# MICROARCSECOND MODELS FOR THE CELESTIAL MOTIONS OF THE CELESTIAL INTERMEDIATE POLE (CIP) AND THE CELESTIAL EPHEMERIS (OR INTERMEDIATE) ORIGIN (CEO/CIO)

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ABSTRACT. The Celestial intermediate pole (CIP) and Celestial ephemeris (or intermediate) origin (CEO/CIO) have been adopted by the IAU (c.f. IAU 2000 Resolution B1.8) as the celestial pole and origin, respectively, to be used for realizing the intermediate celestial system between the International Terrestrial System (ITRS) and Geocentric Celestial Reference System (GCRS). Resolution B1.8 has also recommended that the International Earth Rotation and Reference Systems Service (IERS) continue to provide users with data and algorithms for the conventional transformation. The IAU 2000 Resolutions have been implemented in the IERS 2003 Conventions including Tables and routines that provide the celestial motions of the CIP and the CEO with a theoretical accuracy of one microarcsecond after one century using either the classical or the new transformation. This paper reports on the method used for acheiving this accuracy in the positions of the CIP and CIO and on the difference between this rigorous procedure and the pre-2003 classical one.

## 1. INTRODUCTION

Resolution B1.8 adopted by the IAU in August 2000 has recommended that the transformation between the International Terrestrial System (ITRS) and Geocentric Celestial System (GCRS) be specified by the position of the Celestial Intermediate Pole (CIP) in the GCRS, the position of the CIP in the ITRS and the "Earth Rotation Angle" (ERA). This resolution has also recommended that UT1 be linearly proportional to the ERA, defined as the angle measured along the equator of the CIP between the Celestial Ephemeris Origin (CEO) and the Terrestrial Ephemeris Origin (TEO) through a conventional relationship. This resolution was implemented by the International Earth Rotation and Reference Systems Service (IERS) beginning on 1 January 2003, together with Resolution B1.6 adopting the IAU 2000A precession-nutation model for the position of the CIP in the GCRS and Resolution B1.7 for the definition of the CIP. As required in Resolution B1.6, the IERS is continuing to provide users with data and algorithms for the conventional transformation.

Expressions for the position of the Celestial intermediate pole (CIP) and the Celestial ephemeris origin (CEO) (also called Celestial intermediate origin, CIO) which have been provided in the IERS Conventions 2003 are achieving a theoretical accuracy of 1 microarcsecond after one century. Such an accuracy can be achieved using either the new transformation, or the classical transformation if this latter follows the rigorous way for taking into account the frame biases, which was not the case for the pre-2003 classical procedure. More details on the procedures and models on which these expressions are based are provided in Capitaine et al. (2003a, 2003b, 2003c).

After having recalled (in Section 2) the definition and use of the CIP and CEO/CIO, we report (Sections 3 and 4) on the accuracy of the models for their celestial motions and compare this accuracy with that obtained when using the pre-2003 classical procedure.

## 2. DEFINITION AND USE OF THE CIP AND CEO/CIO

The Celestial Intermediate Pole (CIP) has been defined by IAU 2000 Resolution B1.7 as the intermediate pole separating nutation from polar motion explicitly at the 2-day period (i.e. nutations with periods less than 2 days being modeled by their equivalent polar motion). This resolution has recommended that the motion of the CIP in the GCRS be realized "by the IAU 2000A model (Mathews et al. 2002) for precession and forced nutation for periods greater than two days plus additional time-dependent corrections provided by the IERS through appropriate astro-geodetic observations" (*i.e.* through VLBI observations).

The CEO and TEO are the names used in Resolution B1.8 for designating the "non-rotating origin" (Guinot 1979, Capitaine et al. 1986) in the GCRS and ITRS, respectively. In recent IAU discussions they have also been called Celestial and Terrestrial "intermediate" origins, CIO and TIO, for emphazing that they provide together with the CIP the "intermediate" systems (celestial and terrestrial, respectively) between the GCRS and ITRS.

