Comparison of “Old” and “New” Concepts: The Celestial Intermediate Pole and Earth Orientation Parameters

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1 Introduction

The adoption of the International Celestial Reference System (ICRS) since the 1st January 1998 by the IAU, associated with significant improvements in the theory and observation of Earth’s rotation, required an extended definition of the celestial pole as well as more basic Earth Orientation Parameters (EOP). This has been under discussion, from 1998 to 2000, within the subgroup T5 (for more detail, see http://danof.obspm.fr/T5.html) untitled “Computational consequences” of the IAU Working Group ICRS and has been taken into account by two IAU 2000 resolutions. Resolution B1.7 defines the “Celestial Intermediate Pole” (CIP), which replaces the “Celestial Ephemeris Pole” (CEP) in the new IAU 2000 precession and nutation model and specifies the way for taking into account the high frequency terms in polar motion and nutation. Resolution B1.8 recommends the use of the “non-rotating origin” (NRO) (Guinot 1979) both in the GCRS (Geocentric Celestial Reference System) and ITRS (International Terrestrial Reference System) for defining UT1; it also recommends the use of the position of the CIP in the GCRS and in the ITRS in the transformation between GCRS and ITRS.

This report provides a comparison of Old and New concepts for the pole and the EOP, except for the use of the NRO which is more largely developed in B. Guinot’s report for the same session of the Workshop.

2 Comparison of the CIP to other reference poles

2.1 The Instantaneous Pole of rotation (IRP)

The instantaneous axis of rotation is the most natural axis to be considered when studying Earth’s rotation. The Instantaneous Rotation Pole (IRP) has thus been the pole of reference for nutation up to the IAU 1964 theory of nutation (Woolard 1953) in use until 1984. Referring to the IRP separates the forced luni-solar 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 space (Jeffreys 1963). Following Atkinson (1975) who showed that optical astrometric observations cannot provide the IRP and several other papers showing that the IRP is not “observable” from any kind of available observations (Murray 1979, Kinoshita et *al.* 1979), the IAU 1980 Theory of nutation (Seidelmann 1982) has been referred to the *Celestial Ephemeris Pole* (cf. Atkinson’s Pole) (CEP). The forced diurnal polar motion was thus included into the celestial nutation and this “diurnal nutation” has no more to be considered as a separate part of the forced motion of the pole. However, it must be noted that the IRP is still the reference pole for gravimetric or gyroscopic observations (Capitaine 1986, Loyer *et al.* 1999).

2.2 The Celestial Ephemeris Pole (CEP)

Observations of Earth Orientation are sensitive to the offset between the pole, T, of the TRS and the pole, C, of the GCRS. The CEP is actually closer than the IRP to the "observed pole" based on astrometric or space geodetic measurements and its use simplifies the computation of the predictable part of the celestial motion of the pole. The IAU 1980 Theory of nutation has provided a tentative conceptual definition of the CEP as the "pole that has no nearly-diurnal motion with respect to a space-fixed coordinate system or an Earth-fixed coordinate system" which would correspond to the "axis of figure for the Tisserand mean outer surface of the Earth" as used by Wahr (1981) in his theory of rotation of a non-rigid Earth. However, such a conceptual definition is not clear and the significance of the change from the instantaneous pole of rotation to the CEP has been discussed (Capitaine *et al.* 1985).

The CEP was actually defined by its realization using the IAU-1980 nutation series. The consideration of the "celestial pole offsets" as estimated by VLBI observations and, afterwards, the use of an improved precession-nutation model in the IERS 1996 Conventions (McCarthy 1996), modified the realization of the CEP. The pole offsets, which contain the deficiencies in the precession-nutation model, provide the whole retrograde diurnal motion with respect to the ITRS, or, equivalently, the whole long period motion of the CEP with respect to the GCRS. Similarly, the "pole coordinates" provide, when estimated from observations, with a time resolution of a few days, the whole long period motion of the CEP with respect to the ITRS. The realization of the CEP then depends both on the model for precession and nutation and on data processing; this is illustrated by Figure 1 which shows different realizations of the CEP (C', C", C"') according to the precession-nutation model and to the processing of the data, especially on whether the celestial pole offsets are estimated (C", C"') or not estimated (C').

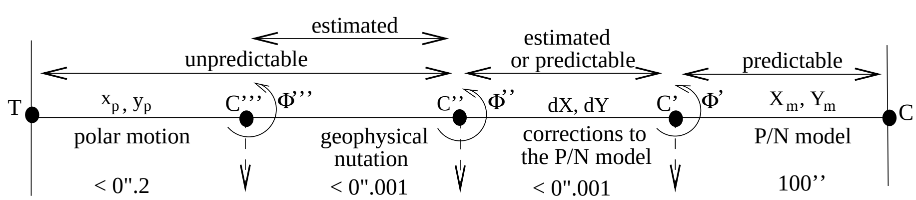

Figure 1: Different realizations of the CEP as an intermediate pole between the pole T of the TRS and the pole C of the CRS (Brzeziński & Capitaine 1995)

The definition of the CEP did not give any convention for the high frequency motions (periods shorter than two days) in the GCRS or ITRS and the definition is moreover not valid (Brzeziński & Capitaine 1993) for sampling intervals shorter than 1 day.

