Proposed terminology for Fundamental Astronomy based on IAU 2000 resolutions

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IAU Division 1 WG on "Nomenclature for Fundamental Astronomy" (NFA)

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Resolutions of the 2000 IAU GA on the celestial reference systems

- IAU Resolution B1.3
  Definition of BCRS and GCRS
  Aim: to provide coordinate systems in the framework of GR

- IAU Resolution B1.6
  IAU 2000 Precession-Nutation Model
  Aim: to provide a model with submilliarcsecond accuracy

- IAU Resolution B1.7
  Definition of Celestial Intermediate Pole
  Aim: to refine the CEP definition and realize the pole in the high frequency domain

- IAU Resolution B1.8
  Definition and use of the TEO and CEO
  Aim: to allow an accurate estimation of UT1, precession-nutation separately

- IAU Resolution B1.9
  Re-definition of TT
  Aim: to clarify the TT/TCG relationship

- *The IERS and SOFA*

have made available the models and procedures to implement these resolutions operationally (including both the new and classical paradigms)

- *The Almanac offices*

have begun to implement the resolutions with their 2006 editions

IAU WG "Nomenclature for Fundamental Astronomy" (NFA)

http://syrte.obspm.fr/iauWGnfa

NFA IAU Division 1 WG created at the 24th IAU General Assembly (July 2003)

General task of the NFA Working group:
to provide proposals for new nomenclature associated with the implementation of the IAU 2000 resolutions and to make related educational efforts for addressing the issue to a large community of scientists.

step 1) in the work of the WG: Newsletters + NFA Questionnaire (2003-2004)
step 2) in the work of the WG: detailed e-mail discussion for preparing the NFA documents (2004-2006) + open WG discussion during *Journées 2004 & 2005*

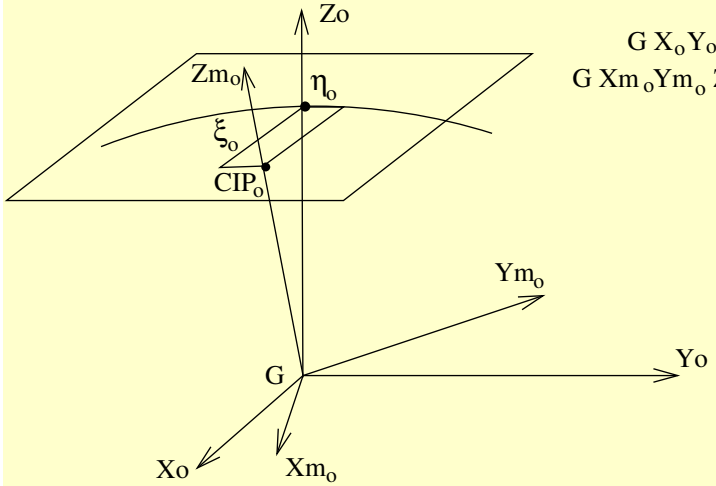
NFA Recommendations
IAU Resolution proposals
Explanatory documents
A: Basis and implementation of the IAU 2000 Resolutions
B: Explanation of the proposed terminology

Nomenclature issues

The IAU2000 precession-nutation and the frame bias

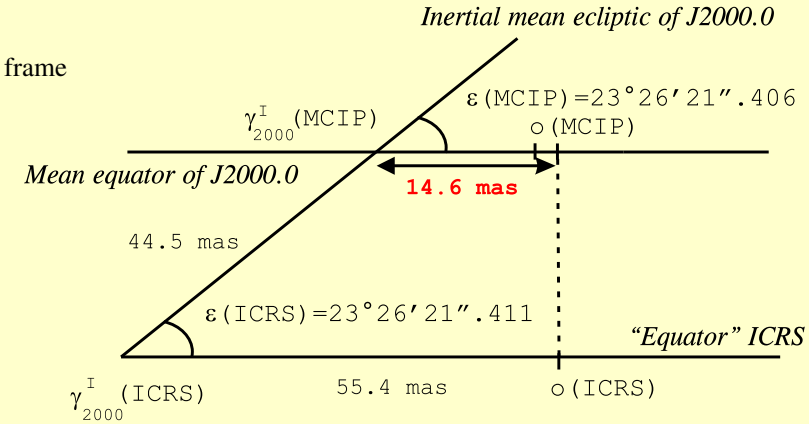
Nutation : IAU2000A : 678 luni-solar terms & 687 planetary terms at 1 μas (IAU 2000 B: shorter version at 1 mas)

