Implementing the IAU 2006 resolutions in the transformation between celestial and terrestrial systems

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IAU 2000 Resolutions (and IUGG 2003)

concerning the transformation between the celestial and terrestrial systems

IAU Resolution B1.3

Definition of BCRS and GCRS

IAU Resolution B1.6

IAU 2000 Precession-Nutation Model

IAU Resolution B1.7

Definition of Celestial Intermediate Pole

IAU Resolution B1.8

Definition and use of CEO and TEO

The transformation
between celestial and terrestrial systems

celestial motion of the reference pole
(model + observed celestial pole offsets)
IAU **IERS-EOP**

rotation angle
(model + observed UT1−TAI variations)
IAU **IERS-EOP**

terrestrial motion of the reference pole
(observed pole coordinates + predictions)
IERS-EOP

$$[GCRS]=Q(t)\,R(t)\,W(t)\,[ITRS]$$

use of intermediate reference systems

Celestial system (GCRS)

Terrestrial system (ITRS)

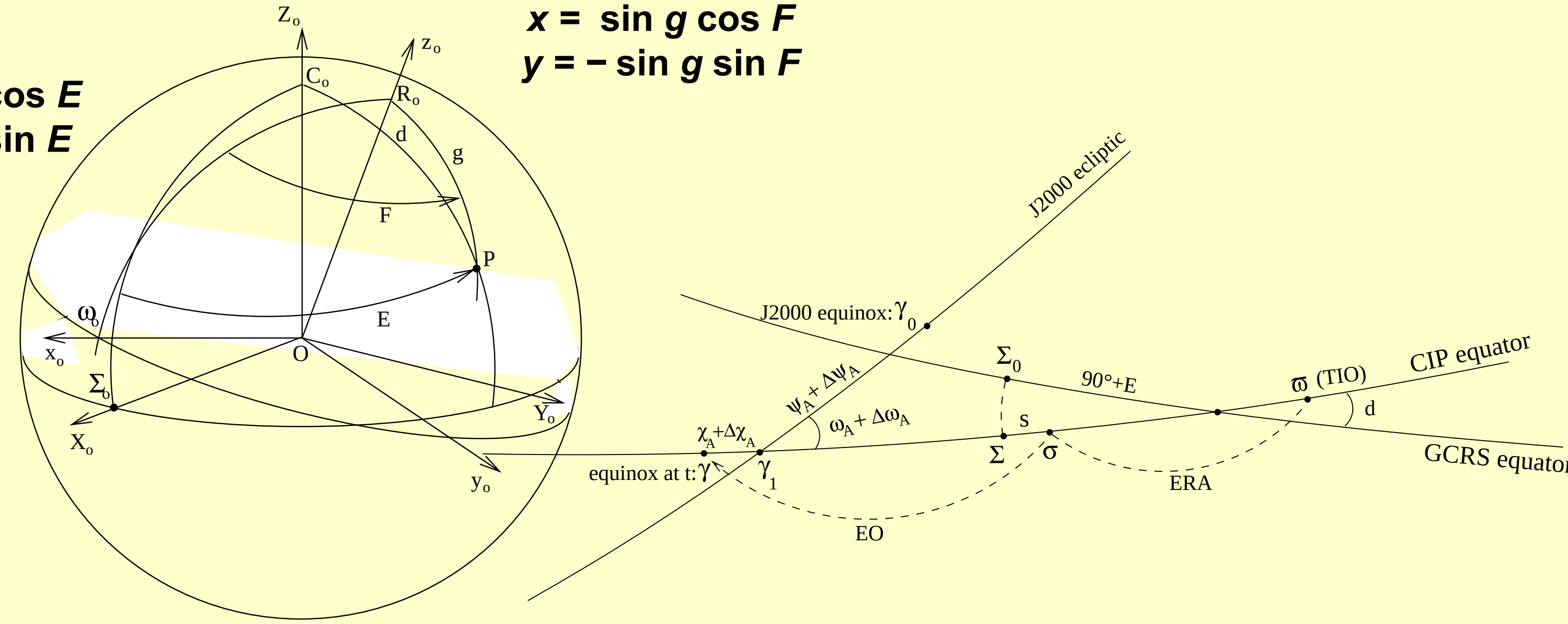
The celestial and terrestrial motions of the CIP and the ERA (IAU 2000 Resolution B1.8)

GCRS position of the CIP : *E*, *d*

$$X = \sin d \cos E$$
$$Y = \sin d \sin E$$

ITRS position of the CIP : *F*, *g*

$$x = \sin g \cos F$$
$$y = -\sin g \sin F$$



Main recommendations

of the IAU Working Group on Nomenclature for fundamental astronomy related to the pole and origin