2.3 The Celestial Intermediate Pole (CIP)

Since the adoption of the CEP, significant improvement in precision and temporal resolution of the observations of Earth rotation, as well as in the development of theory have been achieved. GPS and intensive VLBI observations provide EOP with a submilliarcsecond accuracy over a few hours, whereas diurnal and semi-diurnal terms are now considered in the theory at a microarcsecond accuracy both for pole motion and nutation. A new definition of the pole of reference had thus become necessary.

Tidal variations in polar motion, which are dominated by diurnal and semi-diurnal terms, have been both predicted by models and estimated from observations (see for example Gross 1993 and Herring & Dong 1994). On the other hand, the prograde semi-diurnal terms of nutation, whereas they have already been theoretically computed by Tisserand (1891) and numerically by Woolard (1953) and Kinoshita (1977), have been considered to be negligible until they have been introduced in the solutions for nutation for a rigid Earth at a microarcsecond level (Bretagnon *et al.*, 1997; Souchay *et al.*, 1999; Roosbeek, 1999). They are produced by the luni-solar torque exerted on the tesseral coefficients (2,2) of the terrestrial potential and there are moreover prograde diurnal nutations which are due to the coefficient (3,1).

It is important to note that the prograde semi-diurnal nutations can also be considered as prograde diurnal variations (Chao *et al.* 1991) in polar motion and the prograde diurnal nutations as prograde and retrograde variations in polar motion. Similarly, the retrograde diurnal tidal variations in polar motion are actually included in the recent nutation models for a non-rigid Earth. A clear convention is therefore necessary for the high frequency domain and especially for the overlapping between the motions in the GCRS and the ITRS.

The amplitudes of the largest components of tidal variations in polar motion are shown in Table 1. The most important nutations with 1 day and 0.5 day periods, with their corresponding periods and amplitudes in the Earth, are given in Table 2 for a non-rigid Earth model. Both tables refer to the fundamental arguments of nutation, l, l', F, D, Ω. ϕ is for Greenwich Mean Sidereal time (GMST) plus a phase lag and θ is for GMST + π. The amplitudes provided in Table 2 (Folgueira *et al.* 2001), which are based on a preliminary version of the transfer function of Mathews *et al* (2002), are in good agreement with more recent results (not yet published), based on more complete models for the influence of the non-rigidity of the Earth.

Several approaches have been considered for extending the definition of the CEP in the high frequency domain through additional conventions (Capitaine & Brzeziński 1999, Capitaine 2000 a, 2000 b, T5 Newsletters). The preferred approach has been to define the pole of reference neither by a physical property, nor by a model, but as an intermediate pole in the coordinate transformation between the GCRS and the ITRS. The selected definition was the pole of the

Tide	l	l'	F	D	Ω	θ	phase	Period	Δx		Δy	
							(deg.)	(days)	Sin	Cos	Sin	Cos
Q_1	-1	0	-2	0	-2	1	-90	1.11951	- 26	6	-6	-26
O_1	0	0	-2	0	-2	1	-90	1.07581	-133	49	-49	-133
P_1	0	0	-2	2	-2	1	-90	1.00275	-50	25	-25	- 50
K_1	0	0	0	0	0	1	90	0.99727	-152	78	-78	-152
N_2	-1	0	-2	0	-2	2	0	0.52743	- 57	-13	11	33
M_2	0	0	-2	0	-2	2	0	0.51753	-330	-28	37	196
S_2	0	0	-2	2	-2	2	0	0.50000	-145	64	59	87
K_2	0	0	0	0	0	2	0	0.49863	- 36	17	18	22

Table 1 : Periods and amplitudes (in μas) of the most important diurnal and subdiurnal tidal variations in the two coordinates of polar motion (Δx and Δy) (IERS Conventions 1996, from Ray *et al.* 1994).

Argument in space						Period	Period	in-phase	out-of phase
Φ	l	l'	F	D	Ω	in space	in Earth	(a_r^+)	(a_i^+)
1	0	0	-1	0	-1	1.03505	-27.3216	15.6	2.0
1	1	0	-1	0	-1	0.99758	-3231.496	12.2	2.1
1	-1	0	1	0	1	0.99696	3231.496	-15.8	-3.0
1	0	0	1	0	1	0.96215	27.3216	16.6	2.0
2	0	0	-2	0	-2	0.51753	1.07581	11.3	-6.5
2	0	0	0	0	0	0.49863	0.99727	-14.0	8.0

Table 2 : Periods (revised values) and amplitudes (in μas) of the largest diurnal and sub-diurnal circular nutations and of their corresponding components in polar motion (from Folgueira *et al.* 2001)

intermediate equator (between those of the GCRS and the ITRS), of which motion, with respect to the GCRS, is mainly produced by the external torque on the Earth, with a limitation to the long periodic part (periods greater than two days). With such a definition, all the motions with frequencies belonging to the retrograde diurnal band in the ITRS, are conventionally considered in the GCRS; this includes all the forced nutations with periods greater than 2 days, as well as the Free Core Nutation (FCN). On the contrary, the whole high frequency motion both in the GCRS and in the ITRS (outside the retrograde diurnal band), is conventionally considered as being a part of the polar motion.

