The IAU Commission “Earth Rotation” and the IAU definition of the pole and UT1

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Introduction

At the occasion of the centenary of the IAU Commission 19,

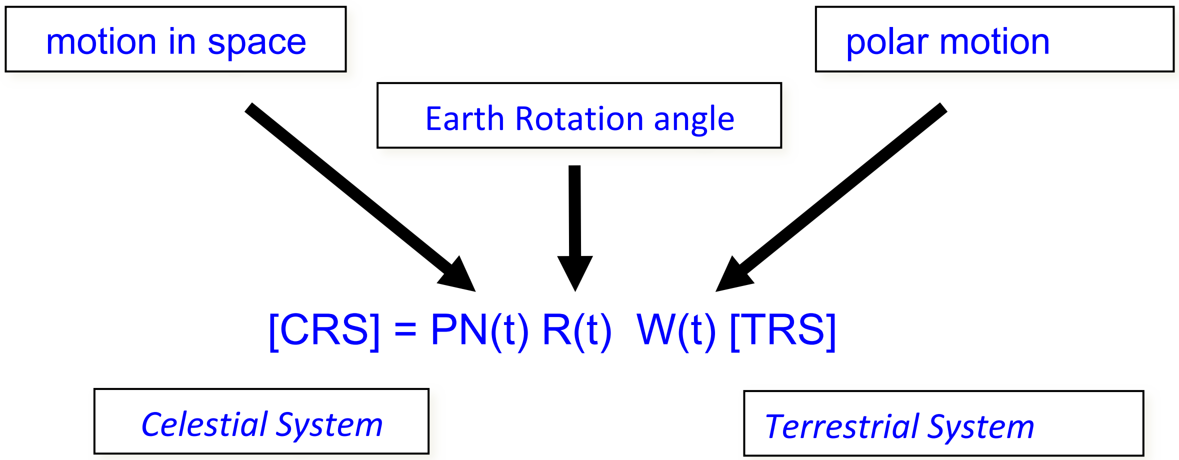
this presentation recalls the progresses (*theoretical, observational and nomenclature aspects)* in two issues of importance for IAU Commission *"Earth Rotation" which have been discussed within several IAU WG, in meetings and Resolutions, from 1964 to 2019:*

- *The definition of the pole*
  - *the pole that is provided by the observations*
  - *the pole to be used in the theory of nutation*
- *The definition of UT1*
  - *based on the IAU system of astronomical constants and PN model*
  - *based on the origin adopted on the mean celestial equator*

The definition of the pole

Reference axis in theory and observations of Earth rotation

The general form of the coordinate transformation form the TRS to the CRS at the date t is :



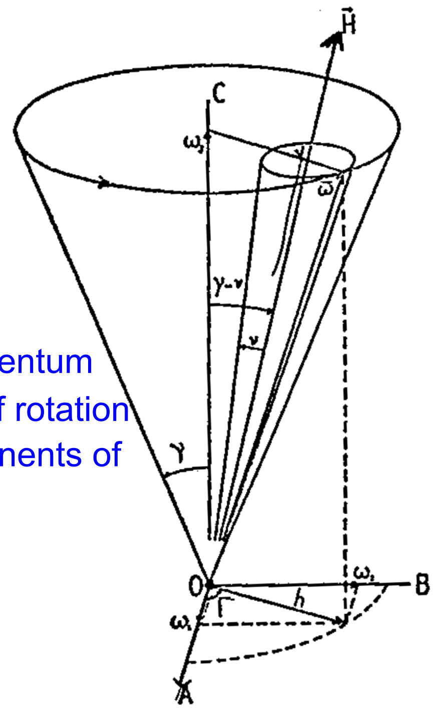
This transformation makes use of a pole of reference which is the pole as realized by the matrix transformation PN(t) for precession-nutation using the conventional model.