Precession: IAU 1976 + corrections to precession rates: $d\psi_A$ (IAU 2000) = –0".29965/cy, $d\varepsilon_A$ (IAU 2000) = –0".02524 /cy



G $X_o Y_o Z_o$: GCRS

G $Xm_o Ym_o Zm_o$: mean celestial frame at epoch



offsets of the direction of the mean pole at J2000.0 w.r.t. the GCRS

VLBI estimates

ξ_0 (IAU 2000) = –0".0166170

η_0 (IAU 2000) = –0".0068192

offset in right ascension of the J2000 mean dynamical equinox w.r.t. the GCRS

estimate from simultaneous analysis of VLBI and LLR data

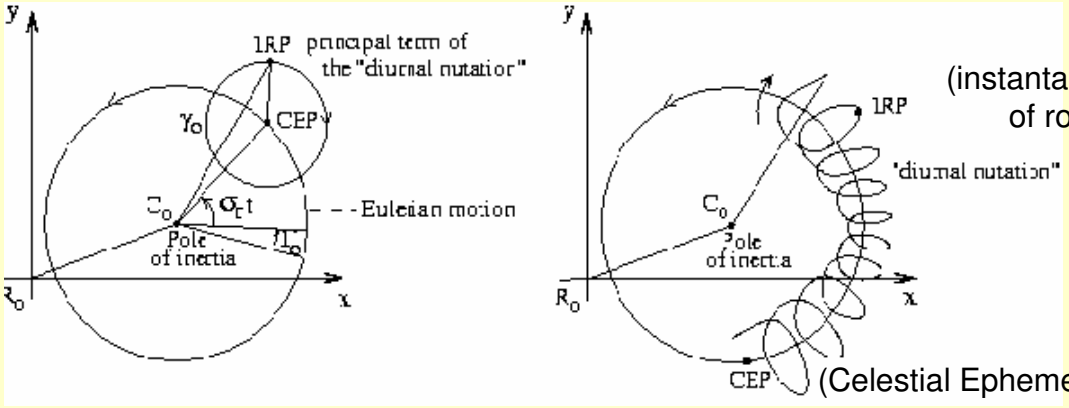
$d\alpha_0$= –14.6 mas

→ *nomenclature associated with the IAU 2000 precession-nutation in the GCRS*

The IAU2000 precession-nutation and the Celestial Intermediate Pole

IAU 1980: the CEP definition

IRP-CEP: 8.7 mas at 1s.d.



(instantaneous pole of rotation)

(Celestial Ephemeris Pole)

IAU 2000: the CIP definition

extension of the CEP definition in the high frequencies

20 µas at 1s.d., 40 µas at 0.5 s.d. in the GCRS
150 µas at 1s.d., 350 µas at 0.5 s.d. in the ITRS

(with frequency σ, such that : $\sigma_{TRS} = \sigma_{CRS} - 1$)

frequency in the ITRS

–3.5 –2.5 –1.5 –0.5 +0.5 +1.5 (cpsd)

------ **polar motion** | | **polar motion** ------

|nutation|

frequency in the GCRS

–2.5 –1.5 –0.5 +0.5 +1.5 +2.5 (cpsd)

celestial motion: IAU 2000 precession-nutation for periods > 2 days + offsets

nutations with periods < 2 days included in model for the pole motion in the ITRS

→ *nomenclature associated*

- *with the precession-nutation of the CIP*
- *with the use of the "intermediate" pole and equator*

Nomenclature associated with the change of the origin on the intermediate equator