In the new paradigm, the GCRS position of the CIP is provided by the quantities $X(t)$ and $Y(t)$ which are the components of the CIP unit vector in the GCRS (Capitaine 1990). These quantities have been derived from (i) the expressions for the precession-nutation angles referred to the J2000 mean ecliptic, (ii) the corresponding biases $(\xi_0, \eta_0)$ at J2000, and (iii) the equinox offset at J2000 $d\alpha_0$ (see Figure 1). $X$ and $Y$ are usually called "coordinates" and their numerical expressions are multiplied by the factor $1296000''/2\pi$ in order to provide in arcseconds the value of the corresponding "angles" (strictly their sines) with respect to the $z$-axis of the GCRS. The classical form of the GCRS to ITRS transformation is written, following a rigorous procedure, as the product of the individual rotation matrices $\mathbf{B}$ (bias) followed by $\mathbf{P}$ (precession) then $\mathbf{N}$ (nutation) and finally $\mathbf{T}$ (Earth rotation). Elements $(3,1)$ and $(3,2)$ of the resulting matrix $\mathbf{R}_{class}$ provides the classical expression for the GCRS position of the CIP.

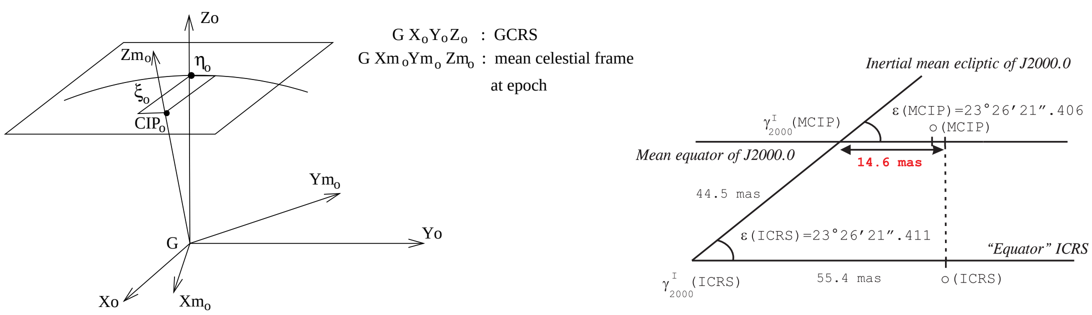


Figure 1: Frame biases between the mean equatorial system at J2000 and the Geocentric celestial reference system (GCRS); celestial pole offsets (left) and equinox offset (right)

Prior to the IAU 2000 definition, UT1 was formally defined by an expression which relates it to mean sidereal time, whereas the new defining relation of UT1 is the IAU 2000 conventional relationship between ERA and UT1. The implementation of this new definition requires using an expression for positioning the CIO in space.

The celestial position of the CIO is provided through a quantity $s$ for the finite displacement of the CIO between epochs $t_0$ and $t$ with respect to the GCRS $x$-origin (Capitaine et al. 1986). This computation implements the basic kinematical property of the non-rotating origin when the CIP pole is moving in the GCRS. Other implementations of the kinematical property of the CIO are possible either analytically or numerically (Kaplan 2003, Fukushima 2003b) and the position of the CIO can be referred to other references than the GCRS $x$-origin, such as the true equinox or the intersection of the CIP meridian or the GCRS zero-meridian with the intermediate equator. The difference GST-ERA for example is the right ascension of the CIO measured from the equinox along the moving equator. It represents the angular distance between the CIO and the equinox which is due to the accumulated precession and nutation in right ascension from J2000 to the epoch $t$ (Aoki &Kinoshita 1983, Capitaine & Gontier 1993).

The IERS has implemented IAU Resolutions in parallel for the CEO/CIO-based transformation and the equinox-based transformation in order (i) to ensure consistency to microarcsecond accuracy between these two procedures and (ii) to ensure continuity on 1st January 2003 between the pre-2003 classical and the post-2003 procedures.

## 3. MICROARCSECOND MODELS FOR THE CELESTIAL MOTION OF THE CIP

Computation of the IAU 2000 expression for the CIP $X$, $Y$ coordinates in the GCRS is based either directly on their semi-analytical expression as function of time, or on the elements of the classical rigorous expression of the bias-precession-nutation matrix, $\mathbf{R}_{class}$, both being based on the IAU 2000A precession-nutation (Capitaine et al. 2003a).

The IAU 2000A nutation series, based on the rigid Earth nutation of Souchay et al. (1999) and on the MHB transfer function (Mathews et al. 2002), includes 678 lunisolar terms and 687 planetary terms and provides the direction of the celestial pole in the GCRS with an observed accuracy of 0.2 mas. The Free Core Nutation (FCN), which cannot be predicted rigorously, is not included in the IAU 2000A model, the resulting"noise level" in the derived "celestial pole offsets" being of a fraction of 1 mas. The precession component of the IAU 2000 model is provided by corrections to the IAU 1976 precession of $-0.29965$"/c in longitude and $-0.02524$"/c in obliquity and is associated with VLBI estimates for celestial pole offsets at J2000 of $\delta\psi_0 = -41.775$ mas and $\delta\epsilon_0 = -6.8192$ mas. The equinox offset at epoch, $d\alpha_0$ between the $x$-origin of the GCRS and the mean equinox at J2000, that was omitted in the pre-2003 classical transformation, has also to be considered. The IAU 2000 implementation has used the equinox offset derived from lunar laser ranging observations referred to IERS parameters for Earth's orientation in the GCRS (Chapront et al. 2002).

