The IAU Recommendations on Reference Systems and their Applications

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Why?

- Previous definitions were not precise at the level of μseconds of arc
- Improved geophysical nutation model delivered by IAU/IUGG Working Group
- Defining astronomical observations not sensitive to the ecliptic

AAS 204th Meeting, Special Session « The Reference System Resolutions of the IAU », 31 May2004

IAU Resolutions for the Celestial Reference System

IAU GA 1988 extragalactic objects to define the celestial reference frame,

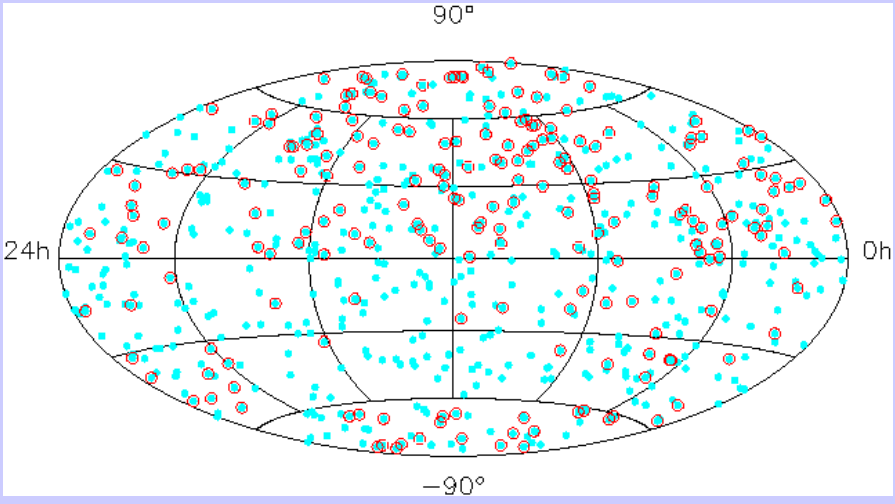
IAU GA 1991

- adopts GR as the fundamental theory
- specifies continuity with existing stellar and dynamic realizations,

IAU GA 1997

- from 1 January 1998, the IAU celestial reference system is the *International Celestial Reference System (ICRS)*
- corresponding fundamental reference frame is the *International Celestial Reference Frame (ICRF)*

The ICRF



Adopted as the International Celestial Reference System by the IAU (1st January 2003)

Change from FK5 catalog to ICRF

- FK5 -

- realized by positions and proper motions of bright stars

  (precision : 20 mas, 80 mas/c)

- positions and proper motions referred to the mean pole and mean equinox

- ICRF –

- realized by barycentric directions of extragalactic objects

  (precision = 0.4 mas)