Using the CIO

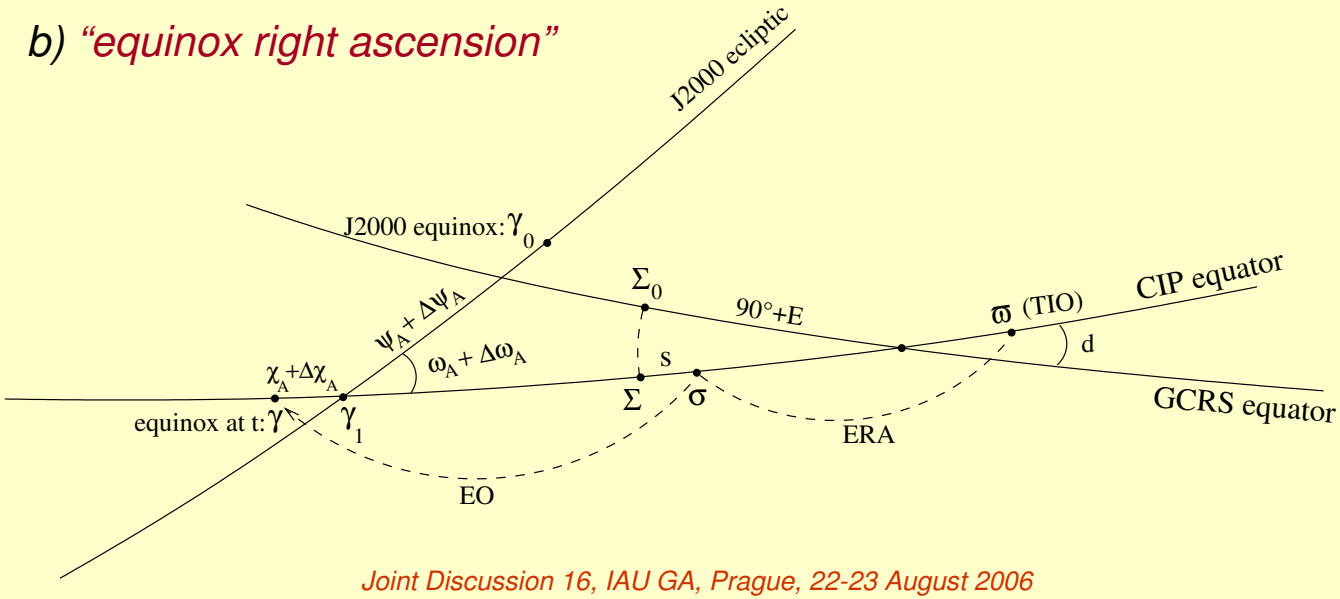
a) ERA = θ = *k* UT1 *;* dθ/dt = ω_3

b) *"intermediate" right ascension, or "CIO right ascension"*

Using the equinox *(with implicit use of CIO)*

a) sidereal time = GMST (UT1, TT) + *"equation of the equinoxes"*
= θ (UT1) + *"equation of the origins"* (EO)

b) "equinox right ascension"



Nomenclature associated with the use of "intermediate" pole, equator and origins

- The term ``intermediate'' has been chosen

  - to specify that these systems (celestial and terrestrial) are "intermediary" systems between the geocentric celestial system and the terrestrial system, which are realized by using the models, constants and procedures that are conventionally accepted,

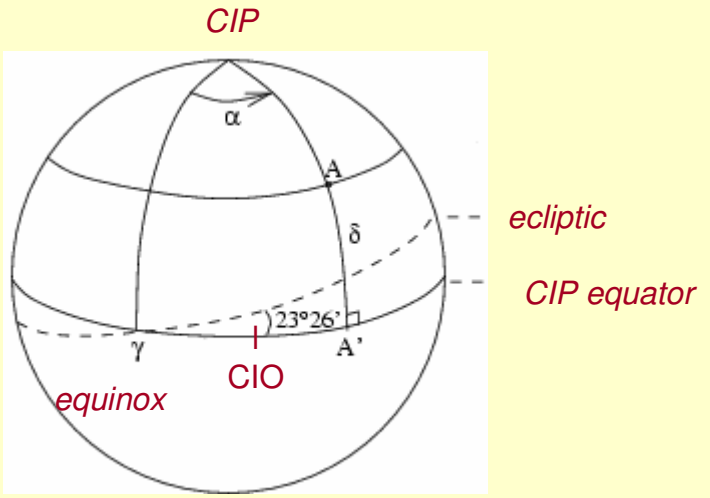
  - it conventionally separates the instantaneous celestial orientation of the Earth into components we label "polar motion" (in the terrestrial system) and "precession-nutation" (in the celestial system).