- 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.
- Harmonizing the name of the pole and the origin to “intermediate” and therefore changing CEO/TEO to CIO/TIO.
- Using “system” in a broad sense rather than “frame” in this context of the intermediary system/frame.
- 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 Resolutions (and IUGG 2007)

concerning the transformation between the celestial and terrestrial systems

IAU Resolution B1

Adoption of the P03 Precession and definition of the ecliptic

(recommended by the IAU WG « Precession and the ecliptic »: 2003-2006)

IAU Resolution B2

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

(recommended by the IAU WG « Nomenclature for Fundamental Astronomy »: 2003-2006)

IAU Resolution B3

Re-definition of TDB

(recommended by the IAU WG « Nomenclature for Fundamental Astronomy »: 2003-2006)

The NFA WG Glossary

a few examples of newly proposed terms

<u>Celestial Intermediate Origin (CIO):</u> 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.

<u>equation of the origins:</u> 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).

<u>CIO locator (denoted s)</u> : 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*.

<u>TIO locator (denoted s′):</u> 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.

The NFA WG Glossary

a few examples of newly proposed terms

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.

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."

IAU Precession-nutation

1) 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 and with IAU 2000A nutation

2) IAU 2006 Resolution B1

- adopted the P03 precession (Capitaine et al. 2003) : ***2nd 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*

$$dJ_2/dt = -0.3001 \times 10^{-9}\ century^{-1}.$$

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 $\epsilon_0 \equiv \epsilon_A(t=0)$.

IAU 2006 expressions for the GCRS coordinates of the CIP

$$X = -0.''016617 + 2004.''191898\, t - 0.''4297829\, t^2$$
$$- 0.''19861834\, t^3 - 0.''000007578\, t^4 + 0.''0000059285\, t^5$$
$$+ \sum_i [(a_{s,0})_i \sin(\text{ARGUMENT}) + (a_{c,0})_i \cos(\text{ARGUMENT})]$$
$$+ \sum_i [(a_{s,1})_i\, t \sin(\text{ARGUMENT}) + (a_{c,1})_i\, t \cos(\text{ARGUMENT})]$$
$$+ \sum_i [(a_{s,2})_i\, t^2 \sin(\text{ARGUMENT}) + (a_{c,2})_i\, t^2 \cos(\text{ARGUMENT})]$$
$$+ \ldots$$

$$Y = -0.''006951 - 0.''025896\, t - 22.''4072747\, t^2$$
$$+ 0.''00190059\, t^3 + 0.''001112526\, t^4 + 0.''0000001358\, t^5$$
$$+ \sum_i [(b_{c,0})_i \cos(\text{ARGUMENT}) + (b_{s,0})_i \sin(\text{ARGUMENT})]$$
$$+ \sum_i [(b_{c,1})_i\, t \cos(\text{ARGUMENT}) + (b_{s,1})_i\, t \sin(\text{ARGUMENT})]$$
$$+ \sum_i [(b_{c,2})_i\, t^2 \cos(\text{ARGUMENT}) + (b_{s,2})_i\, t^2 \sin(\text{ARGUMENT})]$$
$$+ \ldots$$

precession; frame-bias effects; nutation; cross terms precession x *nutation*

IAU 2006 expressions for the Earth rotation angle

- CIO based

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

  $ERA(UT1) = 2\pi$ (0.7790572732640 + 1.00273781191135448 × (Julian UT1date − 2451545.0) (Capitaine, Guinot, McCarthy 2000)

***not dependent** on the precession-nutation model*

- equinox based

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

  $= \theta$ (UT1) − EO

  $$GMST_{P03} = 0''.014\,506 + \theta + 4612''.156\,534\, t + 1''.391\,5817\, t^2 \square$$
  $$- 0''.000\,000\,44\, t^3 + 0''.000\,0299\,56\, t^4 - 0.000000\,0368\, t^5$$

  (Capitaine, Chapront, Wallace 2003)

***dependent** on the precession-nutation model*

P03 adjustments to IAU 2000 nutation

effects of obliquity and J2 rate on nutation

$$d_1\psi = -8.1 \ \sin\Omega - 0.6 \ \sin(2F - 2D + 2\Omega)$$

Obliquity effect : *x* ($\sin\varepsilon_{IAU}/\sin\varepsilon_{P03}$)

$$\begin{aligned} d_2\psi &= +47.8\,t\,\sin\Omega + 3.7\,t\,\sin(2F - 2D + 2\Omega) \\ &\quad +0.6\,t\,\sin(2F + 2\Omega) - 0.6\,t\,\sin 2(\Omega) \\ d_2\omega &= -25.6\,t\,\cos\Omega - 1.6\,t\,\cos(2F - 2D + 2\Omega) \end{aligned}$$