- no proper motions
- no reference to the mean pole and mean equinox

Resolutions of the 2000 IAU GA on the celestial reference systems

- IAU Resolution B1.3

Definition of BCRS and GCRS

Aim: coordinate systems in the framework of GR

- IAU Resolution B1.6

IAU 2000 Precession-Nutation Model

Aim: submilliarcsecond accuracy

- IAU Resolution B1.7

Definition of Celestial Intermediate Pole

Aim: realization of the pole in the high frequency domain

- IAU Resolution B1.8

Definition and use of CEO and TEO

Aim: accurate estimation of parameters : UT1, Precession-nutation separately

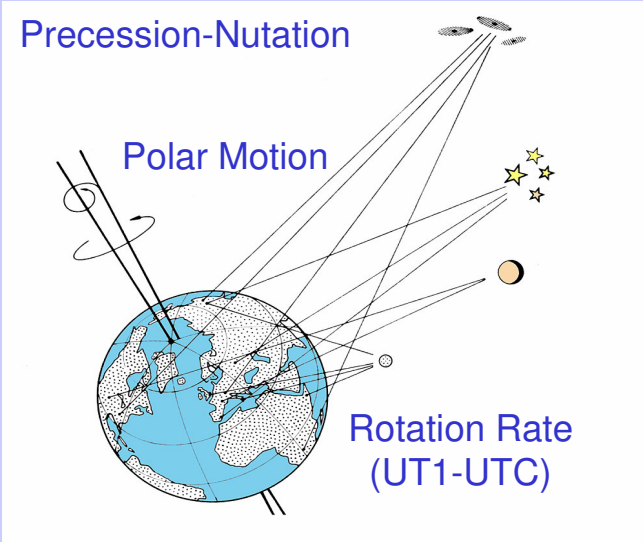
IAU 2000 Resolution B1.3

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

- 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*

Earth Orientation Parameters

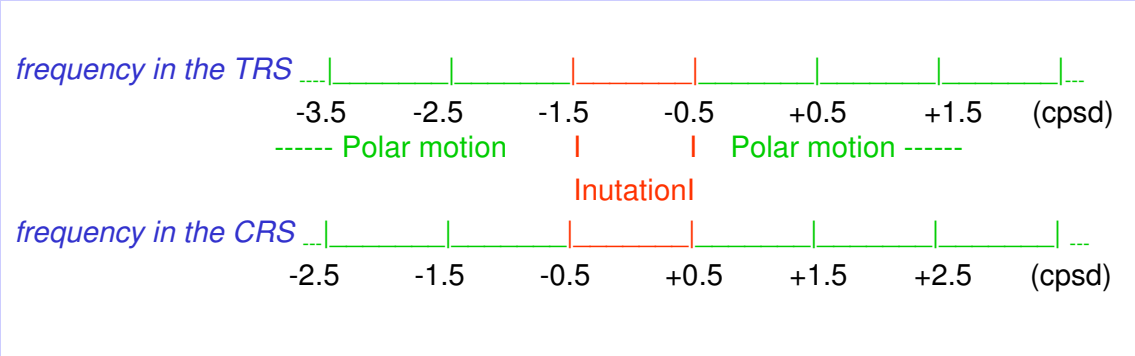


Definition of the Celestial Intermediate Pole (IAU Resolution B1.7)

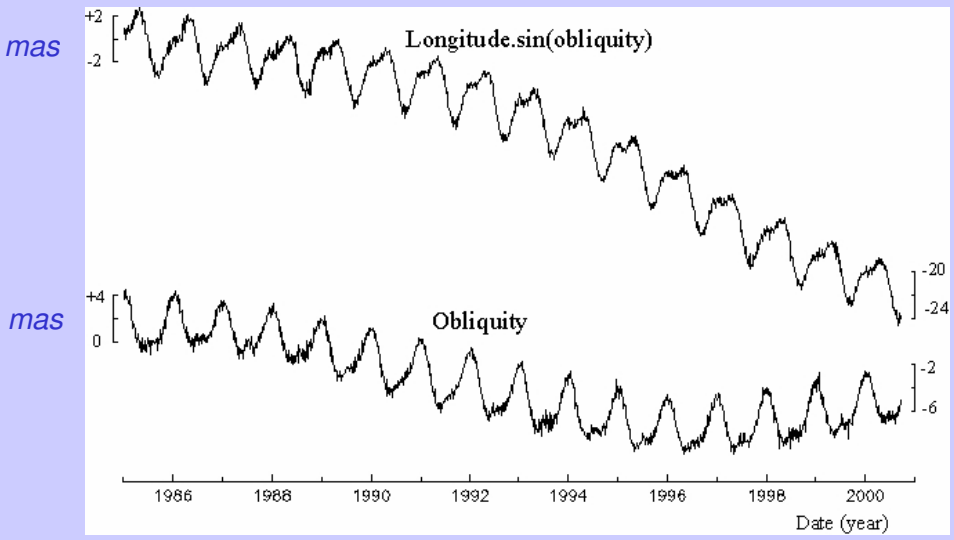
Definition of the CIP for high frequency variations

- Celestial motion is the IAU 2000 precession-nutation for periods > two days + offsets

- Nutations with periods < two days included in the model for motion in the TRS



VLBI estimates of celestial pole offsets w.r.t. the IAU 1976/1980 precession-nutation model



