resolutions lead to post-Newtonian equations of motion for solar system bodies. Keeping only the masses in the BCRS equations of motion it can be shown that they reduce to the well known EIH equations of motion that have been used for the JPL DE ephemerides. In satellite theory the post-Newtonian Schwarzschild acceleration caused by the mass of the Earth and the Lense-Thirring acceleration due to the Earth's total angular momentum that dominate the relativistic effects in the orbital motion can be derived from the resolutions. Expressions for post-Newtonian tidal forces that can also be obtained from the resolutions can be found in the literature.

Finally I would like to state that much more work is needed in order to formulate theories of Earth's rotation compatible with the resolutions. Even the best theories for the rotational motion of a rigid Earth definitively are NOT compatible though all the tools are available for that goal.

## 3 Consequences for the IERS

Presently used models for observing techniques (VLBI etc.) are practically in agreement with the IAU2000 resolutions. Presently used theories of Earth's rotation, however, are not. To be consistent the two celestial systems, BCRS and GCRS, should carefully be distinguished. This involves a clear distinction between TCG and TCB.

# Practical Consequences of Resolution B1.6 "IAU2000 Precession-Nutation Model," Resolution B1.7 "Definition of Celestial Intermediate Pole," and Resolution B1.8 "Definition and Use of Celestial and Terrestrial Ephemeris Origin"

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## 1 Practical consequences of Resolution B1.6 "IAU2000 Precession-Nutation Model"

Resolution B1.6 (see Annex) recommends a new precession/nutation model.

Beginning on 1 January 2003, the IAU 1976 Precession Model and the IAU 1980 Theory of Nutation are replaced by the precession-nutation model IAU 2000 A (MHB 2000) based on the transfer functions of Mathews *et al.* (2002) for those who need a model at the 0.2 mas level. Alternatively one can use a shorter version IAU 2000 B (McCarthy and Luzum, 2002) if precision at the 1 mas level is required. In both cases the associated celestial pole biases must be used.

The IAU2000 A model contains 678 luni-solar terms and 687 planetary terms and provides the direction of the celestial pole in the Geocentric Celestial Reference System (GCRS) with an accuracy of 0.2 mas. The series includes the geodesic nutation contributions to the annual, semi-annual, and 18.6-year terms. (Fukushima 1991). The Free Core Nutation (FCN), being a free motion that cannot be predicted rigorously, is not a part of the IAU2000A model.

The abridged model, designated IAU2000B includes 80 luni-solar terms plus a planetary bias to account for the effect of the planetary terms in the time period under consideration. It provides the celestial pole motion with an accuracy that does not result in a difference greater than 1 mas with respect to the IAU2000A model during the period 1995-2050.

Currently the International Earth Rotation Service (IERS) provides “celestial pole offsets” for routine use in transformations between the terrestrial and celestial reference systems. These are corrections to the angles $\psi$ (longitude) and $\varepsilon$ (obliquity) that one currently computes using the IAU 1976 Precession (Lieske *et al.* 1977) and the IAU 1980 Nutation Theory (Seidelmann, 1982). For most users these corrections will no longer be necessary if they use the IAU2000A/B models. The IERS will continue to publish celestial pole offsets with respect to IAU2000A, but these are expected to be less than 1 mas.

The IAU 2000 series of nutation must be used with improved numerical values for the precession rate of the equator in longitude and obliquity:

$$\Delta\psi_A = (-0.2997 \pm 0.0008)\ "/c, \quad \text{and} \quad \Delta\omega_A = (-0.0252 \pm 0.0003)"/c,$$

as well as with the following biases in the direction of the Celestial Intermediate Pole (CIP) at J2000.0 from the direction of the pole of the Geocentric Celestial Reference System (GCRS)

$$\xi_0 = (-0.016617 \pm 0.000010)", \quad \text{and} \quad \eta_0 = (-0.006819 \pm 0.000010)".$$

The IAU 2000 nutation model is given by series for nutation in longitude $\Delta\psi$ and obliquity $\Delta\varepsilon$, referred to the mean equator and equinox of date, with t measured in Julian centuries from epoch J2000.0:

$$\Delta\psi = \sum_{i=1}^{N} (A_i + A_i' t)\sin(\text{ARGUMENT}) + (A_i'' + A_i''' t)\cos(\text{ARGUMENT}),$$

$$\Delta\varepsilon = \sum_{i=1}^{N} (B_i + B_i' t)\cos(\text{ARGUMENT}) + (B_i'' + B_i''' t)\sin(\text{ARGUMENT}).$$

The IAU2000A subroutine, provided by T. Herring, is available electronically on the IERS Convention Center website at ftp://maia.usno.navy.mil/conv2000/chapter5/IAU2000A.f. It produces the total nutation in longitude and obliquity based on the adopted MHB2000 model with the exception of the FCN. The software can also be used to model the expected FCN based on the most recent astronomical observations. The IAU2000B subroutine is available at ftp://maia.usno.navy.mil/conv2000/chapter5/IAU2000B.f.

There are two ways to implement the IAU 2000A /B models. If one uses the revised procedure to transform between reference systems that makes use of the Celestial Intermediate Pole (CIP) and Celestial Ephemeris Origin (CEO) (see below), the expressions for the positions of the CIP and CEO in the Celestial Reference System will already contain the proper expressions for the new precession-nutation model. If one elects to continue using the classical expressions based on the IAU 1976 Precession Model and IAU 1980 Theory of Nutation, one should proceed as in the past and then apply the corrections to the IAU 1980 Theory of Nutation $\Delta\psi$ and $\Delta\varepsilon$ provided by the appropriate IAU2000A/B software. This process is outlined in McCarthy (1996). For either mode, the user should consider the additional application of observed corrections to the IAU2000A model provided by the IERS.

## 2 Practical consequences of Resolution B1.7 "Definition of Celestial Intermediate Pole"

Resolution B1.7 (see Annex) recommends that the Celestial Intermediate Pole (CIP) be used in place of the Celestial Ephemeris Pole (CEP) on 1 January 2003 and specifies how to implement its definition through its direction at J2000.0 in the GCRS as well as the realization of its motion both in the GCRS and ITRS. Its definition is an extension of that of the CEP in the high-frequency domain and coincides with that of the CEP in the low-frequency domain (Capitaine, 2000). The reason for the adoption of the CIP is to clarify the current ambiguity about the difference between nutation and polar motion at high frequencies (motions with periods less than two days).

The realized celestial pole is to be the CIP. This requires an offset at epoch in the conventional model for precession-nutation as well as diurnal and higher frequency variations in the Earth's orientation. According to this resolution, the direction of the CIP at J2000.0 is offset from the direction of the GCRS in a manner consistent with the IAU2000A/B precession-nutation model. The motion of the CIP in the GCRS is to be realized by the IAU 2000A/B model for precession and forced nutation for periods greater that two days plus additional time-dependent corrections provided by the IERS through appropriate observations. The motion of the CIP in the ITRS is to be provided by the IERS through appropriate observations and models including high frequency variations.

The realization of the CIP thus requires that the IERS monitor the observed differences (reported as "celestial pole offsets") with respect to the conventional celestial position of the CIP in the GCRS based on the IAU 2000A precession-nutation model together with its observed offset at epoch. It also requires that the motion of the CIP in the TRS be provided by the IERS by observations taking into account a predictable part specified by a model including the terrestrial motion of the pole corresponding to the forced nutations with periods less than two days (in the GCRS) as well as the tidal variations in polar motion.

Recent models for rigid Earth nutation (Bretagnon *et al.* 1997, Souchay *et al.* 1999, Roosbeek 1999) include prograde diurnal and prograde semi-diurnal terms with respect to the GCRS with amplitudes up to ~15μas in $\Delta\psi \sin\varepsilon_0$ and $\Delta\varepsilon$. In order to realize the CIP as recommended by Resolution B1.7, nutations with periods less than two days are to be considered using a model for the corresponding motion of the pole in the ITRS. The prograde diurnal nutations correspond to prograde and retrograde long periodic (13 d to 3300 d) variations in polar motion and the prograde semi-diurnal nutations correspond to prograde diurnal variations in polar motion. The amplitudes for the non-rigid Earth can be derived from the rigid Earth values by applying the transfer function of Mathews *et al.* (2002) extended for the high frequency nutations. Preliminary numbers have been provided by Folgueira *et al.* (2001). An *ad hoc* Working Group has been working to provide a definitive table for operational use.

## 3 Practical consequences of Resolution B1.8 "Definition and use of Celestial and Terrestrial Ephemeris Origin"

Resolution B1.8 recommends the use of the "non-rotating origin"" (Guinot, 1979) both in the GCRS and the ITRS and these origins are designated as the Celestial Ephemeris Origin (CEO) and the Terrestrial Ephemeris Origin (TEO). The "Earth Rotation Angle" is defined as the angle measured along the equator of the CIP between the CEO and the TEO. It recommends that UT1 be linearly proportional to the Earth Rotation Angle and that the transformation between the ITRS and GCRS be specified by the position of the CIP in the GCRS, the position of the CIP in the ITRS, and the Earth Rotation Angle. It is recommended that the IERS takes steps to implement this by 1 January 2003 and that the IERS continue to provide users with data and algorithms for the conventional transformation.

Two equivalent procedures were given in the IERS Conventions (1996) (McCarthy, 1996) for the transformation from the TRS to the CRS using the procedure

$$[\mathrm{CRS}] = \mathrm{PN}(t)\,\mathrm{R}(t)\,\mathrm{W}(t)[\mathrm{TRS}],$$

where PN(t), R(t) and W(t) are the transformation matrices describing the position of the celestial pole in the celestial system, the rotation of the Earth around the axis of the pole, and polar motion respectively. The classical procedure makes use of the equinox for realizing the intermediate reference frame of date t. It uses apparent Greenwich Sidereal Time (GST) in the transformation matrix R(t) and the classical precession and nutation parameters in the transformation matrix PN(t).

The second procedure makes use of the "non-rotating origin" to realize the intermediate reference frame of date t. It uses the "Earth Rotation Angle" originally referred to as "stellar angle" in the matrix R(t) and the two coordinates of the celestial pole in the CRS (Capitaine, 1990) in the transformation matrix PN(t).

Resolutions B1.6 and B1.7 can be implemented in either of these procedures if the requirements described above are followed for the space-time coordinates in the geocentric celestial system, for the precession and nutation model on which are based the precession and nutation quantities used in the transformation matrix PN(t) and for the polar motion used in the matrix W(t). However, only the second procedure can be in agreement with Resolution B1.8, which requires the use of the "non-rotating origin" both in the CRS and the TRS as well as the position of the CIP in the

GCRS and in the ITRS. The IERS must also provide users with data and algorithms for the conventional transformation. This implies that the expression of GST has to be consistent with the new procedure.

# 4 Implementation of the Resolutions

A direction vector given in a terrestrial reference system (TRS) can be expressed in a celestial reference system (CRS) by the following

$$[\mathrm{CRS}] = \mathrm{PN}(t)\mathrm{R}(t)\mathrm{W}(t)[\mathrm{TRS}],$$

where PN(t), R(t) and W(t) are the transformation matrices describing the position of the celestial pole in the celestial system, the rotation of the Earth around the axis of the pole, and polar motion respectively. The parameter t is defined by

$$t = (\mathrm{TT} - 2000\ \text{January 1d 12h TT})\ \text{in days}/36525.$$

This complies with IAU Resolution C7 (1994) recommending that the epoch J2000.0 be defined at the geocentre and at the date 2000 January 1.5 TT = Julian Date 2451545.0 TT.

## 4.1 Polar Motion

Referring to (Capitaine, 1990), if we designate $R_1$, $R_2$ and $R_3$ as rotations about the axes 1, 2 and 3 of the coordinate frame, then,

$$W(t)=R_3(-s')\ R_1(y_p)\ R_2(x_p),$$

$x_p$ and $y_p$ being the polar coordinates of the Celestial Intermediate Pole (CIP) in the TRS and s' the accumulated displacement of the TEO on the true equator due to polar motion. The use of the quantity s', which is neglected in the classical form, is necessary to provide an exact realization of the "instantaneous prime meridian." The pole coordinates to be used for the parameters $x_p$ and $y_p$, if not estimated by analysis of the observations, are those published by the IERS. Models for the diurnal and semi-diurnal tidal variations in pole coordinates are described in the IERS Conventions and are available on the website of the IERS Conventions. The quantity s' is only slightly dependent on polar motion. Some components of s' have to be evaluated, in principle, from the measurements and can be extrapolated using the IERS data. Its main component can be written as

$$s' = -0.0015(a_c^2/1.2 + a_a^2)\ t,$$

$a_c$ and $a_a$ being the average amplitudes (in arc seconds) of the Chandlerian and annual wobbles, respectively in the period considered (Capitaine *et al.*, 1986). The value of s' is less than 0.4 mas after a century. Using the current mean amplitudes for the Chandlerian and annual wobbles gives s'= - 47 μas t, t being in Julian centuries from J2000. (see Lambert & Bizouard, this Volume).

## 4.2 Earth Rotation

Using the same rotational designations as for polar motion, R(t) is given by

$$R(t) = R_3(-\theta),$$

θ being the Earth Rotation Angle between the CEO and the TEO at date t on the equator of the CIP, which provides a rigorous definition of sidereal rotation of the Earth. It is obtained by using its relationship with UT1 as given by Capitaine *et al.*, (2000),

$$\theta(T_u) = 2\pi\ (0.7790572732640 + 1.00273781191135448\ T_u),$$

where $T_u$ = (Julian UT1 date - 2451545.0),
and UT1 = UTC + (UT1-UTC), or equivalently
$\theta(T_u)$ = $2\pi$ (UT1 Julian day number elapsed since 2451545.0 + 0.7790572732640 + 0.00273781191135448 $T_u$).

The quantity UT1-UTC to be used (if not estimated in the analysis of the observations) is the value published by the IERS. This definition of UT1 is insensitive at the microarcsecond level to the precession-nutation model and to the observed celestial pole offsets. Therefore in the processing of observational data, the quantity s (see below) must be considered as independent of observations.

### 4.3 Precession-Nutation

Again, using the same rotational designations,

$$PN(t) = R_3(-E)\, R_2(-d)\, R_3(E)\, R_3(s),$$

E and d being such that the coordinates of the CIP in the CRS are

$$X = \sin d \cos E, \qquad Y = \sin d \sin E, \qquad \text{and} \qquad Z = \cos d.$$

s is the accumulated rotation, between the epoch and the date t, of the CEO on the true equator due to the celestial motion of the CIP. Its expression, accurate to 1 microarcsecond after one century, is given as a function of the coordinates X and Y by

$$s = -\frac{1}{2}\left[X(t)Y(t) - X(t_0)Y(t_0)\right] + \int_{t_0}^{t} \dot{X}(t)Y(t)\,dt\,,$$

Equivalently, PN(t ) can be given by

$$PN(t) = \begin{pmatrix} 1 - aX^2 & -aXY & X \\ -aXY & 1 - aY^2 & Y \\ -X & -Y & 1 - a\left(X^2 + Y^2\right) \end{pmatrix} \cdot R_3(s),$$

where $a = \frac{1}{2} + \frac{1}{8}(X^2 + Y^2)$.

Developments of X and Y based on the IAU 2000 A or IAU 2000 B model for precession-nutation and on their corresponding pole offset at J2000.0 will be available on the website of the IERS Conventions. These developments have the form (Capitaine *et al.* 2002)

$$\begin{aligned} X \;=\; & -0.''016617 + 2004.''191743\; t - 0.''4272190\; t^2 \\ & - 0.''1986205\, t^3 - 0.''0000460\, t^4 + 0.''0000060\, t^5 \\ & + \sum_i \left[ (a_{s,0})_i \sin(ARGUMENT) + (a_{c,0})_i \cos(ARGUMENT) \right] \\ & + \sum_i \left[ (a_{s,1})_i\, t \sin(ARGUMENT) + (a_{c,1})_i\, t \cos(ARGUMENT) \right] \\ & + \sum_i \left[ (a_{s,2})_i\, t^2 \sin(ARGUMENT) + (a_{c,2})_i\, t^2 \cos(ARGUMENT) \right] + \ldots \end{aligned}$$

$$\begin{aligned} Y = & -0.''006951 - 0.''025376\; t - 22.''407251\; 0\, t^2 \\ & + 0.''0018423\; t^3 + 0.''0011131\; t^4 + 0.''0000099\; t^5 \\ & + \sum_i \left[ (b_{c,0})_i \cos(\text{ARGUMENT}) + (b_{s,0})_i \sin(\text{ARGUMENT}) \right] \\ & + \sum_i \left[ (b_{c,1})_i\, t \cos(\text{ARGUMENT}) + (b_{s,1})_i\, t \sin(\text{ARGUMENT}) \right] \\ & + \sum_i \left[ (b_{c,2})_i\, t^2 \cos(\text{ARGUMENT}) + (b_{s,2})_i\, t^2 \sin(\text{ARGUMENT}) \right] + \ldots \end{aligned}$$

where t = ( TT –2000 January 1d 12h TT) in days/36525 and ARGUMENT represents the fundamental arguments of the nutation theory. Each of the lunisolar terms in the nutation series is characterized by a set of five integers $N_j$ that determine the ARGUMENT for the term as a linear combination of the five fundamental arguments $F_j$, namely the Delaunay variables l, l', F, D, Ω.

$$\text{ARGUMENT} = \sum_{j=1}^{5} N_j F_j \equiv \vec{N} \cdot \vec{F} ,$$

where $\vec{N}$ is the five-vector composed of the values $N_1 \ldots, N_5$ that characterize the term, and $\vec{F}$ is the five-vector $F_1 \ldots, F_5$, which are functions of time.

Planetary nutation terms differ from the above only in that

$$\text{ARGUMENT} = \sum_{j=1}^{14} N'_j F'_j ,$$

$F_6$ to $F_{13}$ are the mean longitudes of the planets (Mercury to Neptune) including the Earth ($l_{Me}$, $l_{Ve}$, $l_E$, $l_{Ma}$, $l_{Ju}$, $l_{Sa}$, $l_{Ur}$, $l_{Ne}$), and the general precession in longitude, $p_a$.

The expressions for the fundamental arguments are

$F_1 \equiv$ l = Mean Anomaly of the Moon
$=$ 134.°96340251 + 1717915923."2178 t + 31."8792 $t^2$ + 0."051635 $t^3$ - 0."00024470 $t^4$,

$F_2 \equiv$ l' = Mean Anomaly of the Sun
$=$ 357.°52910918 + 129596581."0481 t – 0."5532 $t^2$ + 0."000136 $t^3$ - 0."00001149 $t^4$,

$F_3 \equiv$ F = L - Ω ( L is the Mean Longitude of the Moon.)
$=$ 93.°27209062 + 1739527262."8478 t – 12."512 $t^2$ – 0."01037 $t^3$ + 0."00000417 $t^4$,

$F_4 \equiv$ D = Mean Elongation of the Moon from the Sun
$=$ 297.°85019547 + 1602961601."2090 t – 6."706 $t^2$ + 0."006593 $t^3$ - 0."0003169 $t^4$,

$F_5 \equiv$ Ω = Mean Longitude of the Ascending Node of the Moon
$=$ 125.°04455501 – 6962890."5431 t + 7."4722 $t^2$ + 0."07702 $t^3$ - 0."0005939 $t^4$,

where t is measured in Julian Centuries of 36525 days of 86400 seconds of TDB since J2000.0 (Simon *et al.*, 1994).

The arguments for the planetary nutations are those of Souchay *et al.* (1999), based on the mean longitudes of the planets of VSOP82. The developments are given below in radians and t in Julian centuries of TDB.

$l_{Me}$ = 4.402 608 842 + 2608.7903 141 574 t,
$l_{Ve}$ = 3.176 146 697 + 1021.3285 546 211 t,
$l_E$ = 1.753 470 314 + 628.3075 849 991 t,
$l_{Ma}$ = 6.203 480 913 + 334.0612 426 700 t,
$l_{Ju}$ = 0.599 546 497 + 52.9690 962 641 t,
$l_{Sa}$ = 0.874 016 757 + 21.3299 104 960 t,
$l_{Ur}$ = 5.481 293 871 + 7.4781 598 567 t,
$l_{Ne}$ = 5.311886287 + 3.8133035638 t,
$p_a$ = 0.024381750 t +0.00000538691 $t^2$.

TT can be used in these expressions as the difference TDB -TT (of which the largest term is 1.7 x $10^{-5}$ t sin l' ) has a quite negligible effect (lower that $10^{-2}$ μas with a period of one year) in the amplitudes of nutation.

The numerical development of s compatible with the IAU 2000 A precession-nutation model and the corresponding celestial offset at J2000.0, retaining terms larger than 0.5 μas, is provided in Table 1 for terms larger than 0.5 μas over 25 years and Table 2 for additional terms extending the development over one century. The quantity s is such that the CEO moves less than 70 mas from the GCRS prime meridian during one century.

Table 1. Development of all terms of s(t) exceeding 0.5 μas during the interval 1975-2025 compatible with the 2000A precession-nutation model. Units are μas. (Capitaine *et al.* 2002)

$$s(t) = -XY/2 + 2184 + 3812\,t\text{-}121t^2 + 72574\,t^3 + \sum_k C_k \sin\alpha_k + 2t\sin\Omega$$
$$+ 4t\cos 2\Omega + 744t^2\sin\Omega + 57t^2\sin(2F\text{-}2D + 2\Omega) + 10t^2\sin(2F + 2\Omega)$$
$$- 9t^2\sin 2\Omega$$

| Argument $\alpha_k$ | Amplitude $C_k$ |
|---|---|
| Ω | -2641 |
| 2Ω | -63 |
| 2F-2D+3Ω | -12 |
| 2F-2D+Ω | -11 |
| 2F-2D+2Ω | +5 |
| 2F+3Ω | -2 |
| 2F+Ω | -2 |
| 3Ω | +2 |
| l'+Ω | +1 |
| l'-Ω | +1 |
| l+Ω | +1 |
| l-Ω | +1 |

Table 2. Development of all terms of s(t) exceeding 0.5 μas during the intervals 1900-1975 and 2025-2100 compatible with the 2000A precession-nutation model. Units are μas. (Capitaine *et al.* 2002)

$$\Delta s(t) = +28t^4 + 15t^5 - 22t^3\cos\Omega\text{-}1t^3\cos(2F\text{-}2D + 2\Omega) + \sum_i D_i t^2\sin\alpha_i$$

| Argument $\alpha_i$ | Amplitude $D_i$ |
|---|---|
| l' | -6 |
| l | -3 |
| l'+2F-2D+2Ω | +2 |
| 2F+Ω | +2 |
| L+2F+2Ω | +1 |

VLBI observations show that there are deficiencies in the IAU2000 A of the order of 0.2 mas (Mathews *et al.* 2002). The IERS will continue to publish observed estimates of the corrections to the IAU 2000 precession-nutation model. The observed differences with respect to the conventional pole position are monitored and reported by the IERS as celestial pole offsets. These are provided as corrections

$\delta X \approx \delta\psi \sin\varepsilon_0$ and $\delta Y \approx \delta\varepsilon$ to the X and Y coordinates.

Using these offsets the corrected celestial position of the CIP is given by

$X = X(IAU2000) + \delta X,$ and $Y = Y(IAU2000) + \delta Y.$

This is practically equivalent to replacing the transformation matrix PN with the rotation

$$PN = \begin{pmatrix} 1 & 0 & \delta X \\ 0 & 0 & \delta Y \\ -\delta X & -\delta Y & 1 \end{pmatrix} PN_{IAU}$$

where $PN_{IAU}$ represents the PN(t) matrix based on the IAU 2000 precession-nutation model.

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# Comparision of "Old" and "New" Concepts: Coordinate Times and Time Transformations

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**Foreword:** The first three parts of this paper are largely based on the paper "The new IAU'2000 Conventions for coordinate times and time transformations" presented at the Journées Systèmes de Référence Spatio-temporels, Brussels, September 2001. The fourth part is largely based on draft parts of the IERS Conventions 2000 (`http://maia.usno.navy.mil/conv2000.html`), interpreted here under the sole responsibility of the author.

**Abstract:** At its 2000 General Assembly, the International Astronomical Union has adopted a set of Resolutions that provide a consistent framework for defining the barycentric and geocentric celestial reference systems at the first post-Newtonian level. This extends and completes the IAU'1991 framework defined in Resolution A4 at the 1991 General Assembly. This paper describes in some detail the two Resolutions that define time coordinates and allow to realize time transformations. The application of the IAU'1991 and IAU'2000 framework to several fields of space geodesy and astrometry is discussed.

## 1 Introduction

At its 1991 General Assembly the International Astronomical Union (IAU) explicitly adopted the general theory of relativity as the theoretical framework for the definition and realization of space-time reference frames (IAU, 1991). Barycentric and geocentric coordinate time scales and the relativistic transformations between them were defined, together with procedures for their realization. In section 2, we recall the content of the IAU 1991 resolution A4 dealing with the definition of reference systems, time coordinates and time transformations, and we expose some of the limitations of this framework. For many applications in space geodesy, it is sufficient to discuss within the IAU'1991 framework, with the IAU'2000 framework providing an extension which is necessary for a few applications. It is therefore important to have in mind the basis of the IAU'1991 framework.

The IAU Working Group on Relativity in Celestial Mechanics and Astrometry (RCMA), since 1994, and the BIPM/IAU Joint Committee on relativity for space-time reference systems and metrology (JCR), from 1997 to 2001, have worked to provide an extension of the IAU'1991 framework at the first post-Newtonian level (Soffel, 2000; Petit, 2000). This work resulted in a set of Resolutions passed at the IAU 2000 General Assembly. The complete text of the Resolutions may be found in IAU publications (`http://danof.obspm.fr/IAU-resolutions/Resol-UAI.htm`) and a complete explanatory supplement may be found in (Soffel et al., 2002). The new IAU'2000

framework is precisely specified in Resolutions B1.3(2000) "Definition of barycentric celestial reference system and geocentric celestial reference system" and B1.4(2000) "Post-Newtonian potential coefficients".

In Section 3 of this paper, we briefly present the two Resolutions which deal with time transformations and the definition of coordinate times, namely Resolutions B1.5(2000) "Extended relativistic framework for time transformations and realization of coordinate times in the solar system" in section 3.1 and B1.9(2000) "Re-definition of Terrestrial Time TT" in section 3.2, and discuss at which level time transformations and coordinate times are affected by the IAU'2000 framework.

Finally section 4 discusses the application of the IAU'1991 and IAU'2000 framework to several fields of space geodesy and astrometry which are based on time and frequency measurements.

## 2 The IAU'1991 framework and its limitations

The IAU resolution A4 (1991) contains nine recommendations, the first five of which are directly relevant to our discussion.

In the first recommendation, the metric tensor for space-time coordinate systems $(t, \mathbf{x})$ centered at the barycenter of an ensemble of masses is recommended in the form

$$\begin{aligned} g_{00} &= -1 + \frac{2U(t,\mathbf{x})}{c^2} + \mathcal{O}(c^{-4}), \\ g_{0i} &= \mathcal{O}(c^{-3}), \\ g_{ij} &= \delta_{ij}\left(\frac{1+2U(t,\mathbf{x})}{c^2}\right) + \mathcal{O}(c^{-4}). \end{aligned} \tag{1}$$

where $c$ is the speed of light in vacuum ($c = 299792458$ m/s), $U$ is the sum of the gravitational potentials of the ensemble of masses and of a tidal potential generated by bodies external to the ensemble, the latter potential vanishing at the barycenter. The algebraic sign of $U$ is taken to be positive. This recommendation recognizes that space-time cannot be described by a single coordinate system. The recommended form of the metric tensor can be used not only to describe the barycentric reference system (BRS) of the whole solar system (which is called BCRS where C stands for Celestial since the IAU'2000 Resolutions), but also to define the geocentric reference system (GRS) centered in the center of mass of the Earth, which is now called GCRS. In analogy to the GRS, a corresponding reference system may be defined for any other body of the Solar system.

In the second recommendation, the origin and orientation of the space coordinate grids for the solar system (BRS) and for the Earth (GRS) are defined. Notably it is specified that the space coordinate grids of these systems should show no global rotation with respect to a set of distant extragalactic objects. It also specifies that the SI (International System of units) second and the SI meter should be the physical units of proper time and proper length in all coordinate systems. It states in addition that the time coordinates should be derived from an Earth atomic time scale.

The third recommendation defines $TCB$ (Barycentric Coordinate Time) and $TCG$ (Geocentric Coordinate Time) – the time coordinates of the BRS and GRS, respectively. The recommendation also defines the origin of the times scales (their reading on 1977 January 1, $0^{\mathrm{h}}\,0^{\mathrm{m}}\,0^{\mathrm{s}}$ $TAI$ ($JD = 2443144.5\,TAI$)

must be 1977 January 1, $0^{\rm h}\,0^{\rm m}\,32.184^{\rm s}$) and declares that the units of measurements of the coordinate times of all reference systems must be coincide with the SI second and SI meter. The relationship between $TCB$ and $TCG$ is given by a full 4-dimensional transformation

$$TCB - TCG = c^{-2} \left[ \int_{t_0}^{t} \left( \frac{v_E^2}{2} + U_{ext}(t, \mathbf{x}_E(t)) \right) dt + v_E^i r_E^i \right] + \mathcal{O}(c^{-4}), \quad (2)$$

where $x_E^i$ and $v_E^i$ are the barycentric coordinate position and velocity of the geocenter, $r_E^i = x^i - x_E^i$ with $x^i$ the barycentric position of the observer, and $U_{ext}(t, \mathbf{x}_E(t))$ is the Newtonian potential of all solar system bodies apart from the Earth evaluated at the geocenter.

In the fourth recommendation another time coordinate, Terrestrial Time ($TT$), is defined for the GRS. It differs from $TCG$ by a constant rate only

$$TCG - TT = L_G \times (JD - 2443144.5) \times 86400, \qquad L_G \approx 6.969291 \times 10^{-10}, \quad (3)$$

so that the unit of measurement of $TT$ agrees with the SI second on the geoid. $TT$ represents an ideal form of $TAI$, the divergence between them being a consequence of the physical defects of atomic clocks.

The fifth recommendation states that the former dynamical barycentric time $TDB$ may still be used where discontinuity with previous work is deemed to be undesirable.

**Limitations to the IAU'1991 framework**

Because of the form of the metric (1) in the IAU'1991 framework, time transformations and the realization of coordinate times in the barycentric system are not specified at the $c^{-4}$ level, i.e. at a level of a few parts in $10^{16}$ in rate. The new IAU'2000 framework allows to remove this limitation. Nevertheless, within the IAU'1991 approximation, constants $L_B$ and $L_C$ were introduced in notes to the Recommendation 3 (1991) to express the mean rates between time scales as

$$\begin{aligned} TCB - TDB &= L_B \times (JD - 2443144.5) \times 86400, \\ &\quad L_B \approx 1.550505 \times 10^{-8}, \text{ and} \\ TCB - TCG &= L_C \times (JD - 2443144.5) \times 86400 + v_E^i r_E^i / c^2 + P, \\ &\quad L_C \approx 1.480813 \times 10^{-8}, \end{aligned} \quad (4)$$

where $P$ represents periodic terms. Since JD is not specified to be a particular time scale, these constants were not properly defined so that confusion appeared in their usage. This point was adressed in Resolution B1.5(2000) by defining $< TCG/TCB >= 1 - L_C$ and $< TT/TCB >= 1 - L_B$, where $<>$ means a sufficiently long term average taken at the geocenter. The actual computation of $L_C$ and $L_B$ requires the integration of solar system ephemerides and the specification of an averaging duration, and this process may be applied to the utmost accuracy, after a choice of ephemerides and averaging duration. For example Irwin and Fukushima (1999) determined $L_C = 1.48082686741 \times 10^{-8} \pm 2 \times 10^{-17}$. However, no completely unambiguous definition may be provided for $L_B$ and $L_C$ because they always depend on the ephemerides and time span used for their computation. Therefore the use of these constants is not advised to formulate time transformations when it would require knowing their value with an uncertainty of order $1 \times 10^{-16}$ or less.

Another problem arising from the situation before IAU'1991 is that the barycentric dynamical time TDB did not have a good definition. This could have

been corrected by turning a specific value of $L_B$ into a defining constant thus providing in retrospect a definition of TDB. It was not felt necessary to address explicitly this point in a recommendation. Prior to IAU'1991, authors had developped analytical formulas to transform TT (known as TDT prior to 1991) to TDB (e.g. Fairhead and Bretagnon, 1990). Such formulas may be used along with a further linear transformation to obtain TCB from TDB, i.e. $dTDB/dTCB = 1 - L_B$, under the same provisions as above for possible ambiguities in the definitions, and therefore in the applicability of the formulas. See more details in section 4.5 and see (Irwin and Fukushima, 1999) for a comparison of some transformation formulas and the level of uncertainty that may be associated with them.

## 3 Time Coordinates in the IAU'2000 framework

For practical applications concerning time and frequency measurements in the solar system, it is necessary to consider a conventional model for the realization of time coordinates and time transformations. This model should be chosen so that i) its accuracy is significantly better than the expected performance of clocks and time transfer techniques, ii) it is consistent with the general framework of IAU Resolutions B1.3 and B1.4 (2000) and may readily be used with existing astrometric quantities, e.g. solar systems ephemeris.

For the first condition, it was determined that time coordinates and time transformations should be realized with an uncertainty not larger than $5 \times 10^{-18}$ in rate or, for quasi-periodic terms, not larger than $5 \times 10^{-18}$ in rate amplitude and 0.2 ps in phase amplitude. For the spatial domain of validity, the formulations in the barycentic system are valid up to a few solar radii from the Sun and, in the geocentric system, locations from the Earth's surface up to geostationary orbits ($|\mathbf{X}| < 50000$ km) have been considered.

### 3.1 Resolution B1.5(2000): Extended relativistic framework for time transformations and realization of coordinate times in the solar system

Following Resolutions B1.3(2000) and B1.4(2000), the metric tensor in the BCRS is expressed as

$$\begin{aligned} g_{00} &= -(1 - \tfrac{2}{c^2}(w_0(t,\mathbf{x}) + w_L(t,\mathbf{x})) + \tfrac{2}{c^4}(w_0^2(t,\mathbf{x}) + \Delta(t,\mathbf{x}))) \\ g_{0i} &= -\tfrac{4}{c^3} w_i(t,\mathbf{x}) \\ g_{ij} &= \left(1 + \tfrac{2w_0(t,\mathbf{x})}{c^2}\right)\delta_{ij} \end{aligned} \tag{5}$$

where $(t \equiv TCB, \mathbf{x})$ are the barycentric coordinates, $w_0 = G\sum_A M_A/r_A$, with the summation carried out over all solar system bodies A, $\mathbf{r}_A = \mathbf{x} - \mathbf{x}_A$, $r_A = |\mathbf{r}_A|$, and where $w_L$ contains the expansion in terms of multipole moments, as defined in Resolution B1.4(2000) and references therein, required for each body. In many cases the mass-monopole approximation ($w_L = 0$) may be sufficient to reach the above mentioned uncertainties but this term should be kept to ensure the consistency in all cases. The values of masses and multipole moments to be used may be found in IAU or IERS documents (IERS, 1996), but care must be taken that the values are in SI units (not in so-called TDB units or TT units). The vector potential $w^i(t,\mathbf{x}) = \sum_A w_A^i(t,\mathbf{x})$ and the function $\Delta(t,\mathbf{x}) = \sum_A \Delta_A(t,\mathbf{x})$ are given in the text of IAU Resolutions.