- The NFA WG has recommended using "system" in a broad sense rather than "frame" in this context of the intermediary system/frame.

  e.g. "the IAU 2000A system" designates the system which is realized by transforming the geocentric celestial system GCRS to the "intermediate" system using the IAU 2000A precession-nutation and associated frame biases at J2000

Nomenclature associated with the equatorial coordinates

- *nomenclature associated with the use of the new origins,*
- *homogenization to « intermediate » (CIO, TIO)*
- *nomenclature associated with the ICRS*



α	RA	right ascension	generic term	
α_i	RA_i	intermediate right ascension, CIO right ascension	ERA-compatible	CIO
α_e	RA_e	equinox right ascension, right ascension with respect to the equinox, apparent right ascension	ST-compatible	equinox
α_{ICRS}	RA_{ICRS}	ICRS right ascension		
δ	Dec, DEC	declination	generic term	CIO & equinox
δ_{ICRS}	Dec_{ICRS}	declination measured from the ICRS equator		

Nomenclature associated with the use of the BCRS and GCRS

Definition of BCRS and GCRS

IAU Resolution *B1.3 : Clarification of IAU's 1991* definition of the coordinate systems in the framework of GR : *distinction between the celestial systems*

- a) for Solar System (BCRS) which can be considered to be *a global coordinate system* that contain all the 'far away regions'
- b) for the Earth (GCRS) which can only be considered as a *local coordinate system*

Transformation BCRS/GCRS

BCRS → GCRS

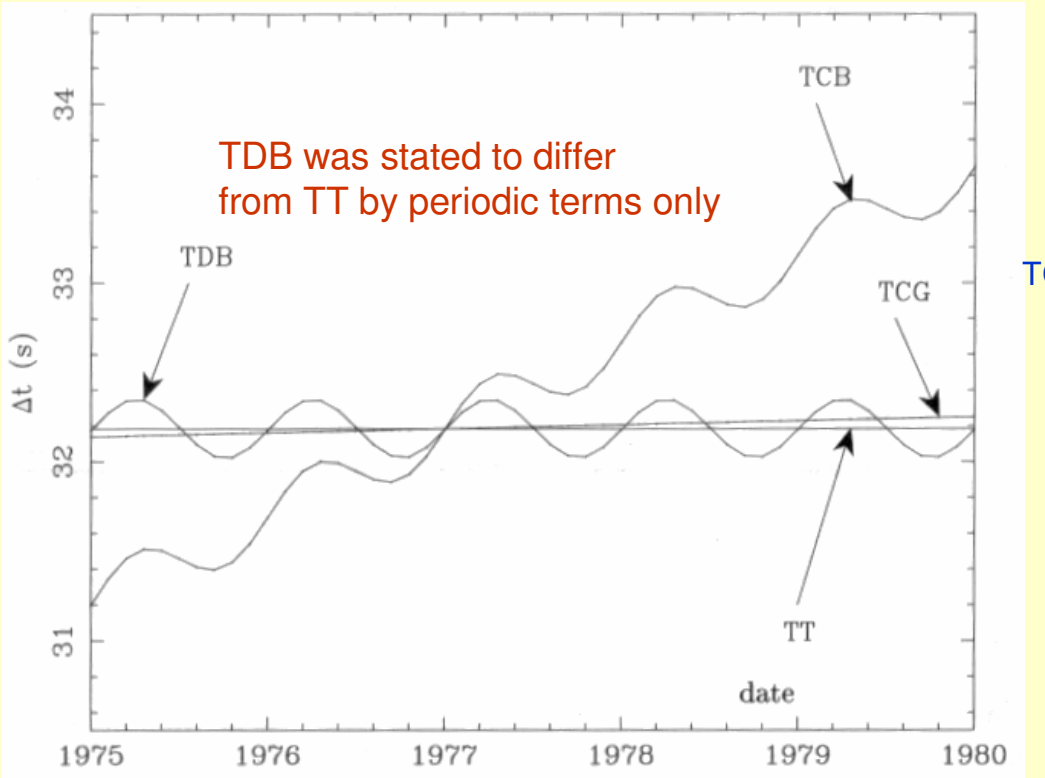
$$\mathbf{X}^a = \delta_{ai}\left[r_E^i + \frac{1}{c^2}\left(\frac{1}{2}v_E^i v_E^j r_E^j + w_{ext}(\mathbf{x}_E) r_E^i + r_E^i a_E^j r_E^j - \frac{1}{2}a_E^i r_E^2\right)\right] + O\left(c^{-4}\right),$$

TCB → TCG

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

Orientation issue: *relationship ICRS/BCRS; orientation of the BCRS axes?*

Relations between TT, TCG, TCB, TDB



Differences in seconds w.r.t. TAI

$TCG - TT = L_G \times (JD - 2443144.5003725) \times 86400$

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

$TT = TAI + 32.184\ s$

TDB issue : question on a description of TDB as it is currently understood:

- how literally to take “periodic terms”,
- lack of a rigorous definition of TDB even in principle,
- JPL had independently implemented the TDB “idea” and had called the result T_{eph}

source Bdl

Re-definition of TDB – the NFA WG proposal

TDB to be defined through a conventional relationship with TCB:

$$TDB = TCB - L_B \times (JD_{TCB} - T_0) \times 86400 + TDB_0$$

T_0 = 2443144.5003725 exactly.
$JD_{TCB} = T_0$ for the event 1977 Jan 1.0 TAI at the geocenter and increases by 1.0 for each 86400s of TCB.