IAU discussion/recommendations on the reference pole: 1963-1979

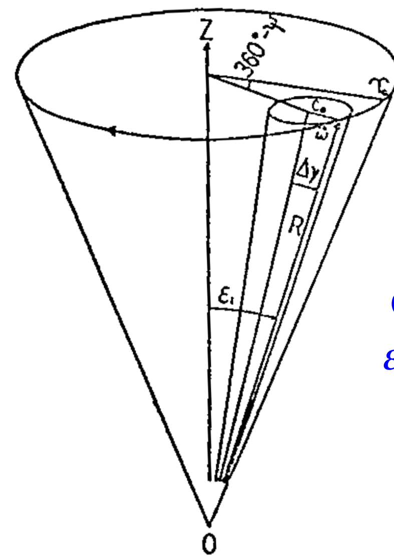
- The instantaneous pole of rotation (IRP) was the pole of reference in the IAU 1964 nutation based on Woolad (1953) theory of nutation (providing nutation for the various axes).
- Fedorov (1963), Jeffreys (1963) and Atkinson (1975) questioned this choice and recommended to use rather the pole either of the axis of figure (Tisserand axis for a non-rigid Earth model: geophysical concept), or the axis of angular momentum (kinematical concept).
- Referring to the IRP or to the pole of the axis of angular momentum separates the forced motion in the CRS into two parts: the celestial part (PN) and the terrestrial part (the forced « diurnal polar motion », or « diurnal nutation », or « forced variation of latitude »), which corresponds to the « Oppolzer terms » in space.
- Atkinson (1975) showed that optical astrometric observations cannot directly provide the IRP. An IAU 1976 recommendation was to refer to the Atkinson's pole, obtained by adding the « Oppolzer terms » to the celestial motion of the IRP.
- After long and detailed discussions within IAU WGs, and the IAU Symposium 78 (Kiev, 1977), the final 1979 IAU recommendation was to refer to the *Celestial Ephemeris Pole* (cf. Atkinson's pole) by including the forced diurnal polar motion into the celestial nutation.

Relative motions between various Earth reference axes: Poinsot representation

OC: axis of figure
OH: axis of angular momentum
0ω: instantaneous axis of rotation
ω_1, ω_2: equatorial components of Euler's motion



(a) The free Eulerian motion within the Earth
and the diurnal motion of **ω** *around* **H**



OZ: axis of the ecliptic
ε : obliquity of the ecliptic

(b) The forced precession-nutation in space
and the diurnal motion of **ω** *around* **C**

from E. Woolard, 1953 « Theory of the rotation of the Earth around its center of mass »,

Oppolzer terms in space or forced « diurnal nutation »

$$\delta\psi = +AC\gamma_0 \sin\theta \cos(\varphi + \Gamma_0)$$

sin	*l*	*l'*	*F*	*D*	Ω
+0.01615″	0	0	+2	0	+2
− 338	0	0	0	0	+1
+ 334	0	0	+2	0	+1
+ 309	+1	0	+2	0	+2
+ 753	0	0	+2	−2	+2

$$\delta\theta = +AC\gamma_0 \sin\theta \cos(\varphi + \Gamma_0) - 0.00868''$$

cos	*l*	*l'*	*F*	*D*	Ω
+0.00590″	0	0	+2	0	+2
+ 113	+1	0	+2	0	+2
− 100	0	0	0	0	+1
+ 99	0	0	+2	0	+1
− 97	+1	0	0	0	0
+ 275	0	0	+2	−2	+2

Free motion and Oppolzer terms (difference of the PN motion between **C** *and* **H**)
for a rigid Earth (Woolard 1953) (terms larger than 1 mas)

$$\Delta\varphi = +0.0066''\sin(S) - 0.0051''\sin(S - 2\leftmoon) - 0.0022''\sin(S - 2L) - 0.0010''\sin(S - 2\leftmoon - \Omega) - 0.0010''\sin(S - 3\leftmoon + \Gamma') + 0.0009''\sin(S - \Omega).$$

Fedorov's expression (1963) for the variation of latitude for an elastic Earth due to the « forced diurnal nutation » (of **H** *within the Earth due to PN).*
S: local sidereal time

The Celestial Ephemeris Pole

- The IAU-1980 theory of nutation (Seidelamnn et al. 1982), resulting for the work of the WG on nutation (1977-1978) adopted a new reference pole, the *Celestial Ephemeris Pole (CEP)*, to which the numerical values of the conventional model refers.

- These numerical values have been computed such as they include the *forced diurnal polar motion*, which thus has no more to be considered as a separate part of the forced motion of the pole.

- A tentative conceptual definition of the CEP has been given as the « pole that has no nearly-diurnal motion with respect to a space-fixed coordinate system or an Earth-fixed coordinate system », or « the center of the quasi-circular paths of the stars in the sky.

IAU discussion/recommendations on the reference pole: 1980-2000

- Significant improvements have been achieved in the PN and PM models :
  - The semi-diurnal and diurnal prograde nutations, which were considered to be negligible, have been computed in the nutation therory for a rigid Earth at a microarsecond level (1997).
  - Models for the daily and subdaily tidal variations in polar motion have been developped and included in the models for polar motion.
- Significant improvements have been achieved in processing EOP observations:
  - *« Celestial pole offsets »* (i.e. estimated corrections to the IAU precession-nutation) are published on a regular basis by the IERS since 1980,
  - Intensive EOP series are available (since 1994).
- A new definition of the CEP appeared to be necessary :
  - In order to be in agreement with modern models and observations and to take into account the overlapping between the GCRS and ITRS pole motions in the high frequency domain.
  - Several options were considered (1998-2000) by the IAU (mainly C19) WG T5 *« Computational Consequences » of the IAU Working Group ICRS.* https://syrte.obspm.fr/iau/iauWGT5/index.html
  - These proposals were discussed at the IAU Colloquium 180 "Towards Models and Constants for Sub Microsecond Astrometry » and the JD Discussion at the IAU 2000 GA.