From (5) the transformation between proper time and $TCB$ may be derived.

It reads:

$$\begin{aligned} \mathrm{d}\tau/\mathrm{d}TCB &= 1 - \frac{1}{c^2}\left(w_0 + w_L + \frac{v^2}{2}\right) \\ &\quad + \frac{1}{c^4}\left(-\frac{1}{8}v^4 - \frac{3}{2}v^2 w_0 + 4v^i w^i + \frac{1}{2}w_0^2 + \Delta\right) \end{aligned} \tag{6}$$

Evaluation of the significance of the terms in $w^i(t, \mathbf{x})$ and $\Delta(t, \mathbf{x})$ may be found in (Petit, 2001).

Similarly, the transformation between $TCB$ and $TCG$ may be written as

$$\begin{aligned} TCB - TCG = c^{-2}\left[\int_{t_0}^{t}\left(\frac{v_E^2}{2} + w_{0ext}(\mathbf{x}_E)\right)dt + v_E^i r_E^i\right] \\ -c^{-4}[\int_{t_0}^{t}\left(-\frac{1}{8}v_E^4 - \frac{3}{2}v_E^2 w_{0ext}(\mathbf{x}_E) + 4v_E^i w_{ext}^i(\mathbf{x}_E) + \frac{1}{2}w_{0ext}^2(\mathbf{x}_E)\right)dt \\ -(3w_{0ext}(\mathbf{x}_E) + v_E^2/2)v_E^i r_E^i] \end{aligned} \tag{7}$$

where $t$ is $TCB$ and where the index ext refers to all bodies except the Earth. This equation is composed of terms evaluated at the geocenter (the two integrals) and of position dependent terms in $r_E$, with position dependent terms in higher powers of $r_E$ having been found to be negligible. The first integral may be computed from existing planetary ephemeris (Fukushima, 1995; Irwin and Fukushima, 1999). Since, in general, the planetary ephemeris are expressed in terms of a time argument $T_{eph}$ which is close to $TDB$ (see section 4.4), rather than in terms of $TCB$, the first integral will be computed as

$$\int_{t_0}^{t}\left(\frac{v_E^2}{2} + w_{0ext}(\mathbf{x}_E)\right)dt = \left[\int_{t_{eph_0}}^{t_{eph}}\left(\frac{v_E^2}{2} + w_{0ext}(\mathbf{x}_E)\right)dt_{eph}\right]/(1-L_B) \tag{8}$$

where a rough value of $L_B = 1.5505.. \times 10^{-8}$ may be used.

Terms in the second integral of (7) are secular and quasi periodic. They amount to $\sim 1.10 \times 10^{-16}$ in rate ($\mathrm{d}TCB/\mathrm{d}TCG$) and primarily a yearly term of $\sim 30$ ps in amplitude (i.e. corresponding to periodic rate variations of amplitude $\sim 6\times10^{-18}$). Besides the position dependent terms in $c^{-2}$ which may reach several microseconds, position dependent terms in $c^{-4}$ (the last two terms in (7)) may reach, for example, an amplitude of 0.4 ps (corresponding to $\sim 3 \times 10^{-17}$ in rate) in geostationary orbit.

To summarize, the IAU'1991 framework is sufficient for applications with an uncertainty not smaller than about $2 \times 10^{-16}$ in rate or, for quasi-periodic terms, not smaller than a few parts in $10^{17}$ in rate amplitude. For a smaller uncertainty, Resolution B1.5(2000) provides all the necessary information to perform time transformations in the domain of validity specified in the Resolution (typically $5 \times 10^{-18}$ in rate). Applications considered are e.g. future space missions carrying high accuracy cold atoms clocks, the frequency comparison of two clocks in two different locations in the solar system or the realization of TCB from an Earth atomic time scale. Finally, when the accuracy specified in Resolution B1.5 will be deemed insufficient, formulas extending those given above should be re-derived from resolutions B1.3 and B1.4.

### 3.2 Resolution B1.9(2000): Re-definition of Terrestrial Time TT

Evaluating the contributions of the higher order terms in the metric of the geocentric reference system (Resolution B1.3), it is found that the IAU'1991 framework with the metric of the form (1) is sufficient for time and frequency

applications in the GCRS in the light of present and foreseeable future clock accuracies. Although TCG is the time coordinate of the GCRS, presently, the time scale of reference for all practical matters on Earth is Terrestrial Time $TT$ or one of the scales realizing it and differing by some time offset (e.g., $TAI, UTC, GPS$-time). TT was defined in IAU Resolution A4 (1991) as: "a time scale differing from the Geocentric Coordinate Time $TCG$ by a constant rate, the unit of measurement of $TT$ being chosen so that it agrees with the SI second on the geoid". According to the transformation between proper and coordinate time, this constant rate is given by $\mathrm{d}(TT)/\mathrm{d}(TCG) = 1 - U_g/c^2 = 1 - L_G$, where $U_g$ is the gravity (gravitational + rotational) potential on the geoid.

Some shortcomings appeared in this definition of TT when considering accuracies below $10^{-17}$. First, the uncertainty in determination of $U_g$ is of order 1 $\mathrm{m^2\,s^{-2}}$ or slightly better (Groten, 2000). Second, even if it is expected that the uncertainty in $U_g$ improves with time the surface of the geoid is difficult to realize (so that it is difficult to determine the potential difference between the geoid and the location of a clock). Third, the geoid is, in principle, variable with time. Therefore it was decided to desociate the definition of TT from the geoid while maintaining continuity with the previous definition. The constant $L_g$ was turned into a defining constant with its value fixed to $6.969290134 \times 10^{-10}$ to ensure the continuity with the current best estimation of $U_G/c^2$, from the value $U_G = 62636856$ $\mathrm{m^2\,s^{-2}}$ provided by the International Association of Geodesy Special Commission 3 (Groten 2000).

Thus Resolution B1.9 will allow to use the full potential of future high accuracy clocks on board terrestrial satellites to realize TT.

## 4 Some applications of the IAU'1991+2000 framework

All space geodesy techniques must be considered in the framework of general relativity. The use of a relativistic model implies several steps e.g. as adapted from (Wolf 2001):

1. to choose of an appropriate coordinate system and associated metric, in which to model the technique measurement.
2. to transform all input quantities (measurements + other information e.g. positions, velocities) into this coordinate system.
3. to obtain the results (usually by fitting parameters to measurements) in this coordinate system.
4. to transform the results, if necessary, into proper quantities or into another coordinate system.

The IAU'2000 framework allows to model unambiguously all space geodesy and astrometry techniques using the BCRS and GCRS metric and coordinate systems as defined in Resolution B1.3. It is always possible to define different coordinates e.g. TT is defined as a time coordinate for the GCRS and TDB may be defined as a time coordinate for the BCRS.

$$dTT/dTCG = 1 - L_G, \qquad dTDB/dTCB = 1 - L_B$$

The linear factor between the scale units of the different time coordinates is of order $U/c^2$ or $v^2/c^2$ i.e. $7 \times 10^{-10}$ in the GCRS and $1.5 \times 10^{-8}$ in the BCRS. It is possible to use the metric of the GCRS or BCRS along with time measurements (input quantities) expressed in another coordinate time but care must be taken when interpreting the results, such as space coordinates or other quantities (e.g. $GM$). For example, in VLBI analysis the input quantities are generally in TT so that the space coordinates obtained are expressed in "TT

units" in the GCRS (see section 4.1); Or the $GM$ of the solar system bodies are generally obtained from the determination of planetary ephemerides in "TDB units" (see section 4.4). These quantities are related to the true GCRS (TCG) or BCRS (TCB) quantities by the same scaling factors.

For the present time, the approach that seems universally used in space geodesy and astrometry is to transform measurements (input quantities) to TT or TDB, use them in models developed in BCRS or GCRS, and appropriately scale the results, when necessary. One practical reason for this approach is that, in most cases, a quantity of proper time may be directly identified to its value after transformation to a coordinate quantity in TT or TDB. This procedure, when used correctly, may be satisfactory for the present level of uncertainty of the space geodesy or astrometry techniques (e.g. one to a few parts in $10^{10}$ in relative value). However it offers potential sources of error and confusion and, at some level of uncertainty (possibly of order $v^3/c^3$ i.e. $10^{-12}$ in scale or a fraction of $\mu$as in angle) it may no longer be adequate. This discussion is purely qualitative and more study will be necessary to precise these possible limitations.

In steps 2 and 4 defined above, one has to perform some of the following tasks: transforming proper quantities to coordinate quantities; transforming between different coordinate quantities; assigning a date (coordinate time) to an event. In section 4.1 to 4.4 below, we review how these tasks are performed for different space geodesy techniques and products and what influence the underlying choice of coordinate system may have on the space geodesy results. Finally in section 4.5 some details are provided on the transformation between TCG and TCB, which is to be used to transform time coordinates when a technique is modeled in the BCRS.

### 4.1 VLBI delay

The VLBI model (note that we consider here only the vacuum propagation delay and also do not account for the desynchronization or desyntonization of the station clocks) presented in the IERS Standards (1992) and in the draft IERS Conventions (2000) relates the TCG coordinate interval $d_{TCG} = t_2 - t_1$ to a baseline $\vec{b}$ expressed in GCRS coordinates.

$$t_2 - t_1 = \frac{\Delta T_{grav} - \frac{\hat{K}\cdot\vec{b}}{c}[1 - \frac{(1+\gamma)U}{c^2} - \frac{|\vec{V}_\oplus|^2}{2c^2} - \frac{\vec{V}_\oplus\cdot\vec{w}_2}{c^2}] - \frac{\vec{V}_\oplus\cdot\vec{b}}{c^2}(1 + \hat{K}\cdot\vec{V}_\oplus/2c)}{1 + \frac{\hat{K}\cdot(\vec{V}_\oplus+\vec{w}_2)}{c}} \quad (9)$$

It is not the purpose of this paper to present proper definitions of the quantities used in this formula, which may be found in the mentioned documents. This expression is presented only for evidencing that, with a relative uncertainty of order $v/c$ at least, a scaling in the time coordinate in the left part results in the corresponding scaling of the baseline coordinates in the right part.

In principle, the observable quantities in the VLBI technique are recorded signals measured in the proper time of the station clocks. But, for practical considerations, particularly because the station clocks do not produce ideal proper time (they even are, in general, synchronized and syntonized to UTC to some level, i.e. they have the same rate as the coordinate time TT), the VLBI delay produced by a correlator center may be considered to be, within the uncertainty of the model, equal to the TT coordinate time interval $d_{TT}$ between two events: the arrival of a radio signal from the source at the reference point of the first station, and the arrival of the same signal at the reference point of the second station. In the following, two different approaches are presented to interpret the VLBI delay which use two different geocentric coordinate systems with either TCG or TT as coordinate time.

In the first approach, which could be termed "fully IAU compliant", we consider that all quantities have been transformed to GCRS coordinate quantities i.e. with TCG as a coordinate time. In particular, the VLBI delay obtained from the correlator would have to be scaled to a TCG coordinate interval $d_{TCG} = d_{VLBI}/(1 - L_G)$. The results of the VLBI analysis, i.e. baseline $\vec{b}$ from formula (9) would then be directly obtained in terms of the spatial coordinates of the GCRS, as is recommended by the IUGG Resolution 2 (1991) and IAU Resolution B6 (1997), i.e. one would obtain coordinates that are termed "consistent with TCG", here denoted $x_{TCG}$.

In the second approach, if the VLBI model (9) is used with VLBI delays as directly provided by correlators (i.e. equivalent to a TT coordinate interval $d_{TT}$ without transformation to TCG), the baseline $\vec{b}$ is not expressed in GCRS but in some other coordinate system. The transformation of these coordinates to GCRS reduces, at the level of uncertainty considered here, to a simple scaling. The space coordinates resulting from the VLBI analysis (here denoted $x_{VLBI}$) are then termed "consistent with TT" and the coordinates recommended by the IAU and IUGG resolutions, $x_{TCG}$, may be obtained *a posteriori* by $x_{TCG} = x_{VLBI}/(1 - L_G)$.

### 4.2 Laser ranging to a satellite or to the Moon

In a reference system centered on an ensemble of masses, as considered in the IAU framework, if a light signal is emitted from $x_1$ at coordinate time $t_1$ and is received at $x_2$ at coordinate time $t_2$, the coordinate time of propagation is given by

$$t_2 - t_1 = \frac{|\vec{x}_2(t_2) - \vec{x}_1(t_1)|}{c} + \sum_J \frac{2GM_J}{c^3} \ln\left(\frac{r_{J1} + r_{J2} + \rho}{r_{J1} + r_{J2} - \rho}\right) \qquad (10)$$

where the sum is carried out over all bodies J with mass $M_J$ centered at $x_J$ and where $r_{J1} = |\vec{x}_1 - \vec{x}_J|$, $r_{J2} = |\vec{x}_2 - \vec{x}_J|$ and $\rho = |\vec{x}_2 - \vec{x}_1|$.

Because the space coordinates $x_i$ are generally determined from the same data set through the equations of motion of the satellite or of the Moon, it is not so trivial to directly evaluate the impact of the choice of the reference system on the model given by (10). Nevertheless it is possible to specified the coordinate transformations that are to be used in steps 2/4 defined above. The IAU'1991 formalism is sufficient to obtain (10) and to perform the necessary coordinate transformations (it is however not sufficient for the equations of motion, but this subject is not treated here).

For near-Earth satellites (SLR), practical analysis is done in the geocentric frame of reference, and the only body to be considered in the summation of (10) is the Earth (Ries *et al.*, 1988). Measurement of the time of flight of the laser signal is obtained with a clock on Earth, which rate is usually close to that of TT (or corrected to that of TT). The coordinate interval $t_2 - t_1$ is therefore usually taken as a TT interval and the $GM$ value and space coordinates obtained from the dynamical analysis are termed to be "in TT units".

For lunar laser ranging (LLR), which is formulated in the solar system barycentric reference frame, the Sun and the Earth must be taken into account in the summation of (10), with the contribution of the Moon being of order 1 ps (i.e. about 1 mm for a return trip). Moreover, in the analysis of LLR data, the body-centered coordinates of an Earth station and a lunar reflector should be transformed into barycentric coordinates. The transformation of $\vec{r}$, a geocentric position vector expressed in the GCRS, to $\vec{r}_b$, the vector expressed in the BCRS, is provided with an uncertainty lower than 1 mm by the equation

$$\vec{r}_b = \vec{r}\left(1 - \frac{U}{c^2}\right) - \frac{1}{2}\left(\frac{\vec{V}\cdot\vec{r}}{c^2}\right)\vec{V} \tag{11}$$

where $U$ is the gravitational potential at the geocenter (excluding the Earth's mass) and $\vec{V}$ is the barycentric velocity of the Earth. A similar equation applies to the selenocentric reflector coordinates. The time of flight measured by the Earth clock has to be transformed into the corresponding interval of TCB and time tags of measurements expressed in UTC have to be transformed to TCB.

The actual practice of LLR analysis centers is not studied here.

### 4.3 Scale of ITRF2000

The scale of ITRF2000 is based on "a weighted average of VLBI and most consistent SLR solutions" (draft IERS Conventions 2000). All VLBI analysis centers submitting to the IERS have used the second approach described in section 4.1 and, therefore, the VLBI space coordinates are of the type $x_{VLBI}$. Similarly all SLR analysis centers perform their analysis using TT as a coordinate time in the geocentric system and presumably provide space coordinates "consistent with TT". For continuity, a ITRF workshop (November 2000) decided to continue to use this approach, making it the present conventional choice for submission to the IERS. At the ITRF workshop, it was also decided that the coordinates should not be re-scaled to $x_{TCG}$ for the computation of ITRF2000 (see IERS Conventions 2000) so that the scale of ITRF2000 does not comply with IAU and IUGG resolutions. Space coordinates "consistent with TCG" may be obtained by $x_{TCG} = x_{ITRF2000} \times (1 + L_G)$.

Note that, contrary to ITRF2000, previous realizations ITRF94 to ITRF97 had been scaled to be in compliance with IAU and IUG resolutions (see IERS Conventions 2000).

Note also that other differences exist between the conventions used to generate ITRF2000 and IAU/IUGG resolutions. They concern mainly the treatment of the permanent tide and the geocenter motion. The IERS Conventions 2000 will provide the formulas to transform coordinates expressed in ITRF2000 to the coordinates that would be obtained in a coordinate system fully compliant with IAU/IUGG resolutions.

### 4.4 Solar system Ephemerides

The metric tensor of the BCRS, as defined in the IAU'2000 resolutions, allows one to derive (see Soffel et al. 2002) the Einstein-Infeld-Hoffman equations of motion which have been used since the 70s to construct the JPL numerical ephemerides of planetary motion of the DE series (Newhall et al. 1983). These planetary and lunar ephemerides have been recommended for the successive IERS Conventions. For the Conventions 2000, these are DE405 and the Lunar Ephemeris LE405, available on a CD from the publisher, Willmann-Bell. See also the website `http://ssd.jpl.nasa.gov/iau-comm4`; click on the button, "Where to Obtain Ephemerides".

Like for all ephemerides in the DE series, the time scale for DE405/LE405 is not TCB but rather, a coordinate time, $T_{eph}$, which is related to TCB by an offset and a rate. Because $T_{eph}$ varies with each realization, it can be identified as being essentially the same as, but not exactly equivalent to, TDB (and prior to 1976, ET) (Standish 1998). The $GM$ values of the solar system bodies and the space coordinates obtained from the dynamical analysis are termed to be "in TDB units".

### 4.5 Transformation between TCG and TCB

The relation between TCG and TCB is given by (2) in the IAU'1991 framework and by (7) in the IAU'2000 framework. We consider here only the location-independent part of (2), i.e. the $c^{-2}$ term of the relation between TCG and TCB at the geocenter, noted $(TCB - TCG)_{c^{-2}}(Geo, TT)$. It is the integral in (2), i.e. the first integral in (7), and may be computed, through (8), from the Solar system ephemerides as an integral of the argument $T_{eph}$ of the ephemerides. This integral in $T_{eph}$ has been termed "time ephemeris" and its current conventional realization is TE405 (Irwin and Fukushima, 1999). It is based on the JPL ephemerides DE405/LE405 (see previous section) and is available in a Chebyshev form at `ftp://astroftp.phys.uvic.ca/pub/irwin/tephemeris`. An analytic formula approximating TE405 to 0.5 ns RMS over 1600-2200 is in preparation (Fukushima, 2002, personal communication). While the time argument of TE405 is, strictly speaking, $T_{eph}$, it may be replaced by TT for computing TCB-TCG because the error in doing so is at the ps level.

Actually TE405, as it is computed and distributed, here noted $TE405(TT)$, does not provide directly the integral in $T_{eph}$, defined above, but this integral minus a linear term so that

$$(TCB-TCG)_{c^{-2}}(Geo, TT) = (TE405(TT)+\Delta L_C \times (TT-TT_0))/(1-L_B) \quad (12)$$

where $\Delta L_C = 1.48082685594 \times 10^{-8}$ and where $TT_0$ corresponds to JD 2443144.5 TAI. The uncertainty is estimated to be of order $1 \times 10^{-17}$ in rate and a few ns in periodic terms over 1600-2200.

Analytical formulas which had been developed to compute the transformation TDB-TDT before 1991 may still be used to compute the TCB-TCG relation. Among these formulas, one version of the formula developped by (Fairhead and Bretagnon, 1990) has been made available with the IERS Conventions 1996 (`ftp://maia.usno.navy.mil/conventions/chapter11/fbl.f`). It is referenced in (Irwin and Fukushima, 1999) as FB3B and they have shown that $FB3B(TT) - FB3B(TT_0)$ is equivalent to $TE405(TT)$ to within $\pm 15ns$ over 1600-2200 and may be used in (12) to this level of uncertainty,

To obtain the full transformation (7) at the geocenter one should also take into account terms in $c^{-4}$, as indicated in section 3.2. For completeness, on may add a small ($c^{-2}$) contribution from the asteroids which is not included in $(TCB-TCG)_{c^{-2}}(Geo, TT)$ as computed in (12), an estimate of which is given in (Irwin and Fukushima, 1999). Finally

$$(TCB-TCG)(Geo, TT) = (TE405(TT)+L_C \times (TT-TT_0))/(1-L_B) \quad (13)$$

where $L_C = 1.48082686741 \times 10^{-8}$. To obtain the full transformation (7) for any event, one should also take into account position dependent terms in $c^{-2}$ (position dependent terms in $c^{-4}$ being generally negligible), as indicated in section 3.2.

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# Comparision of "Old" and "New" Concepts: Reference Systems

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**Abstract:** As a consequence of the IAU 2000 resolutions, the old celestial dynamical reference system, materialized by the FK5, is replaced by the ICRS, which consists of the BCRS and the GCRS, both kinematically defined by the position of the same extragalactic radiosources. The relation between them involves the geodesic precession and nutation, and the Lense-Thirring precession. Then, the reduction procedures for the intermediate reference system to the GCRS and the BCRS are sketched. The effect of the galactic rotation is not taken into account.

## 1 The old and the new Reference Systems

From 1991 to 2000, the IAU has introduced, and progressively established in a well defined manner, a new reference system, the International Celestial Reference System (ICRS) and its associated frame, the International Celestial Reference Frame (ICRF). Ideally, a reference system is a set of space coordinates, which is fixed in some defined way, and a time scale. The theoretical background that allowed to construct such a *fixed* or *inertial* (following the old terminology) has evolved with time. Under the pressure of the improvement of the accuracy of observations, more sophisticated definitions of what space and time are in our environment became necessary.

### The old system

The old system was essentially derived from Newtonian Mechanics. General Relativity was only superficially present under the form of so called *relativistic corrections*, which were treated as perturbations to Newtonian equations. Different time-scales were introduced (geocentric and barycentric), but the space coordinates were essentially Euclidean, even if corrections for geodesic precession and light deflection were introduced.

Actually, the main drawback of the old system was that the reference axes were based upon the position of two moving planes (equator and ecliptic) at some epoch. The consequence was that it was necessary to have a theoretically based motion of these planes. But sometimes, it was necessary to replace the equinox provided by the theory by an extrapolation of positions obtained by observations. This situation was particularly inconvenient for the definition of the equinox J2000.0, which had to be placed despite an erroneous constant of precession and an insufficient nutation/precession theory. The result is that there were three different equinoxes (the FK5 equinox and two different dynamical).

The reference system was theoretically dynamical, defined using the solutions of the planetary equations of motion with the condition that there is no Coriolis acceleration that would be caused by a rotation of the coordinate axes. The fiducial points defining the reference frame (the FK5) were stars, whose positions were not accurately linked to planets, in particular at high latitudes. So the FK5 was also constrained by a value of the Oort's constants, which describe the differential rotation of the Galaxy in the vicinity of the Sun. This

gave rise to the inconsistencies between the FK5 equinox, and those based upon dynamical theories.

**The new system**

The new system is kinematic, because it is defined through the positions of extragalactic objects, whose proper motions are assumed to be negligible in comparison with the accuracy of observations. The space-time is described by a metric tensor in the framework of the theory of General Relativity, which is a geometric theory, and does not imply dynamics in the definition of the reference system. The ICRS consists of the ensemble of the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS), whose definitions, as well as their relationship in terms of a generalized Lorentz transformation, are given in the IAU Resolution B1.3 (2000). They have the particularity of being both kinematically defined by a set of extragalactic objects and realized by the ITRF in radio wavelengths. The axes are chosen in such a way that the discontinuity with the old ones is as small as observations permit.

## 2 The Barycentric Celestial Reference System

Let us first consider the BCRS. The axes are fixed in time. I suggest that the coordinates of an object in these axes are referred as right ascension and declination without any additional qualification. Since they are barycentric, stellar objects are not subject to parallax, and the only variations in the coordinates are due to their proper motions and the perspective acceleration effect. Therefore, one must still indicate the date $t$ of the position: $\alpha(t)$ and $\delta(t)$. This date does not correspond to what used to be called *epoch*. Because the BCRS is, by construction, kinematically fixed, there is no epoch in the old sense (e. g. J2000.0 or B1950). which corresponded to the position of reference axes. Actually, the ICRS positions behave like the old mean places referred to the mean equator and equinox at a standard epoch, but here, there is no epoch involved.

**The International Celestial Reference Frame**

The frame realizing the ICRS is the ITRF, defined by the positions of extragalactic radiosources, assumed to be fixed. The optical realization is the Hipparcos Catalogue from which the problem stars have been removed. It is the Hipparcos Celestial Reference Frame (HCRF). The positions are in the ICRS, but the reference date $t$ is 1991.25. So, to obtain the position of a star $A$ at a date $T$ observed with respect to $n$ stars $S_i$, $i = 1$ to $n$, one must first transform the positions of $S_i$ by the displacement due to their proper motions from $t$ to $T$:

$$\begin{aligned} \alpha_i(T) &= \alpha_i(t) + \mu_\alpha(T-t), \\ \delta_i(T) &= \delta_i(t) + \mu_\delta(T-t). \end{aligned}$$

Similar precautions must be taken when the position of $A$ is referred to stars of other catalogues such as TYCHO2 or AC2000, which are in ICRS, but whose reference date is different, and not necessarily J2000.0.

## 3 The Geocentric Celestial Reference System

Since observations are generally made from the Earth, they refer to the GCRS, which is consequently in motion around the barycenter. But since it has fixed

directions with respect to extragalactic sources, there is a Coriolis-like effect from the relativistic theory of the transformation if we refer it to the BCRS. This transformation, given in the IAU 2000 recommendation B1.3 must be applied. In practice, it is the geodesic precession and nutation, and in some cases, also the Lense-Thirring precession. Both are, in essence, very different effects from the classical precession and nutation due to gravitational forces.

1. *Geodesic precession.* It is a rotation around an axis perpendicular to the ecliptic. Its magnitude is given by:

$$\psi_G = \frac{3}{2}\frac{Gm_\odot n}{c^2 r},$$

where $n$ is the mean motion of the Earth's orbit and $r$ is the distance of the Earth-Moon system to the origin of the BCRS. Its value, a circular-orbit average, is

$$\psi_G = 19.194 \text{ mas per year.}$$

There are also periodic terms in this transformation, called geodesic nutation, along the ecliptic, whose largest term is $\Delta\psi_G = -0.153 \sin l$, where $l$ is the mean anomaly of the Sun.

2. *Lense-Thirring precession.* If the accuracy of observations is very high, it may be necessary to take into account the $c^{-3}$ terms of the transformation. It is the Lense-Thirring precession corresponding to the gravitomagnetic field. Until now, it is neglected.

In describing the motions of artificial satellites or the Moon, one must use the GCRS. This *natural* reference system moves with the Earth around the Sun, so that the equations of motion of these bodies must take into account the Coriolis-like accelerations in the framework of General Relativity. Therefore, when writing the equations of motion of these objects, one must stay in the GCRS and not include the geodetic precession-nutation terms in the reduction algorithms. If one uses the IAU precession-nutation series in which geodesic precession is included, it will be necessary to subtract these terms, before using the observations for dynamical studies, but then include the additional accelerations in the equations.

## 4 The Instantaneous Axes of Reference

Earth based observations are normally referred to an instantaneous system of reference axes. In the old system, it was defined by the direction of the Celestial Ephemeris Pole (CEP) perpendicular to the true (instantaneous) equator and the true ecliptic as the origin on the equator. The new system is called Intermediate Reference System (IRS) with a slightly different pole (the Celestial Intermediate Pole, CIP) and, on the corresponding true equator, the Celestial Ephemeris Origin (CEO). In the general case, one wishes to transform the intermediate (or true) coordinates $\alpha_i$ and $\delta_i$ in the IRS into the BCRS coordinates $\alpha$ and $\delta$. To do this, one must apply the IAU-2000 precession-nutation series and the geodesic precession-nutation. Both are actually included there. This is a simplification for the user, but may be misleading from the point of view of the physical interpretation. One must, of course, also apply the aberration correction and, if the stellar parallax is known, the parallactic correction as well. For the bodies of the solar system, the situation is more complicated and one should compute the planetary parallax and the light time in the BCRS.

## 5 Further Remarks

1. The motion of the barycenter of the solar system is not linear in its orbit about the center of the Galaxy. There is therefore a Coriolis-like acceleration, which gives rise to a *galactic* geodesic precession. It is not included in the definition of the ICRS. This means that on should either distinguish between a *natural* barycentric system from the BCRS, or to apply, in the dynamical representations of the motion of planets in the BCRS, the corresponding acceleration.

2. The ICRF provides a fixed coordinate system for computing solar system ephemerides. It is generally convenient to use a coordinate system based on an approximation to the principal plane of the solar system, like a fixed ecliptic, as used in the past. To be consistent with ICRS and its origin, a fixed ecliptic should be defined as a fixed plane through the origin of the ICRS with a fixed inclination $\varepsilon_0$ equal to the mean obliquity at J 2000.0.

3. Although the IERS will introduce the new system in 2003, the old system will continue to be used. It is not a satisfactory situation. All the new star catalogues are now published in the ICRS, which is not exactly the FK5 J2000.0 system. Astrometrists should be encouraged to shift entirely to the new system, including the IRS, to avoid misleading comparisons between results, and use systematically a completely consistent environment.

# Comparison of "Old" and "New" Concepts: The Celestial Intermediate Pole and Earth Orientation Parameters

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## 1 Introduction

The adoption of the International Celestial Reference System (ICRS) since the 1st January 1998 by the IAU, associated with significant improvements in the theory and observation of Earth's rotation, required an extended definition of the celestial pole as well as more basic Earth Orientation Parameters (EOP). This has been under discussion, from 1998 to 2000, within the subgroup T5 (for more detail, see http://danof.obspm.fr/T5.html) untitled "Computational consequences" of the IAU Working Group ICRS and has been taken into account by two IAU 2000 resolutions. Resolution B1.7 defines the "Celestial Intermediate Pole" (CIP), which replaces the "Celestial Ephemeris Pole" (CEP) in the new IAU 2000 precession and nutation model and specifies the way for taking into account the high frequency terms in polar motion and nutation. Resolution B1.8 recommends the use of the "non-rotating origin" (NRO) (Guinot 1979) both in the GCRS (Geocentric Celestial Reference System) and ITRS (International Terrestrial Reference System) for defining UT1; it also recommends the use of the position of the CIP in the GCRS and in the ITRS in the transformation between GCRS and ITRS.

This report provides a comparison of Old and New concepts for the pole and the EOP, except for the use of the NRO which is more largely developed in B. Guinot's report for the same session of the Workshop.

## 2 Comparison of the CIP to other reference poles

### 2.1 The Instantaneous Pole of rotation (IRP)

The instantaneous axis of rotation is the most natural axis to be considered when studying Earth's rotation. The Instantaneous Rotation Pole (IRP) has thus been the pole of reference for nutation up to the IAU 1964 theory of nutation (Woolard 1953) in use until 1984. Referring to the IRP separates the forced luni-solar motion into two parts : the celestial part (precession and nutation), and the terrestrial part, or forced "diurnal polar motion", also called "diurnal nutation" or "forced variation of latitude" (Fedorov 1963), which corresponds to "Oppolzer terms" in space (Jeffreys 1963). Following Atkinson (1975) who showed that optical astrometric observations cannot provide the IRP and several other papers showing that the IRP is not "observable" from any kind of available observations (Murray 1979, Kinoshita et *al.* 1979), the IAU 1980 Theory of nutation (Seidelmann 1982) has been referred to the *Celestial Ephemeris Pole* (cf. Atkinson's Pole) (CEP). The forced diurnal polar motion was thus included into the celestial nutation and this "diurnal nutation" has no more to be considered as a separate part of the forced motion of the pole. However, it must be noted that the IRP is still the reference pole for gravimetric or gyroscopic observations (Capitaine 1986, Loyer *et al.* 1999).

### 2.2 The Celestial Ephemeris Pole (CEP)

Observations of Earth Orientation are sensitive to the offset between the pole, T, of the TRS and the pole, C, of the GCRS. The CEP is actually closer than the IRP to the "observed pole" based on astrometric or space geodetic measurements and its use simplifies the computation of the predictable part of the celestial motion of the pole. The IAU 1980 Theory of nutation has provided a tentative conceptual definition of the CEP as the "pole that has no nearly-diurnal motion with respect to a space-fixed coordinate system or an Earth-fixed coordinate system" which would correspond to the "axis of figure for the Tisserand mean outer surface of the Earth" as used by Wahr (1981) in his theory of rotation of a non-rigid Earth. However, such a conceptual definition is not clear and the significance of the change from the instantaneous pole of rotation to the CEP has been discussed (Capitaine *et al.* 1985).

The CEP was actually defined by its realization using the IAU-1980 nutation series. The consideration of the "celestial pole offsets" as estimated by VLBI observations and, afterwards, the use of an improved precession-nutation model in the IERS 1996 Conventions (McCarthy 1996), modified the realization of the CEP. The pole offsets, which contain the deficiencies in the precession-nutation model, provide the whole retrograde diurnal motion with respect to the ITRS, or, equivalently, the whole long period motion of the CEP with respect to the GCRS. Similarly, the "pole coordinates" provide, when estimated from observations, with a time resolution of a few days, the whole long period motion of the CEP with respect to the ITRS. The realization of the CEP then depends both on the model for precession and nutation and on data processing; this is illustrated by Figure 1 which shows different realizations of the CEP (C', C", C"') according to the precession-nutation model and to the processing of the data, especially on whether the celestial pole offsets are estimated (C", C"') or not estimated (C').

The definition of the CEP did not give any convention for the high frequency motions (periods shorter than two days) in the GCRS or ITRS and the definition is moreover not valid (Brzeziński & Capitaine 1993) for sampling intervals shorter than 1 day.

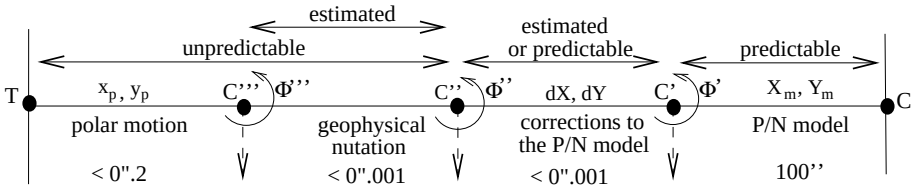


**Figure 1**: Different realizations of the CEP as an intermediate pole between the pole T of the TRS and the pole C of the CRS (Brzeziński & Capitaine 1995)

### 2.3 The Celestial Intermediate Pole (CIP)

Since the adoption of the CEP, significant improvement in precision and temporal resolution of the observations of Earth rotation, as well as in the development of theory have been achieved. GPS and intensive VLBI observations provide EOP with a submilliarcsecond accuracy over a few hours, whereas diurnal and semi-diurnal terms are now considered in the theory at a microarcsecond accuracy both for pole motion and nutation. A new definition of the pole of reference had thus become necessary.

