THE IAU COMMISSION "EARTH ROTATION" AND THE IAU DEFINITION OF THE POLE AND UT1

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ABSTRACT. During the period 1964-2019, a number of IAU/IUGG resolutions on reference systems have introduced improved definitions and concepts concerning the Earth's rotation. The aim of this presentation is to report on the successive improvements of the IAU definition of the pole and UT1 and on the role of IAU Commission 19 and the IERS in this evolution. This presentation is part of the session on "The 100-year history of the IAU Commission 19/A2".

INTRODUCTION

The Earths orientation in space is traditionally represented by five Earth orientation parameters (EOP), which provide the direction of the pole in the International terrestrial reference system (ITRS) due to polar motion, the direction of the pole in the Geocentric celestial reference system (GCRS) due to precession-nutation, and the variations in the Earths diurnal rotation based on Universal Time, UT1. At the occasion of the centenary of IAU Commission 19 "Earth Rotation", this presentation recalls the evolution during the latest fifty five years regarding 1. the definition of the pole and 2. the definition of UT1, which have been regularly discussed and updated within several IAU Working Groups, meetings and resolutions during that period.

1. THE DEFINITION OF THE POLE

1.1 Relationships between various reference axes: Poinsot representation

Different axes (and the corresponding poles) are considered in the Earth's precession-nutation theory: the axis of figure, $\vec{C}$, the axis of angular momentum, $\vec{H}$, the instantaneous axis of rotation, $\vec{\Omega}$, and the axis of the ecliptic, $\vec{Z}$, ε being the obliquity of the ecliptic. In the case of a rigid Earth, according to Poinsot's representation, $\vec{\Omega}$ undergoes the following motions:

(a) The free *Eulerian motion* within the Earth (around $\vec{C}$), known as *polar motion* (PM) and its corresponding diurnal motion (i.e. the *sway*) in space around $\vec{H}$,

(b) The forced precession-nutation (PN) in space around $\vec{Z}$ and its corresponding retrograde nearly diurnal motion within the Earth, known as *diurnal nutation* or *forced diurnal polar motion*.

The differences between the forced motions of $\vec{C}$ and $\vec{H}$ (or $\vec{\Omega}$), are called *Oppolzer terms* (see Fig. **??**, Woolard 1953); they are responsible for corresponding (dynamical) *variations of latitude* in the astronomically observed values (see Fig. **??**, Fedorov 1963).

Referring to $\vec{\Omega}$ or $\vec{H}$ separates the forced motion in the GCRS into two parts: the celestial part (PN) and the terrestrial part (diurnal nutation), corresponding to Oppolzer terms in space.

1.2 IAU discussion/recommendations on the reference pole: 1964-1979

- The instantaneous pole of rotation (IRP) (of the axis of rotation) was the pole of reference of the IAU 1964 nutation based on Woolard (1953) theory of nutation for a rigid Earth (providing nutation for various axes). The corresponding forced diurnal polar motion of the IRP was considered separately.

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

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

Figure 1: Free motion and Oppolzer terms (with Delaunay variables $\ell, \ell', F, D, \Omega$) in ecliptic longitude ($\delta\psi$) and obliquity ($\delta\theta$) for a rigid Earth: terms larger than 1 mas (Woolard 1953).

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

Figure 2: Fedorov's expression (1963) for the *variation of latitude* for an elastic Earth, S being the local sidereal time.

- Fedorov (1963), Jeffreys (1963) and Atkinson (1973) questioned the choice of the axis of rotation and recommended to use instead the axis of figure (geophysical concept) or the axis of angular momentum (kinematical concept).

- Atkinson (1975) showed that optical astrometric observations "do no ever involve the axis of rotation but do give directly the instantaneous position on the celestial sphere of the pole of figure".

- Recommendation 4 to the IAU 1976 General Assembly (GA), associated with the adoption of the IAU 1976 System of astronomical constants and of the new fundamental reference system (FK5), was to refer the tabular nutation to the axis of figure in place of the axis of rotation.

