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
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
    \[(\text{precision} : 20 \text{ mas}, 80 \text{ mas/c})\]
  • positions and proper motions referred to the mean pole and mean equinox

- ICRF –
  • realized by barycentric directions of extragalactic objects
    \[(\text{precision} = 0.4 \text{ mas})\]
  • 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
  \textit{Definition of BCRS and GCRS}
  \textit{Aim:} coordinate systems in the framework of GR

• IAU Resolution B1.6
  \textit{IAU 2000 Precession-Nutation Model}
  \textit{Aim:} submilliarcsecond accuracy

• IAU Resolution B1.7
  \textit{Definition of Celestial Intermediate Pole}
  \textit{Aim:} realization of the pole in the high frequency domain

• IAU Resolution B1.8
  \textit{Definition and use of CEO and TEO}
  \textit{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

- Precession-Nutation
- Polar Motion
- Rotation Rate (UT1-UTC)
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

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<th>frequency in the TRS</th>
<th>...</th>
<th>-3.5</th>
<th>-2.5</th>
<th>-1.5</th>
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<th>+0.5</th>
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<tr>
<td>frequency in the CRS</td>
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<td>...</td>
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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
    \[ d\varphi_A (IAU 2000) = -0'.29965/cy \quad ; \quad d\omega_A (IAU 2000) = -0'.02524/cy \]

- **Celestial pole offsets at J2000**
  - **IAU 2000** frame biases (VLBI estimates)
    \[ \zeta_0 (IAU 2000) = -16.6 \text{ mas} \quad ; \quad \eta_0 (IAU 2000) = -6.8 \text{ mas} \]
Implementation of Resolutions B1.8

Classical transformation: equinox-based

Recommended new transformation: CEO based

Transforming Coordinates

Reference pole motion in space (model/observed) -> Rotation angle (observed/predicted) -> 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”**

\[ W(t) = R_1(-s')R_2(y_p)R_3(x_p) \]

- 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


SP2000 subroutine produces \( s' \)

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**Earth Rotation Angle**

**“Old”**

\[ R(t) = R_3(-\text{GST}) \]

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

**“New”**

\[ R(t) = R_3(-\theta) \]

- \( \theta \) computed using same UT1-UTC
- Same tidal corrections
- \( \theta \) referred to the CEO


ERA2000 subroutine produces the Earth rotation angle \( \theta \)
Change of the origin on the intermediate equator

Using CEO/CIO

\[ \text{ERA} = \theta = k \, UT1 \quad \text{d} \theta / \text{d}t = \omega_3 \]

b) “intermediate” right ascensions referred to the CEO/CIO

Using equinox (with implicit use of CEO/CIO)

a) Sidereal time = \( \theta (UT1) + \text{“equation of the origins”} \)
   \[ = \text{GMST} (UT1, TT) + \text{“equation of the equinoxes”} \]

b) right ascensions referred to the true equinox

Motion of the Pole in the Celestial System

“Old”

\[ \mathbf{Q}(t) = [\mathbf{P}][\mathbf{N}] \]
\[ \mathbf{P} = R_3(\zeta, \Delta \psi) R_2(-\theta, \Delta \psi) R_1(z, \Delta \psi) \]
\[ \mathbf{N} = R_1(-\epsilon, \Delta \psi) R_3(\Delta \psi) R_1(\epsilon, \Delta \epsilon) \]

where all quantities are provided as a function of time

- Free-core nutation model available from IERS

“New”

\[ \mathbf{Q}(t) = \begin{pmatrix} 1-aX^2 & -aXY & X \\ -aXY & 1-aY^2 & Y \\ -X & -Y & 1-a(X^2+Y^2) \end{pmatrix} \cdot R_2(s) \]

where \( X \) and \( Y \) are functions of time, and

\[ a = \frac{1}{2} \sqrt{\frac{1}{2} (X^2 + Y^2)} \]
\[ s = \int \left( \frac{dX}{dt} - X \frac{dY}{dt} \right) dt \]

- Same free-core nutation model


- XYS2000A subroutine provides \( X, Y, s \)
- BPN2000 subroutine provides bias-precession-nutation matrix
**Post-2003 rigorous transformation**  
**(microarcsecond level)**

- **B**: Bias : CRS $\rightarrow$ 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 $\rightarrow$ intermediate system

**Equinox-based (Classical) transformation**

$B P N$: product of 3 transformations for (i) bias, (i) precession, (iii) nutation $\rightarrow$ true equator and equinox

Further improvements
(i) IAU WG “Precession and the ecliptic”  
(ii) IAU WG “Nomenclature for fundamental astronomy”

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**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