Tidal variations in polar motion, which are dominated by diurnal and semi-diurnal terms, have been both predicted by models and estimated from observations (see for example Gross 1993 and Herring & Dong 1994). On the other hand, the prograde semi-diurnal terms of nutation, whereas they have

already been theoretically computed by Tisserand (1891) and numerically by Woolard (1953) and Kinoshita (1977), have been considered to be negligible until they have been introduced in the solutions for nutation for a rigid Earth at a microarcsecond level (Bretagnon *et al.*, 1997; Souchay *et al.*, 1999; Roosbeek, 1999). They are produced by the luni-solar torque exerted on the tesseral coefficients (2,2) of the terrestrial potential and there are moreover prograde diurnal nutations which are due to the coefficient (3,1).

It is important to note that the prograde semi-diurnal nutations can also be considered as prograde diurnal variations (Chao *et al.* 1991) in polar motion and the prograde diurnal nutations as prograde and retrograde variations in polar motion. Similarly, the retrograde diurnal tidal variations in polar motion are actually included in the recent nutation models for a non-rigid Earth. A clear convention is therefore necessary for the high frequency domain and especially for the overlapping between the motions in the GCRS and the ITRS.

The amplitudes of the largest components of tidal variations in polar motion are shown in Table 1. The most important nutations with 1 day and 0.5 day periods, with their corresponding periods and amplitudes in the Earth, are given in Table 2 for a non-rigid Earth model. Both tables refer to the fundamental arguments of nutation, $l, l', F, D, \Omega$. $\phi$ is for Greenwich Mean Sidereal time (GMST) plus a phase lag and $\theta$ is for GMST + $\pi$. The amplitudes provided in Table 2 (Folgueira *et al.* 2001), which are based on a preliminary version of the transfer function of Mathews *et al* (2002), are in good agreement with more recent results (not yet published), based on more complete models for the influence of the non-rigidity of the Earth.

Several approaches have been considered for extending the definition of the CEP in the high frequency domain through additional conventions (Capitaine & Brzeziński 1999, Capitaine 2000 a, 2000 b, T5 Newsletters). The preferred approach has been to define the pole of reference neither by a physical property, nor by a model, but as an intermediate pole in the coordinate transformation between the GCRS and the ITRS. The selected definition was the pole of the

| Tide | $l$ | $l'$ | F | D | $\Omega$ | $\theta$ | phase | Period | $\Delta x$ | | $\Delta y$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | (deg.) | (days) | Sin | Cos | Sin | Cos |
| $Q_1$ | -1 | 0 | -2 | 0 | -2 | 1 | -90 | 1.11951 | - 26 | 6 | -6 | -26 |
| $O_1$ | 0 | 0 | -2 | 0 | -2 | 1 | -90 | 1.07581 | -133 | 49 | -49 | -133 |
| $P_1$ | 0 | 0 | -2 | 2 | -2 | 1 | -90 | 1.00275 | -50 | 25 | -25 | - 50 |
| $K_1$ | 0 | 0 | 0 | 0 | 0 | 1 | 90 | 0.99727 | -152 | 78 | -78 | -152 |
| $N_2$ | -1 | 0 | -2 | 0 | -2 | 2 | 0 | 0.52743 | - 57 | -13 | 11 | 33 |
| $M_2$ | 0 | 0 | -2 | 0 | -2 | 2 | 0 | 0.51753 | -330 | -28 | 37 | 196 |
| $S_2$ | 0 | 0 | -2 | 2 | -2 | 2 | 0 | 0.50000 | -145 | 64 | 59 | 87 |
| $K_2$ | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0.49863 | - 36 | 17 | 18 | 22 |

**Table 1** : Periods and amplitudes (in $\mu$as) of the most important diurnal and sub-diurnal tidal variations in the two coordinates of polar motion ($\Delta x$ and $\Delta y$) (IERS Conventions 1996, from Ray *et al.* 1994).

| Argument in space | | | | | | Period | Period | in-phase | out-of phase |
|---|---|---|---|---|---|---|---|---|---|
| $\Phi$ | $l$ | $l'$ | $F$ | $D$ | $\Omega$ | in space | in Earth | ($a_r^+$) | ($a_i^+$) |
| 1 | 0 | 0 | -1 | 0 | -1 | 1.03505 | -27.3216 | 15.6 | 2.0 |
| 1 | 1 | 0 | -1 | 0 | -1 | 0.99758 | -3231.496 | 12.2 | 2.1 |
| 1 | -1 | 0 | 1 | 0 | 1 | 0.99696 | 3231.496 | -15.8 | -3.0 |
| 1 | 0 | 0 | 1 | 0 | 1 | 0.96215 | 27.3216 | 16.6 | 2.0 |
| 2 | 0 | 0 | -2 | 0 | -2 | 0.51753 | 1.07581 | 11.3 | -6.5 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0.49863 | 0.99727 | -14.0 | 8.0 |

**Table 2** : Periods (revised values) and amplitudes (in $\mu$as) of the largest diurnal and sub-diurnal circular nutations and of their corresponding components in polar motion (from Folgueira *et al.* 2001)

intermediate equator (between those of the GCRS and the ITRS), of which motion, with respect to the GCRS, is mainly produced by the external torque on the Earth, with a limitation to the long periodic part (periods greater than two days). With such a definition, all the motions with frequencies belonging to the retrograde diurnal band in the ITRS, are conventionally considered in the GCRS; this includes all the forced nutations with periods greater than 2 days, as well as the Free Core Nutation (FCN). On the contrary, the whole high frequency motion both in the GCRS and in the ITRS (outside the retrograde diurnal band), is conventionally considered as being a part of the polar motion.

The definition of the pole is thus unchanged from that of the CEP at a milliarcsecond level, but is sharpened in the high frequency domain at a submilliarcsecond level of accuracy. The advantages are that : 1) the extension in the frequency domain is consistent with a deterministic approach, 2) the definition is not dependent on further improvements in the model, but can be given as accurately as necessary by a model, 3) the definition is not dependent on the techniques of observation, 4) the change from the current CEP has minimal impact on users. Following the proposal above, the new pole which has been recommended by IAU Resolution B1.7 is such that its name "Celestial Intermediate Pole" (CIP) emphasizes the role of intermediary of this pole between GCRS and ITRS.

The motion of the CIP in the GCRS is provided by the IAU 2000 A model for precession and forced nutation (Dehant *et al.* 1999, Mathews *et al.* 2002), for periods greater than two days, plus the celestial pole offsets estimated from observations. Such offsets include both the errors in the model for precession-nutation and also the FCN, unless this free mode is taken into account by a model (Herring *et al.* 2002). The motion of the CIP in the ITRS is provided by EOP observations and must take into account a predictable part specified by a model including the high frequency variations (see Tables 1 and 2 for the largest terms). The corrections to this model can be estimated by extracting the high frequency signal using a procedure similar to the one described by Mathews & Herring (2000).

## 3 Comparison of the celestial coordinates of the CIP to other EOP

### 3.1 Classical parameters referred to the FK5

The current precession angles (see Fig 4) are those defined by Lieske *et al.* (1977) in the FK5 system. The classical nutation angles $\Delta\psi$ in longitude and $\Delta\epsilon$ in obliquity are referred to the ecliptic of date (see Fig 4) and $\chi_A + \Delta\chi$ is the angular distance between the ecliptic of epoch and the ecliptic of date along the equator of date. The classical procedure for taking into account precession and nutation is to use the matrix transformation using the developments as function of time of the precession angles, $\zeta_A, \theta_A, z_A$, followed by the matrix transformation using the nutation quantities $\Delta\psi$ and $\Delta\epsilon$ provided by the conventional series of nutation (Seidelmann 1982, McCarthy 1996). Such a transformation corresponds to a sequence of 6 consecutive rotations for precession and nutation. As the precession and nutation angles are referred to the ecliptic of date, the resulting matrix mixes the precession and nutation of the equator and the motion of the ecliptic whereas the two phenomena are of different physical origins and have to be considered in different celestial reference systems. The motion of the equator is due to the luni-solar and planetary torque exerted on the oblate Earth and has to be considered in the GCRS. On the other hand, the ecliptic motion, which is due to planetary perturbations on the orbit of the Earth, has to be considered in the BCRS (Barycentric Celestial Reference System).

The classical procedure for taking into account Earth rotation in the FK5 system is to use the relationship between Greenwich sidereal time and UT1 (Aoki *et al.* 1982), giving GMST at date t, followed by the relationship between GST and GMST including the complete equation of the equinoxes (Aoki & Kinoshita 1983). Additionally to Earth rotation, the angle GST includes a part due to the accumulated precession and nutation along the equator as well as cross terms between precession and nutation (Capitaine & Gontier 1993). It refers to the ecliptic of date and thus mixes Earth rotation and precession-nutation.

### 3.2 Alternative choices for new EOP in the GCRS

To take advantage of the fundamental properties of the new ICRS (Ma *et al* 1998), it is necessary to use more basic quantities for precession-nutation and Earth rotation, and therefore :

- to reduce the number of parameters by combining precession and nutation of the equator,
- not to refer these parameters to the ecliptic of date, but to a fixed plane,
- to clearly separate the precession-nutation of the equator from the Earth's rotation.

Alternative choices are summarized and compared below.

The classical representation using Euler's angles as used by Woolard (1953) between the terrestrial system [Oxyz] and the celestial one [OXYZ] (see Figure 2), refers to a fixed ecliptic frame; it can be transformed to the mean equatorial frame at J2000 taking into account a conventional value for the obliquity of the ecliptic at J2000 ($\epsilon_0$) and then transformed to the ICRS, taking into account the offsets between this frame and the ICRS. The transformation matrix from the celestial and terrestrial frames is thus based upon 3 parameters; the two first ones ($\theta$ and $\psi$), includes both polar motion and precession-nutation referred to a fixed ecliptic and the third one ($\phi$) is the angle of rotation along the moving equator of figure, reckoned from the line of nodes on the fixed ecliptic to the x-axis of the terrestrial system. It must be noted that such a representation does not clearly distinguish between BCRS and GCRS.

Aoki and Kinoshita (1983) considered a combined form of 3 rotations, using the parameters $\psi_A + \Delta\psi_1$, $\omega_A + \Delta\epsilon_1$ and $\chi + \Delta\chi$, the two first ones including precession and nutation referred to the fixed ecliptic (see Fig 4) which can easily be referred to the GCRS.

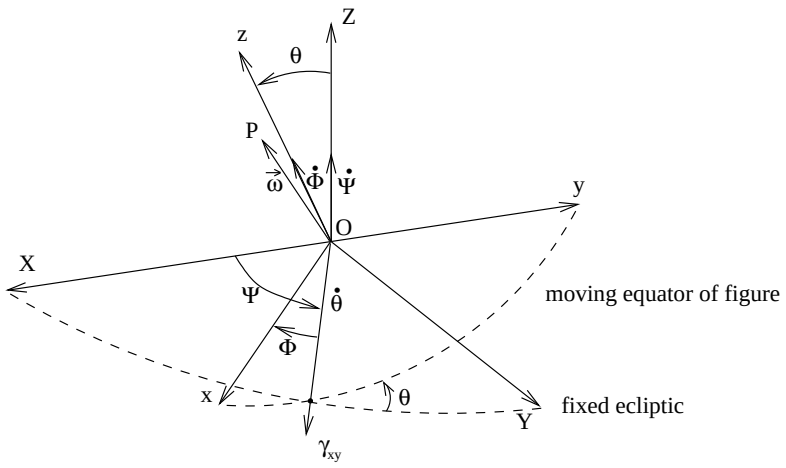


**Figure 2**: Euler's angles between terrestrial and celestial systems and the angular velocity vector $\vec{\omega}$

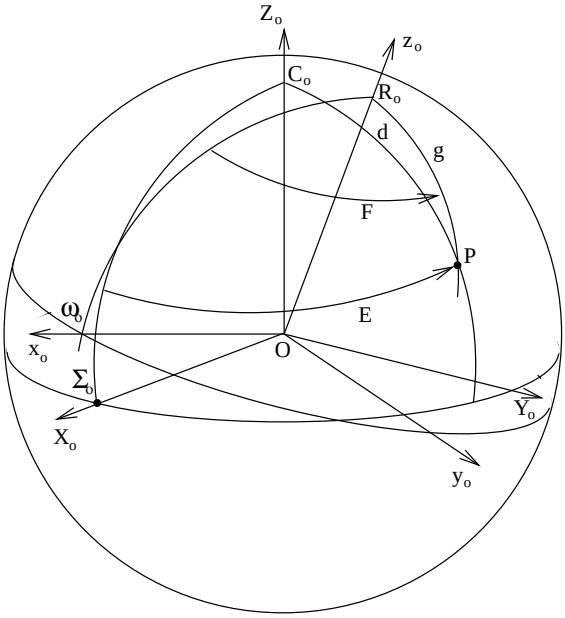


**Figure 3**: The coordinates of the pole P in the CRS and the TRS

Williams (1994) also proposed a restricted number of parameters in order to minimize the number of rotations by combining the rotations for precession and nutation, but the angles considered in longitude and obliquity are referred to the ecliptic of date.

The coordinates of the CIP in the GCRS (Capitaine 1990, Capitaine *et al.* 2000), $X = sind \cos E$ and $Y = sind \sin E$ (see Figure 3), are the direction cosines (wrt GCRS) of the vector directed to the CIP (designated by P on the Figure). They include precession, nutation, the coupling effects between precession and nutation and the offsets $\xi_o, \eta_o$, $d\alpha_0$ of the precession-nutation models at J2000 wrt the pole and equatorial origin of the GCRS. These quantities, which appear in a symmetrical form to the coordinates of P in the ITRS, are easily associated with the use of the NRO. It is interesting to note that the use of celestial coordinates of the mean celestial pole of date had already been proposed by Fabri (1980) for replacing the classical precession angles.

Fukushima (1994) proposed the use of the magnitude components of the angular momentum vector, $\overrightarrow{G}$, in the GCRS (XYZ) and in the ITRS (ABC) and the longitude of $A$-axis measured from $X$-axis along the great circle perpendicular to the angular momentum of date. The orientation matrix from the ITRS to the GCRS is thus generated by five successive rotations and the corresponding origin on the moving equator is the intersection of the zero-line meridian of the GCRS relative to the plane perpendicular to the angular momentum axis.

Mathews & Herring (2000) proposed to use the celestial coordinates of the z-axis of the TRS, which is similar to Euler's angles between GCRS and ITRS, replacing angles by coordinates.

A comparison of the parameters considered above shows that Euler's angles, or equivalently the celestial coordinates of the z-axis of the TRS, which reduce to 3 the number of EOP, do not use any intermediate pole and consequently include both high frequency and low frequency components of the motion of the Earth's axis of figure wrt the GCRS. On the contrary, the position of the CIP in the GCRS, which combines precession and nutation, separates the celestial components from the terrestrial ones using an intermediate pole (the CIP) in order to facilitate the estimation of the parameters from observations. The use of the angular momentum vector, whereas it is very useful for a dynamical

approach of Earth's rotation, cannot easily be linked to the observations. Other proposed EOP are not referred to a fixed plane and do not thus take benefit of the properties of the GCRS.

### 3.3 Comparison between Old and New EOP

The position of the CIP in the GCRS, of which use is recommended by Resolution B1.8, can be expressed by the direction cosines $X = \sin d \cos E$ and $Y \sin d \sin E$ (see Figures 3 and 5), which can be related to the combined classical angles for precession and nutation (see Figure 4) by (Capitaine 1990) :

$$X = \bar{X} + \xi_o - d\alpha_0 \bar{Y}; \quad Y = \bar{Y} + \eta_o + d\alpha_0 \bar{X} \ , \ (1)$$

with :

$$\begin{aligned} \bar{X} &= \sin(\omega_A + \Delta\epsilon_1) \sin(\psi_A + \Delta\psi_1) \\ \bar{Y} &= -\sin\epsilon_o \cos(\omega_A + \Delta\epsilon_1) + \cos\epsilon_o \sin(\omega_A + \Delta\epsilon_1) \cos(\psi_A + \Delta\psi_1) \ , \ (2) \end{aligned}$$

$\bar{X}$ and $\bar{Y}$ being the coordinates of the CIP in the mean equatorial frame at J2000 and the relation (1) being given at the first order in the offsets quantities at J2000, $\xi_o$, $\eta_o$ and $\alpha_0$. These quantities can be developed at a microarcsecond accuracy as a polynomial form of t plus a series of Poisson terms, valid over an interval of several centuries (Capitaine *et al.* 2000).

The new EOP, as adopted by the IAU (Resolution B1.8) in consistency with the ICRS, abandon the current parameters and formulation in the FK5 System which combine the motions of the equator and the ecliptic wrt the ICRS. The new parameters X and Y include both precession and nutation and refer directly to the GCRS. They use the intermediate reference system of the CIP, which allows to clearly separate high frequency and low frequency motions. The Earth's angle of rotation is no more reckoned from the true equinox, but from the NRO (Guinot 1979), which is an unavoidable origin to separate the precession-nutation from Earth's rotation.

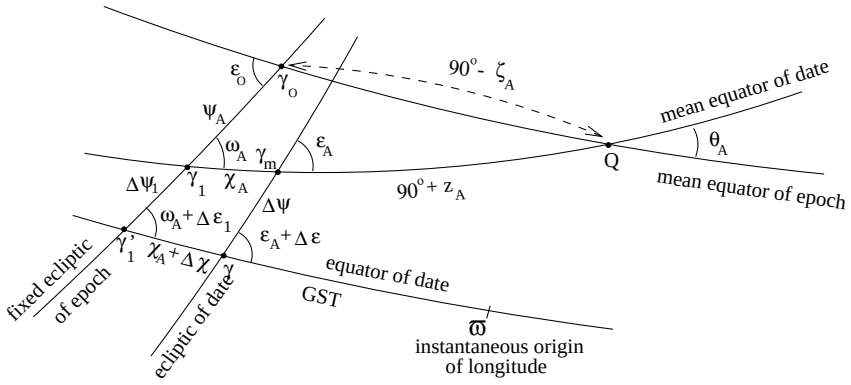


**Figure 4**: Earth orientation parameters (precession, nutation, GST) in the FK5

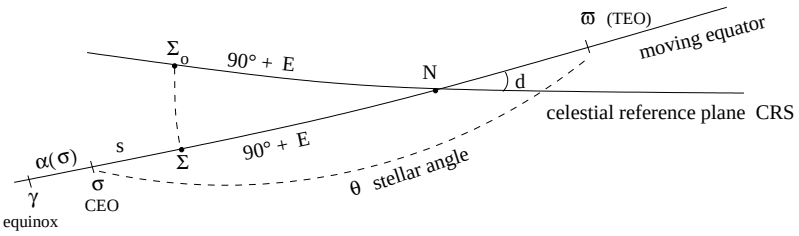


**Figure 5**: Earth orientation parameters (E, d, $\theta$) (see (1)) referred to the GCRS

This reduces to 5 the parameters for the transformation between ITRS and GCRS (see Figure 3): two (E, d) (or $X$ and $Y$) for the position of the CIP in the GCRS (instead of 6 current precession and nutation angles), two (F, g) (or polar coordinates $u$ and$-v$) for the position of the CIP in the ITRS and one for the Earth's angle of rotation.

In order to refer the Earth Rotation Angle (ERA) to the NRO (designated by CEO in the GCRS and TEO in the ITRS, respectively), as required by Resolution B1.8, the angle of position of the CEO (resp. TEO) in the GCRS (resp. ITRS) has also to be provided; it is given by the quantity $s$ (see Figure 5) (resp. $s'$). This can be expressed by a development as function of time (Capitaine *et al.* 2000). The relationship between the ERA (also called the "stellar angle" $\theta$) and UT1 is linear and ensures the continuity in phase and rate of UT1 with the value obtained by the conventional relationship between Greenwich Mean Sidereal Time (GMST) and UT1 (Aoki *et al.* 1982). Such a linearity represents a significant improvement in the definition of UT1.

## 4 Acknowledgements

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# Comparison of "Old" and "New" Concepts: Celestial Ephemeris Origin (CEO), Terrestrial Ephemeris Origin (TEO), Earth Rotation Angle (ERA)

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The following pages, with their notes, summarise the definitions of the CEO, TEO and ERA, their properties in theory and in practice. They show comparisons with traditional concepts, equinox, origin of terrestrial longitudes (not rigorously defined), Greenwich Sidereal Time.

These elements intervene in the transformation between terrestrial and celestial systems and frames.

This transformation does not require necessarily the use of celestial and terrestrial intermediate reference systems, and corresponding frames, attached to the pole of rotation and to some origins on the equators : the use of three Eulerian angles is sufficient and has been suggested. However, such intermediate systems are convenient for practical and scientific reasons. They introduce quantities which vary slowly or almost linearly with time, and which have a astronomical and geophysical interest. This is, in particular, the case of UT1, historically intended to be proportional to the angle of sidereal rotation of the Earth (Earth Rotation Angle, ERA).

The five parameters of the transformation are noted :

- $X$, $Y$, direction cosines of the Celestial Intermediate Pole (CIP) in the Geocentric Celestial Reference System (GCRS) or Frame (GCRF) [usually multiplied by 1296000''/2π and referred to as coordinates of the CIP] ;
- $x$, $y$, direction cosines [or coordinates] of the CIP in the International Terrestrial Reference System (ITRS) or Frame (IRTF) :
- $\theta$ Earth Rotation Angle, ERA.

The observations bring corrections to approximate values of these quantities provided by models ($X$, $Y$) or previsions ($x$, $y$, $\theta$). In the spirit of the IAU resolutions of the XXIVth IAU General Assembly (2000), the goal is to ensure that definitions and processes of the involved quantities maintain an accuracy at the level of the microarcsecond.

The main differences between old and new concepts, in this field, are :

- the use of the CIP in place of the Celestial Ephemeris Pole ;
- the direct use of the coordinates $X$, $Y$ of the CIP ;
- the adoption of the Celestial Ephemeris Origin (CEO) in place of the equinox on the equator of the CIP, and of the corresponding longitude origin, TEO, on the terrestrial equator of the CIP ;
- the adoption of the ERA in place of the Greenwich Sidereal Time.

The explicit use of the CEO is not the only possible route between the Geocentric Celestial Reference Frame (GCRF) and the International Terrestrial Reference Frame (ITRF), using an intermediate frame attached to the CIP, but it has the advantage of avoiding the complexities introduced by a conventional ecliptic which plays no direct role in the transformation between frames and in the observations of the

Earth rotation. In particular, *GST* depends on the observed position of the CIP and, therefore, the conventional relation *GST-UT1* needs to be corrected when precession-nutation model is changed and when the position of the CIP is measured. In the relation *GST-UT1*, the use of the CEO is implicit in order to ensure that *UT1* is proportional to the sidereal rotation of the Earth, represented by $\theta$.

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# Celestial Ephemeris Origin

## Definitions and Basic Properties

| CEO | Equinox |
|---|---|
| **Definitions** | |
| On the CIP equator at *t* (Terrestrial Time). | On the CIP equator at *t*. |
| Defined cinematically : The Celestial Intermediate Reference System linked to the CIP and the CEO has no component of instantaneous rotati along the axis of the CIP in the GCRS, at any time. | Defined geometrically : Intersection of the true equator with a conventional plane passing through the geocentre, called 'ecliptic', |
| Requires a quantity *s*. | Usual expressions for precession-nutation. |
| *s* is the composite arc CEO-N (on the tru equator) minus $\Sigma_0$N (on the equator of GCRS), N being the node and $\Sigma_0$ the orig of right ascensions in the GCRS. | |
| *s* obtained by an integration along the CI (*X,Y*) trajectory from $t_0$ = J2000.0 to *t*. (Note 1) | Requires only the position of the CIP at *t*. |
| *X , Y* and *s* are the three parameters for the transformation GCRS - Celestial Intermediate Reference System. They include precession and nutation | Usual matrices. |
| **Realisations** | |
| *s* is computed from a model of precession-nutation. | |
| *s* is a small quantity (2) (*s* = 0 at J2000.0, reaches 70 mas in 2100). | Large variation of right ascensions (reaches 1.3° in 2100). |
| *s* is practically insensitive (at the microarcsecond level until 2100) - to changes of model of precession-nutation, - to the difference observation-model. | Sensitivity of the equinox to differences models of the motion of the CIP and to observed pole offsets. |

# Terrestrial Ephemeris Origin

## Definitions and Basic Properties

## TEO Usual longitude origin

### Definitions

| | |
|---|---|
| On the CIP equator at *t*. | On the CIP equator at *t*. |
| Defined cinematically : | No precise definition |
| The Terrestrial Intermediate Reference System linked to the CIP and the TEO has no component of rotation along the axis of the CIP in the ITRS | |
| Requires an integration along the CIP (coordinates *x* and *y*) trajectory from $t_0$ to *t* providing a quantity denoted *s'*. | |
| *x, y* and *s'* are the three parameters for the transformation ITRS <-> Terrestrial Intermediate Reference System. | |

### Realisations

| | |
|---|---|
| *s'* is a very small quantity which varies almost linearly with time (<0,4 mas in 2100) (3). | Errors at the microarcsecond level on UT1. |
| *s'* is computed from the observed pole coordinates by numerical integration and can be extrapolated several years in advance at the microsecond level. | |

**COMPLETE SYMMETRY WITH CEO**

# UT1

| Use of CEO and TEO | Use of the equinox |
|---|---|
| **Definitions and Theory** | |
| *UT1* based on the Earth Rotation Angle $\theta$. | *UT1* based on the Greenwich Sidereal Time *GST* |
| $\theta$ is the hour angle of CEO reckoned from TEO. | *GST* is the hour angle of the equinox reckoned from ? |
| The time derivative of $\theta$ is strictly the component of the rotation vector of the Earth along the axis of the CIP. | |
| The relationship between $\theta$ and *UT1* is linear (conceptual definition of UT1). | The relationship between *GST* and *UT1* involves polynomial, periodic and Poisson terms.<br>The relationship between *GST* and *UT1* is based on the implicit use of the CEO (4). |
| **Application** | |
| The linear relationship between $\theta$ and *UT1* is practically insensitive to the model and to the observations of the CIP path (at the level of 1 μas until 2100). It provides a stable operational definition of UT1. | The relationship between *GST* and *UT1* is very sensitive to the model and to the observations of the CIP position. |

# NOTES

## 1 Integration for CEO

The fact that the CEO depends on an integration along the CIP path is sometimes seen as a major drawback. One may argue that an interruption of the observations of the motion of the CIP would lead to the loss of the CEO and therefore of UT1. The answers to that objection are as follows.

- The model of precession-nutation we have presently would suffice to bridge a gap of several decades in the observations, without error larger than 1 microarcsecond in UT1 (70 ns).
- Anyway, the CEO is required for evaluating UT1, even when the equinox is used.
- Let us remark also that the values of UT1 are referred to TAI, which is another integrated quantity and which would be lost without possibility of precise recovery if all atomic clocks stop.

## 2 Form of *s*

The form of $s(t)$ compatible with IAU 2000A precession-nutation model, including all terms exceeding 0.5 μas during the interval (1975-2025) is (Capitaine et al., 2000) :

$s(t) = -X(t)\,Y(t)/2$ + polynomial terms up to $t^3$
+ 13 periodic terms (largest term : amplitude 2641 μas)
+ 6 Poisson terms in $t^2$.

The extension of validity to (1900-2100) requires the additional terms

$\Delta s(t) =$ polynomial terms in $t^4$ and $t^5$
+ 9 periodic terms
+ 2 Poisson terms in $t^3$.

## 3 Maximum value

The maximum value of 0.4 mas in 2100 is computed assuming an amplitude of 0.5'' of the Chandlerian nutation. The maximum observed amplitude since 1900 is about 0.25''.

## 4 Equation of the equinox

The concept of the CEO is required for providing the 'equation of the equinox'. It was already implicitly used in 1982 in 'The New Definition of Universal Time', Aoki et al., Astron. Astrophys., 105, 359-361.

# Comparison of "Old" and "New" Concepts: Astrometry

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## SUMMARY

The introduction of the International Celestial Reference System (ICRS) and the newly adopted system of the Celestial Intermediate Pole (CIP), Celestial Ephemeris Origin (CEO), Terrestrial Ephemeris Origin (TEO), and new precession-nutation model IAU2000A will require a transitional period of use of the old classical and the new systems. The new system is to be introduced in January 2003. The two systems are described in detail in Seidelmann and Kovalevsky (2002).

The contrast of old and new systems for astrometry can be summarized as below.

The changes for astrometry are the fixed frame is fixed and epoch independent; mean positions are no longer needed; the Celestial Ephemeris Origin (CEO), Celestial Intermediate Pole (CIP), and Stellar Angle, or Earth Rotation Angle, are introduced replacing the equinox and Celestial Ephemeris Pole (CEP); milli & micro arcsecond accuracies are now possible; relativity is the basis; the Time Scales are TT, TCG, and TCB; the precession-nutation are combined in the new model IAU 2000A; there is a pole offset; geodesic precession and nutation are included; new definitions are introduced; the observation reduction procedures are modified; the ephemerides are on a fixed frame; and the equinox and ecliptic are only needed for phenomena.

For astrometry the old and new can be tabulated as:

| **"OLD"** | **"NEW"** |
|---|---|
| FK5 | ICRS |
| Dynamical | Kinematic |
| Bright Stars | Extragalactic Sources |
| Precessing Equinox | Stable Fiducial Point |
| Moving Reference Frame | Fixed Reference Frame |
| Newtonian | Relativistic |
| Sidereal Time | Stellar Angle |
| CEP | CIP |
| Equinox | CEO |
| Equation Cross Talk | Purer Equations. |

The observational reduction process can be summarized in the table, with the steps that are different indicated by an x:

| **POSITIONS** | **CORRECTIONS** | |
|---|---|---|
| Raw Observations | | |
| | refraction | |
| | instrument parameters | |
| Local Place | | |
| | diurnal aberration | |
| | TT-UTC | |
| Topocentric Apparent Place | | |
| | polar motion | (x) |
| | diurnal parallax | |
| | UT1 irregularities | (x) |
| | TCG-TT | (x) |
| Geocentric Apparent Place | | |
| | Stellar Parallax | |
| | Stellar Aberration | |
| | deflection of light | |
| | light time | |
| | precession-nutation | (x) |
| | geodesic precession | (x) |
| | TCB-TCG | (x) |
| Barycentric Catalog Place | | |
| (ICRF) | | |

The following changes in definitions must be introduced for the new system : the CEP is replaced by CIP; the CEO replaces the equinox; the equinox is defined by and for the ephemerides only; the division between polar motion and nutation is in part by periods of terms; there is no need for mean places; geodesic precession is included; and right ascension origins must be specified; either from the CEO or the equinox. For accuracy purposes the classical system must include the corrections to the CIP, the new precession-nutation model, and geodesic precession.

The oustanding issues remaining for astrometry are the transitional period for the dual system and when the new system can be really introduced; are the values in the precession-nutation model finalized; should geodesic precession be included in the precession-nutation model or should it be treated as a separate correction ( it is a very separate phenomena.); is standardized software available to provide for the change; what is the potential for confusion as two systems are in use; and how can the astronomical community be educated about the changes ?

In conclusion the ICRS is a logical progression with greater rigor and a theoretical bases. The ICRS has some simplifications: fixed, epoch independent, reference frame; independent of solar system dynamics; fiducial point not precessing along moving equator; proportionality between stellar angle and UT1; microsecond accuracy predictability of fiducial point; and a lack of interaction in expressions for motions of reference frames.

Seidelmann, P.K. and Kovalevsky, J. 2002, "Applications of the new concepts and definitions( ICRS, CIP, and CEO) in fundamental astronomy", *Astron Astrophys*, in press.

# Implementing the IAU 2000 Resolutions in Almanacs

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## 1 Introduction

Almanacs play the important role of providing practical astronomical data in an accessible form to satisfy a wide variety of user needs. The Nautical Almanac Office of the United States Naval Observatory (USNO), and Her Majesty's Nautical Almanac Office (HMNAO) of the Rutherford Appleton Laboratory, United Kingdom, co-produce several printed almanacs to meet the requirements of specific classes of users. In addition, each office provides almanac data via computer-accessible products, such as data services on the World Wide Web and executable computer applications.

The International Astronomical Union (IAU) adopted a set of resolutions at its 2000 General Assembly (IAU 2000), several of which, if implemented, will directly affect the information published in these almanacs. This paper discusses current plans for implementing the IAU 2000 resolutions in the main almanac products produced by USNO and HMNAO. The implementation plans depend on the specific almanac; therefore, Section II provides brief descriptions of the various products that are potentially affected by the resolutions. Section III discusses some general guidelines that govern the introduction of changes into the almanacs. These guidelines must be taken into consideration when formulating an implementation plan. Finally, Section IV presents the plans for implementing the resolutions that directly affect the almanacs. These plans reflect current thinking, and may change depending on evolving technical factors, or possible programmatic changes in each almanac office.

## 2 The Almanacs

USNO and HMNAO co-produce several almanac products, each tailored for a particular application or class of applications. The application determines the content and format of the almanac. The primary, jointly produced almanacs are *The Astronomical Almanac*, *The Nautical Almanac*, and *The Air Almanac*. Each one is published annually.

*The Astronomical Almanac* (AsA) is the flagship publication that contains: precise ephemerides in several coordinate systems for all the major observable objects in the solar system; positions of selected objects outside the solar system; tables of astronomical phenomena; and other reference information. The data in the AsA are tabulated at various precisions: the most precise being the nutation components, which are tabulated to a precision of 1 milliarcsecond (mas), and the geocentric coordinates of the planets, which are given to a precision of 10 mas. The material in the AsA supports applications in a diverse set of disciplines, including astronomy, space science, geodesy, surveying, astrodynamics, military operations planning, litigation, and various types of engineering.

*The Nautical Almanac* (NA) contains the astronomical data required for celestial navigation at sea. The main pages contain: the Greenwich hour angle and declination of the Sun, Moon, and navigational planets; the Greenwich hour angle of Aries (the vernal equinox); positions of the navigational stars; rise and set times of the Sun and Moon for a range of latitudes; and other data. Most data on the main pages are tabu-

lated at hourly intervals to a precision of 0.1 arcminute. Each edition also contains a sight reduction table, sight reduction formulas, and various correction tables for sight reduction. Both military and civilian marine navigators use the NA.

