Part 7.

Modern Definition of the Celestial Ephemeris Pole

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Overview and Proposition for a Modern Definition of the CEP

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Abstract. The current IAU conventional models for precession and nutation are referred to the Celestial Ephemeris Pole (CEP). However, the concept corresponding to the CEP is not clear and cannot easily be extended to the most recent models and observations. Its realization is actually dependent both on the model used for precession, nutation and polar motion and on the observational procedure for estimating the Earth orientation parameters. A new definition of the CEP should therefore be given in order to be in agreement with modern models and observations at a microarsecond level. This paper reviews the various realizations of the pole according to the models and observations and discusses the proposals for a modern definition of the CEP that are under consideration within the work of the subgroup T5 entitled "Computational Consequences" of the "ICRS" IAU Working Group.

1. Introduction

The coordinate transformation from the Terrestrial Reference System (TRS) to the Celestial Reference System (CRS) makes use of an intermediate pole which is provided by the conventional model for precession and nutation. The Celestial Ephemeris Pole (CEP) is the current pole of reference for the IAU conventional models for precession and nutation. Although this pole of reference is supposed to be such that it has no diurnal or quasi-diurnal motions both in space and within the Earth, the concept corresponding to the CEP is not clear and cannot easily be extended to the most recent models and observations. The realization of the CEP is actually dependent both on the model used for precession, nutation and polar motion and on the observational procedure for estimating the Earth Orientation Parameters (EOP). Since 1980, there has been much improvement in the models for precession, nutation and polar motion as well as in processing observations of the EOP. Concerning the models now developed at a microarsecond level, the most recent series of nutation includes diurnal and semidiurnal nutations in space and models for polar motion include diurnal and semidiurnal variations within the Earth due to oceanic tides. Concerning the observations, estimates of the corrections to the IAU precession and nutation (*i.e.* "celestial pole offsets") are published on a regular basis by the IERS and, moreover, intensive EOP series are available. A new definition of the CEP should therefore be given in order to be in agreement with modern models and observations. Proposals for such a modern definition are under discussion within

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the subgroup T5 untitled "Computational Consequences" of the "ICRS" IAU Working Group. The membership of T5 is: N. Capitaine (Chair), V. Dehant, A.-M. Gontier, B. Kołaczek, J. Kovalevsky, J. Lieske, C. Ma, D.D. McCarthy, O. Sovers, J. Vondrák and other contributors to the discussion have been C. Bizouard, P. Bretagnon, A. Brzeziński, S. Loyer, P. Mathews, M. Rothacher, H. Schuh, and Y. Yatskiv. The whole discussion is available in T5 Newsletters (1998, 1999).

2. Definition and properties of the CEP

2.1. The celestial pole of reference

The Instantaneous Rotation Pole (IRP) has been the pole of reference from 1886 (Oppolzer 1886) to the IAU 1964 theory of nutation (Woolard 1953) in use until 1984. Referring to the IRP separates the forced lunisolar motion into two parts: the celestial part (precession and nutation), and the terrestrial part, or forced "diurnal polar motion," also called "diurnal nutation" or "forced variation of latitude" (Fedorov 1963) which corresponds to "Oppolzer terms" in the CRS. Following Atkinson (1975) who showed that optical astrometric observations cannot provide the IRP, there was, in 1976, an IAU Recommendation to refer to the "Atkinson's Pole" which is obtained by adding the Oppolzer terms to the celestial motion of the IRP. But, in 1977, after much discussion for the choice of a new model of nutation, a Resolution of the IAU78 Symposium was made to keep the reference to the IRP. Afterwards, several papers reconsidered the use of Atkinson's pole (Murray 1979, Kinoshita *et al.* 1979), showing that the IRP is not "observable" from any kind of available observations. Then, the 1979 IAU Recommendation was made to refer the IAU 1980 Theory of Nutation (Seidelmann 1982) to the *Celestial Ephemeris Pole* (*cf.* Atkinson's Pole) by including the forced diurnal polar motion in the celestial nutation.

2.2. Definition of the CEP

The 1980 IAU Theory of Nutation (Seidelmann 1982) gives the following properties defining the CEP:

Conceptual definition
The CEP is a pole that has no nearly diurnal motion with respect to a space-fixed coordinate system or an Earth-fixed coordinate system and thus corresponds to the axis of figure for the mean surface of a model earth in which the free motion has zero amplitude (this is the axis B introduced by Wahr (1981) for the nutation of a nonrigid Earth) and further the CEP is the center of the quasi-circular paths of the stars in the sky.