$L_B = 1.550519768 \times 10^{-8}$ exactly.

$TDB_0 = -6.55 \times 10^{-5}$ s exactly.

WG Results

- *WG recommendations*
  - equinox based/CIO based
  - harmonization to « intermediate »
  - updated definition of BCRS/GCRS
  - re-definition of TDB

  } → Resolution proposals

- *WG explanatory document*
  - updated definitions (BCRS, GCRS, CIO, TIO, TDB, TT …)
  - new definitions (equinox based/CIO based, intermediate, …)
  - chart: ICRS → observed places
  - summary of terms and definitions, procedures
  - Glossary

- *WG educational documents*
  - PPT presentations
  - examples

The NFA WG recommendations

NFA WG recommendations and guidelines on terminology

- 1. Using existing terms (e.g. right ascension) in extended ways for the terminology associated with the new paradigm with a clear specification, rather than introducing new names.
- 2. Using “equinox based" and “CIO based” for referring to the classical and new paradigms, respectively.
- 3. Using “intermediate” to describe (i) the moving geocentric celestial reference system defined in the IAU 2000 Resolutions (i.e. containing the CIP and the CIO), and (ii) the moving terrestrial system containing the CIP and the TIO.
- 4. Harmonizing the name of the pole and the origin to “intermediate” and therefore changing CEO/TEO to CIO/TIO.
- 5. Using “system” in a broad sense rather than “frame” in this context of the intermediary system/frame.
- 6. Using special designations for particular realizations of the intermediate celestial system.
- 7. Keeping the classical terminology for “true equator and equinox” (or “true equinox based”) for the classical equatorial system.
- 8. Choosing “equinox right ascension” (or “RA with respect to the equinox”) and “intermediate right ascension” (or “CIO right ascension”, or “RA with respect to the CIO”), for the azimuthal coordinate along the equator in the classical and new paradigms, respectively.

NFA WG recommendations and guidelines on terminology

- 9. Giving the name “equation of the origins” to the distance between the CIO and the equinox along the intermediate equator, the sign of this quantity being such that it represents the CIO right ascension of the equinox, or equivalently, the difference between the Earth Rotation Angle and Greenwich apparent sidereal time.
- 10. Retaining “apparent places” and “mean places” in the equinox based system.
- 11. Not introducing “apparent intermediate places” in the CIO based system, but introducing instead “intermediate places”.
- 12. Using “ITRF zero-meridian” to designate the plane passing through the geocenter, ITRF pole and ITRF x-origin and using, if necessary, “TIO meridian” to designate the moving plane passing through the geocenter, the CIP and the TIO.
- 13. Fixing the default orientation of the BCRS so that for all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes.
- 14. Re-defining Barycentric Dynamical Time (TDB) so that TDB is a fixed linear function of TCB.

The NFA WG Explanatory document

NFA/B: explanation of the proposed terminology

1) NFA IAU 2000 Glossary

- Provides a set of detailed definitions that best explain all the terms required for implementing the IAU 2000 resolutions.
- Includes a few newly proposed terms, and terms that have some impact on the definitions, as well as some more general definitions.

2) Table containing the categorized list of terms

3) Chart of the transformation process from ICRS to observed places of stars

Illustrates the various stages showing the BCRS→ GCRS→ITRS transformation in GR (Resolution B1.3) and the parallel CIO and equinox based processes (Resolution B1.8).

4) List of abbreviations, acronyms and symbols

Complementary and supporting material to facilitate the understanding and implementation of the IAU 2000 resolutions, as well as illustrating the Glossary.