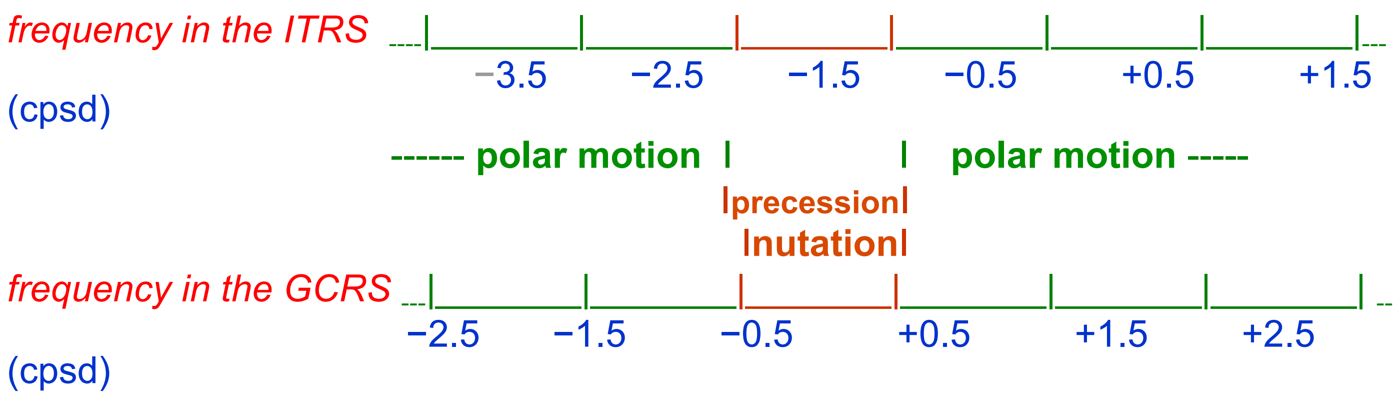
The Celestial Intermediate Pole (CIP)

- Was adopted by IAU 2000 Resolution B1.7
- Definition provided in the Glossary of the IAU Div 1 WG « Nomenclature for Fundamental Astronomy » (2003-2006):
  - Geocentric equatorial pole defined by IAU 2000 Resolution B1.7 as being the intermediate pole, in the transformation from the GCRS to the ITRS, separating nutation from polar motion. It replaced the CEP on 1 January 2003.
  - Its GCRS position results from (i) the part of precession-nutation with periods greater than 2 days, and (ii) the retrograde diurnal part of polar motion (including the free core nutation, FCN) and (iii) the frame bias.
  - Its ITRS position results from (i) the part of polar motion which is outside the retrograde diurnal band in the ITRS and (ii) the motion in the ITRS corresponding to nutations with periods less than 2 days.
  - The motion of the CIP is realized by the IAU precession-nutation plus time-dependent corrections provided by the IERS.

https://syrte.obspm.fr/iauWGnfa/NFA_Glossary.html

Representation of the CIP in the frequency domain

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



- GCRS motion of the CIP: IAU precession-nutation for periods > 2 days + offsets + retrograde diurnal part of polar motion
- nutations with periods < 2 days included in model for the pole motion in the ITRS

CIP definition is not a conceptual definitoon:

it is defined by a convention in the frequency domain

The definition of UT1

IAU procedures to define UT1 (1964-2000)