*The Air Almanac* (AA) contains the astronomical data required for aircraft navigation. The main pages contain: the Greenwich hour angle and declination of the Sun, Moon, and three navigational planets; the Greenwich hour angle of Aries; rise and set times of the Moon for a range of latitudes; and other data. The data on the main pages are tabulated at 10-minute intervals to a precision of 0.1 arcminute for the Sun and Aries, and 1 arcminute for other bodies. Each edition also contains sky diagrams for each month; sunrise, sunset, and twilight tables; and positions of the navigational stars. A different publication, *The UK Air Almanac*, was introduced by HMNAO in 1998 to meet the specific requirements of the Royal Air Force. It contains illumination information, but no navigational data.

An example of a computer-based almanac is USNO's Multi-year Interactive Computer Almanac (MICA). MICA is an executable application program that calculates, in real time, much of the information tabulated in the AsA. However, MICA goes beyond traditional printed almanacs by enabling the user to calculate data for user-specified locations at user-specified times within a relatively long time interval. The current version (1.5), released in 1998, is valid for a 16-year interval (1990-2005). The most precise data in MICA are tabulated to 1 mas. Designed primarily for professional applications, MICA is intended for the same set of users that use the AsA.

## 3 General Guidelines for Changing the Almanacs

At their most basic level, the almanacs must be practical. Users rely on the data in the almanacs to support a wide range of applications, such as navigation, pointing a telescope, planning an observing session, or research efforts. Thus, most users expect the content and format of the almanacs to be the same from year to year. For example, many textbooks on navigation (e.g. Bowditch 1995, Hobbs 1990) explain sight reduction by incorporating actual pages from the NA. These textbooks assume that the content and format of the NA main pages will remain the same over a very long period of time. This expectation of consistency in content and format is the main reason why changes to the almanacs occur infrequently and only after careful consideration.

There are several important questions that the almanac maker must answer in deciding whether or not to make a change to a product:

1. Will the change under consideration result in more accurate data or information in the almanacs? An answer of yes to this question is certainly a good reason for making a change, but does not alone guarantee that the change will be made.
2. Is the change under consideration based on sound, established science? Every effort is made to tie data published in the almanacs to fundamental results published in the refereed literature, and to standards established by international scientific bodies such as the IAU. Like Question 1, a "yes" answer to this question does not alone guarantee that a change will be made.
3. Will the change under consideration result in data and information that are relevant to the users of the publication? This is arguably the most important question. A good example of how the inclusion of more accurate data will result in information that is not useful or relevant to the particular user community involves the physical ephemeris of the Sun. The mean elements of the rotation of the Sun, and the daily tabulation of the Sun's rotational parameters, published in the AsA and MICA, are based on the work of Carrington (1863). More modern determinations of the fundamental quantities required for computing the Sun's physical ephemeris are available (e.g. Stark and Wöhl 1981), but the user community requires and expects that the tabulations will be based on Carrington's work. In this case, a "no" answer to Question 3 overrules a "yes" answer to

Questions 1 and 2, and the change to a more modern basis for the tabulated data is not made.

The almanac offices arrive at the answers to these three questions in several ways. Questions 1 and 2 can be answered by attending scientific meetings, reading the literature, and participating in research activities. The answer to Question 3 is more difficult to obtain. The most important factor is maintaining an ongoing communication with the various communities that use the products. Often, this involves effort on the part of the almanac offices, because users typically do not voice their needs or requirements until after a change has been made. User surveys are sometimes a valuable tool. Users of the AsA were last surveyed in 1998 via a form inserted into the book and a more extensive set of questions available on the Web. A survey of users of the AA also was recently completed. Finally, there are times when it is difficult or impossible to obtain clear answers to the three questions. In these instances, the almanac offices use their judgment, based on experience, to make a decision involving the introduction of a change. In the end, the responsibility for determining the content and format of the almanacs rests with the almanac offices.

As an example of this process, important, substantive changes to the AsA were introduced into the edition for 2003. These changes include:

- Use of star positions and proper motions from the Hipparcos (ESA 1997) and Tycho-2 (Høg *et al.* 2000) catalogs;
- Replacement of the DE200/LE200 solar system ephemerides with DE405/LE405 (Standish 1998);
- Updated rotational elements for the planets and satellites based on Seidelmann *et al.* (2000).
- A completely revised section on asteroids, including precise positional information for 15 of the largest asteroids based on modern ephemerides (Hilton 1999).
- Introduction of a complementary Web site, *The Astronomical Almanac Online*, containing data best provided in computer-accessible form.

A long lead-time is required to introduce changes into the almanacs, especially the AsA. The AsA is available to users one year before the year of the edition (e.g. the edition for 2003 was available by January 2002). Production of the book takes place during the year before the edition is available (in this example, production took place during 2001). Thus, ideally, decisions regarding changes to the AsA are reflected in the book two years after the decision has been implemented. Additional time is needed to develop, implement, and test new production software when major changes are introduced.

## 4 Plans for Implementing the IAU 2000 Resolutions

Three resolutions adopted at the 2000 IAU General Assembly in Manchester, UK, have the potential to impact directly the data provided in future editions of the almanac products. These resolutions are B1.6 (IAU 2000 Precession-Nutation Model), B1.7 (Definition of the Celestial Intermediate Pole), and B1.8 (Definition and Use of Celestial and Terrestrial Ephemeris Origins). An additional resolution, B2 (Coordinated Universal Time), could have an indirect but important effect on the navigational almanacs.

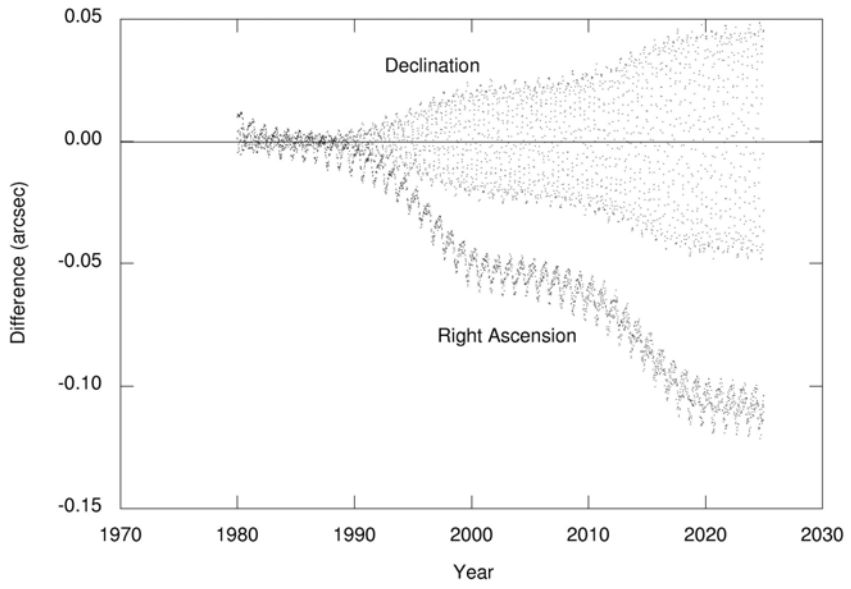
Resolution B1.6 recommends that "… the IAU 1976 Precession Model and IAU 1980 Theory of Nutation be replaced by the precession-nutation model IAU 2000A… for those who need a model at the 0.2 milliarcsecond (mas) level, or its shorter version IAU 2000B for those who need a model only at the 1 mas level, together with their associated precession and obliquity rates, and their associated celestial pole offsets at J2000.0…." The inadequacies of the IAU 1976 precession model and the IAU 1980 Theory of Nutation have been known for some time (see, for example, McCarthy and Luzum 1991), so IAU-sanctioned, improved replace-

ments for these models are strong candidates for use in the almanacs. Software implementations of the two versions of the IAU 2000 model became available during 2001 and early 2002. Both the IAU 2000A and IAU 2000B software modules contain corrections to the IAU 1976 precession model; thus, the new precession-nutation (PN) model does not *replace* the old precession model as the resolution states. Rather, the new PN model must be used *in conjunction with* the old precession model.

Figure 1 gives an example of how the new PN model affects the computation of apparent places. This figure shows the differences between the apparent coordinates of the Moon computed using the new IAU 2000B PN model and the old IAU 1980 Theory of Nutation (Seidelmann 1982). The difference in right ascension grows from approximately 0.05 arcsecond in 2000 to 0.10 arcsecond in 2020. The maximum difference in declination over the same period ranges from approximately 0.02-0.05 arcsecond. Thus, the difference will be evident in the values tabulated in the AsA that involve apparent places.

Current plans call for the IAU 2000 PN model, probably the IAU 2000B version, to be implemented in the AsA beginning with the edition for 2005. The AsA provides data referenced to both the mean and true equinoxes of date. Because the new IAU PN model embeds the precession corrections in the nutation model, only true and apparent places will use the improved algorithm. Unless a new, independent precession model is developed and adopted, all data based on mean places of date must continue to use the IAU 1976 Precession Model, and thus will not include the precession correction. There are no immediate plans to implement the IAU 2000 PN model in the navigational almanacs (i.e. the NA and AA), since the change will have only a small, indirect effect on the tabulated values and will not improve navigational accuracy.

Figure 1: Differences in apparent right ascension ($\Delta\alpha \cos\delta$) and apparent declination ($\delta$) of the Moon, computed using the IAU 2000B Precession-Nutation Model and the IAU 1980 Theory of Nutation. These calculations were made using the DE405/LE405 ephemerides, which are currently used in the AsA.




Neither IAU 2000A nor IAU 2000B is an optimal solution for an interactive computer application, such as the next version (2.0) of MICA. IAU 2000A carries significant computational overhead, with nearly 1400 terms and more precision than is

needed. IAU 2000B has an order of magnitude fewer terms (77), and agreement with IAU 2000A to 1 mas in the interval 1995-2050 (McCarthy and Luzum 2001). However, MICA 2.0 will provide data in the interval 1850-2050, making IAU 2000B also a sub-optimal choice. From a computational viewpoint, the SF2001 PN theory (Shirai and Fukushima 2001) with 194 terms is a good compromise, although it is not IAU-sanctioned.

Resolutions B1.7 and B1.8 will be considered together. Resolution B1.7 introduces and defines the Celestial Intermediate Pole (CIP). Resolution B1.8 introduces and defines two other related concepts: the Celestial Ephemeris Origin (CEO) or "non-rotating origin," and the Earth Rotation Angle (ERA). The practical consequence of these two resolutions is to introduce a fundamental change to the geocentric celestial reference system, the terrestrial reference system, and the transformation between these systems. Concepts such as the vernal equinox as the origin of right ascension, the fundamental role of the ecliptic in defining the reference system, sidereal time, and conventional definitions of precession and nutation ($\Delta\Psi$ and $\Delta\varepsilon$) – the "classical paradigm" – are replaced by concepts such as the CEO, the CIP, the ERA ($\theta$), and the quantities $X$, $Y$, and $s$ – the "new paradigm" (Capitaine *et al.* 2000; Seidelmann and Kovalevsky 2002).

Implementing such a radical change in the almanacs requires a careful approach. This is especially true because the almanac user community is very broad. This community includes not only specialist astronomers, but also many non-specialist scientists and engineers. Many of these users do not read the specialized astrometry literature, and thus are unaware of the resolutions, let alone the practical consequences of the resolutions. Furthermore, it will take a considerable amount of time for many user systems to implement the resolutions. For example, implementing the new paradigm in commercial software systems requires code changes that cost money; cost alone will undoubtedly slow adoption of the new paradigm by some users of the almanacs. In short, premature and exclusive implementation of the new paradigm in the almanacs has the potential to make the almanacs irrelevant to many, if not most, users.

In light of this situation, the almanac offices have formulated a general plan for implementing Resolutions B1.7 and B1.8:

- A considerable amount of education is needed to introduce these resolutions to the broad community that uses the AsA. The IAU and the International Earth Rotation Service (IERS) must take the lead role in this important task. To assist in this effort, USNO and HMNAO have undertaken work on a USNO Circular that will describe in a practical way all IAU resolutions that have affected the almanacs since 1984. This Circular, which will also appear in stages as a supplement inside the AsA, will be ready in 2003. In addition, the two offices are participating in a project to revise the *Explanatory Supplement to The Astronomical Almanac* (Seidelmann 1992). Both of these publications will contain explanatory material on the IAU 2000 resolutions.
- Tabulations of the new-paradigm parameters $X$, $Y$, $s$, and $\theta$ will be published in the AsA or on its associated Web site possibly beginning as early as the edition for 2005.
- More material based on the new paradigm will be introduced into the AsA over time. However, the almanac offices anticipate that it will be necessary to continue to provide material based on the classical paradigm for a considerable period into the future. The time period for providing parallel data in the two paradigms will be determined by user needs and requirements. Careful design of the almanac material will be needed to keep the two paradigms apart.
- There are no plans to introduce the new paradigm into the navigational almanacs.

- To support fully improved data in the classical paradigm, USNO will participate in the development of a new precession theory consistent with the IAU 2000A model, as encouraged by Resolution B1.6. This activity is also consistent with the recommendations of Resolution B1.8.

Resolution B2 recommends that the IAU establish a working group to consider the redefinition of Coordinated Universal Time (UTC). This working group will discuss the requirement for leap seconds, and options for UTC, in cooperation with appropriate groups from other international organizations. Nelson *et al.* (2001) give a review of the history and issues regarding leap seconds. The current practice of celestial navigation, especially sight reduction using printed almanacs and worksheets, relies on the assumption that UT1 is kept close to UTC: a navigator "tags" his/her sights (sextant observations) with a UTC time, and reduces the sights with an almanac whose time argument is UT1. Currently, UTC is maintained to within 0.9 s of UT1; this produces a maximum error of approximately 0.4 km in position (longitude), which is significantly less than the error in the sextant observations (1-2 arcminutes, or approximately 2-4 km at the surface of the Earth). Because of this, typical sight-reduction procedures contain no provision for accounting for UT1-UTC. A significant change to the definition of UTC will likely require a change to the navigational almanacs. Despite the general adoption of the Global Positioning System (GPS) as the worldwide primary navigational system, celestial navigation is still routinely practiced as a backup means of navigation, and is still *required* by navies (e.g the US and UK navies) and merchant marine interests. A change to the definition of UTC will also affect several sections of the AsA that are based on UT1, primarily those sections that tabulate phenomena. Again, in these cases the assumption is made that UT1 and UTC are kept close to each other.

# 5 Summary

Almanacs provide practical astronomical data in an accessible form to satisfy the needs of a wide variety of user applications. HMNAO and USNO co-produce several printed almanacs to meet the requirements of specific classes of users, and each office provides almanac data via the World Wide Web and executable computer applications. *The Nautical Almanac* and *The Air Almanac* provide astronomical data to meet the needs of navigators, while *The Astronomical Almanac* meets the needs of a diverse set of users, including astronomers, other scientists, and engineers. Resolutions B1.6, B1.7, and B1.8, adopted at the 2000 IAU General Assembly, if implemented, will have a direct impact on the data and other information tabulated in the almanacs, especially the AsA. Changes to the almanacs are made as infrequently as possible, and with careful deliberation. The almanac makers implement a proposed change when it results in more accurate information in the almanacs, is based on sound scientific underpinnings, and results in data or information relevant to the users of the almanac. The IAU 2000 resolutions must be considered in this context before they are implemented in the almanacs. Thus, there are no immediate plans to incorporate the resolutions into the navigational almanacs, since the changes will not improve navigational accuracy, and the format changes will not be useful to the users. The current plans for the AsA call for:

- the IAU 2000 PN model to be implemented beginning with the edition for 2005;
- publication of a USNO Circular that will describe in a practical way all IAU resolutions that have affected the AsA since 1984, to be ready in 2003;
- revision of the *Explanatory Supplement to the Astronomical Almanac*, which will contain explanatory material on the IAU 2000 resolutions;
- tabulations of the new-paradigm parameters $X$, $Y$, and $s$, and $\theta$ to be published in the AsA or on its associated Web site possibly beginning as early as the edition for 2005;
- over time, introduction of more material based on the new paradigm;

- continued production of material based on the classical paradigm for a considerable period into the future. The time period for providing parallel data in the two paradigms will be determined by user needs and requirements;
- participation in the development of a new precession theory consistent with the IAU 2000A model, as specifically encouraged by Resolution B1.6.

These plans reflect current thinking, and may change depending on evolving technical factors, or possible programmatic changes in each almanac office. Finally, a possible redefinition of UTC, which is the subject of Resolution B2, could have an impact on the almanacs, especially the navigational almanacs. No change to UTC has been formally proposed, so it is premature to provide a plan.

## 6 Acknowledgments

This paper draws heavily on the ongoing discussions between HMNAO and USNO regarding implementation of the IAU 2000 resolutions in the jointly produced almanacs. Specifically, Patrick Wallace, Catherine Hohenkerk, and Steve Bell of HMNAO, and James Hilton, Sethanne Howard, and George Kaplan of USNO made important contributions to these discussions.

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# Future JPL Ephemerides

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**Abstract:** Future planetary and lunar ephemerides from JPL will not reflect the recent IAU Conventions regarding $TCB$. The ephemerides will continue to be released in the same relativistic coordinate time, "$T_{eph}$", as before. They may be easily converted by the user into SI units.

The new IAU changes regarding earth orientation do not affect the ephemerides directly; they enter the ephemeris creation process only through the reduction of the observational data to which the ephemerides are fit. For the planetary observations, the change is far below even the most accurate measurements (1-2 $m$); for the LLR data, a rough equivalent of the change has already been in place for a number of years, and conversion to the IAU formulation is unlikely in the near future.

The accuracy of the planetary ephemerides is 1 $km$ or better for all relative angles and distances between any of the 4 inner planets; the orientation of the inner planet system onto the ICRF is accurate to about 0.″001. Over time, however, the accuracy deteriorates due to the perturbations of many asteroids whose masses are not well known. For this reason, the ephemerides require constant maintenance using the latest high accuracy observations.

## 1 The Time Argument of the Ephemerides

The JPL ephemerides have never used either $ET$ or $TDB$, as they were defined by the IAU. Instead, the time argument used in the JPL ephemerides since the mid-1960's, "$T_{eph}$", is a true relativistic coordinate time. As shown by the author (1998), the latest IAU-defined time, "$TCB$", is rigorously equivalent to $T_{eph}$, differing by only a rate and an offset. Thus, it is a simple matter to convert from the $T_{eph}$ units provided by the JPL ephemerides into SI units using $TCB$; this involves simply the scale factor, $(1 - L_B) = d(T_{eph})/d(TCB)$, applied to the time (independent argument of the ephemerides), the distances, and the $GM$ values.

Contrary to what has been said in the literature, a conversion to $TCB$ would not allow an increase in accuracy for the JPL ephemerides. One can show that working in $T_{eph}$ is equivalent to working in $TCB$; the resultant ephemerides would be equivalent.

There has been an immense amount of sophisticated and detailed software produced over the past number of decades throughout the astronomical community and within the aerospace industry. A conversion to $TCB$ would involve unacceptable cost and unavoidable risk while providing no improvement in accuracy.

## 2 New Earth Orientation Formulation

For the planetary ephemerides, the most accurate observational data are at the 1-2 $m$ level. This limit applies to the best ranging measurements – those taken with dual-frequency, calibrated transponders aboard a landed or an orbiting

spacecraft. The uncertainties come from the non-constancy of the interplanetary medium, from the imprecisions in the calibrations of the transponders, and, in the case of an orbiter, from the uncertainties of the orbit itself. The IAU improvements to the earth orientation procedures are below the level of 0."001; this is equivalent to 3 *cm* on the earth's surface, an amount which is negligible for planetary ranging observations.

For the reduction of LLR observations, the deficiencies in the existing (1976, 1980) IAU earth orientation procedures are important, and, in fact, have been known for many years. Consequently, the JPL reductions of LLR data have used a modified EOP formulation for increased accuracy. There are no plans at present to adopt the recent IAU formulation.

## 3 Accuracy Level of the Ephemerides

For the four inner planets, the ephemerides are dominated by two types of data: 1) ranging measurements, whether radar reflections from a planetary surface or return signals from a transponder aboard a landed or orbiting spacecraft, and 2) $\Delta$VLBI measurements of an orbiting or landed spacecraft w.r.t. the ICRF catalogue. The ranging measurements, taken over various parts of the planets' orbits, provide all relative angles and distances between the earth and the other three innermost planets, thus locking the whole system together. The ranging measurements also provide accurate mean motions of the planets w.r.t. inertial space. The only feature not provided by the ranging measurements is the orientation of the whole system with respect to some exteroir reference frame. That feature is provided by $\Delta$VLBI measurements which tie the system onto the background ICRF.

Even with such accurate observational data, the planetary motions show rather large uncertainties, for the planets are perturbed by the presence of many asteroids whose masses are quite poorly known. Furthermore, it's not possible to solve for the asteroid masses, other than for the biggest few, because there are too many of them for the data to support such an effort. As shown by Williams (1984) and by Standish and Fienga (2002), the ephemerides of the inner planets, especially Mars, will deteriorate over time. Attempts to fit all of the observational data result in effectively smoothing over the perturbations during the intervals connecting the observations. The result is that the ephemerides have uncertainties at the 1-2 *km* level over the span of the observations and growing at the rate of a few *km*/decade outside that span.

A great deal of effort has been applied in order to represent the asteroid perturbations as well as possible. Studies of the estimations of masses of the most relevant 300 or so asteroids have been made by Fienga (2001) and by Krasinsky *et al.* (2001); Krasinsky *et al.* (2002) have also modeled a ring to represent the perturbations from the remaining thousands of small asteroids.

For Jupiter, a number of spacecraft observations exist, allowing Jupiter's ephemeris to be known better than about 100 *km* (0."02). For the outermost four planets, the only observations are optical; correspondingly, those ephemerides are accurate to only about 0."1 - 0."2.

## 4 Future JPL Ephemerides

There is a choice to be made in creating ephemerides; the choice involves mainly the ephemeris of Mars and is due to the uncertainties imposed by the perturbations of the asteroids.

- One may fit all of the observations as well as possible, thereby smoothing

out the perturbations and creating an ephemeris which is as accurate as possible over extended periods of time.

- One may concentrate on fitting only the most recent observations so that the ephemeris into the near future (a year or two) is as accurate as possible, but thereby sacrificing the accuracy of the long-term ephemeris.

For future JPL planetary ephemerides, the intention is to make available to the general public the former type of ephemerides (such as DE405) and to create the latter type for navigational purposes and for specific scientific studies.

Certainly, any improvement in our knowledge of asteroid masses in general will provide a corresponding improvement in the computed dynamics of the planetary motions.

## 5 Acknowledgement

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# Software for Implementing the IAU 2000 Resolutions

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## 1 Introduction

At its XXIVth General Assembly, the International Astronomical Union adopted a number of resolutions concerning reference frames and time scales (IAU 2000). Many users will encounter the consequences of these resolutions in indirect ways, for example in the form of slightly changed tabulations in the almanacs. But many others will need new tools to help them to implement the changes in their own applications. These tools may be in the form of written prescriptions and special tabulations; however, it is vital also for actual software to be available. Such software not only avoids duplicated effort but also *defines* without ambiguity how the calculations concerned are to be carried out.

These considerations are normal whenever existing standards are changed; however certain aspects of the 2000 resolutions amount to a change in paradigm, requiring quite new strategies.

## 2 Available Software

The IAU *Standards Of Fundamental Astronomy* software (SOFA, Wallace 1996) comprises, at present, 79 Fortran subprograms. The collection provides a number of basic components relevant to implementing the new system:

- Routines for standard vector and matrix operations, formatting angles, dealing with spherical coordinates and so on.
- Facilities for handling calendars, epochs and time scales.
- Some limited solar-system ephemeris models, links between FK5 and ICRS, and pre-2000 Earth attitude models.
- Rigorous handling of star space-motion, taking into account both classical light-time effects and special relativity.

In addition to SOFA, a number of other libraries and packages offer a basis for implementing the 2000 standards, including SLALIB (Wallace 1994) and NOVAS (Kaplan *et al.* 1989).

As well as these general frameworks, two key algorithms have recently been published in the form of Fortran code, namely the IAU 2000A and IAU 2000B precession-nutation models (Luzum 2001, McCarthy and Luzum 2001). The rest of this report concentrates on implementing these models and on the related topic of providing tools for using Earth Rotation Angle and the Celestial Ephemeris Origin. Other aspects of the IAU 2000 system, for example in the area of time scales, will not be further discussed here.

## 3 New Software

The SOFA Review Board is currently considering the next tranche of new routines. These are certain to include provision for implementing elements of the IAU 2000 system, but what form this provision takes will depend on the Board's deliberations, and the proposals set out below must at this stage be regarded as just one possible way forward.

An important issue that must be addressed at the outset is the extent to which existing users of the classical (equinox-based) paradigm should be supported. These users, who comprise the overwhelming majority of the astronomical community, will expect all the benefits of the new resolutions, in terms of improved accuracy and compliance with IAU standards, but in a form that imposes little or no additional inconvenience. It will be many years before most users can make the full transition to the new paradigm, and at present few see the need to do so. Thus for the foreseeable future the suppliers of almanacs and standard software have a duty to offer tools to implement *both* the classical and new methods. With this principle in mind, the following capabilities could be added to the SOFA software:

Supporting both the **classical** and **new** paradigms:

- Implementations of the IAU 2000A and 2000B precession-nutation models.
- A routine that generates the polar-motion matrix (given $x,y$ and, in the new paradigm, $s'$).

Supporting the **classical** paradigm:

- A routine that implements the frame bias (GCRS to dynamical).
- A routine that generates the classical precession matrix.
- Routines that generate the nutation matrix (for both the A and B models).
- Routines that provide the final GCRS-to-true matrices (A and B).
- A GMST routine that includes the IAU 2000A/B precession adjustments.
- Routines that generate the equation of the equinoxes using the new nutation models (A and B).

Supporting the **new** paradigm:

- A routine that generates Earth Rotation Angle.
- Routines that generate the GCRS to intermediate matrix (A and B).
- Routines that generate the GCRS to TRS matrix (A and B).
- Routines to transform between astrometric, topocentric and observed places.

Note that in this scheme the goal of predicting topocentric and observed places is achieved solely by applying the *new* paradigm. The classical provisions are intended to provide "plug-compatible" replacements for users' existing components, consistent with the latest IAU models.

# 4 Implementing IAU 2000A/B

Comparisons have recently been carried out (Capitaine *et al.* 2002), of CIP predictions using (a) a classical precession-nutation formulation and (b) the $X,Y$ formulation described in Capitaine *et al.* (2000), both using the IAU 2000A nutation. These tests have raised doubts about whether the published IAU 2000A algorithm fully meets the requirements of IAU 2000 Resolution B1.6.

The IAU 2000A algorithm is at heart a *nutation* model, and, although the code also provides definitive information about frame bias and precession rates, there are ambiguities over how to form the precession part of the model and how to combine the various corrections. Also, the algorithm does not address the question of offset in Right Ascension between the ICRS and mean dynamical frame at J2000. The consequences of these ambiguities and omissions are not large, but do exceed the stated accuracy objectives after a few decades. They could be resolved as follows:

- It seems most natural to use the frame bias $X,Y$ components from IAU 2000A, together with an agreed $\Delta\alpha$, to implement the GCRS $\leftrightarrow$ dynamical rotation as a separate step.

- The CIP precession model needs to be spelt out, stipulating the specific set of Euler rotations to be used. For example we can use $R_3(\chi_A)R_1(-\omega_A)R_3(-\psi_A)R_1(\varepsilon_0)$ with the angles from Lieske *et al.* (1977) plus corrections $\Delta\psi,\Delta\varepsilon$ from IAU 2000A/B. Once the precession model is fixed, a revised GMST model can be obtained.
- The nutation angles (lunisolar + planetary) given directly by IAU 2000A (or B, depending on the user's accuracy requirements) can be used to form the nutation matrix and to calculate the equation of the equinoxes.
- The various components then play their normal roles in the classical transformation, delivering results that are fully compatible with the new paradigm.

To support the new paradigm, CIP *X,Y* can be obtained from the classical transformation, forming the bridge between the old and new paradigms. Alternatively, *X,Y* can be calculated directly (Capitaine *et al.* 2000), avoiding separate frame bias, precession and nutation stages. After evaluating *s* (*ibid.*), the GCRS $\leftrightarrow$ intermediate matrix can be generated. Figure 1 illustrates the two paradigms in action, both calculating Greenwich apparent hour angle and declination starting from star data in ICRS.

## 5 Options for Future Precession-Nutation Models

It should of course be borne in mind that the IAU resolutions themselves urge further work (on the precession component in particular: B1.6 recommendation 3): the IAU 2000A code itself is not necessarily the last word. In due course, a fully recomputed model, based on the latest results and compatible with IAU 2000A nutation, is needed.

How best to *define* the CIP is a moot point. The alternatives are separately defined transformations—bias, precession, nutation—or direct generation of *X,Y*. The former maintains maximum overlap between the classical and new paradigms and fits in with IAU 2000A/B; the latter is succinct and more in keeping with the post-classical spirit of the IAU 2000 resolutions, eliminates awkward questions about the overlap between precession and very-long-period nutation terms, and sidesteps all the dangers of mixing incompatible precession and nutation models or implementing them in unsuitable ways. Which should form future defining IAU standards is debatable; perhaps the relationship to VLBI observables will be a guide.

A related issue is whether it is appropriate for the IAU precession-nutation model to be truly state-of-the-art. The IAU 2000A model comprises almost 1400 terms, with coefficients as small as 100 nanoarcseconds, yet delivers an absolute accuracy of some tenths of a milliarcsecond. The limitation is the essentially unpredictable Free-Core-Nutations, which effectively set a "noise floor" for any closed-formula model. Users requiring the latest and best results are obliged to supplement their fixed nutation model with continuously updated FCN corrections; it could be argued, therefore, that a concise standard model could be adopted and corrections relative to that model, comprising both FCN and the tiny missing terms, be supplied. An obvious contender for such a "concise standard model" is IAU 2000B. However, in the present context IAU 2000B sacrifices more accuracy than need be, taking it well clear of the FCN noise floor. Perhaps a better compromise is SF2001 (Shirai and Fukushima 2001), which achieves 300 microarcseconds accuracy with only 194 terms.

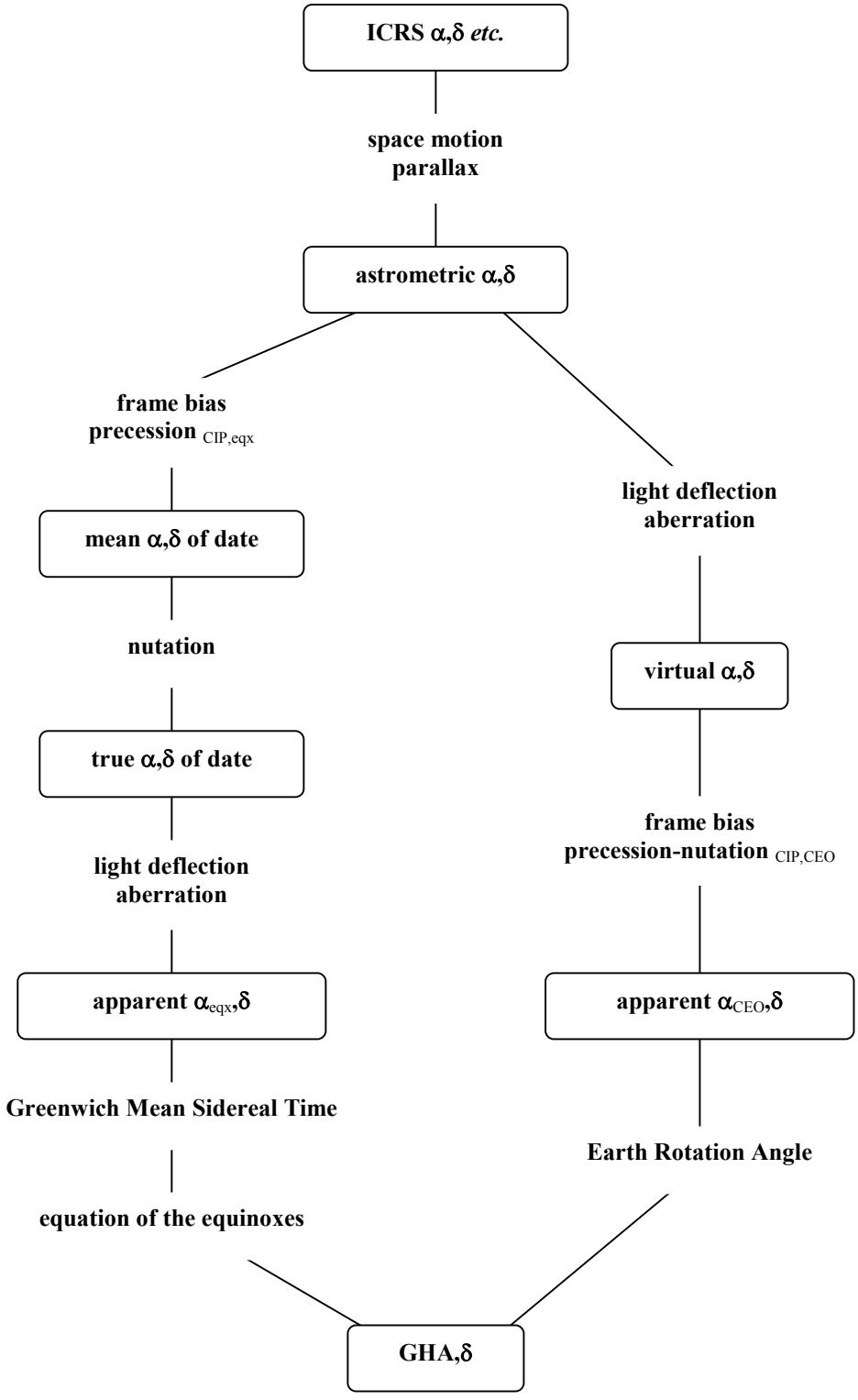


**Figure 1**
Two ways of predicting the Greenwich apparent hour angle and declination of a star. The left-hand branch shows one form of the classical procedure; the right-hand branch follows the IAU 2000 procedure.

## 6 Acknowledgements

This is a good opportunity to thank the members of the SOFA Reviewing Board for all their work in developing the SOFA software collection, and for almanac-office colleagues at RAL and USNO for stimulating discussions and debates over several years. John Bangert , George Kaplan and Dennis McCarthy, all of USNO, have made particularly valuable contributions. Advice from Nicole Capitaine (Observatoire de Paris) since 2000 has been crucial in comparing different ways of performing the celestial-to-terrestrial transformations and devising SOFA implementation strategies.

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# An Implementation of IAU 2000 Resolutions in VLBI Analysis Software

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## Context

The analysis of an Earth based observation of a celestial object requires an astrometric model to express the transformation from a geocentric terrestrial frame to a geocentric celestial one. The classical transformation refers to the equinox of date and use classical precession and nutation quantities. In a new astronomical modelling approach, we refer to the non-rotating origin on the equator of date, proposed by Guinot (1979) and use the celestial coordinates of the CIP (Capitaine, 1990). One of the resolutions adopted by the XXIV General Assembly of the International Astronomical Union (Manchester, August 2000), recommends the use of this new approach. The two paradigms are detailed in IERS Conventions (1996, 2000), in Capitaine et al. (2000) and in McCarthy and Capitaine (see this volume).