- The discussion on a new theory of nutation for a non-rigid Earth began at the IAU Symposium 78 "Nutation and the Earth's rotation", held in Kiev in 1977 and sponsored by Commission 19 (see Fedorov et al. 1977 and Yatskiv & Korsun 2008). It recommended that the theory refers to the instantaneous axis of rotation of the mantle.

- Following a long and detailed discussion within the IAU Working Group (WG) on nutation formed after Symposium 78, the final IAU 1979 recommendation was to refer the new nutation model to a pole called the *Celestial Ephemeris Pole*, which was defined as including the forced diurnal polar motion into the celestial nutation (cf. Atkinson's proposal).

1.3 The Celestial Ephemeris Pole (1980-2000)

- The IAU-1980 theory of nutation (Seidelmann et al. 1982), adopted the Celestial Ephemeris Pole (CEP) to which the numerical values of the conventional model were referred.

- These numerical values have been computed so as to include the forced diurnal polar motion, consequenty this latter has no more to be considered separately in PM.

- 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".

- The following improvements have been progressively achieved in the PN and PM models as well as in processing EOP observations: the semi-diurnal and diurnal prograde nutations, which were considered to be negligible, have been considered in the nutation theory for a rigid Earth at a microarsecond level (1997); models for the daily and subdaily tidal variations in polar motion have been developed and included in the IERS models for polar motion; the "celestial pole offsets" (i.e. estimated corrections to the IAU PN) are published on a regular basis by the IERS since 1980; "intensive" EOP series are available since 1994.

- An improved 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 for an extended definition of the CEP were considered (1998-2000) by the IAU WG T5 "Computational Consequences" of the IAU Working Group ICRS: see `https://syrte.obspm.fr/iau/iauWGT5`.

- These proposals were discussed at the IAU Colloquia 178 (Cagliari, 1999) "Polar Motion: Historical and Scientific Problems" (see Capitaine 2000) and 180 (Washington, 2000) "Towards Models and Constants for Sub Microsecond Astrometry" and during the JD2 Discussion "Models and constants for sub-microarcsecond astrometry" (see Capitaine 2002) at the IAU 2000 GA in Manchester..

- A Resolution proposal on the CIP was submitted to the IAU 2000 GA.

1.4 The Celestial Intermediate Pole, IAU 2000

The Celestial Intermediate Pole (CIP) was adopted by IAU 2000 Resolution B1.7 together with Resolution B1.6 adopting the IAU 2000 IAU precession-nutation. The relevant definitions were specified by the IAU Div 1 WG "Nomenclature for Fundamental Astronomy": NFA WG: 2003-2006 (Capitaine et al. 2007); see the NFA Glossary at `https://syrte.obspm.fr/iauWGnfa`.

- The CIP is the 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.

It is important to note that the CIP definition is not a conceptual definition, but that the CIP is defined by a convention in the frequency domain. This new definition of the pole, extending the

CEP definition to the high frequency domain in both the GCRS and ITRS, has been implemented in the IERS Conventions 2003 (and then 2010) as well as in the astronomical almanacs.

2. THE DEFINITION OF UT1

2.1 IAU procedures to define UT1 (1964-2000)

- Universal time, UT1, was defined by an expression relating it to Greenwich mean sidereal time, GMST, 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 for deriving Apparent Greenwich sidereal time, GST, was (i) to use the relationship between GMST and UT1, giving GMST at date t, (ii) to take into account the interval of GMST from 0h UT1 to the hour of observation and (iii) to use the expression for the difference between GST and GMST, called the *equation of the equinoxes*.
- IAU 1976 Rec 4 recommended that, in certain applications, it may be convenient to remove the effects of the periodic variations by subtracting the equation of the equinoxes, while the origin of apparent right ascension should continue to be the true equinox of date.
- A new expression relating UT1 and GMST developed by Aoki et al. (1982) was adopted in order to be consistent with the IAU 1976 System of astronomical constants, the IAU 1976 precession, the IAU 1980 nutation and the FK5 equinox and to maintain the continuity of UT1 both in value and rate at the epoch of the change.