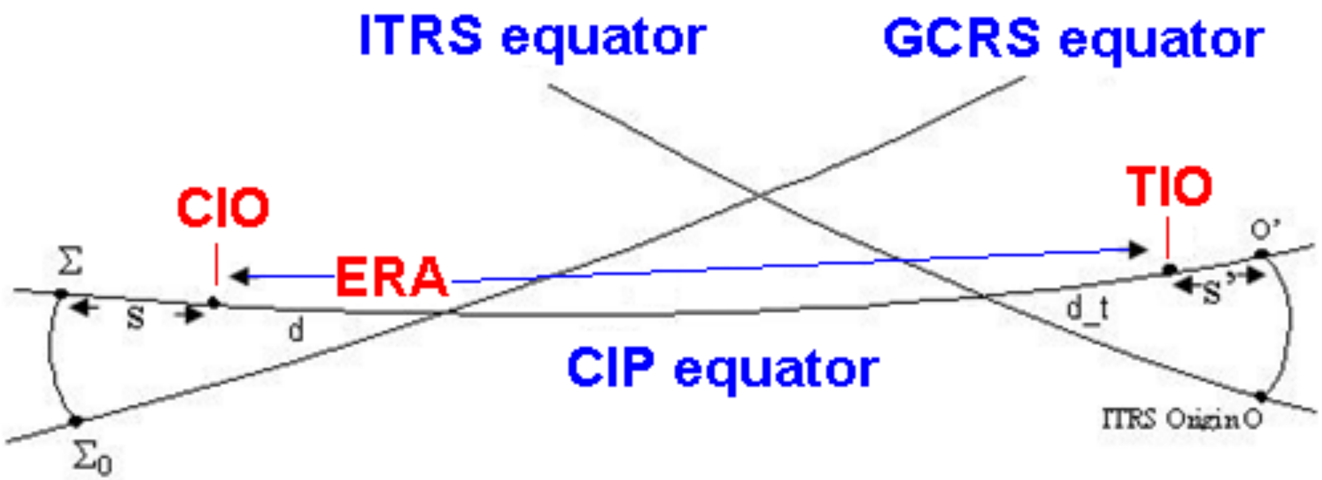
- Universal time, UT1, was defined by an expression relating it to mean sidereal time, which was directly obtained from the apparent right ascensions of transiting stars. The formula was based on Newcomb's (1895) expression for the right ascension of the fictitious mean sun.
- The IAU procedure was to use the relationship between GST and UT1 giving GMST at date t, followed by the relationship between GST and GMST and then to take into account the interval of GMST from 0h UT1 to the hour of observation.
- IAU 1976 Rec 4: The equation of the equinoxes (nutation in right ascension on the equator) causes periodic variations in the location of the true equinox of date and hence a variation in apparent sidereal time. In certain applications it may be convenient to remove the effects of these periodic variations by subtracting the equation of the equinoxes, but the origin of apparent right ascension shall continue to be the true equinox of date.
- The difference GST-GMST was provided, since the 1st January 1997, by the « complete » equation of the equinoxes.

Towards a new definition of UT1

- The IAU 1997 adopted the ICRS and the ICRF, which has no global rotation and is no longer dependent on the Earth's motion as was the FK5.
- There has been a significant improvement during the period 1980-2000 in both the precision and the temporal resolution of ER measurements as well as in the theory.
- These required that the PN parameters and GST, which were defined in the FK5 System, be replaced by more basic parameters referred to the ICRS.
- The important defect of the angle GST, which refers to the equinox of date, for representing ER, is that it mixes Earth rotation and precession-nutation.
- Using the « non-rotating origin », as proposed by Guinot (1979) in place of the the equinox as the origin on the CIP equator, clearly separates ER and PN.
- Such issues have been under consideration by the IAU WG T5 (1998-2000) and several possibilities have been compared. Proposals have been made.

Definition of the Earth rotation angle (ERA)

The Earth Rotation Angle(ERA): the angle from the *Celestial Intermediate Origin* (CIO) to the *Terrestrial Intermediate Origin* (TIO) on the CIP equator



does not involve the equinx

(Source: Capitaine et al. 2003)

The IAU Resolution on ERA and UT1

- The proposals for the Earth orientation parameters in the ICRS have been discussed together with the choice of a new origin on the celestial equator in place of the equinox.

- These have been discussed within the IAU WG T5 and at the IAU Symposium 180 « Towards Models and Constants for Sub Microsecond Astrometry » (Washington, 1999) and then at the IAU JD « Models and Constants for Sub-microarcsecond Astrometry » at the IAU 2000 GA .

- New celestial and terrestrial origins defined by this concept have been adopted (IAU 2000 Resolution B1.8) and afterwards renamed (IAU 2006 Resolution B2) "Celestial and Terrestrial Intermediate Origins" (CIO and TIO), defined as being the NRO on the equator of the Celestial Intermediate Pole (CIP).

- IAU 2000 Resolution B1.7 adopted the definitions of the ERA and UT1.

The IAU 2000 definition of UT1 (Resolution B1.8)

- UT1 is defined by its relation to the ERA in order to be in continuity with the previous definition:

  ERA(UT1)= 2π (0.7790572732640
  + 1.00273781191135448 × (Julian UT1date - 2451545.0)

- *Universal Time (UT1):* angle of the Earth's rotation about the CIP axis defined by its conventional linear relation to the *Earth Rotation Angle* (ERA)*;* dERA/dt **=** ω_3

- *UT1* is related to Greenwich apparent sidereal time through the ERA (and the equation of the origins, EO):

  GST = ERA(UT1) − EO:

$$\mathrm{EO} = -\, dT_0 - \int_{t_0}^{t} (\widehat{\psi_A + \Delta\psi_1}) \cos(\omega_A + \Delta\epsilon_1) dt + \chi_A - \Delta\psi \cos\epsilon_A + \Delta\psi_1 \cos\omega_A,$$

- *UT1 − UTC*: difference between the UT1 parameter derived from observation and the uniform time scale UTC

Thank you for your attention