Conventional definition
The IAU Theory of Nutation represents the motion of the CEP with respect to the mean celestial pole of date hence the CEP may be called the true pole of date.

In fact, observations of Earth rotation are sensitive to the offset between the pole of the TRS and the pole of the CRS and thus, following its conceptual

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definition, the CEP is actually closer to the "observed pole" than the IRP. Following the conventional definition of the CEP, it is clear that the computation of the predictable part of the celestial motion of the pole is simplified.

However, the conceptual definition is not clear and cannot be easily extended to highly accurate theory and observations including high frequency components (Capitaine 1998, Capitaine and Brzeziński 1999) and moreover, the conventional definition is not satisfying as it is dependent on a model which has to be improved in the future.

2.3. CEP and instantaneous pole rotation (IRP)

The classical Poinsot's kinematical representation (Figure 1) shows the relative orientation of the axis of figure and axis of the IRP for Eulerian motion and precession-nutation (Woolard 1953):

(a) The Eulerian motion, in which the large cone rolls on the small cone such that the plane through the axes of figure, $\overrightarrow{OC_0}$, and rotation, $\vec{\omega}$, rotates counterclockwise around the angular momentum vector, $\vec{H}$,

(b) The lunisolar motion, in which the small cone rolls on the large cone whose axis is directed towards the pole of the ecliptic, and progresses clockwise.

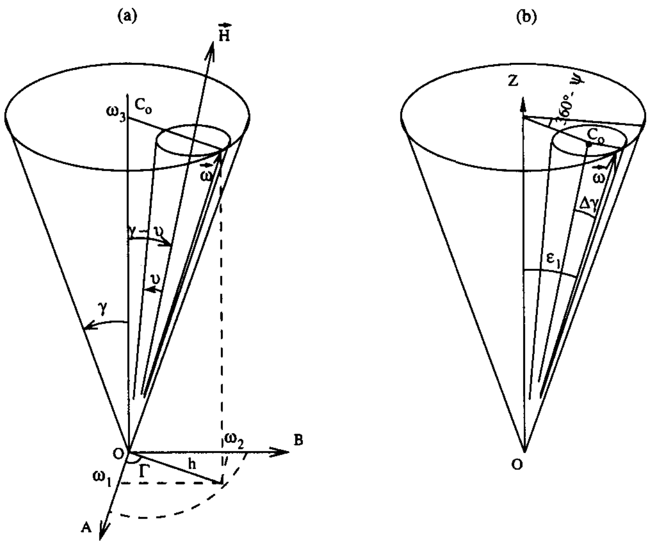

Figure 1. Poinsot's kinematical representation of the motion of the Earth around the center of mass (Woolard 1953).

Applying these properties and the definition of the CEP to the polar motion for a rigid Earth shows that precession and nutation in space result in the so-called "diurnal nutation" of the IRP relative to the CEP, the principal term being due to precession (Figure 2). Moreover, the change from the IRP to the CEP is responsible for a change in the obliquity of the ecliptic (Capitaine *et al.* 1985) as shown in Figure 3. This change is well approximated by $\frac{p \sin \varepsilon}{\omega} = 0''.0087$,

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($\vec{\omega}$ and and $\vec{p}$ being the rotation vectors respectively for Earth's rotation about the axis of the CEP and for precession about the axis of the ecliptic).

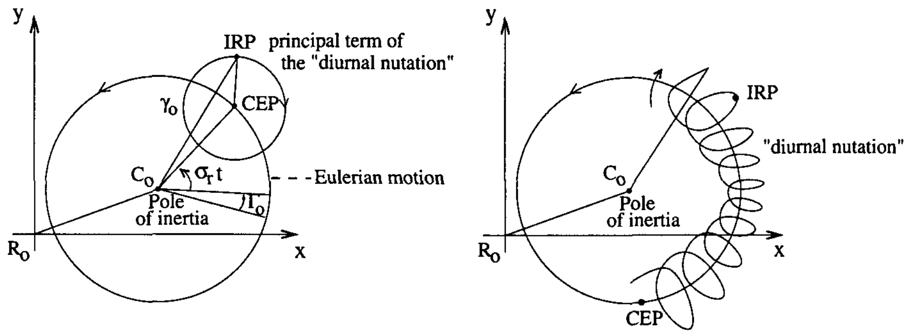

Figure 2. Polar motion for a rigid Earth including the Eulerian free motion of frequency σ_r and the forced diurnal nutation.