The NFA IAU 2000 Glossary detailed discussion

Barycentric Celestial Reference System (BCRS)
Barycentric Dynamical Time (TDB)
Barycentric Ephemeris Time (Teph)
Celestial Intermediate Origin (CIO)
Celestial Intermediate Reference System (CIRS)
CIO locator
CIO right ascension and declination
epoch
equation of the origins (EO)
equinox right ascension
Geocentric Celestial Reference System (GCRS)
Geocentric Terrestrial Reference System (GTRS)
ICRS place
intermediate equator
intermediate place
intermediate right ascension
International Celestial Reference Frame (ICRF)
International Celestial Reference System (ICRS)
International Terrestrial Reference Frame (ITRF)
International Terrestrial Reference System (ITRS)
Julian century
Julian date
Julian year
right ascension
Terrestrial Intermediate origin (TIO)
Terrestrial Intermediate Reference System (TIRS)
Terrestrial Time (TT)
TIO locator

The Glossary: a few examples (1)

Celestial Intermediate Reference System (CIRS): geocentric reference system related to the GCRS by a time-dependent rotation taking into account precession-nutation. It is defined by the intermediate equator (of the CIP) and CIO on a specific date. It is similar to the system based on the true equator and equinox of date, but the equatorial origin is at the CIO. Since the acronym for this system is close to another acronym (namely ICRS), it is suggested that wherever possible the complete name is used.

intermediate right ascension and declination: angular coordinates measured in the celestial intermediate reference system at a specified date**.** They specify a geocentric direction that differs from the ICRS direction by annual parallax, gravitational light deflection due to the solar system bodies except the Earth, annual aberration, and the time-dependent rotation describing the transformation from the GCRS to the celestial intermediate reference system. They are similar to apparent right ascension and declination when referring to the equinox based system. Note that intermediate declination is identical to apparent declination.

The Glossary: a few examples (2)

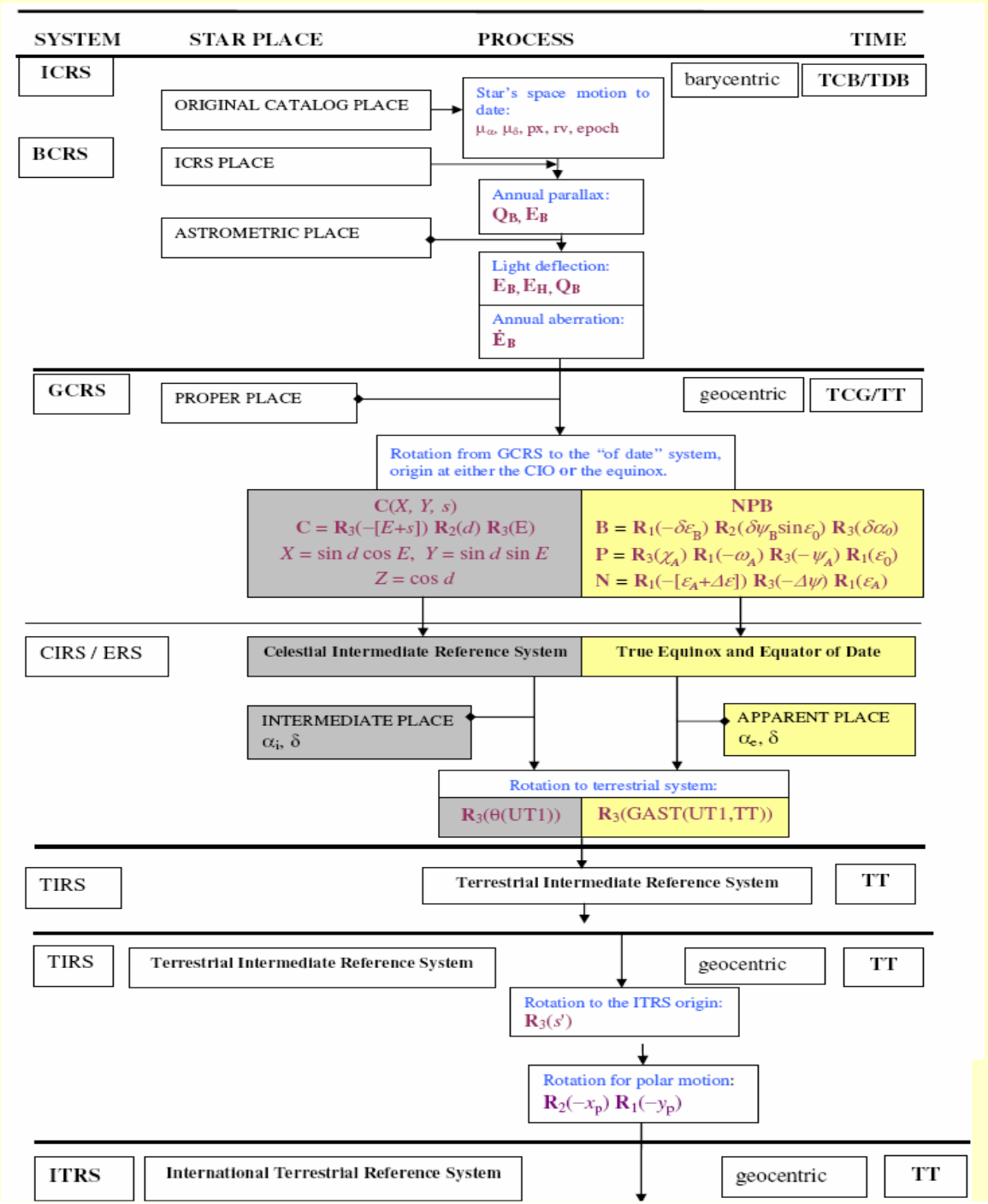
Celestial Intermediate Origin (CIO): origin for right ascension on the intermediate equator in the celestial intermediate reference system. It is the non-rotating origin in the GCRS that is recommended by the IAU 2000 Resolution B 1.8, where it was designated the Celestial Ephemeris Origin. The CIO was originally set close to the GCRS meridian and throughout 1900-2100 stays within 0.1 arcseconds of this alignment.