It should be noted that the pre-2003 VLBI procedures used the IAU 1976 precession and the "total" nutations (*i.e.* the nutations themselves including estimated corrections to the model, plus the contribution of the corrections to the precession rates plus the biases) and omitted the equinox offset. Thus, whereas, there is equivalence to microarcsecond accuracy between the two post-2003 rigorous procedures, there are discrepancies of a few hundred microarcseconds/cy between classical equinox-based pre-2003 procedure and the post-2003 rigorous procedures (Capitaine et al. 2003a). Effects of the VLBI procedure in the estimated $X$, $Y$ CIP coordinates are shown in Figure 2, regarding the way the precession is considered and the fact that the equinox offset was omitted in the pre-2003 procedure. The differences in $X$, $Y$ due to the frame biases are: $dX = 153t - 5t^2$; $dY = -372t - 1.7t^2$ and $dX = -1.6t^2$; $dY = -142t$, for the celestial pole offsets and equinox offset at J2000, respectively; the differences due to the way the correction to the precession rates are applied are: $dX = +64t^2$; $dY = -6t^2$.

This shows that besides the improvement in the model for the GCRS position of the CIP due to the use of the IAU 2000A precession-nutation in replacement of the IAU 1976/1980 which has reduced the inaccuracies from a few tens of mas to a few hundred $\mu$as, an other improvement

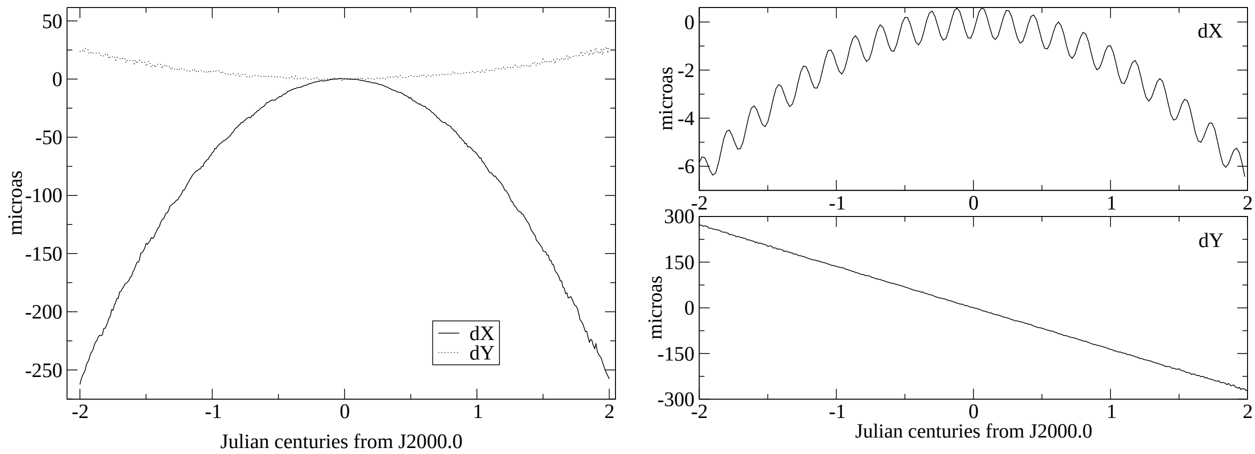


Figure 2: Differences in $X$ and $Y$ between the pre-2003 and post-2003 VLBI procedures (Capitaine et al. 2003a); differences due to precession (left), and to the equinox offset (right)

in the post-2003 expressions comes from the use of a rigorous procedure for taking into account the precession corrections and frame bias that in fact results from the use of the new paradigm as being the "primary" procedure.

Other methods can be used for expressing the GCRS position of the CIP based on different parameters such as the new precession-nutation parameters introduced by Fukushima (2003a), extending those previously considered by Williams (1994) by taking into account the frame biases or the "rotation vector approach", described in Capitaine et al (2003c), that is able to express bias plus precession and nutation.

