Recent progress in concepts, nomenclature and models in fundamental astronomy

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IAU 2000/2006 Resolutions on reference systems
(endorsed by IUGG 2003 and 2007, respectively)

IAU 2000 Resolutions

Resolution B1.3
Definition of BCRS and GCRS

Resolution B1.5
Extended Relativistic framework for time transformation

Resolution B1.6
IAU 2000 Precession-Nutation Model

Resolution B1.7
Definition of Celestial Intermediate Pole

Resolution B1.8
Definition and use of CEO and TEO

Resolution B1.9
Re-definition of TT

IAU 2006 Resolutions

Resolution B1
Adoption of the P03 Precession and definition of the ecliptic

Resolution B2
Supplement to the IAU 2000 Resolutions on reference systems
Rec 1: Harmonizing « intermediate » to the pole and the origin
Rec 2: Default orientation of the BCRS and GCRS

Resolution B3
Re-definition of TDB

IAU 2000 Resolutions (and IUGG 2003)

Resolution	Aim
Definition of BCRS and GCRS	to provide coordinate systems in the framework of GR
Extended Relativistic framework for time transformation	to give a set of formulas for practical transformations between relativistic time scales
IAU 2000 Precession-Nutation Model	to provide a model with submilliarcsecond accuracy
Definition of CIP	to refine the 1980 definition (CEP) and realize the pole in the high frequency domain
Definition and use of the TEO and CEO	to allow an accurate estimation of UT1 and precession-nutation separately
Re-definition of TT	to clarify the TT/TCG relationship

IAU 2006 Resolutions (and IUGG 2007)

Resolution	Aim
Adoption of the P03 Precession and definition of the ecliptic	to adopt a precession model as a replacement to the IAU 2000 precession in order to be consistent with both dynamical theory and the IAU 2000 nutation. *(recommended by the IAU WG « Precession and the eclitptic »)*
Supplement to the IAU 2000 Resolutions on reference systems Rec 1: Harmonizing intermediate to the pole and the origin Recom 2: Default orientation of the BCRS and GCRS	to address definition, terminology or orientation issues relative to reference systems that needed to be specified after the adoption of the IAU 2000 resolutions *(recommended by the IAU WG « Nomenclature for Fundamental Astronomy »)*
Re-definition of TDB	to address definition issue relative to time scales *(recommended by the IAU WG « Nomenclature for Fundamental Astronomy »)*

Progress in concepts in fundamental astronomy

Journées 2007 « Systèmes de référence spatio-temporels », Meudon, September 2007

The Barycentric and Geocentric celestial reference systems, BCRS and GCRS

IAU 2000 Resolution B1.3 **:** Clarification of IAU's 1991 definition of the coordinate systems in the framework of GR : *distinction between the celestial systems*

Definition of BCRS and GCRS

- a) for Solar System (BCRS) which can be considered to be *a global coordinate system*

e.g. to be used for planetary ephemerides

- b) for the Earth (GCRS) which can only be considered as a *local coordinate system*

e.g. to be used for Earth rotation, precession-nutation of the equator

Transformation BCRS/GCRS

BCRS → GCRS

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

TCB → TCG

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

The NFA WG recommendations related to BCRS and TDB and the resulting IAU 2006 Resolutions

- Fixing the default orientation of the BCRS

IAU 2006 Resolution B2: 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.

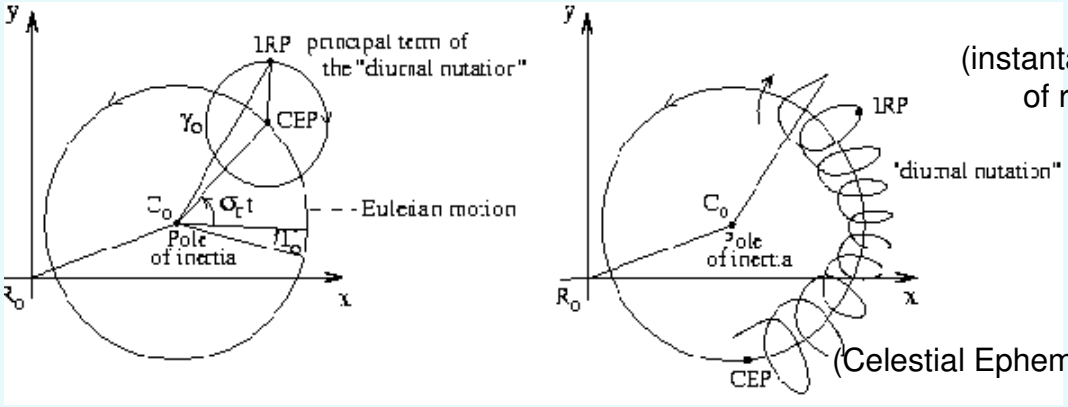
- Re-defining Barycentric Dynamical Time (TDB)