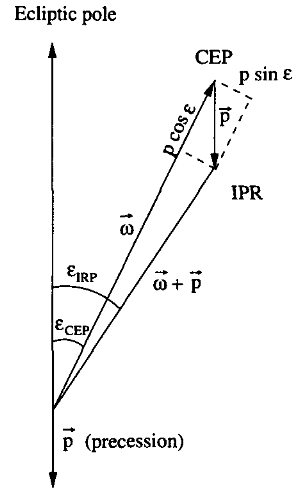

Figure 3. Change of the obliquity of the ecliptic, ε, from the IRP to the CEP (Capitaine *et al.* 1985) corresponding to precession.

3. Practical Realizations of the CEP

3.1. The realization of the pole according to the used procedure

In processing observations, precession and nutation are currently considered through three different procedures:

(1) using the IAU1976 precession and IAU1980 nutation,

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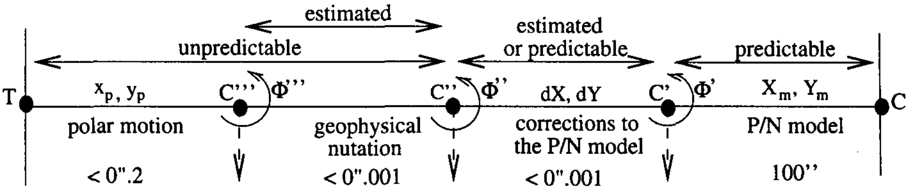

Figure 4. Schematic illustration of the different realizations of the CEP (Brzeziński and Capitaine 1995).

(2) using the IERS1996 precession-nutation series (McCarthy 1996),

(3) using the IAU or IERS model plus the estimated corrections to the model (*i.e.* the *celestial pole offsets* as provided by VLBI observations).

When using (1) or (2), the imperfections of the models appear as retrograde diurnal terms in the TRS with amplitudes of the order of 10 ms (for the IAU1980 nutation) or 1 mas (for the IERS-1996 nutation).

When using (3), every retrograde diurnal term in the TRS is included in the estimated celestial pole offsets and every diurnal prograde motion in the TRS is absorbed in the residuals if not estimated *a priori.*

3.2. Corresponding definitions of the CEP

The CEP is an intermediary pole separating the motion into:

- the celestial motion (precession and nutation) of the CEP which includes terms with periods longer than 2 days in the CRS (*i.e.* frequency σ_{CRS} such that $-1/2 < \sigma_{CRS} < +1/2$ in cpd),

- the terrestrial motion of the CEP (*i.e.* polar motion) which includes terms with periods longer than 2 days in the TRS (*i.e.* frequency σ_{TRS} such that $-1/2 < \sigma_{TRS} < +1/2$ in cpd).

The definition of the CEP does not specify if the free core nutation has to be considered in the TRS or in the CRS.

The relationship between the frequencies relative to the CRS and TRS ($\sigma_{TRS} = \sigma_{CRS} - 1$) shows that long periodic motions in the CRS correspond to frequencies in the TRS such that $-3/2 < \sigma_{TRS} < -1/2$ and long periodic motions in the TRS correspond to frequencies in the CRS such that $+1/2 < \sigma_{CRS} < +3/2$. The present definition of the CEP is valid only in the frequency interval $[-3/2 + 1/2]$ as viewed in the TRS or $[-1/2 + 3/2]$ as viewed in the CRS.

According to the procedure (1), (2) or (3), the realized intermediate pole between the poles T of the TRS and C of the CRS (Figure 4) is C′, C″ and C‴ respectively, corresponding to three different definitions of the CEP about which the Earths's angle of rotation ϕ is measured.

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4. Changes from the IAU1980 Nutation theory

Important changes concerning precession and nutation have appeared since the adoption of the IAU1980 nutation theory:

- the adoption of the ICRS by the IAU on January 1998 (Ma *et al.* 1998) which provides a quasi-ideal non-rotating reference frame to measure Earth rotation and consequently the celestial motion of the pole of reference, requiring a more accurate definition of this pole,

- the estimation by VLBI, on a regular basis, of the celestial pole offsets which include the whole diurnal retrograde polar motion,

- the improvement of the observations providing the EOP with a precision of 0.2 mas and time resolution up to few hours,

- the improvement of the models for nutation and polar motion with μas accuracy, including diurnal and sub-diurnal terms.