Note moreover that the IAU 2000 precession which includes only the MHB corrections to the precession rates in longitude and obliquity should be replaced by an improved model which would be dynamically consistent. New precession models have recently been developed that are compatible with IAU 2000 with improved dynamical consistency. The model by Bretagnon et al. (2003) is based on the analytical VSOP87 ecliptic (Bretagnon & Francou 1988), on the SMART97 nutation theory for a rigid Earth (Bretagnon et. al 1998) and on the MHB precession rate in longitude; the model by Fukushima (2003a) is based on an ecliptic fitted to the JPL numerical ephemerides DE405 on a 600-yr interval, on the SF01 nutation theory for a non-rigid Earth (Shirai & Fukushima 2001) and on a quadratic fit to VLBI; the model by Capitaine et al. (2003c) is based on the VSOP87 ecliptic with improved secular terms fitted to DE406 over a 2000-yr interval and on a non-rigid Earth model from Willams (1994) and Mathews et al. (2002); the integration constants have been derived from the MHB estimates with corrections for perturbing effects on the observed quantities. The largest uncertainty in the effects of non-rigidity on precession is the uncertainty in the J2 rate effect (cf. Bourda & Capitaine 2004 and this Volume).

The IAU Working Group on "Precession and the ecliptic", which has been established at the 2003 IAU General Assembly, is in charge of selecting the next precession model to be recommended to the IAU.

## 4. MICROARCSECOND MODELS FOR THE CELESTIAL MOTION OF THE CEO/CIO

The implementation of the IAU 2000 definition of UT1 has been based on computation of expressions for the celestial positions of the CIO to be used in the transformation between

ITRS and GCRS, once the relationship ERA(UT1) is adopted. This is an important change as compared with the previous procedure in which the GST(UT1) relationship was the primary definition of UT1. A second change is that this new definition has been implemented consistently in the new transformation referred to the CIO and in the classical transformation referred to the equinox.

The determination of the IAU 2000 numerical expressions, linking GST and ERA and locating the CEO, have been performed so that there is no discontinuity in UT1 on 1 January 2003 when changing from the current VLBI procedure to the new one, following the two equivalent options, and in each case compliant with the IAU 2000 precession-nutation (Capitaine et al. 2003b). The CIO-based option uses the quantity providing the GCRS position of the CIO and the equinox-based option uses the equation of the equinoxes providing the position of the equinox w.r.t. the CIO. The polynomial part of $\mathrm{GST}_{IAU2000}$ provides the IAU 2000 expression for Greenwich Mean Sidereal Time, GMST, whereas the periodic part provides the complete equation of the equinoxes of which the non-classical part (also called the "complementary terms") replaces the two complementary terms of the IAU 1994 equation of the equinoxes provided in the IERS Conventions 1996 (McCarthy 1996). For practical reasons, the numerical development used for positioning the CIO on the equator of the CIP is for $s + XY/2$ rather than $s$ itself: firstly the former requires fewer terms to reach a given accuracy (Capitaine 1990) and, secondly, there is a helpful similarity between the quantity $s+XY/2$, which equals, up to the 3rd order in $X$ and $Y$, the GCRS right ascension of the CEO, and the complementary terms in the "complete equation of the equinoxes", which represent the right ascension of the CEO in the mean equatorial frame at J2000.

The differences in the computed UT1 between the post-2003 and pre-2003 procedures due to (i) the frame bias effect already considered in Section 3 regarding its effect in $X$ and $Y$ and (ii) the differences in the expression for the equation of equinoxes (*i.e.* additional periodic terms in the post-2003 expression for the angular distance between the CIO and the equinox) are shown on Figure 3.