IAU 2006 Resolution B3: TDB is re-defined as a linear transformation of TCB

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 to the high frequency domain

(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** ------

Inutation

frequency in the GCRS

–2.5 –1.5 –0.5 +0.5 +1.5 +2.5 (cpsd)

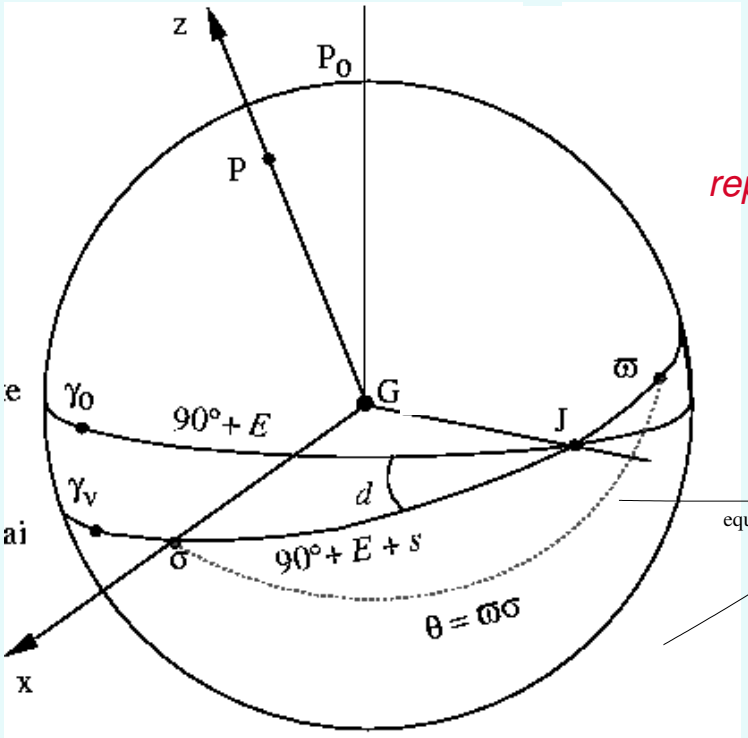
convention

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

The GCRS coordinates of the CIP

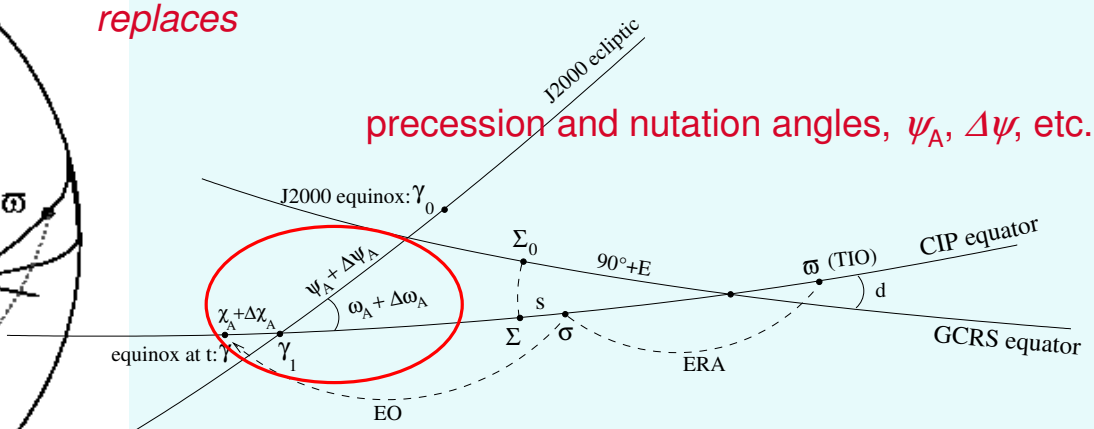
X=sind cosE

Y=sind sinE

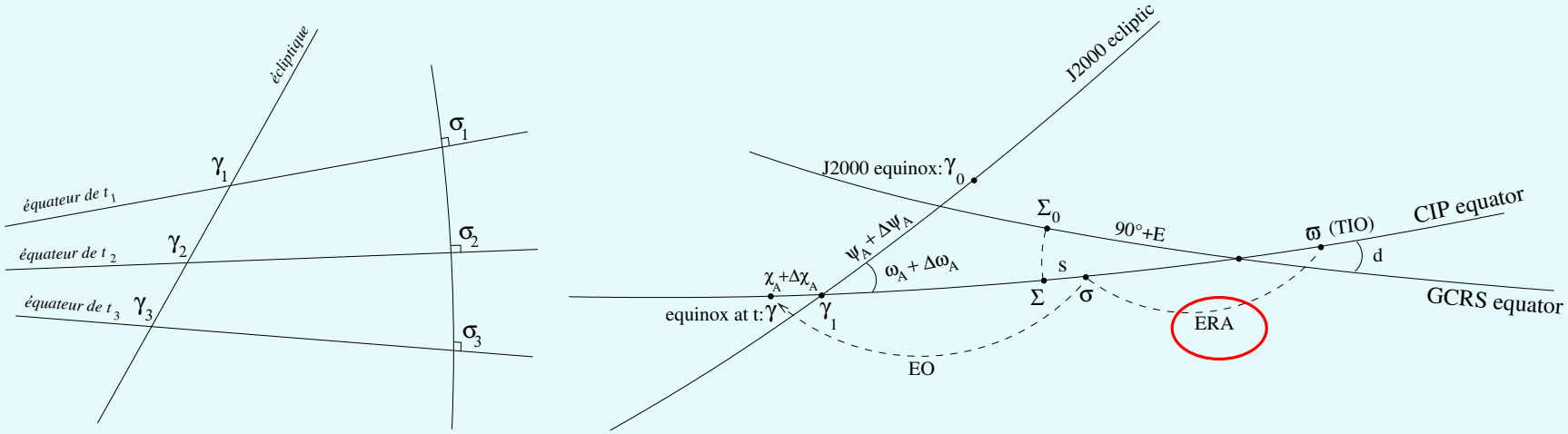


replaces

precession and nutation angles, ψ_A, $\Delta\psi$, etc.



The Earth Rotation Angle



kinematical definition of the non-rotating origin
only dependent on the CIP motion

ERA: *Earth rotation angle*

ERA = Hour angle from the CIO= *k* UT1

« intermediate systems »

replaces

geometrical definition of the equinox, dependent on
both the equator and ecliptic motions

GST: *sidereal time*

Hour angle from the equinox

= *ERA- EO*

EO: *equation of the origins*

Recent progress in nomenclature for fundamental astronomy