4.1. The sub-diurnal terms in nutation and polar motion

The semidiurnal terms of nutation, were theoretically computed by Tisserand (1891) and numerically by Woolard (1953), and considered to be negligible until they were introduced in the solutions for nutation for a rigid Earth at a microarsecond level (Bretagnon *et al.* 1997). They are produced by the lunisolar torque exerted on the tesseral coefficients (2,2) and (3,2) of the terrestrial potential. Moreover, there are diurnal nutations due to the coefficients (3,1) and (4,1). The amplitudes of the most important nutations with 1 day and 0.5 day periods are given in Table 1.

Table 1. Amplitude (in μas) of the most important diurnal and sub-diurnal terms in the three Euler angles ψ, ω and ϕ. The periods are in Julian days (Bretagnon 1999).

argument	period	ψ	ω	ϕ
$\lambda_3 + D + \phi$	0.96	38.42	15.24	35.36
$\lambda_3 + D - \phi$	1.04	35.08	13.47	32.53
$\lambda_3 + D - l + \phi$	1.00	24.12	9.59	22.12
$\lambda_3 + D - l - \phi$	1.00	20.01	7.93	18.38
2ϕ	0.50	36.73	14.61	36.86
$2\lambda_3 + 2D - 2\phi$	0.52	29.24	11.63	0.15
$2\lambda_3 - 2\phi$	0.50	12.26	4.88	0.47
$2\lambda_3 + 2D + l - 2\phi$	0.53	5.94	2.36	0.08

The diurnal prograde nutations in space appear in the Earth as long periodic prograde and retrograde variations in polar motion and the semidiurnal prograde nutations as prograde diurnal variations in polar motion (see Bizouard *et al.* 1999a). It must be noted that such prograde diurnal variations in polar motion have already been computed, for a nonrigid Earth, by Chao *et al.* (1991) as

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resulting from the "polar libration" and are thus included in their model for diurnal polar motion.

The daily and sub-daily tidal variations in polar motion have been included in the most recent models for polar motion. The 1996 IERS Conventions (McCarthy 1996) give the corresponding corrections to be applied (see Table 2) to the coordinates of the pole.

Table 2. Amplitude (in mas) of the most important diurnal and sub-diurnal tide terms in the two coordinates of polar motion (Δx and Δy) (IERS Conventions 1996).

Tide	l	l'	F	D	Ω	θ	phase (deg.)	Period (hours)	Δx Sin	Δx Cos	Δy Sin	Δy Cos
Q_1	-1	0	-2	0	-2	1	-90	26.868	-0.026	0.006	-0.006	-0.026
O_1	0	0	-2	0	-2	1	-90	25.819	-0.133	0.049	-0.049	-0.133
P_1	0	0	-2	2	-2	1	-90	24.066	-0.050	0.025	-0.025	-0.050
K_1	0	0	0	0	0	1	90	23.935	-0.152	0.078	-0.078	-0.152
N_2	-1	0	-2	0	-2	2	0	12.658	-0.057	-0.013	0.011	0.033
M_2	0	0	-2	0	-2	2	0	12.421	-0.330	-0.028	0.037	0.196
S_2	0	0	-2	2	-2	2	0	12.000	-0.145	0.064	0.059	0.087
K_2	0	0	0	0	0	2	0	11.967	-0.036	0.017	0.018	0.022

The overlapping between the motions in the CRS and the TRS in the high frequency domain must be taken into account, as for example:

- the retrograde diurnal terms in the tidal polar motion variations must be excluded from the model of polar motion if they are included in the nutation series (Herring and Dong 1994),
- in particular, the effect of the purely diurnal oceanic tide K_1 must be considered to be included in the constant part of the celestial pole offsets,
- the semidiurnal prograde nutations must not be considered in the model for nutation if the model used for the prograde diurnal polar motion includes the "polar libration."

4.2. The sub-daily observations

Considering only the long periodic terms (longer than 2 days) in polar motion and nutation, both motions can be estimated simultaneously from observations in the case where the two frequency intervals are disjoined, which implies that the sampling interval is larger than 1 day.