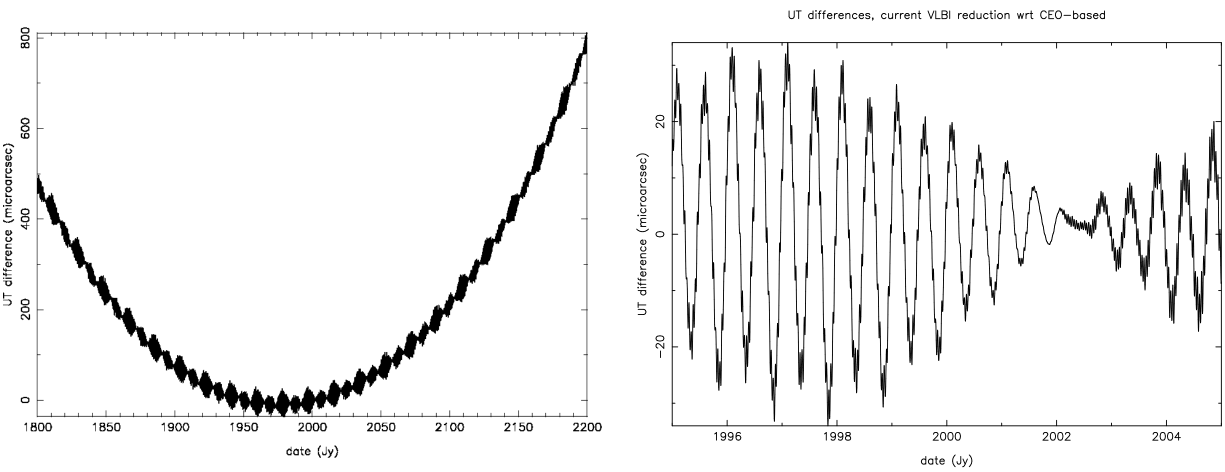


Figure 3: Differences between values of UT1 derived from the pre-2003 and post-2003 VLBI codes (Capitaine et al. 2003b); differences over 4 centuries (left) and five years (right) around J2000

The expected discontinuity in UT1 rate, shown to be unavoidable due to the improved models and the fixed relationship between ERA and UT1, will have an effect on the determination of UT1 less than a few hundreds of microarcseconds over the next century; the corresponding rate variations may reach $5 \times 10^{-15}$.

## 5. REFERENCES


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

Bourda G., Capitaine N., 2003, "Temporal variations of the gravity field and Earth's precession", in preparation.

Bretagnon, P. and Francou, G., 1988, "Planetary theories in rectangular and spherical variables VSOP87 solutions," *Astron. Astrophys.* **202**, 309.

Bretagnon, P., Francou, G., Rocher, P., and Simon, J.-L., 1998, "SMART97: a new solution for the rotation of the rigid Earth," *Astron. Astrophys.* **329**, 329.

Bretagnon P., Fienga A., Simon J.-L., 2003, "Expressions for precession consistent with the IAU 2000A model. Considerations about the ecliptic and the EOP," *Astron. Astrophys.* **400**, 785.

Capitaine, N. and Gontier A.-M., 1993, "Accurate procedure for deriving UT1 at a submilliarcsecond accuracy from Greenwich Sidereal Time or from stellar angle," pp. 645–650. *Astron. Astrophys.* **275**, 645.

Capitaine, N., Guinot, B., and Souchay, J., 1986, "A Non-rotating Origin on the Instantaneous Equator: Definition, Properties and Use," *Celest. Mech. Dyn. Astr.* **39**, 283.

Capitaine N., Chapront J., Lambert S., Wallace P.T, 2003a, Expressions for the CIP and CEO consistent with the IAU 2000A precession-nutation model, *Astron. Astrophys.* **400**, 1145.

Capitaine N., Wallace P.T, McCarthy D.D., 2003b, Expressions to implement the IAU 2000 definition of UT1, *Astron. Astrophys.* **406**, 1135.

Capitaine N., Wallace P.T, Chapront J., 2003c, Expressions for IAU 2000 precession quantities, *Astron. Astrophys.* **412**, 567.

Chapront, J., Chapront-Touzé M., and Francou, G., 2002, 'A new determination of lunar orbital parameters, precession constant and tidal acceleration from LLR measurements," *Astron. Astrophys.* **387**, 700.

Fukushima T., 2003a, A new precession formula, *Astron. J.* **126**, 494.

Fukushima T., 2003b, "New formulae of relations between GAST, UT1 and ERA" submitted to *Astron. J.*.

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 (2003), IERS Technical Note 31, D.D. McCarthy and G. Petit (eds).

Kaplan G., 2003, "Another look at Non-rotating Origins," to appear in the Proceedings of Joint Discussion 16, IAU 2003 GA.

Mathews, P. M., Herring, T. A., and Buffett B. A., 2002, "Modeling of nutation-precession: New nutation series for nonrigid Earth, and insights into the Earth's Interior," *J. Geophys. Res.* **107**, B4, 10.1029/2001JB000390.

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

Shirai, T., Fukushima, T., 2001,"Construction of a new forced nutation theory of the nonrigid Earth," *Astron. J.* **121**, 3270.

Williams, J. G., 1994, "Contributions to the Earth's obliquity rate, precession, and nutation," *Astron. J.* **108**, 711.