Journées 2007 « Systèmes de référence spatio-temporels », Meudon, September 2007

IAU WG "Nomenclature for Fundamental Astronomy" (NFA)

Recommendations related to the pole and origin

- Harmonizing the name of the pole and the origin to “intermediate” and therefore changing CEO/TEO to CIO/TIO.
- Using “equinox based" and “CIO based” for referring to the classical and new paradigms, respectively.
- 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.
- 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.
- 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.

IAU 2006
Resolution B2

Supplement to the IAU 2000 Resolutions on reference systems

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 2006
Resolution B2

Supplement to the IAU 2000 Resolutions on reference systems

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

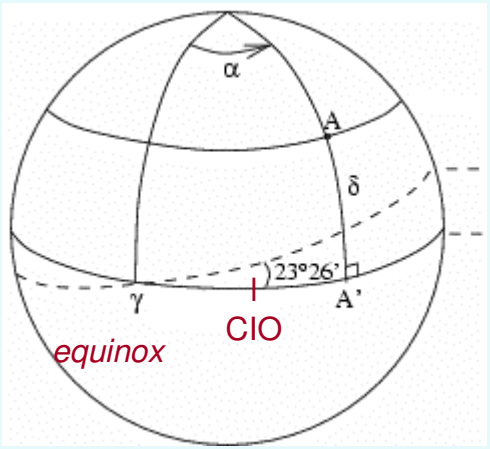
3. that the GCRS is defined such that its spatial coordinates are kinematically non-rotating with respect to those of the BCRS,

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."