VLBI provides the actual position of the celestial pole

Implementation of Resolutions B1.6

- *Nutation*

  IAU2000A : ~ 650 luni-solar terms and ~ 650 planetary terms at 1 μas

  IAU 2000 B (its shorter version): ~80 terms for 1 mas level

- *Precession*

  IAU 2000 : *IAU 1976* + (VLBI) corrections to precession rates

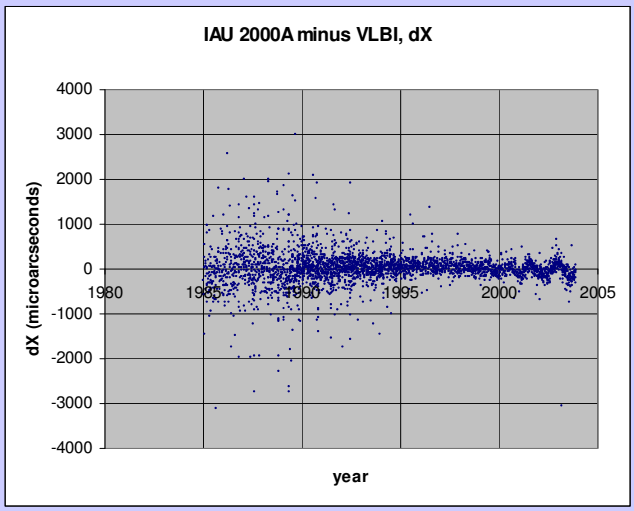
  $d\psi_A$ (IAU 2000) = - 0".29965/cy ; $d\omega_A$ (IAU 2000) = - 0".02524 /cy

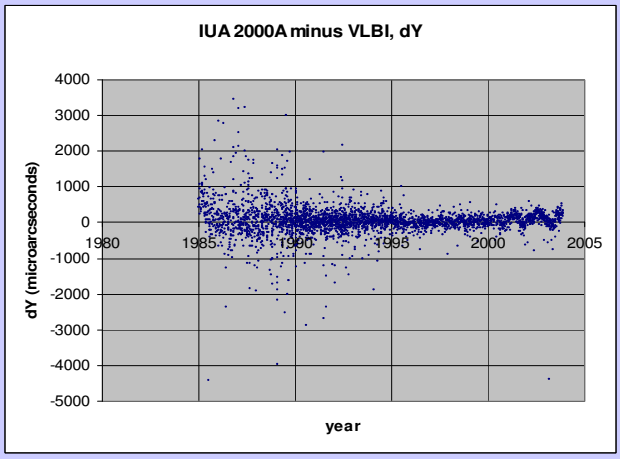
- *Celestial pole offsets* at J2000

  IAU 2000 frame biases (VLBI estimates)

  ξ_0 (IAU 2000) = - 16.6 mas ; η_0 (IAU 2000) = - 6.8 mas

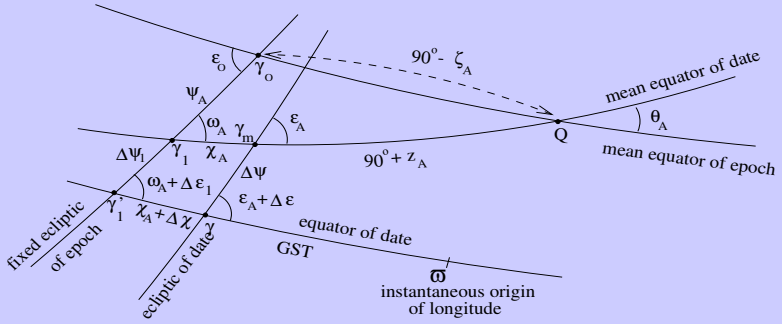
VLBI celestial pole offsets w.r.t. the IAU 2000 precession-nutation model



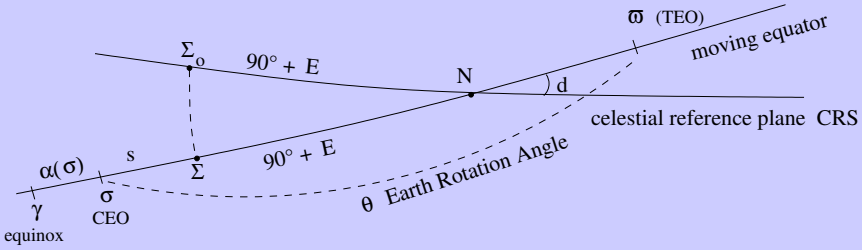


Implementation of Resolutions B1.8

Classical transformation: equinox-based



Recommended new transformation: CEO based



Transforming Coordinates

Rotation angle (observed/predicted)

Reference pole motion in space (model/observed)