For sub-daily observations, the two frequency intervals of polar motion and nutation are no more disjoined and thus, the frequency domain decomposition into polar motion and nutation becomes strongly dependent on the method used for processing the observations (Brzeziński and Capitaine 1993). Hence, the corresponding definition of the CEP depends on this procedure, and simultaneous estimation of polar motion and nutation must be avoided.

5. Towards a modern definition of the CEP

5.1. Requirements for the CEP

The definition of the CEP should have the following properties:
- to be based on clear concepts,
- not to introduce any inaccuracy in the results,
- to allow the data to provide the best physical parameters,
- to not be dependent on the technique.

5.2. Extension of the conceptual definition of the CEP

To fulfill the requirements listed above, the extended definition of the CEP must take account of the high frequency components both in polar motion and nutation at the microarcsecond level and must not be dependent on the techniques and strategy of observations. Two different approaches have been considered, within the subgroup T5, for such an extended definition:

A) a *deterministic approach* separating the motions according to their physical cause,

B) a *frequency approach* separating the motions according to their frequency domain,

these two approaches being considered with the following options :

(i) Deterministic approach

A1
- the *whole predictable part* of the motion in the CRS, including diurnal and sub-diurnal terms, is considered in the model for nutation,
- *other part of the motion* is considered to be polar motion.

A2
- the *whole predictable part* of the motion in the CRS, including diurnal and sub-diurnal terms, is considered in the model for nutation,
- the *predictable high frequency* motion in the TRS is considered in the model for the polar motion of the CEP.

A3
- *only* the *long periodic part* of the predictable motion in the CRS is considered in the model for nutation,
- *other part of the motion* is considered to be polar motion.

(ii) Frequency approach

B1
- all the motions of frequency $\sigma < -1/2$ in the CRS are considered to be celestial motions,
- all the motions of frequency $\sigma > +3/2$ in the CRS are considered to be terrestrial motions.

B2
- all the motions of frequency existing in the nutation model (long periodic, prograde diurnal, prograde semidiurnal, ...) are considered as celestial motions,

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- all the motions of frequency existing in the models for polar motion are considered as terrestrial motions.

The approach B1, as proposed by Mathews (1999), keeps the symmetry in the frequency band between terrestrial motion and celestial motion of the CEP by extending the definition outside the current frequency interval, whereas the approach B2 takes into account the known frequencies of the predictable motion in the CRS and TRS.

5.3. Extension of the realization of the CEP

Whichever is the chosen conceptual definition, it is clear that there is an overlapping in the frequency domain between nutation and polar motion for sub-daily observations as well as for diurnal and sub-diurnal motions. Thus, the realized CEP depends on the procedure that is used in processing observations to extract the high frequency signal. The possible procedures to be used are:

C1 to extract the high frequency signal from both celestial pole offsets and pole coordinates in the processing of the observations,

C2 to extract the high frequency signal, in a second step, from the current estimates of both pole coordinates and celestial pole offsets over a long period,

C3 to extract the high frequency signal from the estimated polar motion only,

C4 to extract the high frequency signal as referred to the *instantaneous axis of rotation* (Bolotin *et al.* 1997) whose properties are such that motions in the TRS and CRS are linked by well-known kinematical relations.

Following the conceptual definition B1 of the pole and its realization C1, Mathews (1999) has proposed a procedure for extracting the high frequency signal in processing the observations by adding complementary estimated parameters of diurnal, semidiurnal, ter-diurnal, *etc.* periods both in the CRS and the TRS. In the proposed procedure, the coordinates of the pole in the CRS, $X(t), Y(t)$, and in the TRS, $x_p(t), y_p(t)$, are estimated through the following expressions:

$$X(t) = \textstyle\sum_{n\geq 0}[X^{(n)}(t)\cos n\Omega_0 t + Y^{(n)}(t)\sin n\Omega_0 t],$$
$$Y(t) = \textstyle\sum_{n\geq 0}[-X^{(n)}(t)\sin n\Omega_0 t + Y^{(n)}(t)\cos n\Omega_0 t].$$

($X \simeq \sin\epsilon_0\Delta\psi(t), Y \simeq \Delta\epsilon(t), \Delta\psi(t), \Delta\epsilon(t)$ being the nutation in longitude and obliquity).

$$x_p(t) = \textstyle\sum_{n\geq 0}[x_p^{(n)}(t)\cos n\Omega_0 t + y_p^{(n)}(t)\sin n\Omega_0 t],$$
$$y_p(t) = \textstyle\sum_{n\geq 0}[-x_p^{(n)}(t)\sin n\Omega_0 t + y_p^{(n)}(t)\cos n\Omega_0 t].$$

Such a procedure provides the current celestial pole offsets ($n = 0$), as well as diurnal ($n = 1$) and semidiurnal ($n = 2$), ... retrograde periodic terms in the celestial motion; it also provides the current polar motion ($n = 0$), as well as diurnal ($n = 1$), semidiurnal ($n = 2$), ... prograde periodic terms in the terrestrial motion. A preliminary test of such a procedure on astrometric modeling of simulated VLBI data has given promising results (Bizouard *et al.* 1999 b).