Nomenclature associated with the equatorial coordinates

- *nomenclature associated with the use of the new origins,*
- *nomenclature associated with the ICRS*



α	RA	right ascension		
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		CIO & equinox
δ_{ICRS}	Dec_{ICRS}	declination measured from the ICRS equator		

Recent progress in models in Fundamental astronomy

Journées 2007 « Systèmes de référence spatio-temporels », Meudon, September 2007

IAU Precession-nutation

IAU 2000 Resolution B1.6

- adopted the IAU2000 precession-nutation (Mathews et al. 2002; Dehant et al. 1999), which was implemented in the IERS Conventions 2003

  IAU 2000A Nutation *(non-rigid Earth)*

  1365 luni-solar and planetary terms *(Mathews et al. 2002)* based on *rigid Earth nutation (Souchay et al. 1999) and transfer function with basic Earth parameters fitted to VLBI data*

  IAU 2000 Precession= IAU 1976 *(Lieske et al. 1977)* + corrections to precession rates

  $d\psi_A$ (IAU 2000) = –0.299 65”/c ; $d\omega_A$ (IAU 2000) = –0.025 24”/c : ***1st step***

  Celestial pole offsets *at J2000 (VLBI estimates)*

  ξ_0 (IAU 2000) = –16.6170 mas ; η_0 (IAU 2000) = –6.8192 mas

- recommended the development of new expressions for precession consistent with dynamical theories, with non-rigid Earth models, and with IAU 2000A nutation

IAU 2006 Resolution B1

- adopted the P03 precession (Capitaine et al. 2003) : ***2d step***
- recommended improved definitions (ecliptic, precession of the equator, precession of the ecliptic)

IAU 2006
Resolution B1

Adoption of the P03 Precession Theory and Definition of the Ecliptic

The XXVIth International Astronomical Union General Assembly,

Noting

1. the need for a precession theory consistent with dynamical theory,
2. that, while the precession portion of the IAU 2000A precession-nutation model, recommended for use beginning on 1 January 2003 by resolution B1.6 of the XXIVth IAU General Assembly, is based on improved precession rates with respect to the IAU 1976 precession, it is not consistent with dynamical theory, and
3. that resolution B1.6 of the XXIVth General Assembly also encourages the development of new expressions for precession consistent with the IAU 2000A precession-nutation model, and

Recognizing

1. that the gravitational attraction of the planets make a significant contribution to the motion of the Earth's equator, making the terms *lunisolar precession* and *planetary precession* misleading,
2. the need for a definition of the ecliptic for both astronomical and civil purposes, and
3. that in the past, the ecliptic has been defined both with respect to an observer situated in inertial space (inertial definition) and an observer comoving with the ecliptic (rotating definition),

Accepts

the conclusions of the IAU Division I Working Group on Precession and the Ecliptic published in Hilton *et al.* (2006, *Celest. Mech.* **94**, 351), and

IAU 2006
Resolution B1

Recommends

1. that the terms *lunisolar precession* and *planetary precession* be replaced by *precession of the equator* and *precession of the ecliptic*, respectively,

2. that, beginning on 1 January 2009, the precession component of the IAU 2000A precession-nutation model be replaced by the P03 precession theory, of Capitaine *et al.* (2003, *A&A*, **412**, 567-586) for the precession of the equator (Eqs. 37) and the precession of the ecliptic (Eqs. 38); the same paper provides the polynomial developments for the P03 primary angles and a number of derived quantities for use in both the equinox based and CIO based paradigms,

3. that the choice of precession parameters be left to the user, and

4. that the ecliptic pole should be explicitly defined by the mean orbital angular momentum vector of the Earth-Moon barycenter in the Barycentric Celestial Reference System (BCRS), and this definition should be explicitly stated to avoid confusion with other, older definitions.

Notes

1. *Formulas for constructing the precession matrix using various parameterizations are given in Eqs. 1, 6, 7, 11, 12 and 22 of Hilton et al. (2006). The recommended polynomial developments for the various parameters are given in Table 1 of the same paper, including the P03 expressions set out in expressions (37) to (41) of Capitaine et al. (2003) and Tables 3-5 of Capitaine et al. (2005).*

2. *The time rate of change in the dynamical form factor in P03 is* $dJ_2/dt = -0.3001 \times 10^{-8}$ *century*$^{-1}$.

References

Capitaine, N., Wallace, P.T., & Chapront, J. 2003, *A&A*, **412**, 567
Capitaine, N., Wallace, P.T., & Chapront, J. 2005, *A&A*, **432**, 355
Hilton, J.L., Capitaine, N., Chapront, J., Ferrandiz, J.M., Fienga, A., Fukushima, T., Getino, J., Mathews, P., Simon, J.-L., Soffel, M., Vondrak, J., Wallace, P., & Williams, J. 2006, *Celest. Mech.*, **94**, 351

P03 precession expressions

TABLE I

The polynomial coefficients for the precession angles.