GLORIA (Global Radio Interferometry Analysis) is the Paris Observatory software, developed in the early 90s, to analyse Very Long Baseline Interferometry (VLBI) observations (Gontier, 1993). At that time, the new transformation as well as the classical one was implemented. The agreement between the developments of the celestial pole coordinates (X,Y) as a function of time and as a function of the IAU 1976 precession (Lieske et al., 1977) and IAU 1980 nutation (Seidelmann 1982) arguments have been checked at the level of $10^{-5}$" (Gontier, 1990). The partial derivatives of the new transformation with respect to the Earth Orientation Parameters ($x_p$, $y_p$, UT1-UTC, X, Y) have also been developed and tested (Capitaine and Gontier, 1991). As partial derivatives were not implemented for the classical procedure, all the results derived until now with GLORIA have been obtained using the new paradigm.

## GLORIA software update

To comply with IAU resolutions adopted in 2000, we modified the GLORIA software for both the new and the classical transformation following the Chapter 5 of IERS Conventions (2000). The changes consisted in:

For the new paradigm:

- Update of the routine that compute the coordinates (X, Y) of the Celestial Intermediate Pole (CIP) and the quantity **s** using the new developments (Capitaine et al. 2002) based on the IAU 2000 A model for precession-nutation.

For the classical paradigm:

- Implementation of the precession matrix from the angles $\epsilon_0$, $\psi_A$, $\epsilon_A$, $\chi_A$ of Lieske et al. (1977) together with precession corrections and offsets of the direction of the CIP at J2000 in the rigorous form recommended by Wallace (2002).

- Update of the routine that compute the nutation matrix using the IAU 2000 A model (Mathews et al. 2002).
- Modification of GST routine to include the IAU 2000A precession adjustments and complementary terms in the equation of equinoxes (Capitaine et al. 2002, IERS Conventions 2000).
- Implementation of partial derivatives with respect to EOP $x_p, y_p$, UT1-UTC, $d\psi, d\epsilon$).

Furthermore, in the classical transformation, we have implemented two different ways of computing the Greenwich Sideral Time GST:

- version *a*: implementation of the numerical relation between GST and the Earth rotation angle $\theta$ referred to the Celestial Ephemeris Origin (IERS Conventions 2000, chapter 5, equation 29) which includes an update of the "equation of the equinoxes".
- version *b*: modification of the current relationship between Greenwich Mean Sideral Time (GMST) and UT1 (Aoki et *al.*, 1982) to include dGMST (IERS Conventions 2000, chapter 5, equation 30) due to the correction in the precession rate, together with an update of the "equation of the equinoxes".

We could notice that, in practice, any future precession and/or nutation models implementation will introduce less software modifications for the new paradigm than for the classical one.

## Comparisons

Various tests have been performed to verify the level of agreement between the two paradigms using the same software package GLORIA. Two kind of VLBI program of observations have been analysed to derive EOP series:

- The Iris Intensive sessions (2 hours) consist of 20 daily observations of about 16 sources observed on a single baseline oriented East-West. The program is established for the determination of UT1-UTC only.
- The NEOS sessions consist of weekly 24h of observations using a network of 5 stations. The program is optimized for the determination of the 5 EOP.

Only the Iris Intensive sessions have been used to compare the new paradigm with the two versions (*a* and *b*) of the classical one.
The comparisons of UT1-UTC series obtained by analysing 174 Iris Intensives sessions in 2001 (figure 1) show a constant difference of 7.4 $\mu$as between the new and the classical paradigm version *a* and 100.5 $\mu$as between the new and the classical paradigm version *b*. The error bars are the standard errors and the mean value for each of the three series is 141 $\mu$as.
The constant difference of the order of 100 $\mu$as in the estimations of UT1-UTC using the two versions of the classical paradigm (figure 1) can be attributed to the different time scales used for computing the contribution of precession in right ascension in GMST (Capitaine et *al.*, 1986). Version *a* (IERS Convention 2000) refers this computation to TT, whereas version *b* (Aoki et *al.*, 1982) refers to UT1, as TT-UTC is about 64.2 s at J2000 it results a difference of the order of -93 $\mu$as on UT1-UTC estimates.

The analyse of 28 NEOS sessions in 1999 show differences less than 1 $\mu$as on $x_p$, $y_p$, $d\psi$ *and* $d\epsilon$ (figure 2 and 3) except for 8 sessions where the differences could reached 81 $\mu$as at maximum. The mean values of the standard errors are 69 $\mu$as for $x_p$, 58 $\mu$as for $y_p$, 54 $\mu$as for $d\psi$ and 53 $\mu$as for $d\epsilon$.

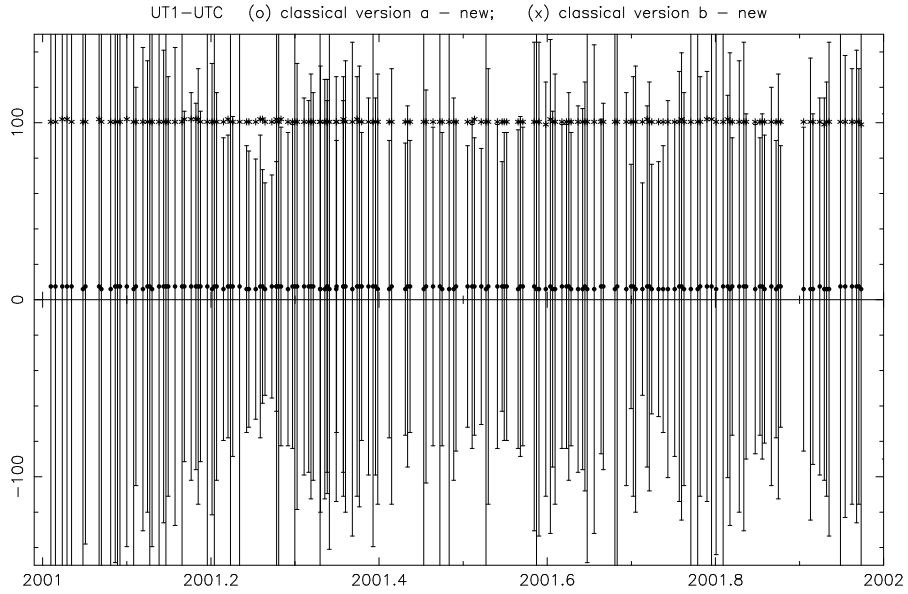


Figure 1: Differences for 2001 between estimated UT1-UTC using the new transformation and the classical one (version *a*: • ; version *b*: ⋆). The plotted error bars are the standard errors of the individual series. Units: $\mu$as.

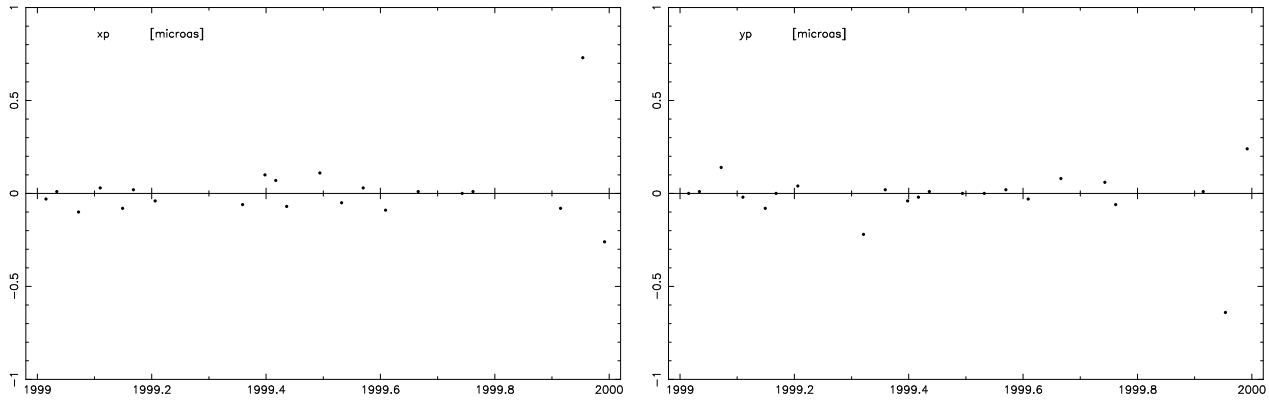


Figure 2: Differences for 1999 between estimated terrestrial pole coordinates (left: $x_p$, right: $y_p$) using the classical (version *a*) paradigm and the new one. Units: $\mu$as.

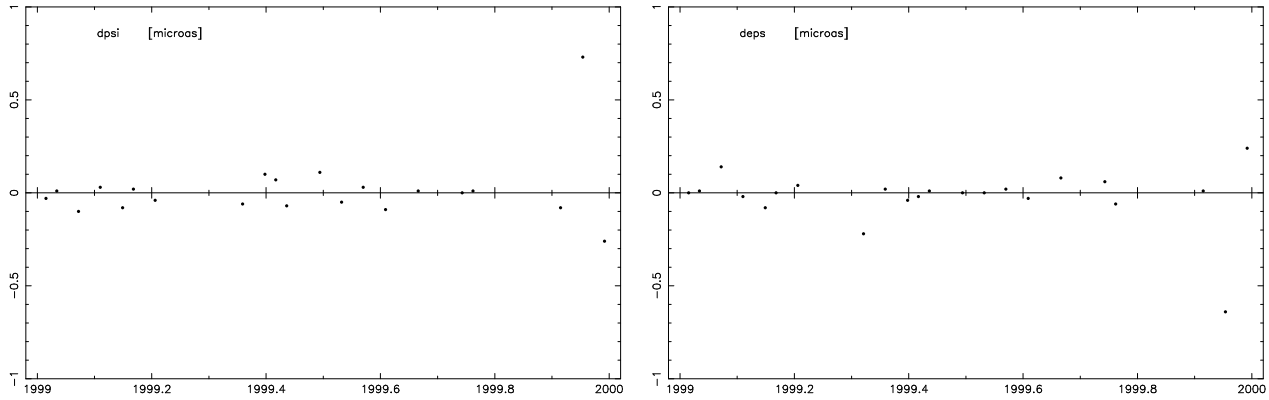


Figure 3: Differences for 1999 between estimated celestial pole offsets (left: $d\psi$, right: $d\epsilon$) using the classical (version *a*) paradigm and the new one. Units: $\mu$as.

A difference of 8 $\mu$as between the new transformation and the classical one version *a* is shown on figure 4 for the UT1 parameter. The series have a mean standard errors of 53 $\mu$as. The remaining small differences between the new and the classical version *a* paradigm are under investigations.

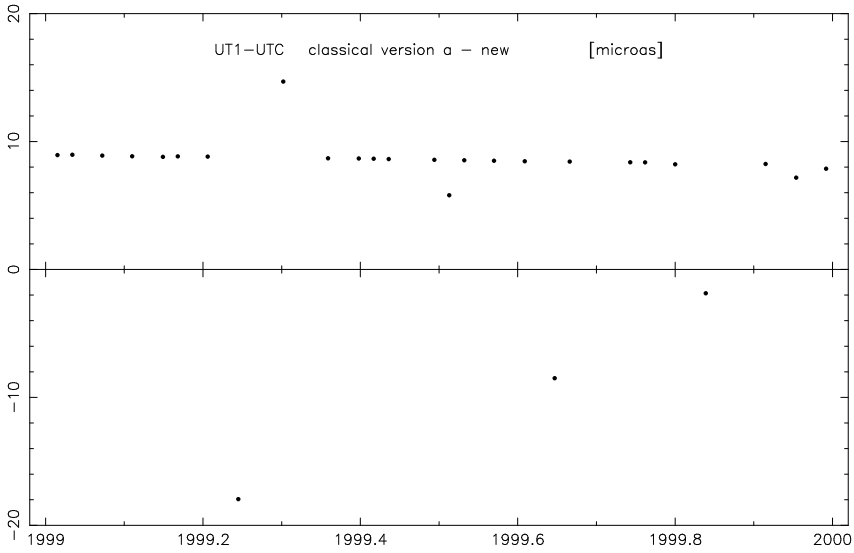


Figure 4: Differences, for the 1999 NEOS sessions, between estimated UT1-UTC using the classical (version *a*) paradigm and the new one. Units: $\mu$as.

## Conclusions

To comply with the IAU resolutions adopted in 2000, we have to modify softwares that compute the transformation between terrestrial and celestial reference frame. The identification of each pieces of software where the modification/update have to be made is the most important and non-trivial step of this process.

Today, with GLORIA we have experienced that the implementation of the new paradigm will require as much work as the correct update of the different part of the classical one. In the future, any changes of precession and/or nutation models will require only the replacement of the provided developments of the celestial pole coordinates (X, Y) and **s** for the new transformation instead of modifying precession and/or nutation and GST computations for the classical one.

The new transformation have been successfully implemented and used in at least two VLBI software STEELBREEZE (S. Bolotin, 2002) and GLORIA. Routines to compute the partial derivatives of the new transformation with respect to the EOP are available for the user community.

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# Future IERS Products Implementation of the IAU 2000 Resolutions

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## 1 Introduction

With the implementation of the IAU resolutions adopted at the IAU 24th General Assembly in 2000 not only the software packages that process space geodetic data but also the IERS products combined from the results of the various techniques will have to be consistently modified and updated and even new products will be necessary to report EOP series consistently with the new resolutions.

On one hand, the new resolutions will have an impact on the software packages used by the analysis centers of the various services (IVS, IGS, ILRS, IDS) to compute their EOP series and the definition and conventions concerning the EOP estimates to be reported to the IERS and, on the other hand, there will be an impact on the IERS products themselves. In this paper we will mainly focus on the latter topic.

For completeness it should be mentioned that the new resolutions will also have to be considered by some of the projects within the services, like, e.g., the time transfer project of the IGS, where the time definitions according to resolution B1.9 will be of importance.

In the following we will first give a list of the IERS products that are affected by the new resolutions and then discuss in more detail the various product modifications that will be necessary.

## 2 IERS Products

A long list of different products are available from the IERS nowadays. Table 1 is not a complete list, but only summarizes the products that are of importance in view of the implementation of the new IAU 2000 resolutions and possible new products discussed at the IERS Workshop 2002 in Paris.

The modifications necessary for the various products given in Table 1 concerning definitions, additions, etc., will be discussed in the next sections. The question of whether leap seconds will also be introduced in future, going hand in hand with the publication of Bulletin C, will not be considered here any further.

## 3 Maintenance of the ICRS/ICRF

Resolution B1.1 stresses the importance of the maintenance of the ICRF as a continuous and ongoing process. In this context the International VLBI and Astrometry Service (IVS) plays a very prominent role. We will, however, not go into more details here. The coordinates of the primary radio sources, the defining sources, will not be changed in the near future unless a considerable improvement can be achieved compared to the present values. The adoption

Table 1: IERS Products affected by the new IAU 2000 Resolutions

| Product(s) | old/ new | Comment | Resolution(s) |
|---|---|---|---|
| ICRS/ICRF | o | Maintenance | B1.1 |
| ITRS/ITRF | o | Scale effect due to change from TT to TCG ($\approx$ 0.7 ppb) | B1.3, B1.5, B1.9 |
| EOP series | o | Clarification of the definitions of x-pole, y-pole, UT1-UTC and celestial pole offsets in the high-frequency domain | B1.6 – B1.8 |
| Series of $X$, $Y$, $dX$, $dY$ | n | Publication of new product files containing these quantities | B1.6 – B1.8 |
| $s$, $s'$ | n | Make available values of $s$, $s'$ to be used in the transformation between GCRS and ITRS | B1.7, B1.8 |
| FCN | n | Size of free core nutation corrections | B1.6 |
| Eulerian Angles | n | New product containing full transformation GCRS $\leftrightarrow$ ITRS for easier use (?) | — |
| Bulletin C | o | Leap seconds (yes or no) | B2 |
| Conventions | o | Modifications according to the new IAU 2000 resolutions | B1.3 – B1.9 |

of the IAU resolutions B1.3 – B1.5 (relativity issues) will only have a very small effect on the radio source positions. Resolutions B1.6 – B1.8 will also have no significant impact on the radio source positions, because nutation corrections were estimated anyway when deriving the ICRF radio source coordinates (which makes these positions independent of the specific nutation model adopted) and the concepts of the CIP, CEO, and TEO do not change the overall transformation between ICRF and ITRF as determined by the space geodetic techniques.

## 4 ITRS/ITRF

The present realization ITRF2000 of the ITRS is not really consistent with some of the IAU/IUGG/IAG resolutions — the IAU 2000 resolutions as well as older IUGG/IAG resolutions — (see also contribution by Gerard Petit):

- The permanent solid Earth tides are not treated according to the IAG XVIII General Assembly Resolution 16.
- The scale of ITRF2000 is not consistent with the TCG time scale (IUGG 1991 Resolution 2 and IAU 2000 resolutions B1.3–B1.5). ITRF2000 is given in TT which differs from TCG by the scale factor $L_G \approx 0.7$ ppb.
- Modeling of geocenter motion is presently not performed to realize a center of mass frame at a center of mass frame at all times.

The permanent tide issue and the scale definition have not been changed so far, because a change will introduce a jump in the time series of the station coordinates. Therefore, for consistency with previous ITRF realizations, the IAU/IUGG/IAG resolutions have not been followed in this respect. Further reasons not to change the ITRF coordinate definition are:

- The ITRF coordinates are used now by many national survey institutions to define their national reference frames. We therefore have to ensure consistency from one realization of the ITRS to the next.
- All IGS, IVS, ILRS, and IDS products will change, if the TCG reference frame definition is adopted. All the existing products of the services would have to be recomputed or corrected.
- Major IERS products will also be affected (ITRF directly and the EOP series indirectly).
- Geodynamics and geophysics have to be able to rely on a consistent and very stable reference frame for their research work (e.g., detection of sea level rise, post-glacial rebound, ...).

It makes sense, however, that formulas and procedures are given in the IERS Conventions that allow the transformation of the site coordinates (and velocities) into an ITRS system that is consistent with the IAU/IUGG/IAG resolutions. It is to be expected that in the near future periodic corrections for the geocenter motion will be taken into account by the various space geodetic techniques.

## 5 Earth Orientation Parameter Series

The most important changes resulting from the IAU resolutions are to be expected in the Earth orientation series published in various forms by the IERS EOP product center and the IERS rapid service and prediction product center. For the users that are not interested in high accuracies the changes in the EOP series resulting from the IAU 2000 resolutions will not be important. Much care is taken to make sure, that the application of the new definitions and concepts will not produce noticeable systematic effects in the EOP products. New products will become available, however, that support the new concepts like, e.g., the celestial coordinates $X$ and $Y$ of the CIP. It should be pointed out here, that the old products will continue to be generated also in the future. But at some point, the high-end users might want to change their software and analysis strategies to comply with the new and more clearly defined EOP concepts.

In the following we will discuss some of the issues to be solved in order to implement the new approaches into the IERS product chain.

### 5.1 Precession and Nutation

The most important effect of the three IAU 2000 resolutions B1.6, B1.7, and B1.8 will be seen in precession and nutation.

First of all, according to the IAU resolutions, the new IAU 2000A precession/nutation model (and its less precise version IAU 2000B) will replace the older models (IAU 1976 precession and IAU 1980 Theory of Nutation) starting on January 1, 2003. There are in principle two ways to implement this new nutation/precession model:

1. stick to the classical procedure and expressions of the IAU 1976 Precession and IAU 1980 Theory of Nutation but apply corrections for the improved numerical values for the precession rate of the equator and for $\Delta\epsilon$ and $\Delta\psi$ according to the new IAU 2000A (or IAU 2000B) model or
2. switch completely to the new formulation using the celestial coordinates of the CIP, $X$ and $Y$.

Only this second approach is consistent with the IAU resolutions B1.7 and B1.8 and should therefore be implemented on the long run.

The total nutation values $\Delta\epsilon$ and $\Delta\psi$ themselves were not published by the IERS. They had to be computed using the formulas of the IAU 1980 Theory of Nutation. The corrections $\delta\Delta\epsilon$ and $\delta\Delta\psi$ from VLBI observations were available in the IERS Bulletins A and C. Because the new precession/nutation model IAU 2000A is accurate to about 0.2–0.4 mas compared to the observed nutation values (assuming that the free core nutation (FCN), which accounts for the bulk of these differences, is not known), some users might not have to care about the corrections $\delta\Delta\epsilon$ and $\delta\Delta\psi$ any longer when using IAU 2000A. For past times, the FCN effects (available as an option in the IAU2000A subroutine) may be added to the IAU 2000A model, improving the quality of the nutation values to about 0.1 mas.

Starting with the implementation of the new nutation/precession model on January 1, 2003, celestial pole offsets will also have to be given with respect to this new nutation/precession model IAU 2000A. The nutation corrections estimated and reported by the IVS and those distributed by the IERS have to follow a clear convention: at least the a priori model these nutation corrections refer to — it may then be the old IAU 1980 Theory of Nutation or the new IAU 2000A model — always has to be stated. It is clear, that the IERS will have to continue to deliver the celestial offsets in the old way for a very long time. It might be a good idea to give different names to those products that refer to the new IAU precession/nutation model and to those that make use of the new concepts so that the user can easily distinguish between old and new products.

It is also evident that the IERS will have to start distributing the new celestial coordinates $X$ and $Y$ of the CIP and the corrections $dX$ and $dY$ to these coordinates as well as the quantities $s$ and $s'$ to be consistent with the new resolutions. A proposal for concrete new products will be given at the end of Section 5.

It is to be expected that VLBI groups will probably continue for quite some time to deliver nutation offsets $\delta\Delta\epsilon$ and $\delta\Delta\psi$, because it will take a considerable effort to change the available software packages to estimate the corrections $dX$ and $dY$ to $X$ and $Y$ instead of the nutation offsets $\delta\Delta\epsilon$ and $\delta\Delta\psi$ presently determined by VLBI (or the nutation rates $\delta\Delta\dot{\epsilon}$ and $\delta\Delta\dot{\psi}$ obtained by GPS). It is therefore necessary to have the appropriate formulas and software available to convert celestial pole offsets from the old representation ($\delta\Delta\epsilon$ and $\delta\Delta\psi$) into the new representation ($dX$ and $dY$). This seems to be reasonably simple, because we only consider very small quantities here and approximate formulas can be used. Eventually, the space geodetic techniques should switch to directly estimating $dX$ and $dY$ and using the CIP coordinates $X$ and $Y$ in their analysis software packages. When most of the IERS components will have switched to the new representation, we will still need the old form to satisfy the users that have no interest to change to the new concepts. It will then become necessary to compute the corrections $\delta\Delta\epsilon$ and $\delta\Delta\psi$ from the new coordinates $X$ and $Y$ and the corresponding corrections $dX$ and $dY$.

When using the new approach, information has to be available concerning the angles $s$ and $s'$, which are part of the transformation formulas between the GCRS (Geocentric Celestial Reference System, using the TCG time coordinate) and the ITRS. The angle $s$ can be computed according to formulas that are given in the IERS Conventions (2000). Because the angle $s'$ depends primarily on the amplitudes of the Chandler and annual wobbles and because these amplitudes become available only after the observations, its value (although very small) is in principle only known after the determination of polar motion, too. In order to have consistent EOP series over long time periods and to avoid any jumps in the series, predicted values of $s'$ of sufficient accuracy

should be made available for the analysis of the space geodetic data. The publication of appropriate and sufficiently accurate values of $s'$ should therefore be part of the new IERS product that comply with the IAU resolutions. More information about $s'$ may also be found in the poster presentation by S. Lambert and Ch. Bizouard of this IERS Workshop 2002.

Because the free core nutation (FCN) is not taken into account in the new IAU 2000A/B models, it would make sense that the IERS is publishing values for the FCN corrections that can be applied by the users to improve the nutation model. It should be mentioned, that the celestial offsets estimated by the IVS and submitted to the IERS should refer (after a transition period) to the IAU 2000A model and it has to be clearly decided and defined, how the effects of the free core nutation are going to be treated.

### 5.2 Polar Motion

There will be almost no impact of the new resolutions (B1.6 – B1.8) on the polar motion (PM) values. Because diurnal and semi-diurnal nutation corrections were not taken into account in the IAU 1980 (or IERS 1996) nutation model, they were reported as part of polar motion also in the past. These diurnal and semi-diurnal nutation terms are small — the largest term has an amplitude of 28.5 $\mu$as, see "Practical consequences of the resolutions B1.6 – B1.8" by Dennis McCarthy and Nicole Capitaine — compared to the present accuracy of about 0.1 mas for the daily polar motion estimates from the best space geodetic techniques.

It should be mentioned here, that, as a convention, the subdaily ocean tide variations (nearly semi-diurnal and diurnal terms with a size of about 1 mas) are not part of the polar motion values reported to the IERS and distributed by the IERS. This is a convention that is necessary in order to allow for a more precise interpolation of the daily PM values. The subdaily part in PM has to be added after the interpolation according to the model given in the IERS Conventions (2000).

We think that the same procedure should be applied for the high-frequency effects in polar motion and UT1 arising from the high-frequency nutation terms. That means, that these variations should not be included in the reported PM values but should be taken into account using an appropriate model (e.g that by Folgueira et al., 2001, for polar motion; no model exists yet for UT1-UTC). This question of the model to be used should be settled soon because in the near future the space geodetic techniques might reach the accuracy level of these high-frequency nutation terms.

Finally, we would like to point out, that the forced "diurnal polar motion" — nearly diurnal retrograde tidal variations in polar motion also known as Oppolzer terms caused by the luni-solar torque — are not considered part of polar motion but are included in the nutation models (IAU 2000A/B). This was already the case in the previous definition of polar motion using the Celestial Ephemeris Pole (CEP). Because the space geodetic techniques and astrometic observations cannot provide the position of the Instantaneous Pole of Rotation (IRP), it makes sense to use the Celestial Intermediate Pole (CIP) as reference axis. We should not forget, however, that gyroscopes and gravimeters are sensitive to the position of the IRP and not to the CIP.

### 5.3 UT1-UTC

The effects of the new resolutions on the UT1-UTC values is expected to be very small. They are mainly the result of an improved precession/nutation model, which might help to better separate between nutation and UT1-UTC parameters. The same is true for UT1 itself. Greenwich Sidereal Time (GST),

however, will be replaced by the "Earth Rotation Angle" (ERA) and this ERA will be related to UT1 by a simple linear relationship.

As in the case of polar motion, the effects due to the semi-diurnal and diurnal ocean tide variations should not be part of the UT1-UTC series reported to and distributed by the IERS (see also Section 5.2). The same is true for the high-frequency variations coming from the high-frequency nutation terms, but no model exists yet to take these terms into account.

It is clear that, depending on the outcome of the studies to be performed according to resolution B2, the values of UT1-UTC might not include any leap second jumps any more in the future.

### 5.4 Old and New IERS EOP Product

The quantities contained in the old and in the new IERS EOP file proposed here and the steps to be performed to compute highly accurate EOP values and the rotation matrix for the transformation between the terrestrial and celestial frame are summarized in Table 2.

Table 2: Old and new procedures to compute with high precision the transformation matrix $\boldsymbol{R}_{tot}$ between terrestrial and celestial reference frame from the IERS EOP products.

| **Old EOP Representation** | **New EOP Representation (preliminary)** |
|---|---|
| EOP file with: TCG, $x'_p$, $y'_p$, UT1-UTC', $\delta\Delta\epsilon$, $\delta\Delta\psi$ | EOP file with: TCG, $x'_p$, $y'_p$, UT1-UTC', $X$, $Y$ (and possibly in addition $X_{IAU2000A}$, $Y_{IAU2000A}$, $s$, $s'$ and FCN) |
| Compute IAU 1976 precession matrix $\boldsymbol{P}$ and IAU 1980 nutation $\Delta\epsilon_{80}$, $\Delta\psi_{80}$: $\Delta\epsilon = \Delta\epsilon_{80} + \delta\Delta\epsilon$ , $\Delta\psi = \Delta\psi_{80} + \delta\Delta\psi$ | Compute $s$ and $s'$ with formulas or take them from EOP file |
| Compute subdaily ocean tide terms: $\Delta x_p$, $\Delta y_p$, and $\Delta$(UT1-UTC) | Compute subdaily ocean tide terms: $\Delta x_p$, $\Delta y_p$, and $\Delta$(UT1-UTC) Compute high-frequency nutation terms in PM and UT1-UTC: $\Delta x_p^N$, $\Delta y_p^N$, and $\Delta(\text{UT1-UTC})^N$ |
| $x_p = x'_p + \Delta x_p$ | $x_p = x'_p + \Delta x_p + \Delta x_p^N$ |
| $y_p = y'_p + \Delta y_p$ | $y_p = y'_p + \Delta y_p + \Delta y_p^N$ |
| UT1-UTC = UT1-UTC$'$ + $\Delta$(UT1-UTC) | UT1-UTC = UT1-UTC$'$+ $\Delta$(UT1-UTC) + $\Delta(\text{UT1-UTC})^N$ |
| Compute Greenwich Sidereal Time: GST(UT1,$\Delta\psi$) | Compute Earth Rotation Angle: $\theta$(UT1) |
| $\boldsymbol{R}_{tot} = \boldsymbol{P} \cdot \boldsymbol{N}(\Delta\epsilon, \Delta\psi) \cdot \boldsymbol{R}_3(-GST) \cdot \boldsymbol{R}_1(y_p) \cdot \boldsymbol{R}_2(x_p)$ | $\boldsymbol{R}_{tot} = \boldsymbol{PN}(X, Y) \cdot \boldsymbol{R}_3(s) \cdot \boldsymbol{R}_3(-\theta) \cdot \boldsymbol{R}_3(-s') \cdot \boldsymbol{R}_1(y_p) \cdot \boldsymbol{R}_2(x_p)$ |

The procedure outlined for the new representation should be considered as preliminary, because the details of the content of the new EOP files is under discussion. The following comments should be added here concerning Table 2:

- The quantities $x'_p$, $y'_p$, and UT1-UTC' given in the EOP files contain neither the subdaily variations due to the ocean tides nor the variations due to the diurnal and semi-diurnal nutation terms to avoid interpolation problems with the 1-day tabular interval. (In the old representation the latter terms were not considered yet).

- $X$ and $Y$ are the total values of the celestial coordinates of the CIP, i.e., they include the IAU 2000A model and the corrections $dX$ and $dY$ (including the free core nutation contribution) derived from VLBI observations. It might well be that these various contributions to $X$ and $Y$ will be included in the new EOP file in addition to the total values.
- Because the total values of $X$ and $Y$ will be given in the new EOP files, the user will not have to compute the IAU 2000A (or 2000B) model with its 1440 terms.
- Values for $s$, $s'$, and $\theta$ may be computed using simple formulas. Most probably $s$ and $s'$ will be included in the new EOP files so that they do not have to be computed by the user.
- Groups that are estimating nutation parameters from space geodetic data should use the IAU 2000A model only (without FCN contribution) as a priori values for $X$ and $Y$ (or as a priori values for $\Delta\epsilon$ and $\Delta\psi$).

Additional information on conventions implied in the new products will be given in the new set of IERS Conventions.

### 5.5 Eulerian Angles

Due to the continuously increasing precision and accuracy as well as time resolution of the Earth orientation parameter series obtained from the various space geodetic techniques, ever complexer and more elaborate models and correction terms have to be considered by the IERS user in order to get the most accurate EOP values. In view of this complexity (precession/nutation models with almost 1400 terms, polar motion and UT1-UTC corrections from IERS Bulletins, knowledge of the parameters $s$ and $s'$, subdaily nutation model in polar motions, subdaily ocean tide corrections for polar motion and UT1-UTC with about 70 terms, effect of the Free Core Nutation (FCN), ...), it might make sense to publish a file with Eulerian angles containing all effects down to a certain accuracy level. For users that are only interested in the transformation between GCRS and ITRS and not in the mechanism and subtleties of Earth rotation itself, tables with Eulerian angles given with a high enough sampling rate to allow for linear (or quadratic) interpolation might be an attractive alternative to the present procedure. Before such a product is envisaged, it would be necessary, however, to estimate the frequency, at which the Eulerian angles would have to be specified, and what amount of data would be needed for, e.g., a table containing the EOP information of one year. Such a study will be performed in the near future and, if the outcome is positive, a new IERS product containing the Eulerian angles will be established.

## 6 IERS Conventions (2000)

The IERS Conventions (2000) should also be considered a product of the IERS. This product is extremely important, because it has to give the guidelines and formulas to be used in analysis software packages in order to be consistent with the IAU resolutions. The IERS Conventions (2000) should therefore have the following characteristics:

- All chapters should be **consistent with the IAU resolutions** to the extent possible.
- All chapters should also be **consistent with each other** (models, numerical values, and notation) to the extent possible.
- The chapters should give a **complete** description of the models, algorithms, processing strategies and parameterizations to be used.

In addition to the information given in the IERS Conventions, it would also make sense to describe (as part of the IERS Conventions or separately) the exact characteristics of the products that the space geodetic services (IGS, IVS, ILRA, IDS, ...) should deliver to the IERS and the IERS delivers to its users. In the case of EOP time series for instance the analysis centers have to know, that the subdaily variations due to the ocean tides are not to be included in the reported ERP values. Similar conventions are needed for the subdaily nutation effects etc. (see Section 5.1).

## 7 Software Changes for Analysis Centers

Although the changes necessary by the analysis centers of the different services (IGS, IVS, ILRS, IDS) to comply with the new IAU resolutions are not part of the topic here, we would like to mention a few of the issues there. It is quite evident, that the software changes required to fully implement all IAU resolutions are not to be underestimated and are certainly much more problematic than the changes required for the IERS products.

The implementation of the exact relativistic formulas according to IAU resolutions B1.3 – B1.5 is cumbersome and difficult to test, because of the rather small effect these modifications will have compared to the relativistic corrections already used now.

It will be quite a heavy task to switch from the classical EOP representation to the new concepts (CIP, CEO, TEO, ...) in the various geodetic software packages. It includes:

- Implementation of the new models (IAU 2000A precession/nutation, model for diurnal and semi-diurnal nutation terms in PM, $X$ and $Y$, formulas for $s$ and $s'$, ...).
- New parameterization with $dX$ and $dY$ instead of $\delta\Delta\epsilon$ and $\delta\Delta\psi$ and computation of the new partials.
- New data structures and formats for the new quantities (e.g., $X$, $Y$, $dX$, $dY$, $s$, $s'$, ...).
- Modifications of the IERS EOP format and the SINEX format.
- All results obtained using the new representation will have to be carefully tested and validated to ensure compatibility with the classical results.