J_2 rate effect : *x* (J_2 *rate* /J_2) *t*

$$\mathrm{d}X = 18.9\,t\,\sin\Omega + 1.5\,t\,\sin(2F - 2D + 2\Omega)$$

$$\mathrm{d}Y = -25.6\,t\,\cos\Omega - 1.6\,t\,\cos(2F - 2D + 2\Omega)$$

(*J2 rate /J2* =-2.78 x 10^{-6})

IERS Conventions Chapter 5: implementation of IAU 2006 Resolutions

Transformation between the celestial and terrestrial reference systems

5.1 The Framework of IAU 2000 Resolutions ***(+ IAU 2006) (+ NFA WG Recom)***

5.2 Implementation of IAU 2000 Resolutions ***(+ IAU 2006) (+ NFA WG Recom)***

5.3 Coordinate Transformation consistent with the IAU 2000 Resolutions
(+ IAU 2006) (+ NFA WG Recom)

5.4 Parameters to be used in the transformation

- 5.4.1 *Schematic representation of the motion of the CIP*
- 5.4.2 *Motion of the CIP in the ITRS*
- 5.4.3 *Position of the TIO in the ITRS* ***(+ NFA WG Recom)***
- 5.4.4 *Earth Rotation Angle* ***(+ NFA WG Recom)***
- 5.4.5 *Motion of the CIP in the GCRS* ***(+ IAU 2006) (+ NFA WG Recom)***
- 5.5.6 *Position of the CIO in the GCRS* ***(+ IAU 2006) (+ NFA WG Recom)***

5.5 IAU 2000A and IAU 2000B Precession-Nutation model ***(+ IAU 2006)***

- 5.5.1 *Description of the model* ***(+ IAU 2006)***
- 5.5.2 *Precession developments compatible with the IAU2000 model* ***(+ IAU 2006)***

(+ IAU 2006): *to be updated with introducing the IAU 2006 Resolutions*
(+ NFA WG Recom): *to be updated with introducing the IAU NFA WG terminology*

IERS Conventions Chapter 5: implementation of IAU 2006 Resolutions

Transformation between the celestial and terrestrial reference systems

5.6 Procedure to be used for the transformation consistent with IAU2000 Resolutions ***(+ IAU 2006) (+ NFA WG Recom)***

5.7 Expression of Greenwich Sidereal Time using the CIO ***(+ IAU 2006) (+ NFA WG Recom)***

5.8 The Fundamental Arguments of Nutation Theory
- 5.8.1 *The multipliers of the fundamental arguments of nutation theory*
- 5.8.2 *Development of the arguments of luni-solar nutation*
- 5.8.3 *Development of the arguments for the planetary nutation*

5.9 Prograde and Retrograde Nutation Amplitudes

5.10 Procedures and IERS Routines for Transformations from ITRS to GCRS (***+ IAU 2006***) ***:*** see P. Wallace presentation)

5.11 Notes on the new procedure to transform from ICRS to ITRS
- Figure 1 ***(+ IAU 2006) (+ NFA WG Recom)***

References ***(+ IAU 2006) (+ NFA WG Recom)***

Changes to be implemented
in the IERS Conventions

1) Implementation of the IAU 2006 precession-nutation procedure in Chapter 5

Suggested method : CIO based computing the IAU 2006 matrix transformation for bias, precession and nutation using direct series for X, Y and s+ XY/2

Capitaine N., Wallace P.T., (2006, A&A 450, 855-872): *"High* precision *methods for locating the celestial intermediate pole and origin"*

Wallace P.T., Capitaine N., (2006, A&A 459, 981-985): *"Precession-nutation procedures consistent with IAU 2006 resolutions"*

2) Suggested changes associated with the IAU 2006 Resolutions implementation

- Make numerical values in Table 1 consistent with the new resolutions (e.g. obliquity and precession rate at J2000)

- improving the way Chapter 5 is organized

- avoid redundancy in formulas or procedures (e.g. expression of EO derived from s)

- introduce a standard interpolation method in order to avoid inconsistencies at μ*as level between interpolated values with various methods*

- introduce the rigorous procedure $(dpsi, deps)_{IAU1976/1980} \rightarrow (dX, dY)_{IAU2006}$