2.2 Towards a new definition of UT1 (1997-2000)

- IAU 1997 Resolution B2 adopted, in replacement of the FK5, the International celestial reference system (ICRS) and the international celestial reference frame (ICRF), which has no global rotation and is no longer dependent on the Earth's motion (as the FK5 was).
- 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 and be based on clarified concepts.
- The important defect of the angle GST, which refers to the equinox of date, for representing the Earth Rotation (ER), is that it mixes ER and PN, while the *non-rotating origin* (NRO) proposed by Guinot (1979) in place of the equinox as the origin on the CIP equator, clearly separates ER and PN.
- Such a proposal for a new equatorial origin extended a proposal from Atkinson & Sadler's (1951) for a new origin both for GST and right ascension (RA) obtained with subtracting nutation, in order to simplify a number of routine calculations.
- The difference GST−GMST was provided, since the 1st January 1997, by the "complete equation of the equinoxes", i.e. the accumulated precession and nutation in right ascension (Aoki & Kinoshita, 1983), which involved the NRO concept.
- The IERS Conventions 1996 considered the NRO as one possible option for the equatorial origin in the ITRS-to-GCRS transformation.

- The proposals for the EOP in the ICRS, including the choice of a new origin on the celestial equator in place of the equinox, have been under consideration by the IAU WG T5 (1998-2000) and several possibilities have been compared.

- Proposals have been discussed at the IAU Colloquium 180 and then at the IAU JD2 at the IAU 2000 GA (see Capitaine 2002).

- A Resolution proposal on the choice of the equatorial origin and its consequence on the definition of the Earth's angle of rotation and UT1 was submitted to the IAU 2000 GA.

2.3 The IAU 2000 Resolution on the Earth rotation angle and UT1

- New celestial and terrestrial origins 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 (w.r.t. the GCRS and the ITRS, respectively) on the equator of the Celestial Intermediate Pole (CIP).

- The *Earth Rotation Angle* (ERA) is the angle from the Celestial Intermediate Origin (CIO) to the Terrestrial Intermediate Origin (TIO) on the CIP equator (see Capitaine et al. 2003).

- ERA is such that dERA/dt = ω_3, i.e. the component of the instantaneous rotation vector along the CIP axis.

- IAU 2000 Resolution B1.8 adopted the definition of the ERA and the corresponding new definition of UT1.

2.4 The IAU 2000 definition of Universal Time (UT1)

- According to IAU 2000 B1.8 Resolution (see also the NFA Glossary), UT1 is the angle of the Earth's rotation about the CIP axis defined by its conventional linear relation to the ERA:

$$ERA(T_u) = 2\pi\,(0.779\,057\,273\,264\,0 + 1.002\,737\,811\,911\,354\,48\,T_u), \qquad (1)$$

  where T_u = (Julian UT1 date $-2\,451\,545.0$).

- The numerical coefficients in (1) ensured continuity in UT1 with the previous (1982) definition both in value and rate at the epoch of the change (Capitaine et al. 2000).

- UT1 can be related to GST through the ERA: GST = ERA(UT1)− EO, EO being the *equation of the origins*, i.e the distance between the CIO and the equinox along the CIP equator.

- UT1 is determined by observations (currently from VLBI observations of the diurnal motions of distant radio sources).

- UT1 can also be obtained from the uniform time scale UTC by using the quantity UT1−UTC, which is provided by the IERS.

These new definitions of the ERA and UT1 and their relationships with other parameters, have been implemented in the IERS Conventions 2003 (and then 2010) as well as in the astronomical almanacs.