Reference pole motion on Earth (observed/predicted)

$$[CRS] = Q(t)\ R(t)\ W(t)\ [TRS]$$

Celestial System

Terrestrial System

Motion of the Pole in the Terrestrial System

"Old"

$$W(t) = R_1(y_p) R_2(x_p)$$

- x_p and y_p provided by IERS

"New"

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

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

- same x_p and y_p
- corrections for ocean tides
- short-period nutations
- a_c and a_a: average amplitudes of Chandler and annual polar motions

Software at http://maia.usno.navy.mil/ch5subs.html
SP2000 subroutine produces s'

Earth Rotation Angle

"Old"

$$R(t) = R_3(-GST)$$

- GST computed using UT1-UTC from IERS
- Tidal corrections to UT1
- GST referred to the equinox

"New"

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

- θ computed using same UT1-UTC
- Same tidal corrections
- θ referred to the CEO

Software at http://maia.usno.navy.mil/ch5subs.html
ERA2000 subroutine produces the Earth rotation angle θ

Change of the origin on the intermediate equator

Using CEO/CIO

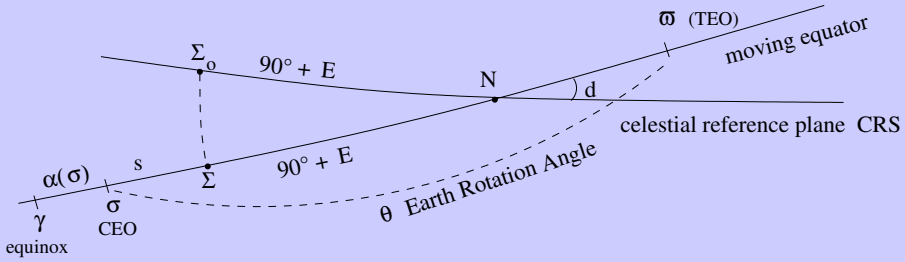
a) ERA = θ = *k UT1 ;* $d\theta/dt = \omega_3$

b) "intermediate" right ascensions referred to the CEO/CIO

Using equinox *(with implicit use of CEO/CIO)*

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

b) right ascensions referred to the true equinox



Motion of the Pole in the Celestial System

"Old"

$$Q(t) = [P][N]$$
$$[P] = R_3(\zeta_A)R_2(-\theta_A)R_3(z_A)$$
$$[N] = R_1(-\varepsilon_A)R_3(\Delta\psi)R_1(\varepsilon_A + \Delta\varepsilon)$$

where all quantities are provided as a function of time

- Free-core nutation model available from IERS

"New"

$$Q(t) = \begin{pmatrix} 1-aX^2 & -aXY & X \\ -aXY & 1-aY^2 & Y \\ -X & -Y & 1-a(X^2+Y^2) \end{pmatrix} \bullet R_3(s)$$

where X and Y are functions of time, and

$$a = \tfrac{1}{2} + \tfrac{1}{8}(X^2 + Y^2)$$
$$s = \int_{t_0}^{t} a\left(\frac{dX}{dt}Y - X\frac{dY}{dt}\right)dt$$

- Same free-core nutation model

Software at http://maia.usno.navy.mil/ch5subs.html
- XYS2000A subroutine provides X, Y, s
- BPN2000 subroutine provides bias-precession-nutation matrix
- IAU2000A available at ftp://maia.usno.navy.mil/conv2000/chapter5/IAU2000A.f.
- IAU2000B is available at ftp://maia.usno.navy.mil/conv2000/chapter5/IAU2000B.f

Post-2003 rigorous transformation (microarcsecond level)

- B : Bias : CRS → mean matrix at epoch $(\xi_0, \eta_0, d\alpha_0)$
- P : Precession
- N : Nutation *IAU 2000A*

CEO-based (New) transformation

Q(X, Y, s) includes bias + precession + nutation + cross terms

→ intermediate system

Equinox-based (Classical) transformation

B P N: product of 3 transformations for (i) bias, (i) precession, (iii) nutation

→ true equator and equinox

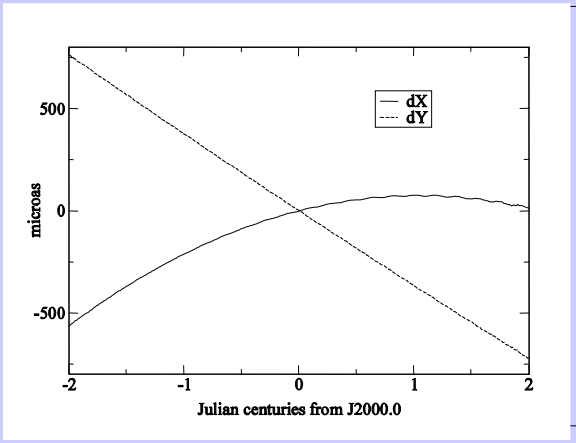
Further improvements

(i) IAU WG "Precession and the ecliptic"