It is no question that the new IAU 2000A precession/nutation model will be implemented very soon in all major space geodetic software packages. It is also clear that the implementation of the new approach with CEO, TEO and ERA will take much more time to realize. The use of the new concepts only makes sense, if they are fully implemented into all major space geodetic software packages, too. It will certainly take quite some time to reach this status, especially in view of the fact that the new EOP representation "per se" will not change the quality of the transformation between ICRF and ITRF. However, clear and more concise EOP concepts will be beneficial to all EOP series in the long run.

# Compatibility with Past Observations

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This topic addresses the issue of the compatibility of observations made in the past with observations made using the new system. It is not likely that there would any requirement to adjust past observations to put them into a system that complies with the newly adopted IAU Recommendations. However, it may be important to look at the specifics of each case.

Recall that, in the new system, the ICRS is realized by the ICRF (Hipparcos Celestial Frame, HCRF, in the visual) and that those positions can be considered as being analogous to a catalog of positions and motions related to the equinox and equator of J2000.0. The definitions have been made more rigorous and it has now been made clear that the ICRS is a barycentric system with the time tags in TCB. The direction of the x axis of this system (ICRS) is very close to that of the dynamical mean equinox of J2000, the offset being 78±10 mas (Folkner *et al.*, 1994; Arias, *et al.*, 1995). Note that the FK5 origin of right ascension is only known with a precision of ± 80 mas. According to Mignard & Froeschle (1997), this origin is offset by -22 mas from the ICRS. The ICRF provides positions with respect to a fixed equator that does not move. To treat the effects of proper motion correctly, the epoch related to each star position should be noted.

The procedure to be followed in transforming from the celestial (ICRS) to the terrestrial (ITRS) systems has been clarified to be consistent with the improving observational accuracy. See Figure 1 for a diagram of the new and old procedures to be followed. As before, we make use of an intermediate reference system in transforming to a terrestrial system. In this case we call that system the Intermediate Celestial Reference System. The Celestial Intermediate Pole (CIP) that is realized by the IAU2000A/B Precession-Nutation model defines its equator. Previously we made use of the Celestial Ephemeris pole that was defined by the IAU1976 precession and the IAU1980 Nutation. The Conventional Ephemeris Origin replaces the concept of the equinox in this system. Whereas the CEP did not address high-frequency nutation the definition of the CIP makes it clear that the effects of nutation terms with periods less than 2 days are to be included in the polar motion.

The position in this reference system is called the intermediate right ascension[1] and declination and is analogous to the previous designation of "apparent right ascension and declination." After the new procedures are fully implemented in the national almanacs, it is expected that they would provide positions of stars and solar system information in these geocentric apparent positions for the appropriate TCG epoch.

The relationships between the coordinates X and Y and the traditional precession-nutation quantities to first order in offset quantities are (Capitaine, 1990)

$$\mathrm{X} = \overline{\mathrm{X}} + \xi_0 - \mathrm{d}\alpha_0\, \overline{\mathrm{Y}},$$

$$\mathrm{Y} = \overline{\mathrm{Y}} + \eta_0 + \mathrm{d}\alpha_0\, \overline{\mathrm{X}},$$

where $\xi_0$ and $\eta_0$ are the celestial pole offsets at the J2000.0 and $\mathrm{d}\alpha_0$ the right ascension of the mean equinox of J2000.0 in the CRS. The traditional precessional angles $\theta$ and $\zeta$ can be expressed in the context of the IAU 2000 recommendations (see Hilton 2002, this Volume).

[1] Please note that the terminology used in this paper to refer to the system of coordinates in this intermediate reference system has not been sanctioned officially by the IAU.

The mean equinox of J2000.0 to be considered is not the "inertial dynamical mean equinox of J2000.0" (Standish 1981) but the origin of right ascension in the mean equatorial system of the CIP at J2000.0. The numerical value for $d\alpha_0$ as provided by Chapront *et al.* (1999) is -14 mas. The quantities $\overline{X}$ and $\overline{Y}$ are given by

$$\overline{X} = \sin\omega \sin\psi,$$

$$\overline{Y} = -\sin\varepsilon_0 \cos\omega + \cos\varepsilon_0 \sin\omega \cos\psi,$$

where $\varepsilon_0$ is the obliquity of the ecliptic at J2000, $\omega$ is the inclination of the true equator of date on the fixed ecliptic of epoch and $\psi$ is the longitude, on the ecliptic of epoch, of the node of the true equator of date on the fixed ecliptic of epoch. These quantities are such that

$$\omega = \omega_A + \Delta\varepsilon_1, \quad \psi = \psi_A + \Delta\psi_1,$$

where $\psi_A$ and $\omega_A$ are the precession quantities in longitude and obliquity (Lieske, *et al.,* 1977) referred to the ecliptic of epoch and $\Delta\psi_1$, $\Delta\varepsilon_1$ are the nutation angles in longitude and obliquity referred to the ecliptic of epoch. $\Delta\psi_1$, $\Delta\varepsilon_1$ can be obtained from the nutation angles $\Delta\psi$, $\Delta\varepsilon$ in longitude and obliquity referred to the ecliptic of date. The following formulation from Aoki and Kinoshita (1983) provides accuracy better than one microarcsecond after one century:

$$\Delta\psi_1 \sin\omega_A = \Delta\psi \sin\varepsilon_A \cos\chi_A - \Delta\varepsilon \sin\chi_A,$$

$$\Delta\varepsilon_1 = \Delta\psi \sin\varepsilon_A \sin\chi_A + \Delta\varepsilon \cos\chi_A,$$

$\omega_A$ and $\varepsilon_A$ being the precession quantities in obliquity referred to the ecliptic of epoch and ecliptic of date respectively and $\chi_A$ the precession quantity for planetary precession along the equator (Lieske, *et al.,* 1977).

In transforming from this intermediate system to the terrestrial system in which observations are made, there should be no systematic shifts in polar motion or in UT1-UTC. While UT1 will now be defined differently by using the stellar angle, $\theta$, between the CEO and the meridian origin of the ITRS (or ITRF), where

$$\theta(T_u) = 2\pi\,(0.779\,057\,273\,2640 + 1.002\,737\,811\,911\,354\,48\,T_u),$$

and $T_u$ = (Julian UT1 date 2451 545.0) (Capitaine *et al.*, 2000),

no "jumps" in UT1-UTC will be seen. This definition replaces the use of Greenwich Mean Sidereal Time as the basis for the definition of UT1.

The numerical expression for Greenwich Sidereal Time consistent with the IAU 2000 precession and nutation model can be obtained using computations similar to those used to obtain the expression for s (Capitaine, *et al.*, 2002).

$$\mathrm{GST} = \theta + 4612.\text{"}157482t + 1.\text{"}39667841t^2 - 0.\text{"}00009344t^3 + 0.\text{"}0000188t^4 + \Delta\psi\cos\varepsilon_A - \sum_k C_k \sin\alpha_k - 0.\text{"}002106$$

where t = (TT-2000 January 1d 12h TT) in days / 36525. GST - $\theta$ provides the right ascension of the CEO. $-\sum_k C_k \sin\alpha_k - 0.\text{"}002106$ contains the complementary terms to be added to the current "equation of the equinoxes"', $\Delta\psi\cos\varepsilon_A$, to provide the relationship between GST and $\theta$ at a microarcsecond accuracy. This replaces the two complementary terms provided in the IERS Conventions 1996. (see McCarthy and Capitaine 2002, this Volume, Table 1, for more detail on the periodic terms appearing in $\Sigma_k C_k \sin\alpha_k$ ). A secular term similar to that appearing in the quantity s is included. The change in the polynomial part of GST due to the correction in the precession rates and offset in obliquity at J2000 corresponds to a change dGMST (see Williams, 1994) in the current relationship between GMST and UT1 (Aoki , *et al.*, 1982) which can be written in microarcseconds as:

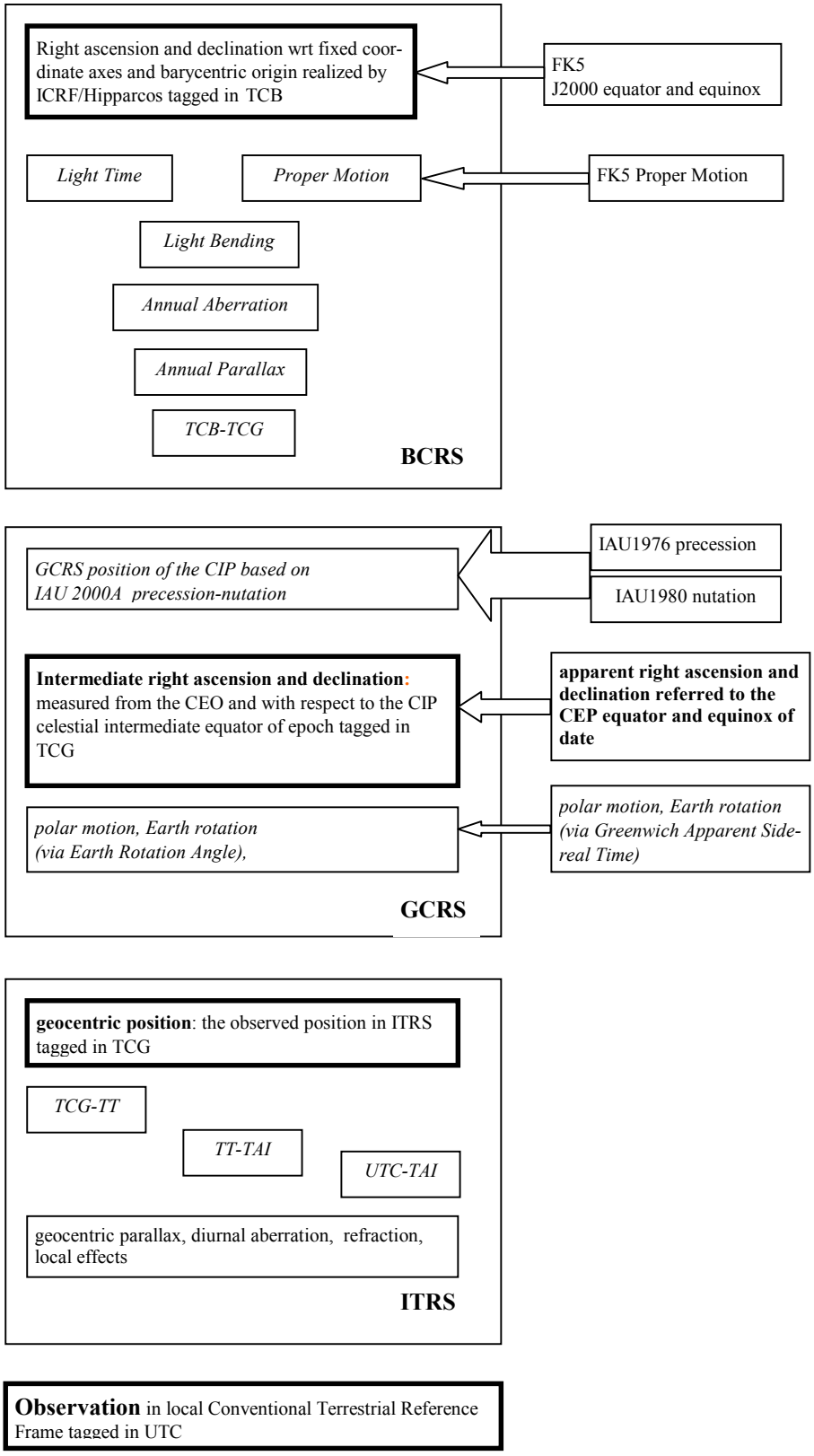


Figure 1. Process to transform from celestial to terrestrial systems. Differences with the past process are shown on the right of the diagram.

$dGMST = GMST_{NEW} - GMST_{OLD} = - 274868\ t + 118\ t^2 + 19\ t^4$.

The convention for the constant term in GST will be such that it provides for no discontinuity in UT1 on 01/01/2003.

In the newly adopted system, the ecliptic remains as the mean plane of the Earth's orbit. In practice it is realized by an ephemeris of the Earth. Analogous with previous definitions, the equinox is either of two points where the ecliptic intersects the celestial intermediate equator.

A conventional ecliptic can be defined at an epoch (Seidelmann and Kovalevsky, 2002) as a fixed plane in the ICRF with a fixed inclination $\varepsilon_0$ equal to the mean obliquity at J2000.0. The transformation from the ICRS (x, y, z) coordinates to the ecliptic fixed coordinates ($X_e$, $Y_e$, $Z_e$) is then

$X_e = x$,
$Y_e = y \cos \varepsilon_0 + z \sin \varepsilon_0$,
$Z_e = -y \sin \varepsilon_0 + z \cos \varepsilon_0$,

$\varepsilon_0 = 23^\circ\ 26'\ 21.''4059$ (IERS Conventions 2000). This conventional ecliptic plays no role in the transformation between the ICRS and the ITRS. It may be useful for some specialized purposes.

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# Expressions for the Coordinates of the CIP and the CEO using IAU 2000 Precession-Nutation

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## 1 Introduction

Expressions for the position of the Celestial Intermediate Pole (CIP) and the Celestial Ephemeris Origin (CEO) in the Geocentric Celestial Reference System (GCRS) have been computed using the IAU 2000A precession-nutation. These expressions are for use in the new transformation between the GCRS and the International Terrestrial Reference System (ITRS) which is recommended by IAU Resolution B1.8. Various comparisons and numerical checks have been performed between the classical and the new transformations based on the IAU 2000A precession-nutation. These comparisons revealed necessary improvements to be applied to the classical form of the transformation in order to achieve the required level of accuracy. Once these improvements are applied, the consistency between the positions of the CIP in the GCRS corresponding to the classical and the new transformations is at a level of a few microarcseconds after one century. This paper summarizes the main points of this work, which will be described in more detail in a paper in preparation (Capitaine *et al.* 2002).

## 2 Expressions for the position of the CIP and the CEO in the GCRS

The expressions for the position of the CIP and the CEO in the GCRS are based on the definitions and formulations described in Capitaine *et al.* (2000). The position of the CIP in the GCRS is provided by the coordinates $X$ and $Y$ which are expressed as function of combined quantities for precession and nutation; these coordinates include precession, nutation, the coupling effects between precession and nutation and the offsets at J2000. The quantity $s$ is used along with $X$ and $Y$ to predict the position of the CEO as a function of time. It is computed by an integration along the CIP path, from J2000.0 to $t$. The developments of $X$, $Y$ and $s$ can be provided at microarcsecond accuracy as a polynomial form of $t$ plus a series of Poisson terms, valid over an interval of several centuries, the expression for $s$ being derived from those obtained for $X$ and $Y$. The precession and nutation quantities used in these computations are the MHB 2000 nutation series and IAU 1976 precession corrected for the rates in longitude and obliquity (Mathews *et al.* 2002), and the associated values for the celestial pole offsets at J2000.0, with respect to the pole of the GCRS. The quantity ($d\alpha_0$ =14 mas) used for the offset in right ascension (opposite of the right ascension of the mean equinox at J2000) results from simultaneous analysis of VLBI and LLR data (Chapront *et al.* 2002). The manipulation of the Fourier and Poisson series have been performed using the software package GREGOIRE, which handles Fourier and Poisson series and allows a rapid manipulation of large series. The resulting expressions for $X$,

$Y$ and $s$ are given in the IERS Conventions 2000 (McCarthy and Capitaine, session 3.2, this Volume).

## 3 Comparison between new and classical transformations

### 3.1 Internal checks of the developments for $X$ and $Y$

In order to check the developments as function of time of the quantities $X$ and $Y$, an internal comparison in the time domain over 4 centuries around J2000 has been performed (see Figure 1) between ephemerides using the developments as functions of time for $X$ and $Y$ (index a) and the values at the same dates based on the analytical formulation as functions of the classical precession and nutation quantities (index b). The differences are less than five microarcseconds over the considered interval. Spectra of the differences show no amplitude greater than 0.3 $\mu$as.

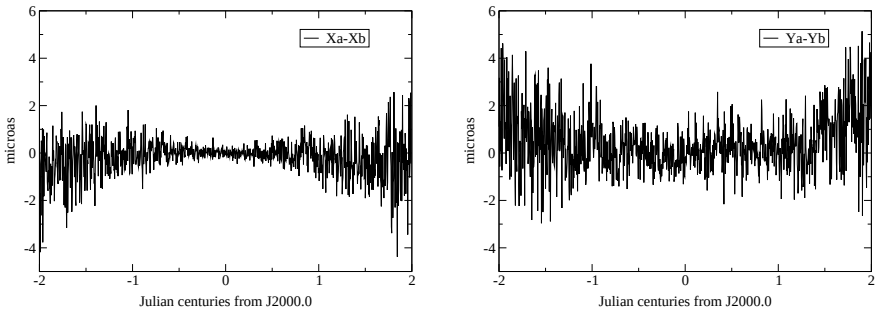


**Figure 1**: *Comparison between the development of the quantity X (left) and Y (right) and ephemerides for the analytical formulation as functions of the combined IAU 2000A precession-nutation quantities*

### 3.2 Comparisons with the classical formulation

Comparison of the series for X, Y with a classical formulation, in which elements (3,1) and (3,2) of the NP matrix are the CIP X, Y, revealed differences at one milliarcsecond level after two centuries. These differences have been explained by the following effects appearing in the classical transformation when the IAU 2000A nutation code is used (Wallace, session 5.1, this Volume) :

- disagreement (at 1 mas level over 2 centuries) between the two ways of forming the precession matrix using the angles of Lieske *et al.* (1977): the 3-rotation transformation based on the quantities $\zeta_A, \theta_A, z_A$ and the 4-rotation one based on the quantities $\epsilon_0$, $\psi_A$, $\omega_A$ and $\chi_A$,
- cross terms becoming significant after a few decades (see Figure 2) due to the use of the IAU 2000A precession contributions rather than applying the changes directly to $\psi_A$, $\omega_A$ and $\epsilon_A$,
- cross terms becoming significant after a few decades due to the effect of using the IAU 2000A bias contributions rather than applying this offset at J2000 rigorously, as a separate rotation,
- cross-terms of non-negligible amplitudes over long periods of time appearing in $X$, $Y$, due to the effect of omitting the offset in right ascension, $\mathrm{d}\alpha_0$.

After correcting these effects, agreement to a few microarcseconds is achieved between classical and new transformations (see Figure 3), but only because, in the classical transformation, the "total" $d\psi$, $d\epsilon$ from IAU 2000A have been rejected in favour of rigorous precession and bias corrections.

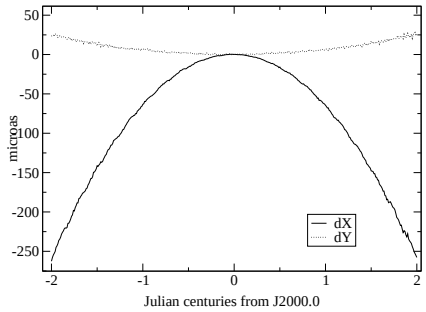


**Figure 2**: *Effect of using the IAU 2000 precession contribution rather than applying directly to $\psi_A$ and $\omega_A$*

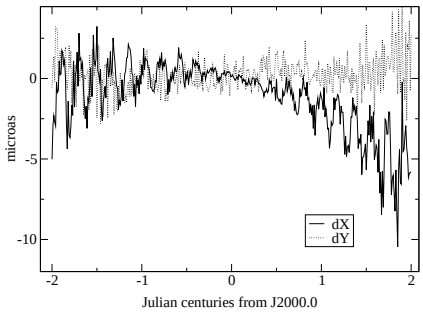


**Figure 3**: *Comparisons with the series for $X$, $Y$ elements (3,1) and (3,2) of the classical $NP$ matrix*

These comparisons have demonstrated that the new method is more simple, compact and direct than the classical formulation, predicting the position of the CIP to accuracies of a few microarcseconds with greatly reduced scope for misuse. The clean separation between precession-nutation of the equator from Earth rotation is a further advantage of the new method.

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# 2005 French Ephemerides: Implementation of new Constants and Theories

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**Abstract:** With the implementation of the new IAU resolutions, the IMCCE wants also to regenerate its ephemerides. Since 1984, no major modification was made in the IMCCE-BDL publications. The IAU recommandations for implementing the XXIVth General Assembly resolutions are then a good opportunity. In this poster, the major modifications expected to be made in the 2005 Connaissance des Temps and in the other 2005 publications of the IMCCE-BDL are presented: new planetary ephemerides, new satellite ephemerides, original ephemerides of meteor showers and of course implementations of the new IAU resolutions.

## 1 Introduction

The IMCCE-BDL produces ephemerides of planets, satellites, comets and asteroids, available via the Internet (`http://www.bdl.fr`), via the Minitel (3615 bdl) or via classic publications (Connaissance des Temps, Annuaire du Bureau des longitudes), via the Internet (`http://www.bdl.fr`) or via the Minitel (3615 bdl). Since 1984 and the implementation of the VSOP82 solution of planetary motions, no major modification or implementation was done in the IMCCE-BDL ephemerides. However, because of the IAU recommandations for implementing the XXIVth General Assembly resolutions and also because of the constant improvement of the techniques of observations and the correlated need of accuracy of the professional users of our ephemerides, it appears that a complete modification of the theories and the constants used for the publications was needed. After a quick presentation of the new IAU recommandations, we present the new original theories and the new services (meteor shower forecasting), set up at the IMCCE.

## 2 Implementing the IAU resolutions in the IMCCE ephemerides

The IAU 2000 has adopted several resolutions, some of which involving important changes in the ephemerides: coordinates and metrics of the (BCRS) and (GCRS), relation between TCB and TCG and new definition of TT, precession-nutation model IAU 2000, new concepts such as the Celestial Intermediate Pole (CIP), the Celestial Ephemeris Origin (CEO) etc.. The impact of the IAU resolutions on the IMCCE ephemerides will be the following. Positions will be given in the ICRF, following IAU 2000 resolution, with associated transformations for the precession and nutation. Therefore, the precession-nutation model IAU 2000A will be introduced in the Web server of the IMCCE and in the Connaissance des Temps and the other ephemerides of the IMCCE beginning with the editions for 2005. The masses of the IERS92 system will be used. The

time used in the theories of the celestial bodies build at the IMCCE will be TCB. Beginning with the edition 2005, the time argument of the ephemerides of the Connaissance des Temps will be TAI. The coordinates of the CIP and the parameters linked to the CEO will be computed on the Web server. For the physical ephemerides, the new rotational elements for the planets and satellites issued of Seidelmann et al. (2002) will be used.

## 3 New Ephemerides of Planets, Satellites and Meteors

The new planetary solution is an analytical solution of the motion of the planets of the solar system, including Pluto, fitted to observations. The time scale is TCB and the main characteristics of the model (Moisson et Bretagnon, 2001) include a relativistic model (Brumberg, 1991), mutual planetary and lunar perturbations, IERS 1992 planet masses and asteroid perturbations (a few hundreds). No solar flattening is included. The modeling of the perturbations induced by the main belt asteroids on the Mars orbit is a complex problem (several kilometers uncertainties over a decade). Different models will be investigated. The mean internal accuracy of our analytical solution is about 7 km (0.01 for Mercury, 0.60 for Mars and 23 km for Neptune), the external precision would be about 40 mas (4 for Mercury, 2 for Mars and 100 mas for Neptune). Thanks to VLBI spacecraft tracking observations, the planetary solution is directly linked to ICRF and for optical observations, IAU recommandations (precession-nutation IAU 2000A) will be applied.

For Saturn satellites, a new dynamical model, named TASS, of the main Saturnian satellites has been developed (Duriez & Vienne 1997). For the first time, this analytical model, fitted on more than 50000 astrometric observations over 110 years, deals with the complete dynamical problem of the motion of the eight major satellites, including the oblateness of Saturn and the solar perturbations. The main interest of this theory is its ability to remain accurate on long intervals of time. Programs are already available on the bdl ftp server. The internal accuracy is below ten kilometers and thanks to recent comparisons with CCD astrometric observations, the external accuracy has been estimated to 40 mas. We intend to introduce this model in Connaissance des Temps for 2005.

Using a model taking into account new effects such as satellites' oblateness (Lainey et al. 2001) coupled with techniques like frequency analysis and classical analytical development, we develop a new semi-analytical theory of the Galilean satellites motion, inlcuding mainly the satellites and Jupiter oblateness and the solar perturbations. We expect to obtain an internal precision of about ten kilometers. Original IMCCE ephemerides of JV Amalthea, JXIV Thebe, JXV Adrastea and JXVI Metis are under development. The dynamical model is based on an eleven-bodies problem, numerically integrated, disturbed by the oblateness of the primary and relativistic effects. Fit to observations is performed using a 20-year set of optical, spatial and IR observations. The standard deviation in the O-C of the satellites positions is approximately 200 mas. With more accurate observations and improved stellar catalogs, it should be possible to reduce them to 50 mas. The IMCCE original ephemerides of the JVI to JXIII and JXVII are modelized as described in (Rocher et Chapront, 1996). The ephemerides are fitted to observations. Extension of the observation sets and creation of ephemerides for new discovered objects are the future evolution of the outer satellite IMCCE service.

Concerning Neptune satellites, we are going to put on the web server the ephemerides of Triton, Nereid and Proteus (Le Guyader, 1993). These ephemerides are numerical integration of their motion from 1800 to 2050.

The new Meteor shower forecasting service of the IMCEE publications is ded-

icated to professional and non-professional users. We are now able to give the ephemerides of time of the maximum, and of the level of the storm of the showers, such as Leonids. We take into account the path of the parent body close to the sun, the population of dust grains ejected, the ejection process, the orbit of each particle (radiation pressure, Poynting-Robertson drag, and eventually seasonal Yarkovsky force), the encounter with the Earth at the right epoch, the profile encountered, and some statistical consideration to extrapolate the real level of the shower.

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# New Precession Formula

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In order to find a substitute of IAU 1976 precession formula (Lieske *et al.* 1977) to be used with latest nutation theories such as SF2001 (Shirai and Fukushima 2001), we modified J.G. Williams' formulation of the precession and the nutation by using the 3-1-3-1 rotation (Williams 1994) so as to express them in an arbitrary inertial frame of reference.

It gives the precession-nutation matrix as the product of four rotation matrices as

$$\mathcal{NP} = \mathcal{R}_1(-\epsilon)\mathcal{R}_3(-\psi)\mathcal{R}_1(\varphi)\mathcal{R}_3(\gamma), \tag{14}$$

and the precession one similarly as

$$\mathcal{P} = \mathcal{R}_1\left(-\bar{\epsilon}\right)\mathcal{R}_3\left(-\bar{\psi}\right)\mathcal{R}_1(\varphi)\mathcal{R}_3(\gamma). \tag{15}$$

Here $\varphi$ and $\gamma$ are the angles to specify the location of the ecliptic pole of date in the given inertial frame, $\psi$ and $\bar{\psi}$ are the true and mean ecliptic angles of precession, respectively, and $\epsilon$ and $\bar{\epsilon}$ are the true and mean obliquities of the ecliptic, respectively. In other words, we (1) first specify the ecliptic pole of date in the given inertial reference frame and shift from the inertial frame to an ecliptic reference frame of date, (2) then specify the mean or true equatorial pole of date, $\bar{\mathrm{P}}$ or P, in the ecliptic reference frame and shift from the ecliptic frame to the mean or true equatorial reference frame of date. Although the expression of nutation matrix is unchanged, we recommend the usage of the above form of $\mathcal{NP}$ instead of preparing $\mathcal{P}$ and $\mathcal{N}$ separately because of faster evaluation.

As Williams stressed, this unified treatment is a merit of the original Williams' formulation, which is inherited to the modified one. Note that the usual nutations are used in this formulation. This is another merit. Further the number of rotational operations needed to express the precession-nutation matrix reduces from six of the IAU formulation to four of the new one. This is yet another merit of the new formulation.

The formulation is robust in the sense it avoids a singularity caused by finite pole offsets near the epoch. Facing the singularity is inevitable in the current IAU formulation. This is clear from the differential relation $\delta\zeta_\mathrm{A} \approx -\delta\epsilon_\mathrm{A}/\sin\theta_\mathrm{A}$, which shows the possibility of divergence in the correction to $\zeta_\mathrm{A}$ due to a small divisor, $\sin\theta_\mathrm{A}$, in the vicinity of the epoch.

By using SF2001, we converted the true pole offsets referred to the ICRF, observed by VLBI for 1979-2000, and compiled by USNO, to the offests in the above three angles of precession, $\bar{\psi}$, $\varphi$, and $\gamma$, while we fixed $\bar{\epsilon}$ as the combination of the linear part provided in SF2001 and the quadratic and higher terms derived by Williams (1994) as

$$\bar{\epsilon}(t) = 84381.4428 - 46.8388\,t - 0.0002t^2 + 0.0020t^3, \tag{16}$$

where we set the cut-off level so that the resulting precision be 0.1 mas for 1900-2100. From the converted offsets, we determined the best-fit polynomial expressions of the differences of the three precession angles in the ICRF from

the polynomial expressions of Williams' counterparts, $\eta_{\rm A}, \epsilon'_{\rm A}, \xi_{\rm A}$, by a weighted least square method as

$$\bar{\psi} - \eta_{\rm A} = -(0.0431 \pm 0.0006) + (0.0174 \pm 0.0100)\ t, \tag{17}$$

$$\varphi - \epsilon'_{\rm A} = +(0.0389 \pm 0.0003) - (0.0044 \pm 0.0040)\ t, \tag{18}$$

$$\gamma - \xi_{\rm A} = -(0.0000 \pm 0.0000_1) - (0.0052 \pm 0.0000_2)\ t. \tag{19}$$

Then, by adding the Williams' original polynomial expressions, we obtained the final forms as

$$\bar{\psi}(t) = -0.0431 + 5038.4739\ t + 1.5584\ t^2 - 0.0002\ t^3, \tag{20}$$

$$\varphi(t) = 84381.4479 - 46.8140\ t + 0.0511\ t^2 + 0.0005\ t^3, \tag{21}$$

$$\gamma(t) = 10.5525\ t + 0.4932\ t^2 - 0.0003\ t^3, \tag{22}$$

where we again set the cut-off level so as to keep the precision as 0.1 mas for 1900-2100. Note that the constant term of $\gamma$ is practically equal to zero. This means that the ecliptic pole of the epoch precisely lies on the $yz$-plane of the ICRF.

In conclusion, the above set of four formulas constitute a new set of fundamental expressions of the precessional quantities. The combination of the new precession formula and the periodic part of SF2001 serves a good approximation of the precession-nutation matrix in the ICRF.

Note that the procedure to determine the polynomial forms of the new precession angles described here is applicable to any combination of the observation and the nutation theory as long as the latter gives the corrections to the IAU precession formula in polynomial form of the corrections in nutation. Thus the results presented here will be easily updated.

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# Celestial Ephemeris Origin (CEO), Terrestrial Ephemeris Origin (TEO)

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The posters recalled some basic definitions and properties.

## 1 Definition of CEO and TEO

The CEO is defined so that the Intermediate Celestial Reference System attached to the Celestial Intermediate Pole (CIP) and to the CEO has no component of rotation along the axis of the CIP, at any instant, in the Geocentric Celestial Reference System.

The TEO has a similar definition in the ITRS.

## 2 Definition and properties of the Earth Rotation Angle

The Earth Rotation Angle, $\theta$, is defined as the hour angle of the CEO reckoned from the TEO.

By definition of the CEO and the TEO, the time derivative of $\theta$ is the component along the axis of the CIP of the Earth rotation vector (practically, the modulus of that vector).

Universal Time UT1 is defined by a linear relation with $\theta$ (definition implicitly used in the past).

## 3 Position of the CEO and of the TEO

The equatorial origin of the ICRF being $\Sigma_0$, the node of the equator of the CIP at $t$ (in Terrestrial Time) being $N(t)$, the CEO ($\equiv \sigma(t)$) is provided by the quantity $s(t)$ defined by

$$s(t) = \sigma(t)N(t) - \Sigma_0 N(t). \quad (1)$$

Quantity $s(t)$ is computed by an integration along the CIP path, from J2000.0 to $t$. This small quantity (varying from 0 to 70 mas between 2000 and 2100) should be, in theory, derived from the observed path. However it has been shown that the values derived from the current model of precession/nutation are sufficient, at the microarcsesond level, until 2100. In other terms, the dependence of $s$ on the observations of the CIP can be neglected when procession the observations.

The TEO is similarly provided by a quantity $s'$. In the long term, over several decades, $s'$ has to be computed by numerical integration over the unpredictable motion of the CIP in the ITRF. However, it can extrapolated, at the microarcsecond level, over about a decade.

As the CEO and the TEO are obtained from an integration, their positions depend on arbitrary constants. These have been conventionally selected so that $s = 0$, $s' = 0$ at J2000.0

The positions of the CEO and the TEO are independent of the system of coordinates used in the celestial and terrestrial reference systems, after initial adjustment of the integration constants.

## 4 Secular motion of the CEO

The CEO (as the TEO) has a secular motion. For example, if the pole describes a closed loop between $t_1$ and $t_2$, the equators at these dates coincide, but $\sigma(t_1)$ and $\sigma(t_2)$ are different. This property is often a cause of concern. However, as shown by the posters in a simple example, this secular motion of the CEO is necessary to cancel a component of rotation induced by the motion in loop of the pole.

In the case of the precession, the compensating mean drift of the CEO is about 4.2'' per year, a large value, but it does not appear in *s* for the following reasons.

It can be demonstrated that, at any instant, the velocity of the CEO in the ICRF has the important property that it is perpendicular to the equator of the CIP. As at J2000.0 the equator of the CIP is very close to that of the ICRF, the secular terms in *s* are quite small ; then their value progressively increases.

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# A Simple Method for Conversion Between the Celestial Ephemeris Origin, the ICRF, and the Equinox of Date

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Eq. 21 of Capitaine et al. (2000) simplifies the equation for the CEO parameter *s* based on the assumption that the position of the CEO pole is the same as the Celestial Intermediate Pole at J2000.0. For this particular case, comparison of Fig. 2 of Lieske et al. (1977) and Fig. 1 of Capitaine et al. (2000) shows that:

$$d = \theta_A + \Delta\psi \quad \text{and} \quad E = \zeta_A + \Delta\varepsilon$$

where $\Delta\psi$ and $\Delta\varepsilon$ are the nutations in longitude and latitude, respectively. Thus, the precession parameters $\theta_A$ and $\zeta_A$ are orthogonal and in the same directions as $\Delta\psi$ and $\Delta\varepsilon$, respectively.

The third precession parameter, $z_A$, contains all of the information on the motion of the equinox both with respect to the ecliptic of date and none of the information on the motion of the pole itself.

Inspection of Fig. 2 of Lieske et al. (1967) also shows that the position of the node of the equator of date on the ecliptic of epoch is simply $z_A + \chi_A$. $z_A$ is also easy to derive since, as shown in Lieske (1967) the parameters $\zeta_A$ and $z_A$ are derived from $(z_A + \zeta_A)$ and $(z_A - \zeta_A)$.