equation of the origins: distance between the CIO and the equinox along the intermediate equator; it is the CIO right ascension of the equinox; alternatively the difference between the Earth rotation angle and Greenwich apparent sidereal time (ERA – GAST).

CIO locator (denoted s) : the difference between the GCRS right ascension and the intermediate right ascension of the intersection of the GCRS and intermediate equators. The CIO was originally set close to the mean equinox at J2000.0. As a consequence of precession-nutation the CIO moves according to the kinematical property of the non-rotating origin. The CIO is currently located by using the quantity *s*.

TIO locator (denoted *s'*): the difference between the ITRS longitude and the instantaneous longitude of the intersection of the ITRS and intermediate equators. The TIO was originally set at the ITRF origin of longitude. As a consequence of polar motion the TIO moves according to the kinematical property of the non-rotating origin. The TIO is currently located using the quantity s′, whose rate is of the order of 50 mas/cy which is due to the current polar motion.

Chart: tansformation from ICRS to apparent places of stars



The NFA WG resolutions proposed to the XXVIth IAU GA

IAU Resolution 2

Supplement to the IAU Resolutions on reference systems

Proposed by the IAU Division 1 WG on « Nomenclature for Fundamental Astronomy » Supported by Division 1

RECOMMENDATION 1. Harmonizing the name of the pole and origin to "intermediate"

The XXVIth International Astronomical Union General Assembly,

Noting

1. the adoption of resolutions IAU B1.1 through B1.9 by the IAU General Assembly of 2000,

2. that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFA) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Offices have begun to implement them beginning with their 2006 editions, and

3. the recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVIA, 2005), and

Recognizing

1. that using the designation "intermediate" to refer to both the pole and the origin of the new systems linked to the Celestial Intermediate Pole and the Celestial or Terrestrial Ephemeris origins, defined in Resolutions B1.7 and B1.8, respectively would improve the consistency of the nomenclature, and

2. that the name "Conventional International Origin" with the potentially conflicting acronym CIO is no longer commonly used to refer to the reference pole for measuring polar motion as it was in the past by the International Latitude Service,

Recommends

1. that, the designation "intermediate" be used to describe the moving celestial and terrestrial reference systems defined in the 2000 IAU Resolutions and the various related entities, and

2. that the terminology "Celestial Intermediate Origin" (CIO) and "Terrestrial Intermediate Origin" (TIO) be used in place of the previously introduced "Celestial Ephemeris Origin" (CEO) and "Terrestrial Ephemeris Origin" (TEO), and

3. that authors carefully define acronyms used to designate entities of astronomical reference systems to avoid possible confusion.