The advantage of this procedure is that it realizes a definition of the CEP that extends the current one in a symmetric way in the frequency domain.

The disadvantage is that the estimated terms do not correspond to predictable high frequency motions, which are prograde within the CRS (see Table 1) and both prograde and retrograde in the TRS (see Table 2).

However, a modified procedure should be proposed, following option C3, in order to estimate only the long periodic terms in the CRS (the current celestial pole offsets) and the whole high frequency signal (prograde and retrograde diurnal components as well as prograde and retrograde semidiurnal ones) in the TRS.

6. Concluding remarks

The preliminary conclusions of the discussion within T5 relative to the concept and realization of the CEP are given in the following.

(i) Concept

- The reference pole has not to be defined by its realization but by a clear concept not dependent on further improvements in the model,
- a change of name could be considered as the "Celestial Reference Pole" (CRP), or the "Celestial Intermediate Pole" (CIP),
- this pole must be realizable by a model as accurately as possible,
- the change from the CEP to the new definition has to be as small as possible in its practical realization,
- the deterministic approach seems to be preferable, as it appears to be more easily realizable and A3 is the preferred option,
- it is necessary to abandon the IAU1980 conceptual definition which specifies that "this pole has no nearly-diurnal motion..."

A tentative conceptual definition is "the Pole of the intermediate equator of which motion with respect to the CRS is produced by the lunisolar and planetary torque" (or ... "by the external gravitational forces acting on the Earth").

A much debated question is whether to include the diurnal and semidiurnal terms of nutation in the CRS. As these terms appear respectively as long periodic and prograde diurnal terms in the TRS and as they are strongly influenced by geophysical perturbation, one can rather consider them to be a part of the polar motion. Hence it may be possible to add to the conceptual definition that "the motion of the equator with respect to the CRS is considered for an Earth with an equatorial symmetry," or that "the motion is considered after filtering out terms of period shorter than 2 days."

Concerning the motion with respect to the TRS, the choice should be to sharpen the definition of the pole of reference by taking account of the diurnal and sub-diurnal variations as a predictable part of the polar motion.

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Perhaps it should be necessary to define a "Mean CRP" (MCRP) including only the long periodic part of the motion both in the TRS and the CRS, and then a "True CRP" as obtained by adding the high frequency components to the polar motion of the MCRP.

(ii) Realization

Considering the celestial part of its motion, the pole can be realized at date t by providing its polar coordinates in the CRS (angular distance from the pole of the CRS and azimuth from the zero-line meridian in the CRS). Such parameters (Capitaine 1990) include the accumulated precession from J2000.0, the nutation at date t, the coupling effects between precession and nutation as well as the offsets of the precession-nutation model at J2000.0 from the pole of the CRS. Precession and nutation must be given by a conventional model, including or not the high frequency nutations according to the chosen option for the conceptual definition. As the nutation model should be as accurate as possible, it will automatically include all the geophysical perturbations such as the retrograde diurnal motion due to ocean tides.

Considering the terrestrial part of the motion, the diurnal and sub-diurnal terms can be provided by an empirical model, the corrections to this model being estimated from observations. This will minimize the dependence of the realized pole on the processing of the observations. A conventional procedure must be given for providing the best realization of the pole. In order to specify such a procedure, it is first necessary that a consensus be found on the option to be chosen (C1, C2 or C3).

The preferred option is to specify the celestial motion by convention and to extract the high frequency signal (or corrections to an empirical model for this signal) from the pole coordinates only (C3), but a much debated question is if the high frequency signal in polar motion must be estimated together with the long periodic motion in the software for processing the data or must rather be estimated in a second step from the currently estimated coordinates of the pole.

The discussions must be continued within the subgroup T5 before a definitive conclusion can be reached.

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