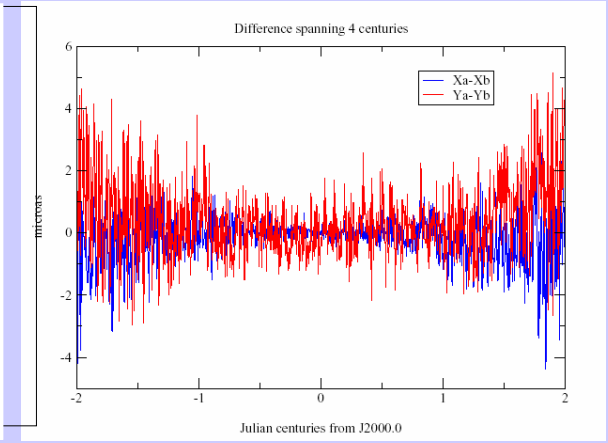
(ii) IAU WG "Nomenclature for fundamental astronomy"

Differences in the X, Y celestial position of the pole

period 1800- 2200



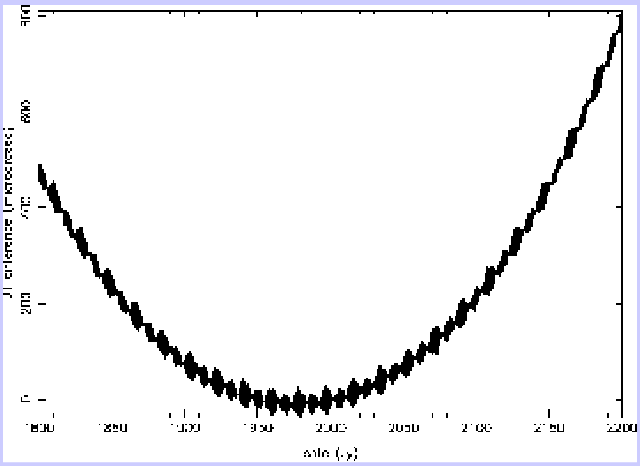
post-2003 - pre-2003 procedures



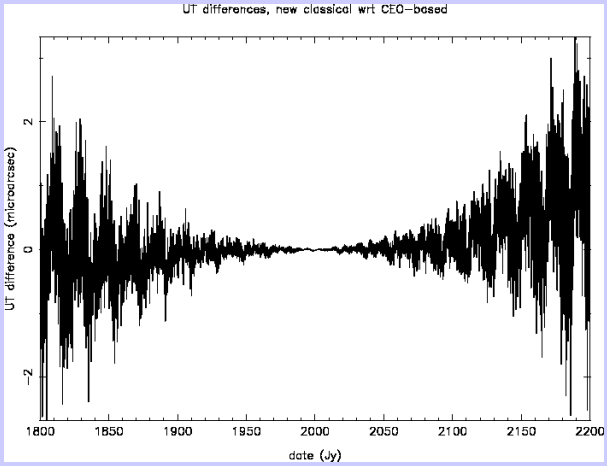
CEO-based - rigorous equinox-based

Differences in UT1

period 1980-2020



post-2003 - pre-2003 procedures



CEO-based - rigorous equinox-based

Concluding remarks

- *IAU 2000 recommendations bring significant improvements in the*
  - definition of the International Celestial Reference System
  - procedures to be used in its realization
- *The IAU recommendations include*
  - an improved precession-nutation formulation
  - more rigorous definitions of the pole and equatorial origin of the reference system
- *The consequences for the whole astronomical community are*
  - improvement of the IAU precession-nutation model,
  - a new definition of Universal Time and its relationship to sidereal time
  - the abandonment of the intermediary reference to the ecliptic and equinox
- *The International Earth Rotation Service (IERS)*
  - has implemented these recommendations
  - provides the data necessary to implement the previous definitions