The IAU 2000 precession-nutation theory provides the precession and nutation with respect to the Lieske et al. (1977) precession using the ecliptic angles $\Delta\psi$ and $\Delta\varepsilon$. The conversion to *X*, *Y*, and *Z* is given as equation (4.16) of Capitaine et al. (1986):

$$X = \sin(\omega_A + \Delta\varepsilon)\sin(\psi_A + \Delta\psi)$$
$$Y = -\sin\varepsilon_0\cos(\omega_A + \Delta\varepsilon) + \cos\varepsilon_0\sin(\omega_A + \Delta\varepsilon)\cos(\psi_A + \Delta\psi)$$
$$Z = \cos\varepsilon_0\cos(\omega_A + \Delta\varepsilon) + \sin\varepsilon_0\sin(\omega_A + \Delta\varepsilon)\cos(\psi_A + \Delta\psi)$$

where $\varepsilon_0$ is the obliquity at epoch, $\omega_A$ is the angle between the ecliptic pole of epoch and the rotational pole of date, and $\psi_A$ is the luni-solar precession angle (see Fig. 1). The coefficients for $\psi_A$ and $\omega_A$ through third order are (Lieske, 1967; Andoyer, 1911):

$$\psi_1 = P + \chi_1\cos\varepsilon_0$$

$$\psi_2 = \frac{c_1\psi_1}{\tan 2\varepsilon_0} + \frac{1}{2}\left(P_1\cos\varepsilon_0 - c_1 p_g\tan\varepsilon_0\right)$$

$$\psi_3 = \frac{1}{3}\left\{\left[c_1 P_1 + \frac{1}{2}\left(c_2 - \frac{1}{2}s_1 P\right)\frac{\left(P + p_g\right)}{\cos\varepsilon_0} + \chi_1\right]\frac{\cos 2\varepsilon_0}{\sin\varepsilon_0} - \psi_1\left(\frac{\omega_2}{\tan\varepsilon_0} + 2c_1^2 + \frac{1}{2}\chi_1^2\right) - \frac{1}{2}p_g\left[3c_1^2 + \frac{\left(2c_2 - s_1 P\right)}{\tan\varepsilon_0}\right]\right\}$$

$$\omega_1 = 0\,^*$$

$$\omega_2 = \frac{1}{2} s_1 \psi_1$$

$$\omega_3 = \frac{\sin \varepsilon_0}{3} \left( 2\psi_2 \chi_1 + \psi_1 \chi_2 \right)$$

where $P$ is the rate of general precession in longitude at J2000.0, $P_1$ is the rate of change of Newcomb's precession constant [due mainly to changes in the Earth's eccentricity (de Sitter & Brouwer, 1938)], $p_g$ is the geodetic precession (Lieske et al., 1977), $\varepsilon_0$ is the obliquity of the ecliptic at J2000.0, $c_1$ and $c_2$ are the first and second order coefficients for sin $i$ cos $\Omega$ (where $i$ is the inclination of the mean ecliptic of date on the mean ecliptic of epoch and $\Omega$ is the node of the mean ecliptic of date on the mean ecliptic of epoch), $s_1$ and $s_2$ are the first and second order coefficients of sin $i$ sin $\Omega$, and $\chi_1$ and $\chi_2$ are the first and second order coefficients for the planetary precession, $\chi_A$ given by (Lieske et al., 1977; Andoyer, 1911):

$$\chi_1 = \frac{s_1}{\sin \varepsilon_0}$$

$$\chi_2 = s_2 + \frac{c_1 P}{\sin \varepsilon_0}$$

Thus conversion of the IAU 2000 precession nutation from its $\Delta\psi$–$\Delta\varepsilon$ form to $X$–$Y$–$Z$ form requires knowledge of the motion of the mean ecliptic of date. Thus when $P_0$ is the pole of the inertial reference system, the angles $d$ and $E$ used in the CEO paradigm are simply:

$$d = \theta_A + \Delta\psi \qquad \text{and} \qquad E = \varsigma_A + \Delta\varepsilon$$

where $\theta_A$ and $\zeta_A$ are two of the Lieske et al. (1977) precession angles. The third precession angle, $z_A$, contains all of the information on the motion of the equinox on the mean ecliptic of date. The parameter $z_A$ is a natural byproduct of the easiest way to determine either $\zeta_A$ or $E$.

The equations to determine the position of the pole and the CEO requires knowledge of the motion of the mean ecliptic of date. The planetary precession is a byproduct of the information needed.

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* $\omega_1$ is not strictly 0 because, as shown by Williams (1994), the Moon has a slight proper inclination with respect to the ecliptic. This inclination causes a small linear rate of change in the Earth's obliquity with respect to inertial space.

# Positioning the Terrestrial Ephemeris Origin in the ITRF

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## 1 Introduction

Resolution B1.8 adopted by the XXIV General Assembly of the International Astronomical Union (Manchester, August 2000) recommends the use of the Non-Rotating Origins (NRO) on the moving equator for reckoning the angle of rotation of the Earth. The NRO in the Terrestrial Reference System (TRS) is defined by the kinematical condition of non-rotation of this point around the rotation axis when the Celestial Intermediate Pole (CIP) moves on the CRS (Guinot 1979).

Astrometric and geodetic data analysis involves the computation of the transformation between the CRS and the TRS. In the framework of the IAU 2000 recommendations, they need an expression for the displacement of the Terrestrial Ephemeris Origin both for the classical transformation and for transformation based on the Non-Rotating Origin representation.

The displacement of the TEO in the ITRS, $s'$, is related, for a date $t$, to the CIP coordinates $u$ and $v$ in the TRS by the formula (Capitaine *et al.* 2000) :

$$s' = \varpi M - \Pi_0 M = -\int_{t_0}^{t} \frac{u\dot{v} - \dot{u}v}{2} \mathrm{d}t \tag{23}$$

where $u$ corresponds to the coordinate $x_p$ of the CIP in the ITRS, $v$ refers to $-y_p$, and the dot is for the time derivative (see Figure 1).

This poster presents the computation of the quantity $s'$. Fore more details on this study, see the paper Lambert and Bizouard 2002.

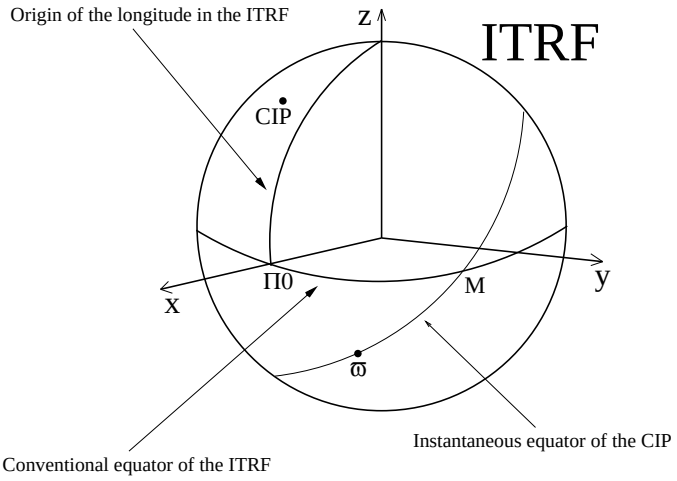


Figure 5: The Non-Rotating Origin with respect to the ITRF.

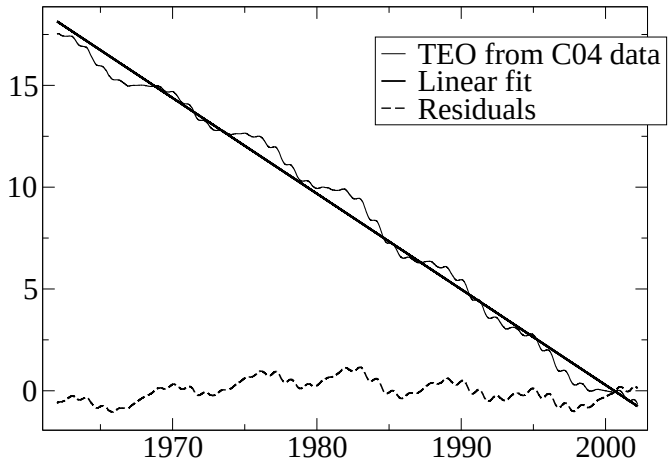


Figure 6: Displacement $s'$ of the TEO from the IERS C04 series and model given by expression (2) (time in years, amplitudes in $\mu$as).

## 2 Computation of the position of the TEO from geodetic data

The computation of $s'$ is based upon combined time series C04 for polar motion which is provided by the Earth Orientation Parameters Product Center of the International Earth Rotation Service (IERS EOP-PC) based at the Paris Observatory. Such a series is obtained by the combination of individual polar motion series from various spatial and geodetic techniques such as Very Long Baseline radio Interferometry (VLBI), Global Positioning System (GPS, GLONASS), Satellite Laser Ranging (SLR) or Lunar Laser Ranging (LLR). This series give daily averaged values for the CIP coordinates $x_p$, $y_p$. For a sampling of one day (at 0h $UTC$) the data covers the period from 1962 January 1st until 2002. Quantity $s'$ given by equation (1) is obtained with a numerical derivative using three points and a time integral based on the trapeze method. The curve is plotted on Figure 2. It shows periodic variations of period 6.4 years coming from a combination of Chandler oscillation (1.2 year) and annual oscillation. Changes in amplitudes of these wobbles (Guinot 1972 and Vondrak 1985) make the trend varying along the 40 years of the computation.

GPS technique allows to estimate directly the rates $\dot{x}_p$ and $\dot{y}_p$. Differences between $s'$ computed with the numerical derivative using C04 series and $s'$ computed with the estimated rates using various GPS data never reach more than 0.1 $\mu$as and are not significant at the present level of EOP accuracy. This validates the two independant methods of computation.

The contribution of the tidal diurnal polar motion on $s'$ (Ray 1994) is only about 0.06 $\mu$as per century and is therefore negligible.

## 3 Expression for positioning the TEO in the ITRF

As conclusion, we propose a numerical expression for the quantity $s'$. Although such a model is limited in time because of unprevisible changes in the wobbles amplitudes, it is possible to provide a numerical expression for $s'$ which represents the motion of the TEO in the ITRS with an accuracy of 1 $\mu$as over the last 40 years. On this span, variations in the amplitudes of the wobbles will

not produce an error larger than 1 $\mu$as. The following expression is fitted on the curve obtained from C04 data :

$$s' = -47.0 \times t \tag{24}$$

where $s'$ is in $\mu$as. Parameter $t$ is defined as the Terrestrial Time (TT) expressed in Julian centuries from epoch J2000.0 :

$$t = (\mathrm{TT} - 2000\ \mathrm{January\ 1d\ 12h\ TT})/36525 \tag{25}$$

with TT in days.

If Chandler amplitude in the next years does not present variations larger than during the span 1962-2002, the uncertainty on the linear trend is 13 $\mu$as per Julian century. We can ensure that the 1 $\mu$as accuracy linear model can be extended on the 10 next years. Figure 2 shows the linear model of $s'$ corresponding to expression (2) together with the numerical computation from observations. If unexpected variations in the amplitudes of the wobbles occur in the coming years, such a model will have to be updated. We propose this model be maintained by the IERS EOP-PC.

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# A Comparison of the VLBI Nutation Series With Model

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**Abstract:** The paper presents preliminary results of determination of corrections to precession and obliquity rate from analysis of differences between four VLBI nutation series and MHB2000 model.

## 1 Introduction

This paper continues an investigation of the VLBI results of determination of nutation of the Earth's rotation axis in comparison with the latest nutation models (Malkin 2001). Some results of mutual comparison of the VLBI nutation series and possible sources of systematic differences are considered in Malkin 2001, Malkin 2002. The latter includes inconsistency in CRF realizations and different models of daily and subdaily EOP variations used by various Analysis Centers. Influence of non-stability of ICRF on observed precession parameters is discussed in Feissel 2002.

We used for comparison four long-time VLBI EOP series available in the IVS data base (BKG00001, GSF2001C, USN2001D, IAAO0106) at common interval 1984.0–2001.9 and the latest available version of MHB2000 nutation series of the end of 2001 (`http://www-gpsg.mit.edu/~tah/`) which provides FCN amplitudes for period ended at epoch Jun 1, 2001. After that date only predicted FCN amplitude is available and one should keep this in mind during comparison the model with observations.

## 2 Corrections to precession parameters

Precession parameters (precession in longitude and obliquity rate) were estimated as linear trend along with largest long-period terms $6798.38^d$, $3399.19^d$, $365.26^d$, $182.62^d$, $121.75^d$ from differences between VLBI nutation series and MHB2000. Since VLBI results show significant improvement beginning from epoch ≈1990.0, we have computed the precession parameters both for whole interval 1984.0–2001.9 and for 1990.0–2001.4 (in the latter case the term with period $6798.38^d$ was not included in adjustment procedure).

The results of computation are presented in Table 1. For more detailed comparison we compute those both for individual series and for al their combinations. Table 1 contains results for individual series, averaged CALC/SOLVE series and averaged over all four compared series. One can see that there is no evident systematic differences between OCCAM and CALC/SOLVE results for $\Delta\psi$, however such a difference obviously exists for $\Delta\epsilon$.

Obtained corrections to $\Delta\psi$ and $\Delta\epsilon$ rates averaged over all the series are in reasonable good agreement with those found in Feissel 2001, Feissel 2002.

## 3 Acknowledgement

Author is very grateful to the organizers of the IERS Workshop for financial support of his trip to the meeting. This research is partially supported by the Russian Science Support Foundation and St.Petersburg Scientific Center of the Russian Academy of Sciences.

Table 3: Corrections to precession parameters, bias in $\mu$as and rate in $\mu$as/y.

| Series | 1984.0–2001.9 | | | | 1990.0–2001.4 | | | |
|---|---|---|---|---|---|---|---|---|
| | $\Delta\psi$ | | $\Delta\epsilon$ | | $\Delta\psi$ | | $\Delta\epsilon$ | |
| | bias | rate | bias | rate | bias | rate | bias | rate |
| BKG | $-14\pm9$ | $+42\pm4$ | $-25\pm4$ | $+11\pm2$ | $-42\pm5$ | $+24\pm2$ | $-10\pm2$ | $-6\pm1$ |
| GSF | $+18\pm9$ | $+20\pm4$ | $-27\pm3$ | $+6\pm2$ | $-36\pm5$ | $+13\pm2$ | $-20\pm2$ | $-9\pm1$ |
| IAA | $+12\pm9$ | $+34\pm4$ | $+37\pm3$ | $-5\pm2$ | $-72\pm5$ | $+25\pm2$ | $+29\pm2$ | $-2\pm1$ |
| USN | $-23\pm9$ | $+27\pm4$ | $-34\pm4$ | $+8\pm2$ | $-71\pm6$ | $+14\pm2$ | $-14\pm2$ | $-8\pm1$ |
| BKG GSF USN | $-7\pm8$ | $+31\pm4$ | $-28\pm3$ | $+8\pm2$ | $-50\pm5$ | $+17\pm2$ | $-14\pm2$ | $-8\pm1$ |
| BKG GSF IAA USN | $-2\pm8$ | $+32\pm4$ | $-11\pm3$ | $+4\pm1$ | $-57\pm5$ | $+19\pm2$ | $-5\pm2$ | $-6\pm1$ |

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# The JCET/GSFC Satellite Laser Ranging TRF and EOP Series

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We present here the re-analysis of Satellite Laser Ranging (SLR) data to LAGEOS and LAGEOS 2 for the definition of the Terrestrial Reference Frame (TRF) and its crust-fixed orientation (Earth Orientation Parameters –EOP). The TRF plays an important role in the multi-technique monitoring of temporal variations in the gravitational field and its very low degree and order components. This area is becoming extremely important with the launch of recent and future geopotential mapping missions for the referencing and calibration of the data and products from these missions. Satellite laser ranging (SLR) has for a long time monitored the continuous redistribution of mass within the Earth system through concomitant changes in the Stokes' coefficients of the terrestrial gravity field. Secular changes in $J_2$ due to post-glacial relaxation have been observed since many years and similar changes in $J_3$, $J_4$ $J_5$, etc. are attributed to changes in the ice sheets of Greenland and Antarctica. Seasonal changes in these coefficients have also been closely correlated with mass transfer in the atmosphere and oceans. The hydrological cycle contributions however are the most difficult to measure accurately so far. This latest analysis of the 1993-present SLR data set from LAGEOS and LAGEOS 2 data for the International Earth Rotation Service (IERS) TRF (ITRF) development includes the weekly monitoring of such compound changes in the low degree and order harmonics. Along with the static parameters of the TRF we have determined a time series of variations of its origin with respect to the centre of mass of the Earth system (geocentre). These estimates provide a measure of the total motion due to all sources of mass transport within the Earth system and can be used to either complement the estimates from the future missions or to validate them through comparisons with their estimates for the same quantities. The data were reduced using NASA Goddard's GEODYN/SOLVE II software, resulting in a final RMS error of ~8 mm – close to the data noise level. We will discuss our solution for the GM, the geocentre (degree one terms), and the $C_{2,1}$, $S_{2,1}$, $C_{2,2}$, $S_{2,2}$ time series, compare them to variations inferred from geophysical processes, and examine their spectrum.

A miniature version of the presented poster is attached. For a more detailed discussion of the solution and results can be found in the recently published proceedings of the 2001 IAG Scientific Assembly: *Vistas for Geodesy in the New Millennium*, in [Pavlis, 2002].

## Reference:

Pavlis, E. C. Dynamical Determination of Origin and Scale in the Earth System from Satellite Laser Ranging, in *Vistas for Geodesy in the New Millennium*, proceedings of the 2001 International Association of Geodesy Scientific Assembly, Budapest, Hungary, September 2-7, 2001, J. Adam and K.-P. Schwarz (eds.), Springer-Verlag, New York, 2002.

**Poster Presentation**

# The JCET/GSFC Satellite Laser Ranging TRF and EOP Series


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**Abstract**

We present the new re-analysis of Satellite Laser Ranging (SLR) data to LAGEOS and LAGEOS 2 for the definition of the Terrestrial Reference Frame (TRF) and its crust-fixed orientation (Earth Orientation Parameters –EOP). The TRF plays an important role in the multi-technique monitoring of temporal variations in the gravitational field and its very low degree and order components. This area is becoming extremely important with the launch of recent and future geopotential mapping missions for the referencing and calibration of the data and products from these missions. Satellite laser ranging (SLR) has for a long time monitored the continuous redistribution of mass within the Earth system through concomitant changes in the Stokes' coefficients of the terrestrial gravity field. Secular changes in $J_2$ due to post-glacial relaxation have been observed since many years and similar changes in $J_3$, $J_4$, $J_5$, etc. are attributed to changes in the ice sheets of Greenland and Antarctica. Seasonal changes in these coefficients have also been closely correlated with mass transfer in the atmosphere and oceans. The hydrological cycle contributions however are the most difficult to measure accurately so far. This latest analysis of the 1993-present SLR data set from LAGEOS and LAGEOS 2 data for the International Earth Rotation Service (IERS) TRF (ITRF) development includes the weekly monitoring of such compound changes in the low degree and order harmonics. Along with the static parameters of the TRF we have determined a time series of variations of its origin with respect to the center of mass of the Earth system (geocenter). These estimates provide a measure of the total motion due to all sources of mass transport within the Earth system and can be used to either complement the estimates from the future missions or to validate them through comparisons with their estimates for the same quantities. The data were reduced using NASA Goddard's GEODYN/SOLVE II software, resulting in a final RMS error of ~8 mm – close to the data noise level. We will discuss our solution for the GM, the geocenter (degree one terms), and the $C_{2,1}$, $S_{2,1}$, $C_{2,2}$, $S_{2,2}$ time series, compare them to variations inferred from geophysical processes, and examine their spectrum.


## MODELING STANDARDS:

- § IERS Conventions 1996 as close as possible
- § Identify and quantify the effect of exceptions
- § Use state-of-the-art force and s/c models
- § A priori Reference Frame: **ITRF2000**
- § Use the latest data releases from CDDIS

## FORCE & MEASUREMENT *A PRIORI* MODELS:

Gravity from *EGM-96* and *GOT99.2* ocean tides
Extended ocean tides' model from hydrodynamics
Secular rates for $C_{2,0}$, $C_{2,1}$, $S_{2,1}$ and rotational deformation
Solar Pressure and Thermal Drag with LAGEOS' spin axes modeled by Vokrouhlicky's models
Earth Albedo (Knocke-Rubincam)
J2000 and 1996 Nutation Reference frame (DE403)
EOP from **IERS C04**
Ocean loading from **Scherneck** and **GOT99.2** tides
"Center-of-mass" and EOP tide-induced variations (**IERS**)
Adopt ILRS-info on calibrated measurement biases

## DATA ANALYSIS:

Data analyzed in 7 $^{day}$ arcs (473 total), ***930103 - 020127***
State-vector estimated for each arc
Constant and 1 *cpr* along-track accelerations (per $2^d$)
Cross-track 1 *cpr* accelerations (per $2^d$)
Data biases estimated in combination (L-1 & 2)
Polar motion, UT1-UTC, Pole Rates and LOD estimated daily
Site positions and velocities estimated from 9 year span

## TRF CONSTRAINTS APPLIED:

**TRF 2001 Solution:**

**POSITIONS & VELOCITIES:**

**Minimum Constraints:**

Latitude, Longitude & rates on **GGAO** (Greenbelt, MD) and,
Latitude & its rate for **Haleakala** (Hawaii)

**EOP and EOP Rates:**

Loose constraints on $X_P$,$Y_P$, $X_P$-rate, $Y_P$-rate, and LOD
UT1-UTC: One value per arc constrained to IERS C04

## SUMMARY

§ The combined analysis of **SLR** data from **LAGEOS 1 & 2** produces accurate, high resolution determination of Earth kinematics (**EOP**) with **daily resolution**, and provides an independent source of EOP information (**x, y, LOD, xdot, ydot**) to IERS.

§ Comparisons to other **SLR** solutions and independent techniques indicate that the TRF **scale** uncertainty is at **< 1 ppb** and the weighted RMS difference in **position** and **velocity** is about **3 mm** and **1 mm/y** respectively. Weekly "geocenter" variations have a precision of **~1 mm** for X and Y , and **~2 mm** for Z. The estimated value of GM consistent with these results, is: **398600.4418 ± 0.0001 [$10^9$ $m^3/s^2$]**

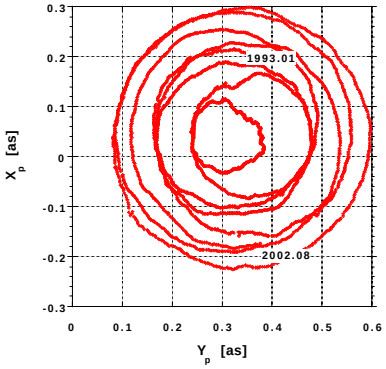
§ EOP series of daily averages have internal precision of **~120 µas** in Pole **x** and **y**, and the newly derived products of **x and y rates**, have an internal precision of **~200 µas/d**. The corresponding number for **LOD** is **90 µs**.

§ External comparisons to **IERS C 04** and **SPACE2001*** series, indicate that the accuracy of these estimates is **~0.5 mas** for **x** and **y**, **~170 µs** for **LOD**, and **~1 mas/d** for **xdot** and **ydot**.

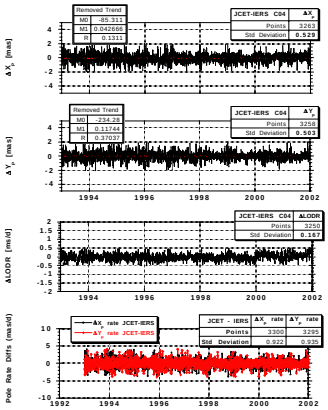
*Thanks to Richard Gross for this test. Special SPACE2001 series without SLR contributions.

### Daily Polar Motion from SLR

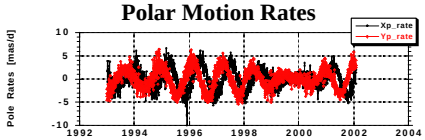
EOP (JCET) 02 L12



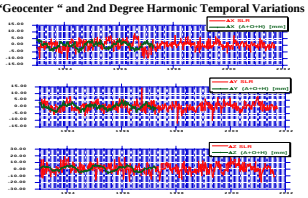

### Differences from IERS C 04



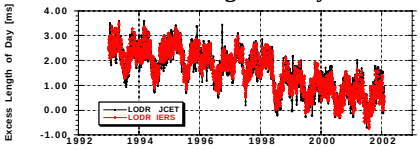

### Polar Motion Rates

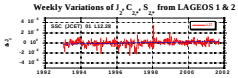


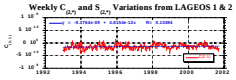

### "Geocenter " and 2nd Degree Harmonic Temporal Variations

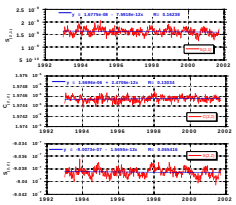


### Excess Length of Day



### Seven Parameter Helmert Transformation Results for (JCET) L 02 vs. ITRF2000

| Parameters | $T_X$ mm | $T_Y$ mm | $T_Z$ mm | $D_S$ ppb | $R_X$ mas | $R_Y$ mas | $R_Z$ mas |
|---|---|---|---|---|---|---|---|
| **(JCET) L 02** | -2.80 | -3.91 | -3.27 | 0.03 | -0.06 | -0.11 | +0.15 |
| *σ* | *4.68* | *4.57* | *4.21* | *0.66* | *0.18* | *0.19* | *0.15* |

**Tuesday, April 23, 2002,**
**Session G6 08:00 - 18:00**
**EGS02-A-01955 G019**

**EGS XXVII General Assembly**
**21 - 26 April 2002**
**Nice, France**

# The Tables of Differences Between the Nutation Series IAU2000, IERS1996 and IAU1980

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## 1 Introduction

The work has been initiated by the EOP Product Center of IERS in Paris since they need a table of differences between the IAU2000 and IAU1980 nutation models (term by term) to incorporate it into the program IERS EOPC04 combinations.

Moreover, the usefulness of such tables has been proved in practice during the transition to the new astronomical constants in 1984, before the MERIT Campaign, and also in the recalculation of the observations of optical astrometry into the Hipparcos Reference Frame (Vondrák et al., 1998). We used effectively for these purposes the tables of differences between IAU1980 and Woolard's nutations (Seidelman, 1982).

The similar table of the differences between IERS1996 and IAU1980 nutations has been made by Gambis (1996). This table has been truncated to assure the precision of 1mas and it contains 25 terms only.

## 2 The series and method used

The differences between two nutation models can be obtained in two ways. Either, in time domain, one calculates the nutation angle for a given date for both models by such routines as `MHB2000A.f` of Herring (2001) and `iau_NUT80.f` of SOFA (2000) and than subtracts the nutation angles, or, in frequency domain, one can prepare table of the term by term differences and then compute the difference of the nutation angles directly. Here we will show the latter approach. The series of the differences that have been computed are following IAU2000 – IAU1980, IAU2000 – IERS1996, IERS1996 – IAU1980. We reached after the same results from both approaches, but due to the truncation we have got to the agreement to $\pm 0.5\mu$as in case IAU2000A – IAU1980 and IAU2000A – IERS1996 and to $\pm 2\mu$as in case IERS1996 – IAU1980, respectively.

## 3 IAU1980 theory of nutation

This set of nutation coefficients was published in the final report of the IAU working group on nutation (Seidelmann, 1982) and came into the regular use in 1984. The series consists of 106 lunisolar terms without any planetary terms and they are of the precision level of $100\mu$as. The set of Delaunay's fundamental arguments is referred to the FK5 reference system.

## 4 IERS1996 model of nutation

In 1996, Tom Herring has analyzed the recent VLBI and LLR data for geophysical parameters required for non-rigid Earth theory. The coefficients were

meant to be used for prediction purposes. They were not meant to replace IAU1980 theory. This series was presented in the McCarthy (1996). It consists of 273 lunisolar terms and 122 planetary terms that reach 5$\mu$as precision. The fundamental arguments (Simon et al., 1994) are the same as that recently adopted for nutation IAU2000A.

## 5 IAU2000A model of nutation

The IAU2000A Precession-Nutation model (Mathews et al. 2002) has been adopted by the IAU (Resolution B1.6) to replace the IAU 1976 Precession and IAU 1980 Theory of Nutation. The original tables of the new nutation theory and the routines for calculation of the nutation angles for a given date from the Tom Herring's web site Herring (2001). The series IAU2000A consists of 678 lunisolar terms and 687 planetary terms that reach the precision level of 0.3$\mu$as .

| | | | | | $\Delta\psi$ cos | | $\Delta\varepsilon$ sin | |
|---|---|---|---|---|---|---|---|---|
| l | l' | F | D | $\Omega$ | $A''$ | $A'''$ | $B''$ | $B'''$ |
| 0 | 0 | 0 | 0 | 1 | -98 | 32 | -53 | 4 |
| 0 | 0 | 0 | 0 | 2 | 2 | 0 | 1 | 0 |
| 0 | 0 | 2 | -2 | 2 | -175 | 34 | -76 | 7 |
| 0 | 1 | 0 | 0 | 0 | 34 | -16 | -1 | 5 |
| 0 | 1 | 2 | -2 | 2 | -19 | 3 | -8 | 1 |
| 0 | -1 | 2 | -2 | 2 | -2 | 0 | -1 | -1 |
| 0 | 0 | 2 | -2 | 1 | 2 | 0 | 1 | 0 |
| 2 | 0 | 0 | -2 | 0 | 1 | 0 | 0 | 0 |
| 0 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 2 | 2 | -2 | 2 | -1 | 0 | 0 | 0 |
| 0 | 0 | 2 | 0 | 2 | -17 | 8 | -7 | 2 |
| 1 | 0 | 0 | 0 | 0 | 5 | 2 | 0 | 0 |
| 0 | 0 | 2 | 0 | 1 | -3 | 2 | -1 | 1 |
| 1 | 0 | 2 | 0 | 2 | -4 | 0 | -2 | 0 |
| 1 | 0 | 0 | -2 | 0 | -2 | -1 | 0 | 0 |
| -1 | 0 | 2 | 0 | 2 | 0 | -1 | 0 | 0 |
| 1 | 0 | 2 | 0 | 1 | -1 | 0 | 0 | 0 |
| 1 | 0 | 2 | -2 | 2 | 1 | 0 | 0 | 0 |
| 2 | 0 | 2 | 0 | 2 | -1 | 0 | 0 | 0 |

The table on the left side shows the out-phase-terms that are evoked by the different values of fundamental arguments that input into the IAU2000A and IAU1980 nutation theories. The maximum value of 17.5$\mu$as is reached in case of the semiannual term in $\Delta\psi$. The amplitudes of the terms $A''$, $B''$ and its time changes $A'''$, $B'''$ are shown in the units 0.1$\mu$as and 0.1$\mu$as/cy, respectively. The tables of differences has been provided for the nutation series IAU2000A, IERS1996 and IAU1980 and they are displayed at the following ftp servers:

- IAU2000A - IAU1980 at the pages of EOP Product Centre IERS
  `http://hpiers.obspm.fr/eop-pc/models/`
- IAU2000A - IERS1996 and IERS1996 - IAU1980
  `ftp://ftp.ig.cas.cz/incoming/nutdiff`

**Acknowledgment.** The work was done during my stay in Paris Observatory in frame of the joint project of CNRS and the Academy of Sciences of the Czech Republic. The support of the grant LN005 of the Ministry of Education, Youth and Sports is also appreciated.

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# The Celestial Reference System I.C.R.S. Principles & Present Realization

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*(ICRS-PC, Paris Observatory)*

## 1 INTRODUCTION

From 1998 January 1st, and according to the decision taken during the 23rd IAU General Assembly (Kyoto, August 1997), the International Celestial Reference System of the IERS (Arias *et al*., 1995) has been recommended for adoption as the International Celestial Reference System (ICRS), thus replacing the FK5. Moreover the IAU has officially stated that the IERS should accomplish the task of insuring the maintenance of the ICRS. In the following, we present the specificities of the ICRS with related basic definitions, its materialization through the **International Celestial Reference Frame** (**ICRF)**, and the astrometric studies which are undertaken to establish the link between the various galactic or extragalactic objects, and the **ICRS**.

- **ICRS definition**

  A reference system can be defined as a « set of prescriptions and conventions together with the modelling required to define, at any time, a triad of axes ». To complete this definition, we should not forget also the fundamental choice of the origin.

  The **ICRS** is defined in the following way : its origin is located at the barycentre of the solar system, and the directions of its three axes are fixed relative to the distant extragalactic sources (Arias *et al.,*1995).

- **ICRF definition**

  A reference frame can be defined as a « *practical realization with given fiducial directions agreeing with the concepts introduced in the corresponding Reference System* » (Feissel and Mignard, 1998) :

The first realisation of the **ICRF** (Ma *et al*., 1997, 1998) consists of a catalogue of equatorial coordinates of 608 extragalactic radio-sources. Therefore these radio-sources define implicitly and at the fundamental date J2000.0, the reference equatorial plane and the origin on the equator, from which the coordinates in right ascension and declination of any celestial object must be measured. Consequently the triad related to the definition of the ICRS is implicitly defined by the set of coordinates of the radio-sources above. The underlying characteristic for the adoption of these sources is that they do not present significant time variations of their relative positions one to each other. This must be interpreted as a condition of non-rotation of the frame related to the selected radio-sources. More precisely, the sources belonging to the ICRF can be separated into three groups, according to their astrometric stability and the number of observations to which they were subject: The ***defining*** sources (212) The ***candidate*** sources (294) The ***other*** sources (102).

## 2 MAINTENANCE AND EXTENSION OF THE ICRF

The IAU charged the IERS with the responsibility of monitoring the ICRS and maintaining its realization, i.e. the ICRF. Starting in 2001, these activities are run jointly by the ICRS Product Center (Paris Observatory and US Naval Observatory), and the International VLBI Service for Geodesy and Astrometry (IVS).

As a part of the maintenance process, an extension of the initial ICRF was elaborated (IERS, 1998), which is named ICRF-Ext.1, and which consisted in adding 59 new sources to the 608 initial ones, whereas the 212 defining sources of the initial ICRF and their respective coordinates remained unchanged with respect to the first realization of the frame.

Recent investigations conducted by the ICRS Product Centre (2001 IERS Annual Report) concern various topics with respect to the ICRF : these are stability analyses based on time series of source coordinates, additional sources since the construction of the ICRF-Ext.1, and comparisons of the ICRF with newly computed radio catalogues (IERS, 2001).