3. REFERENCES

Aoki, S., Kinoshita, H., Guinot, B., Kaplan, G. et al., 1982, "The new definition of universal time", Celest. Mech. 105(2), pp. 359–361.

Aoki, S. and Kinoshita, H., 1983, "Note on the relation between the equinox and Guinot's non-rotating origin", Celest. Mech. 29, pp. 335–360.

Atkinson R. d'E., 1973, "On the Dynamical Variations of latitude and time, AJ 78, 147.

Atkinson R. d'E., 1975, "On the Earth's axes of rotation and figure", MNRAS 171(1), pp. 381–386.

Atkinson, R.d'E. and Sadler, D.H., 1951, "On the use of mean sidereal time", MNRAS 111, 619.

Capitaine, N., 2000, "Overview and proposition for a modern definition of the CEP" in Polar Motion: Historical and Scientific Problems, ASP Conference Series, Vol. 208, IAU Coll. 178. S. Dick, D.D. McCarthy, and B. Luzum (eds), ISBN: 1-58381-039-0, 2000, pp. 573–584

Capitaine, N., 2002, "New definition for the celestial pole and the celestial origin in the ICRS", in Highlights of Astronomy, Vol. 12, H. Rickmann (ed), CA: Astronomical Society of the Pacific, ISBN 1-58381-086-2, pp. 102–106.

Capitaine, N., Guinot, B. and McCarthy, D.D., 2000, "Definition of the Celestial Ephemeris Origin and of UT1 in the International Celestial Reference Frame", A&A 335, pp. 398-405.

Capitaine, N., Wallace, P.T, McCarthy, D.D., 2003, "Expressions to implement the IAU 2000 definition of UT1", A&A 406, pp. 1135–1149.

Capitaine, N., Andrei A.H., Calabretta M.R., Dehant, V. et al., 2007, "Proposed terminology in fundamental astronomy based on IAU 2000 resolutions", Highlights of Astronomy, 2, Vol 14, pp. 474–475.

Fedorov, E. P., 1963, "Nutation and Forced Motion of the Earth's Pole", The MacMillan Co, New York.

Fedorov, E. P., Smith, M. L., Bender, P. L. (eds), 1977, "Nutation and the Earth's rotation", Proc. IAU Symp. 78 (Kiev 1977), Dordrecht, Holland: Reidel Publ. Comp.

Guinot, B., 1979, "Basic Problems in the Kinematics of the Rotation of the Earth" in Time and the Earth's Rotation, D.D. McCarthy and J.D. Pilkington (eds.), D. Reidel Publishing Company, pp. 7–18.

IERS Conventions 1996, D. McCarthy (ed.), (IERS Technical Note 21), Observatoire de Paris.

IERS Conventions 2003, D.D. McCarthy and G. Petit (eds.), (IERS Technical Note 32).

IERS Conventions 2010, G. Petit and B. Luzum (eds.) (IERS Technical Note 36).

Jeffreys H., 1963, Foreword to "Nutation and Forced Motion of the Earth's Pole" by E.P. Fedorov, Pergamon Press.

Newcomb, S., 1895, in Astronomical Papers for the American Ephemeris and Nautical Almanac, AP, Vol. 5, Part IV-3.

Seidelmann, P. K., 1982, "1980 IAU theory of nutation - The final report of the IAU Working Group on Nutation", Celest. Mech. 27, 79–106.

Woolard, E., "Theory of the Rotation of the Earth Around its Center of Mass", Astron.Pap.Amer.Ephem. XV, Part, I., 165, Washington, D.C., 1953.

Yatskiv, Y. S., Korsun, A., 2008, "IAU Symp. 78 as the first step in the consideration of the non-rigid Earth nutation theory" in Proc. of the Journées 2007 Systèmes de référence spatio-temporels, pp. 88–90, N. Capitaine (ed.), Observatoire de Paris, ISBN 978-2-901057-59-8.