IAU Resolution 2

Supplement to the IAU Resolutions on reference systems

Proposed by the IAU Division 1 WG on « Nomenclature for Fundamental Astronomy »
Supported by Division 1

RECOMMENDATION 2. Default orientation of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS)

The XXVIth International Astronomical Union General Assembly,

Noting

1. the adoption of resolutions IAU B1.1 through B1.9 by the IAU General Assembly of 2000,
2. that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFA) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Offices have begun to implement them beginning with their 2006 editions,
3. that, in particular, the systems of space-time coordinates defined by IAU 2000 Resolution B1.3 for (a) the solar system (called the Barycentric Celestial Reference System, BCRS) and (b) the Earth (called the Geocentric Celestial Reference System, GCRS) have begun to come into use,
4. the recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVIA, 2005), and
5. a recommendation from the IAU Working Group on "Relativity in Celestial Mechanics, Astrometry and Metrology",

Recognizing

1. that the BCRS definition does not determine the orientation of the spatial coordinates,
2. that the natural choice of orientation for typical applications is that of the ICRS, and
3. that the GCRS is defined such that its spatial coordinates are kinematically non-rotating with respect to those of the BCRS,

Recommends

that the BCRS definition is completed with the following: "For all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes. The orientation of the GCRS is derived from the ICRS-oriented BCRS."

IAU Resolution 3

Proposed by the IAU Division 1 WG on « Nomenclature for Fundamental Astronomy » Supported by Division 1

The XXVIth International Astronomical Union General Assembly,

Noting

1. that IAU Recommendation 5 of Commissions 4, 8 and 31 (1976) introduced, as a replacement for Ephemeris Time (ET), a family of dynamical time scales for barycentric ephemerides and a unique time scale for apparent geocentric ephemerides,

2. that IAU Resolution 5 of Commissions 4, 19 and 31 (1979) designated these time scales as Barycentric Dynamical Time (TDB) and Terrestrial Dynamical Time (TDT) respectively, the latter subsequently renamed Terrestrial Time (TT), in IAU Resolution A4, 1991,

3. that the difference between TDB and TDT was stipulated to comprise only periodic terms, and

4. that Recommendations III and V of IAU Resolution A4 (1991) (i) introduced the coordinate time scale Barycentric Coordinate Time (TCB) to supersede TDB, (ii) recognized that TDB was a linear transformation of TCB, and (iii) acknowledged that, where discontinuity with previous work was deemed to be undesirable, TDB could be used, and

Recognizing

1. that TCB is the coordinate time scale for use in the Barycentric Celestial Reference System,

2. the possibility of multiple realizations of TDB as defined currently,

3. the practical utility of an unambiguously defined coordinate time scale that has a linear relationship with TCB chosen so that this coordinate time scale remains close to Terrestrial Time (TT) at the geocenter for an extended time span,

4. the desirability for consistency with the Teph time scales used in the Jet Propulsion Laboratory (JPL) solar-system ephemerides and existing TDB implementations such as that of Fairhead & Bretagnon (*A&A* **229**, 240, 1990), and

5. the 2006 recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVIB, 2006),

Recommends

that, in situations calling for the use of a coordinate time scale that is linearly related to Barycentric Coordinate Time (TCB) and remains close to Terrestrial Time (TT) at the geocenter for an extended time span, TDB be defined as the following linear transformation of TCB:

$$TDB = TCB - L_B \times (JD_{TCB} - T_0) \times 86400 + TDB_0,$$

where $T_0 = 2443144.5003725$,
and $L_B = 1.550519768 \times 10^{-8}$ and $TDB_0 = -6.55 \times 10^{-5}$ s are defining constants.

Notes

1. JD_{TCB} is the TCB Julian date. Its value is $T_0 = 2443144.5003725$ for the event 1977 January 1 00h 00m 00s TAI at the geocenter, and it increases by one for each 86400s of TCB.

2. The value L_B is equal to $L_C + L_G - L_C \times L_G$, where L_G is given in IAU Resolution B1.9 (2000) and L_C has been determined (Irwin & Fukushima, 1999, *A&A* **348**, 642) using the JPL ephemeris DE405. When using the JPL Planetary Ephemeris DE405, the defining L_B value effectively eliminates a linear drift between TDB and TT at the geocenter. When realizing TCB using other ephemerides, the difference between TDB and TT at the geocenter may include some linear drift which is not expected to exceed 1 ns per year.

3. The difference between TDB and TT at the surface of the Earth remains under 2 ms for several millennia around the present epoch.

4. The independent time argument of the JPL ephemeris DE405, which is called Teph (Standish, *A&A*, **336**, 381, 1998), is for practical purposes the same as TDB defined in this Resolution.

5. The constant term TDB_0 is chosen to provide reasonable consistency with the widely used TDB – TT formula of Fairhead & Bretagnon (1990).
n.b. The presence of TDB_0 means that TDB is not synchronized with TT, TCG and TCB at 1977 Jan 1.0 TAI at the geocenter.

6. For solar system ephemerides development the use of TCB is encouraged.