## 3 THE ICRS-PC (Product Centre)

Since 2001 January 1st, the Paris Observatory and the U.S. Naval Observatory have been charged by the IERS Central Bureau to act jointly as the International Celestial Reference System Product Centre (ICRS-PC) of the IERS. Each of the parts is presently responsible of tasks as summarized below :

- Maintenance and extension of the ICRF
- Investigation of future realizations of the ICRS
- Monitoring of structure to assess astrometric quality
- Maintenance of the time stability of the ICRF
- Maintenance of the link to the Hipparcos catalogue
- Linking the ICRF to frames at various wavelengths
- Maintenance of the link to the dynamical reference frame
- Maintenance of the link to the ITRF

Among these tasks, some of them are fulfilled on a regularly basis (cf. IERS Annual Report, 2001), whereas other ones aim at developing new specific researches with respect to the tasks above: preparation of future space astrometric missions (ex. DIVA, FAME) comparisons inter-catalogues (Hipparcos vs. 2MASS etc…), or optimization of proper motions and positions measurements on specific fields (Pleiades cluster etc…). The maintenance of the link between the Hipparcos Catalogue and the ICRF remains one of the principal tasks of the ICRS-PC.

## References

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# Annex 1

# IAU Resolutions Adopted at the 24th IAU General Assembly (B1.1-B1.9, B2)

### Resolution B1.1 Maintenance and Establishment of Reference Frames and Systems

The XXIVth International Astronomical Union General Assembly,

## 1.1.1.1 Noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies that ”the fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames,”
2. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies ”That the Hipparcos Catalogue shall be the primary realisation of the International Celestial Reference System (ICRS) at optical wavelengths”, and
3. the need for accurate definition of reference systems brought about by unprecedented precision, and

## 1.1.1.2 Recognising

1. the importance of continuing operational observations made with Very Long Baseline Interferometry (VLBI) to maintain the ICRF,
2. the importance of VLBI observations to the operational determination of the parameters needed to specify the time-variable transformation between the International Celestial and Terrestrial Reference Frames,
3. the progressive shift between the Hipparcos frame and the ICRF, and
4. the need to maintain the optical realisation as close as possible to the ICRF,

## 1.1.1.3 Recommends

1. that IAU Division I maintain the Working Group on Celestial Reference Systems formed from Division I members to consult with the International Earth Rotation Service (IERS) regarding the maintenance of the ICRS,
2. that the IAU recognise the International VLBI service (IVS) for Geodesy and Astrometry as an IAU Service Organization,
3. that an official representative of the IVS be invited to participate in the IAU Working Group on Celestial Reference Systems,
4. that the IAU continue to provide an official representative to the IVS Directing Board,
5. that the astrometric and geodetic VLBI observing programs consider the requirements for maintenance of the ICRF and linking to the Hipparcos optical frame in the selection of sources to be observed (with emphasis on the Southern Hemisphere), design of observing networks, and the distribution of data, and
6. that the scientific community continue with high priority ground- and space-based observations (a) for the maintenance of the optical Hipparcos frame and frames at other wavelengths and (b) for links of the frames to the ICRF.

### Resolution B1.2 Hipparcos Celestial Reference Frame

The XXIVth International Astronomical Union General Assembly,

### 1.1.1.4 Noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies, "That the Hipparcos Catalogue shall be the primary realisation of the International Celestial Reference System (ICRS) at optical wavelengths",
2. the need for this realisation to be of the highest precision,
3. that the proper motions of many of the Hipparcos stars known, or suspected, to be multiple are adversely affected by uncorrected orbital motion,
4. the extensive use of the Hipparcos Catalogue as reference for the ICRS in extension to fainter stars,
5. the need to avoid confusion between the International Celestial Reference Frame (ICRF) and the Hipparcos frame, and
6. the progressive shift between the Hipparcos frame and the ICRF,

### 1.1.1.5 Recommends

1. that Resolution B2 of the XXIIIrd IAU General Assembly (1997) be amended by excluding from the optical realisation of the ICRS all stars flagged C, G, O, V and X in the Hipparcos Catalogue, and
2. that this modified Hipparcos frame be labelled the Hipparcos Celestial Reference Frame (HCRF).

## Resolution B1.3 Definition of Barycentric Celestial Reference System and Geocentric Celestial Reference System

The XXIVth International Astronomical Union General Assembly,

### 1.1.1.6 Considering

1. that the Resolution A4 of the XXIst General Assembly (1991) has defined a system of space-time coordinates for (a) the solar system (now called the Barycentric Celestial Reference System, (BCRS)) and (b) the Earth (now called the Geocentric Celestial Reference System (GCRS)), within the framework of General Relativity,
2. the desire to write the metric tensors both in the BCRS and in the GCRS in a compact and self-consistent form,
3. the fact that considerable work in General Relativity has been done using the harmonic gauge that was found to be a useful and simplifying gauge for many kinds of applications,

### 1.1.1.7 Recommends

1. the choice of harmonic coordinates both for the barycentric and for the geocentric reference systems,
2. writing the time-time component and the space-space component of the barycentric metric $g_{\mu\nu}$ with barycentric coordinates (t, **x**) (t = Barycentric Coordinate Time (TCB)) with a single scalar potential w(t, **x**) that generalises the Newtonian potential, and the space-time component with a vector potential $w^i$(t, **x**); as a boundary condition it is assumed that these two potentials vanish far from the solar system,

   explicitly,

$$g_{00} = -1 + \frac{2w}{c^2} - \frac{2w^2}{c^4},$$

$$g_{0i} = -\frac{4}{c^3} w^i,$$

$$g_{ij} = \delta_{ij}\left(1 + \frac{2}{c^2} w\right),$$

with

$$w(t, \mathbf{x}) = G \int d^3\mathbf{x}' \frac{\sigma(t, \mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|} + \frac{1}{2c^2} G \frac{\partial^2}{\partial t^2} \int d^3\mathbf{x}' \sigma(t, \mathbf{x}') |\mathbf{x} - \mathbf{x}'|,$$

$$w^i(t, \mathbf{x}) = G \int d^3\mathbf{x}' \frac{\sigma^i(t, \mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|}.$$

here, $\sigma$ and $\sigma^i$ are the gravitational mass and current densities, respectively,

3. writing the geocentric metric tensor $G_{ab}$ with geocentric coordinates (T, **X**) (T= Geocentric Coordinate Time (TCG)) in the same form as the barycentric one but with potentials W(T, **X**) and $W^a$(T, **X**); these geocentric potentials should be split into two parts - potentials $W_E$ and $W_E^a$ arising from the gravitational action of the Earth and external parts $W_{ext}$ and $W_{ext}^a$ due to tidal and inertial effects; the external parts of the metric potentials are assumed to vanish at the geocenter and admit an expansion into positive powers of **X**,

explicitly,

$$G_{00} = -1 + \frac{2W}{c^2} - \frac{2W^2}{c^4},$$

$$G_{0a} = -\frac{4}{c^3} W^a,$$

$$G_{ab} = \delta_{ab}\left(1 + \frac{2}{c^2} W\right),$$

the potentials W and $W^a$ should be split according to

$$W(T, \mathbf{X}) = W_E(T, \mathbf{X}) + W_{ext}(T, \mathbf{X}),$$
$$W^a(T, \mathbf{X}) = W_E^a(T, \mathbf{X}) + W_{ext}^a(T, \mathbf{X}),$$

the Earth's potentials $W_E$ and $W_E^a$ are defined in the same way as w and $w^i$ but with quantities calculated in the GCRS with integrals taken over the whole Earth,

4. using, if accuracy requires, the full post-Newtonian coordinate transformation between the BCRS and the GCRS as induced by the form of the corresponding metric tensors,

   explicitly, for the kinematically non-rotating GCRS
   (T=TCG, t=TCB, $r_E^i \equiv x^i - x_E^i(t)$, and a summation from 1 to 3 over equal indices is implied),

$$T = t - \frac{1}{c^2}\left[A(t) + v_E^i r_E^i\right] + \frac{1}{c^4}\left[B(t) + B^i(t) r_E^i + B^{ij}(t) r_E^i r_E^j + C(t,\mathbf{x})\right] + O(c^{-5}),$$

$$\mathbf{X}^a = \delta_{ai}\left[r_E^i + \frac{1}{c^2}\left(\frac{1}{2} v_E^i v_E^j r_E^j + w_{ext}(\mathbf{x}_E) r_E^i + r_E^i a_E^j r_E^j - \frac{1}{2} a_E^i r_E^2\right)\right] + O(c^{-4}),$$

   where

$$\frac{d}{dt}A(t) = \frac{1}{2} v_E^2 + w_{ext}(\mathbf{x}_E),$$

$$\frac{d}{dt}B(t) = -\frac{1}{8} v_E^4 - \frac{3}{2} v_E^2 w_{ext}(\mathbf{x}_E) + 4 v_E^i w_{ext}^i(\mathbf{x}_E) + \frac{1}{2} w_{ext}^2(\mathbf{x}_E),$$

$$B^i(t) = -\frac{1}{2} v_E^2 v_E^i + 4 w_{ext}^i(\mathbf{x}_E) - 3 v_E^i w_{ext}(\mathbf{x}_E),$$

$$B^{ij}(t) = -v_E^i \delta_{aj} Q^a + 2\frac{\partial}{\partial x^j} w_{ext}^i(\mathbf{x}_E) - v_E^i \frac{\partial}{\partial x^j} w_{ext}(\mathbf{x}_E) + \frac{1}{2}\delta^{ij} \dot{w}_{ext}(\mathbf{x}_E),$$

$$C(t,\mathbf{x}) = -\frac{1}{10} r_E^2 \left(\dot{a}_E^i r_E^i\right)$$

   here $x_E^i$, $v_E^i$, and $a_E^i$ are the components of the barycentric position, velocity and acceleration vectors of the Earth, the dot stands for the total derivative with respect to t, and

$$Q^a = \delta_{ai}\left[\frac{\partial}{\partial x_i} w_{ext}(\mathbf{x}_E) - a_E^i\right].$$

   The external potentials, $w_{ext}$ and $w_{ext}^i$, are given by

$$w_{ext} = \sum_{A \neq E} w_A, \quad w_{ext}^i = \sum_{A \neq E} w_A^i,$$

   where E stands for the Earth and $w_A$and $w_A^i$ are determined by the expressions for w and $w^i$ with integrals taken over body A only.

## *1.1.1.8 Notes*

*It is to be understood that these expressions for w and $w^i$ give $g_{00}$ correct up to $O(c^{-5})$, $g_{0i}$ up to $O(c^{-5})$, and $g_{ij}$ up to $O(c^{-4})$. The densities $\sigma$ and $\sigma^j$ are determined by the components of the energy momentum tensor of the matter composing the solar system bodies as given in the references. Accuracies for $G_{ab}$ in terms of $c^{-n}$ correspond to those of $g_{\mu\nu}$.*

*The external potentials* $W_{ext}$ *and* $W^a_{ext}$ *can be written in the form*

$$W_{ext} = W_{tidal} + W_{iner},$$
$$W^a_{ext} = W^a_{tidal} + W^a_{iner}.$$

$W_{tidal}$ *generalises the Newtonian expression for the tidal potential. Post-Newtonian expressions for* $W_{tidal}$ *and* $W^a_{tidal}$ *can be found in the references. The potentials* $W_{iner}$, $W^a_{iner}$ *are inertial contributions that are linear in* $X^a$. *The former is determined mainly by the coupling of the Earth's nonsphericity to the external potential. In the kinematically non-rotating Geocentric Celestial Reference System,* $W^a_{iner}$ *describes the Coriolis force induced mainly by geodetic precession.*

*Finally, the local gravitational potentials* $W_E$ *and* $W^a_E$ *of the Earth are related to the barycentric gravitational potentials* $w_E$ *and* $w^i_E$ *by*

$$W_E(T,\mathbf{X}) = w_E(t,\mathbf{x})\left(1+\frac{2}{c^2}v_E^2\right) - \frac{4}{c^2}v^i_E w^i_E(t,\mathbf{x}) + O(c^{-4}),$$
$$W^a_E(T,\mathbf{X}) = \delta_{ai}\left(w^i_E(t,\mathbf{x}) - v^i_E w_E(t,\mathbf{x})\right) + O(c^{-2}).$$

## 1.1.1.9 References

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### Resolution B1.4 Post-Newtonian Potential Coefficients

The XXIVth International Astronomical Union General Assembly,

## 1.1.1.10 Considering

1. that for many applications in the fields of celestial mechanics and astrometry a suitable parametrization of the metric potentials (or multipole moments) outside the massive solar system bodies in the form of expansions in terms of potential coefficients are extremely useful, and
2. that physically meaningful post-Newtonian potential coefficients can be derived from the literature,

## 1.1.1.11 Recommends

1. expansion of the post-Newtonian potential of the Earth in the Geocentric Celestial Reference System (GCRS) outside the Earth in the form

$$W_E(T,\mathbf{X}) = \frac{GM_E}{R}\left[1 + \sum_{l=2}^{\infty}\sum_{m=0}^{+l}\left(\frac{R_E}{R}\right)^l P_{lm}(\cos\theta)\left(C^E_{lm}(T)\cos m\varphi + S^E_{lm}(T)\sin m\varphi\right)\right].$$

here $C^E_{lm}$ and $S^E_{lm}$ are, to sufficient accuracy, equivalent to the post-Newtonian multipole moments introduced by Damour *et al.*

(Damour *et al.*, *Phys. Rev. D*, **43**, 3273, 1991). $\theta$ and $\phi$ are the polar angles corresponding to the spatial coordinates $X^a$ of the GCRS and $R = |\mathbf{X}|$, and

2. expression of the vector potential outside the Earth, leading to the well-known Lense-Thirring effect, in terms of the Earth's total angular momentum vector $\mathbf{S}_E$ in the form

$$W_E^a(T, \mathbf{X}) = -\frac{G}{2}\frac{(\mathbf{X} \times \mathbf{S}_E)^a}{R^3}.$$

## Resolution B1.5 Extended relativistic framework for time transformations and realisation of coordinate times in the solar system

The XXIVth International Astronomical Union General Assembly,

### 1.1.1.12 Considering

1. that the Resolution A4 of the XXIst General Assembly (1991) has defined systems of space-time coordinates for the solar system (Barycentric Reference System) and for the Earth (Geocentric Reference System), within the framework of General Relativity,
2. that Resolution B1.3 entitled "Definition of Barycentric Celestial Reference System and Geocentric Celestial Reference System" has renamed these systems the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS), respectively, and has specified a general framework for expressing their metric tensor and defining coordinate transformations at the first post-Newtonian level,
3. that, based on the anticipated performance of atomic clocks, future time and frequency measurements will require practical application of this framework in the BCRS,
4. that theoretical work requiring such expansions has already been performed,

### 1.1.1.13 Recommends

that for applications that concern time transformations and realisation of coordinate times within the solar system, Resolution B1.3 be applied as follows:

1. the metric tensor be expressed as

$$g_{00} = -\left(1 - \frac{2}{c^2}(w_0(t, \mathbf{x}) + w_L(t, \mathbf{x})) + \frac{2}{c^4}(w_0^2(t, \mathbf{x}) + \Delta(t, \mathbf{x}))\right),$$

$$g_{0i} = -\frac{4}{c^3} w^i(t, \mathbf{x}),$$

$$g_{ij} = \left(1 + \frac{2w_0(t, \mathbf{x})}{c^2}\right)\delta_{ij},$$

where (t ≡ Barycentric Coordinate Time (TCB), $\mathbf{x}$) are the barycentric coordinates, $w_0 = G\sum_A M_A / r_A$, with the summation carried out over all solar system bodies A, $\mathbf{r}_A = \mathbf{x} - \mathbf{x}_A$, $\mathbf{x}_A$ are the coordinates of the center of mass of body A, $r_A = |\mathbf{r}_A|$, and where $w_L$ contains the expansion in terms of multipole moments [see their definition in the Resolution B1.4 entitled "Post-Newtonian Potential Coefficients"] required for each body. The vector potential

$w^i(t,\mathbf{x}) = \sum_A w^i_A(t,\mathbf{x})$, and the function $\Delta(t,\mathbf{x}) = \sum_A \Delta_A(t,\mathbf{x})$ are given in note 2.

2. the relation between TCB and Geocentric Coordinate Time (TCG) can be expressed to sufficient accuracy by

$$\mathrm{TCB} - \mathrm{TCG} = c^{-2}\left[\int_{t_0}^{t}\left(\frac{v_E^2}{2} + w_{0ext}(\mathbf{x}_E)\right)dt + v_E^i r_E^i\right] - c^{-4}\left[\int_{t_0}^{t}\left(-\frac{1}{8}v_E^4 - \frac{3}{2}v_E^2 w_{0ext}(\mathbf{x}_E) + 4v_E^i w^i_{ext}(\mathbf{x}_E) + \frac{1}{2}w^2_{0ext}(\mathbf{x}_E)\right)dt - \left(3w_{0ext}(\mathbf{x}_E) + \frac{v_E^2}{2}\right)v_E^i r_E^i\right],$$

where $v_E$ is the barycentric velocity of the Earth and where the index ext refers to summation over all bodies except the Earth.

### *1.1.1.14 Notes*

*1. This formulation will provide an uncertainty not larger than 5 $\times 10^{-18}$ in rate and, for quasi-periodic terms, not larger than 5 $\times 10^{-18}$ in rate amplitude and 0.2 ps in phase amplitude, for locations farther than a few solar radii from the Sun. The same uncertainty also applies to the transformation between TCB and TCG for locations within 50000 km of the Earth. Uncertainties in the values of astronomical quantities may induce larger errors in the formulas.*

*2. Within the above mentioned uncertainties, it is sufficient to express the vector potential $w^i_A(t,\mathbf{x})$ of body A as*

$$w^i_A(t,\mathbf{x}) = G\left[\frac{-(\mathbf{r}_A \times \mathbf{S}_A)^i}{2r_A^3} + \frac{M_A v^i_A}{r_A}\right],$$

*where $\boldsymbol{S}_A$ is the total angular momentum of body A and $v^i_A$ are the components of the barycentric coordinate velocity of body A. As for the function $\Delta_A(t,\mathbf{x})$ it is sufficient to express it as*

$$\Delta_A(t,\mathbf{x}) = \frac{GM_A}{r_A}\left[-2v_a^2 + \sum_{B\neq A}\frac{GM_B}{r_{BA}} + \frac{1}{2}\left(\frac{(r^k_A v^k_A)^2}{r_A^2} + r^k_A a^k_A\right)\right] + \frac{2Gv^k_A(\mathbf{r}_A \times \mathbf{S}_A)^k}{r_A^3},$$

*where $\mathbf{r}_{BA} = |\mathbf{x}_B - \mathbf{x}_A|$ and $a^k_A$ is the barycentric coordinate acceleration of body A.. In these formulas, the terms in $\boldsymbol{S}_A$ are needed only for Jupiter ($S \approx 6.9\times10^{38}\ m^2 s^{-1} kg$) and Saturn ($S \approx 1.4\times10^{38}\ m^2 s^{-1} kg$), in the immediate vicinity of these planets.*

*3. Because the present Recommendation provides an extension of the IAU 1991 recommendations valid at the full first post-Newtonian level, the constants $L_C$ and $L_B$ that were introduced in the IAU 1991 recommendations should be defined as <TCG/TCB> = 1 - $L_C$ and <TT/TCB> = 1 - $L_B$, where TT refers to Terrestrial Time and <> refers to a sufficiently long average taken at the geocenter. The most re-*

*cent estimate of $L_C$ is (Irwin, A. and Fukushima, T., 1999, Astron. Astroph.* ***348****, 642-652)*

$$L_C = 1.48082686741\times10^{-8} \pm 2\times10^{-17},$$

*From the Resolution B1.9 on "Redefinition of Terrestrial Time TT", one infers $L_B$ = $1.55051976772 \times10^{-8} \pm2\times10^{-17}$ by using the relation $1-L_B=(1-L_C)(1-L_G)$. $L_G$ is defined in Resolution B1.9.*

*Because no unambiguous definition may be provided for $L_B$ and $L_C$ , these constants should not be used in formulating time transformations when it would require knowing their value with an uncertainty of order $1\times10^{-16}$ or less.*

*4. If TCB-TCG is computed using planetary ephemerides which are expressed in terms of a time argument (noted $T_{eph}$) which is close to Barycentric Dynamical Time (TDB), rather than in terms of TCB, the first integral in Recommendation 2 above may be computed as*

$$\int_{t_0}^{t}\left(\frac{v_E^2}{2}+w_{0ext}(\mathbf{x}_E)\right)dt=\left[\int_{T_{eph_0}}^{T_{eph}}\left(\frac{v_E^2}{2}+w_{0ext}(\mathbf{x}_E)\right)dt\right]\Big/(1-L_B).$$

## Resolution B1.6 IAU 2000 Precession-Nutation Model

The XXIVth International Astronomical Union General Assembly,

# 1.1.1.15 Recognising

1. that the International Astronomical Union and the International Union of Geodesy and Geophysics Working Group (IAU-IUGG WG) on 'Non-rigid Earth Nutation Theory' has met its goals by
   a. establishing new high precision rigid Earth nutation series, such as (1) SMART97 of Bretagnon *et al.*, 1998, *Astron. Astroph.* **329**, 329-338; (2) REN2000 of Souchay *et al.*, 1999, *Astron. Astroph. Supl. Ser* **135**, 111-131; (3) RDAN97 of Roosbeek and Dehant 1999, *Celest. Mech.* **70**, 215-253;
   b. completing the comparison of new non-rigid Earth transfer functions for an Earth initially in non-hydrostatic equilibrium, incorporating mantle anelasticity and a Free Core Nutation period in agreement with observations,
   c. noting that numerical integration models are not yet ready to incorporate dissipation in the core, and
   d. noting the effects of other geophysical and astronomical phenomena that must be modelled, such as ocean and atmospheric tides, that need further development;
2. that, as instructed by IAU Recommendation C1 in 1994, the International Earth Rotation Service (IERS) will publish in the IERS Conventions (2000) a precession-nutation model that matches the observations with a weighted rms of 0.2 milliarcsecond (mas);
3. that semi-analytical geophysical theories of forced nutation are available which incorporate some or all of the following - anelasticity and electromagnetic couplings at the core-mantle and inner core-outer core boundaries, annual atmospheric tide, geodetic nutation, and ocean tide effects;
4. that ocean tide corrections are necessary at all nutation frequencies; and
5. that empirical models based on a resonance formula without further corrections do also exist;

### 1.1.1.16 Accepts

the conclusions of the IAU-IUGG WG on Non-rigid Earth Nutation Theory published by Dehant *et al.*, 1999, *Celest. Mech*. **72(4)**, 245-310 and the recent comparisons between the various possibilities, and

### 1.1.1.17 Recommends

that, beginning on 1 January 2003, the IAU 1976 Precession Model and IAU 1980 Theory of Nutation, be replaced by the precession-nutation model IAU 2000A (MHB2000, based on the transfer functions of Mathews, Herring and Buffett, 2000 – submitted to the *Journal of Geophysical Research*) for those who need a model at the 0.2 mas level, or its shorter version IAU 2000B for those who need a model only at the 1 mas level, together with their associated precession and obliquity rates, and their associated celestial pole offsets at J2000, to be published in the IERS Conventions 2000, and

### 1.1.1.18 Encourages

1. the continuation of theoretical developments of non-rigid Earth nutation series,
2. the continuation of VLBI observations to increase the accuracy of the nutation series and the nutation model, and to monitor the unpredictable free core nutation, and
3. the development of new expressions for precession consistent with the IAU 2000A model.

## Resolution B1.7 Definition of Celestial Intermediate Pole

The XXIVth International Astronomical Union General Assembly,

### 1.1.1.19 Noting

the need for accurate definition of reference systems brought about by unprecedented observational precision, and

### 1.1.1.20 Recognising

1. the need to specify an axis with respect to which the Earth's angle of rotation is defined,
2. that the Celestial Ephemeris Pole (CEP) does not take account of diurnal and higher frequency variations in the Earth's orientation,

### 1.1.1.21 Recommends

1. that the Celestial Intermediate Pole (CIP) be the pole, the motion of which is specified in the Geocentric Celestial Reference System (GCRS, see Resolution B1.3) by motion of the Tisserand mean axis of the Earth with periods greater than two days,
2. that the direction of the CIP at J2000.0 be offset from the direction of the pole of the GCRS in a manner consistent with the IAU 2000A (see Resolution B1.6) precession-nutation model,
3. that the motion of the CIP in the GCRS be realised by the IAU 2000 A model for precession and forced nutation for periods greater than two days plus additional time-dependent corrections provided by the International Earth Rotation Service (IERS) through appropriate astro-geodetic observations,
4. that the motion of the CIP in the International Terrestrial Reference System (ITRS) be provided by the IERS through appropriate astro-geodetic observations and models including high-frequency variations,

5. that for highest precision, corrections to the models for the motion of the CIP in the ITRS may be estimated using procedures specified by the IERS, and
6. that implementation of the CIP be on 1 January 2003.

### *1.1.1.22 Notes*

*The forced nutations with periods less than two days are included in the model for the motion of the CIP in the ITRS.*
*The Tisserand mean axis of the Earth corresponds to the mean surface geographic axis, quoted B axis, in Seidelmann, 1982, Celest. Mech. 27, 79-106.*
*As a consequence of this resolution, the Celestial Ephemeris Pole is no longer necessary.*

## Resolution B1.8 Definition and use of Celestial and Terrestrial Ephemeris Origins

The XXIVth International Astronomical Union General Assembly,

### 1.1.1.23 Recognising

1. the need for reference system definitions suitable for modern realisations of the conventional reference systems and consistent with observational precision,
2. the need for a rigorous definition of sidereal rotation of the Earth,
3. the desirability of describing the rotation of the Earth independently from its orbital motion, and

### 1.1.1.24 Noting

that the use of the ”non-rotating origin” (Guinot, 1979) on the moving equator fulfills the above conditions and allows for a definition of UT1 which is insensitive to changes in models for precession and nutation at the microarcsecond level

### 1.1.1.25 Recommends

1. the use of the ”non-rotating origin” in the Geocentric Celestial Reference System ((GCRS) and that this point be designated as the Celestial Ephemeris Origin (CEO) on the equator of the Celestial Intermediate Pole (CIP),
2. the use of the ”non-rotating origin” in the International Terrestrial Reference System (ITRS) and that this point be designated as the Terrestrial Ephemeris Origin (TEO) on the equator of the CIP,
3. that UT1 be linearly proportional to the Earth Rotation Angle defined as the angle measured along the equator of the CIP between the unit vectors directed toward the CEO and the TEO,
4. that the transformation between the ITRS and GCRS be specified by the position of the CIP in the GCRS, the position of the CIP in the ITRS, and the Earth Rotation Angle,
5. that the International Earth Rotation Service (IERS) take steps to implement this by 1 January 2003, and
6. that the IERS will continue to provide users with data and algorithms for the conventional transformations.

### *1.1.1.26 Note*

*The position of the CEO can be computed from the IAU 2000A model for precession and nutation of the CIP and from the current values of the offset of the CIP from the pole of the ICRF at J2000.0 using the development provided by Capitaine et al. (2000).*
*The position of the TEO is only slightly dependent on polar motion and can be ex-*

*trapolated as done by Capitaine et al. (2000) using the IERS data. The linear relationship between the Earth's rotation angle $\theta$ and UT1 should ensure the continuity in phase and rate of UT1 with the value obtained by the conventional relationship between Greenwich Mean Sidereal Time (GMST) and UT1. This is accomplished by the following relationship:*

$$\theta(UT1) = 2\pi(0.7790572732640 + 1.0027378119113544 8 \times (\text{Julian UT1 date} - 2451545.0))$$

## 1.1.1.27 References

Guinot, B., 1979, in D.D. McCarthy and J.D. Pilkington (eds.), Time and the Earth's Rotation, D. Reidel Publ. 7-18.

Capitaine, N., Guinot, B. and McCarthy, D.D., 2000, *Astron.Astrophys.,* **335**, 398-405.

### Resolution B1.9 Re-definition of Terrestrial Time TT

The XXIVth International Astronomical Union General Assembly,

## 1.1.1.28 Considering

1. that IAU Resolution A4 (1991) has defined Terrestrial Time (TT) in its Recommendation 4,
2. that the intricacy and temporal changes inherent to the definition and realisation of the geoid are a source of uncertainty in the definition and realisation of TT, which may become, in the near future, the dominant source of uncertainty in realising TT from atomic clocks,

## 1.1.1.29 Recommends

that TT be a time scale differing from TCG by a constant rate: $dTT/dTCG = 1-L_G$, where $L_G = 6.969290134 \times 10^{-10}$ is a defining constant,

## *1.1.1.30 Note*

$L_G$ was defined by the IAU Resolution A4 (1991) in its Recommendation 4 as equal to $U_G/c^2$ where $U_G$ is the geopotential at the geoid. $L_G$ is now used as a defining constant.

## Resolution B2 Coordinated Universal Time

The XXIVth International Astronomical Union General Assembly,

## 1.1.1.31 Recognising

1. that the definition of Coordinated Universal Time (UTC) relies on the astronomical observation of the UT1 time scale in order to introduce leap seconds,
2. that the unpredictability of leap seconds affects modern communication and navigation systems,
3. that astronomical observations provide an accurate estimate of the secular deceleration of the Earth's rate of rotation,

## 1.1.1.32 Recommends

1. that the IAU establish a working group reporting to Division I at the General Assembly in 2003 to consider the redefinition of UTC,
2. that this study discuss whether there is a requirement for leap seconds, the possibility of inserting leap seconds at pre-determined intervals, and the tolerance limits for UT1-UTC, and
3. that this study be undertaken in cooperation with the appropriate groups of the International Union of Radio Science (URSI), the International Telecommunications Union (ITU-R), the International Bureau for Weights and Measures (BIPM), the International Earth Rotation Service (IERS), and relevant navigational agencies.

# Annex 2: Programme of the Workshop

**THURSDAY 18 APRIL 2002: MORNING (9 h 00 - 13 h 00)**

**9 h 00 : Session 1**. ***Introduction to the IERS Workshop***
J. Vondrak, Chair of the IERS DB
B. Richter, Director of the IERS CB
J. Souchay, Chair of the LOC of the Workshop

**9 h 15 : Session 2**. ***Background reasons for the IAU 2000 resolutions requiring actions from the IERS***
J. Vondrak, IAU Representative in the IERS DB

**Session 3.** ***Consequences of the IAU 2000 Resolutions***

**9h 45** ***: Session 3.1 Practical consequences of***
- Resolution BI.3 "Definition of Barycentric Celestial Reference System and Geocentric Celestial Reference System"
- Resolution B1.4 "Post-Newtonian Potential Coefficients"
- Resolution B1.5 "Extended Relativistic Framework for Time Transformations and Realization of Coordinate Times in the Solar System"
- Resolution B1.9 "Redefinition of Terrestrial Time TT"

M. Soffel, Chair of the IAU WG "RCMAM", and G. Petit, President IAU Commission 31

***Coffee Break*** (10 h 45 - 11 h 15)

**11 h 15 :** ***Session 3.2 Practical consequences of***
- Resolution B1.6 "IAU2000 Precession-Nutation Model"
- Resolution B1.7 "Definition of Celestial Intermediate Pole"
- Resolution B1.8 "Definition and Use of Celestial and Terrestrial Ephemeris Origin"

D.D. McCarthy, IERS Convention Centre, and N. Capitaine, President IAU Commission 19

**12 h 15 :** ***Open discussion***

***Lunch*** (13 h 00 - 14 h 00)

**THURSDAY 18 APRIL 2002: AFTERNOON (14 h 00 -18 h 00)**

**Session 4.** ***Comparison of "Old" and "New" Concepts***

***14 h 00 : Session 4.1 Time***
G. Petit, IERS Convention Centre

***14 h 30 : Session 4.2 Reference Systems***
J. Kovalevsky

***15 h 00 : Session 4.3 Earth Orientation***
N. Capitaine: The Celestial Intermediate Pole and Earth Orientation Parameters
B. Guinot: Celestial Ephemeris Origin (CEO), Terrestrial Ephemeris Origin (TEO), Earth Rotation Angle (ERA)

***Coffee Break*** (15 h 30 – 16 h 00)

**16 h 00 :** ***Session 4.4 Astrometry***
K. Seidelmann

**16 h30 :** ***Review of the answers to the questionnaire***

**17 h 00 : POSTER SESSION (Salle Cassini)**

***Cocktail*** (18 h 15 – 20 h 00)

**FRIDAY 19 APRIL 2002: MORNING (9h 00 - 13h 15)**

**9h 00** ***: Session 4.5 Future Almanacs and Future Ephemerides***
convenor: J. Bangert (USNO)

- Implementing the IAU 2000 Resolutions in Almanacs : J. Bangert
- Future Ephemerides Presentation of M. Standish's report by R. Gross (JPL)

**Session 5.** ***Procedures and software (user oriented)***
convenors : P. Wallace, Chair of SOFA, and A.M. Gontier

**9 h 45:** ***Session 5.1 Software for implementing the IAU 2000 Resolutions*** *: P. Wallace*
**10 h 15** ***: Session 5.2 Software implications of ICRS/GCRS transformation : open discussion***

***Coffee Break*** (10 h 45 – 11 h 15 )

**11 h 15** ***: Session 5.3 Software relative to transformation between GCRS and ITRS:*** A.M. Gontier : An implementation of IAU 2000 resolutions in VLBI analysis software

**11 h 45 : Session 6.** (60 min) ***Future IERS Products***
convenor: M. Rothacher, IERS Analysis Coordinator

**12 h 45 : Session 7.** ***Compatibility with past observations***
convenor: D.D. McCarthy

***Lunch*** (13h 15 - 14 h 00)

**FRIDAY 19 APRIL 2002: AFTERNOON (14 h 00 -17 h 30)**

**14 h 00 : Session 8.** ***Discussion***
Topics prepared by SOC from questionnaire and participant questions/ comments
Led by J. Vondrak, M. Soffel, G. Petit, D.D. McCarthy and N. Capitaine

***Coffee Break*** (16 h 00 – 16 h 30)

**16 h 30 : Session 9.** ***Action Items***
- Publication of Proceedings in IERS Technical Note
- Others...

Led by B. Richter, Director IERS CB

**List of Posters**

Capitaine, N, Chapront, J., Lambert, S., Wallace, P. : *Expressions for the coordinates of the CIP and the CEO using IAU 2000 precession-nutation*

Fienga., A., Arlot, J.E., Berthier, J., Hestroffer,D., Simon, J.L. : *2005 New French Ephemerides: implementing new constants and theories*

Fukushima, T : *VLBI determination of J.G. William's formula*

Guinot, B : *The NRO. Questions and answers*

Hilton, J. : *Method for conversion between the Celestial Ephemeris Origin J2000.0, and the Equinox of Date*

Lambert, S, Bizouard, Ch : *Computation of the position of the TEO in the ITRF*

Malkin Z., *A comparison of the VLBI nutation series with IAU 2000 model*

Pavlis E : *TRF Realization from Satellite Laser Ranging*

Ron C : *Tables of differences between nutation models IAU2000, IERS1996 and IAU1980*

Souchay, J : *The Celestial System ICRS: Principles and present realization*

# Annex 3: List of Participants

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|---|---|
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