Angle	(arcsec.)	Coefficients* $\left(\frac{\text{arcsec.}}{\text{cent.}}\right)$	$\left(\frac{\text{arcsec.}}{\text{cent.}^2}\right)$	$\left(\frac{\text{arcsec.}}{\text{cent.}^3}\right)$	$\left(\frac{\text{arcsec.}}{\text{cent.}^4}\right)$	$\left(\frac{\text{arcsec.}}{\text{cent.}^5}\right)$
ψ_A	—	5038.481507	−1.0790069	−0.00114045	0.000132851	-9.51×10^{-8}
ω_A	84381.406000	−0.025754	0.0512623	−0.00772503	-4.67×10^{-7}	3.337×10^{-7}
P_A		4.199094	0.1939873	−0.00022466	-9.12×10^{-7}	1.20×10^{-8}
Q_A		−46.811015	0.0510283	0.00052413	-6.46×10^{-7}	-1.72×10^{-8}
π_A		46.998973	−0.0334926	−0.00012559	1.13×10^{-7}	-2.2×10^{-9}
Π_A	629546.7936	−867.95758	0.157992	−0.0005371	−0.00004797	7.2×10^{-8}
ϵ_A†	84381.406000	−46.836769	−0.0001831	0.00200340	-5.76×10^{-7}	-4.34×10^{-8}
χ_A		10.556403	−2.3814292	−0.00121197	0.000170663	-5.60×10^{-8}
z_A	−2.650545	2306.077181	1.0927348	0.01826837	−0.000028596	-2.904×10^{-7}
ζ_A	2.650545	2306.083227	0.2988499	0.01801828	-5.971×10^{-6}	-3.173×10^{-7}
θ_A		2004.191903	−0.4294934	−0.04182264	-7.089×10^{-6}	-1.274×10^{-7}
p_A		5028.796195	1.1054348	0.00007964	−0.000023857	3.83×10^{-8}
X	−0.016617	2004.191898	−0.4297829	−0.19861834	7.578×10^{-6}	5.9285×10^{-6}
Y	−0.006951	−0.025896	−22.4072747	0.00190059	0.001112526	1.358×10^{-7}
$s + \frac{1}{2}XY$	0.0000940	0.00380865	−0.00012268	−0.07257411	0.00002798	0.00001562
γ_{J2000}		10.556403	0.4932044	−0.00031238	-2.788×10^{-6}	2.60×10^{-8}
ϕ_{J2000}	84381.406000	−46.811015	0.0511269	0.00053289	-4.40×10^{-7}	-1.76×10^{-8}
ψ_{J2000}		5038.481507	1.5584176	−0.00018522	−0.000026452	-1.48×10^{-8}
γ_{GCRS}	−0.052928	10.556378	0.4932044	−0.00031238	-2.788×10^{-6}	2.60×10^{-8}
ϕ_{GCRS}	84381.412819	−46.811016	0.0511268	0.00053289	-4.40×10^{-7}	-1.76×10^{-8}
ψ_{GCRS}	−0.041775	5038.481484	1.5584175	−0.00018522	−0.000026452	-1.48×10^{-8}

*Centuries (cent.) are Julian centuries of 36,525 days TT.

†The angle $\epsilon_0 \equiv \epsilon_A(t = 0)$.

P03 Earth rotation angle

- Using the new origin CIO

  Earth Rotation Angle: ERA = θ = k UT1 *;* dθ/dt = ω_3

  ERA(UT1)= 2π (0.7790572732640 + 1.00273781191135448 × (Julian UT1date – 2451545.0) (Capitaine, Guinot, McCarthy 2000)

not dependent on the precession-nutation model

- Using the equinox

  Greenwich sidereal Time: GST= GMST (UT1, TT) + “equation of the equinoxes”

  = θ (UT1) – EO

  $GMST_{P03}$ = 0".014 506 + θ + 4612".156 534 t + 1".391 5817 t^2

  - 0".000 000 44 t^3 + 0".000 0299 56 t^4 - 0.000000 0368 t^5

  (Capitaine, Chapront, Wallace 2003)

dependent on the precession-nutation model

The end