The definition of the pole is thus unchanged from that of the CEP at a milliarcsecond level, but is sharpened in the high frequency domain at a submilliarcsecond level of accuracy. The advantages are that : 1) the extension in the frequency domain is consistent with a deterministic approach, 2) the definition is not dependent on further improvements in the model, but can be given as accurately as necessary by a model, 3) the definition is not dependent on the techniques of observation, 4) the change from the current CEP has minimal impact on users. Following the proposal above, the new pole which has been recommended by IAU Resolution B1.7 is such that its name ”Celestial Intermediate Pole” (CIP) emphasizes the role of intermediary of this pole between GCRS and ITRS.

The motion of the CIP in the GCRS is provided by the IAU 2000 A model for precession and forced nutation (Dehant *et al.* 1999, Mathews *et al.* 2002), for periods greater than two days, plus the celestial pole offsets estimated from observations. Such offsets include both the errors in the model for precession-nutation and also the FCN, unless this free mode is taken into account by a model (Herring *et al.* 2002). The motion of the CIP in the ITRS is provided by EOP observations and must take into account a predictable part specified by a model including the high frequency variations (see Tables 1 and 2 for the largest terms). The corrections to this model can be estimated by extracting the high frequency signal using a procedure similar to the one described by Mathews & Herring (2000).

3 Comparison of the celestial coordinates of the CIP to other EOP

3.1 Classical parameters referred to the FK5

The current precession angles (see Fig 4) are those defined by Lieske *et al.* (1977) in the FK5 system. The classical nutation angles $\Delta\psi$ in longitude and $\Delta\epsilon$ in obliquity are referred to the ecliptic of date (see Fig 4) and $\chi_A + \Delta\chi$ is the angular distance between the ecliptic of epoch and the ecliptic of date along the equator of date. The classical procedure for taking into account precession and nutation is to use the matrix transformation using the developments as function of time of the precession angles, ζ_A, θ_A, z_A, followed by the matrix transformation using the nutation quantities $\Delta\psi$ and $\Delta\epsilon$ provided by the conventional series of nutation (Seidelmann 1982, McCarthy 1996). Such a transformation corresponds to a sequence of 6 consecutive rotations for precession and nutation. As the precession and nutation angles are referred to the ecliptic of date, the resulting matrix mixes the precession and nutation of the equator and the motion of the ecliptic whereas the two phenomena are of different physical origins and have to be considered in different celestial reference systems. The motion of the equator is due to the luni-solar and planetary torque exerted on the oblate Earth and has to be considered in the GCRS. On the other hand, the ecliptic motion, which is due to planetary perturbations on the orbit of the Earth, has to be considered in the BCRS (Barycentric Celestial Reference System).

The classical procedure for taking into account Earth rotation in the FK5 system is to use the relationship between Greenwich sidereal time and UT1 (Aoki *et al.* 1982), giving GMST at date t, followed by the relationship between GST and GMST including the complete equation of the equinoxes (Aoki & Kinoshita 1983). Additionally to Earth rotation, the angle GST includes a part due to the accumulated precession and nutation along the equator as well as cross terms between precession and nutation (Capitaine & Gontier 1993). It refers to the ecliptic of date and thus mixes Earth rotation and precession-nutation.

3.2 Alternative choices for new EOP in the GCRS

To take advantage of the fundamental properties of the new ICRS (Ma *et al* 1998), it is necessary to use more basic quantities for precession-nutation and Earth rotation, and therefore :

- to reduce the number of parameters by combining precession and nutation of the equator,
- not to refer these parameters to the ecliptic of date, but to a fixed plane,
- to clearly separate the precession-nutation of the equator from the Earth's rotation.

Alternative choices are summarized and compared below.

The classical representation using Euler's angles as used by Woolard (1953) between the terrestrial system [Oxyz] and the celestial one [OXYZ] (see Figure 2), refers to a fixed ecliptic frame; it can be transformed to the mean equatorial frame at J2000 taking into account a conventional value for the obliquity of the ecliptic at J2000 (ϵ_0) and then transformed to the ICRS, taking into account the offsets between this frame and the ICRS. The transformation matrix from the celestial and terrestrial frames is thus based upon 3 parameters; the two first ones (θ and ψ), includes both polar motion and precession-nutation referred to a fixed ecliptic and the third one (ϕ) is the angle of rotation along the moving equator of figure, reckoned from the line of nodes on the fixed ecliptic to the x-axis of the terrestrial system. It must be noted that such a representation does not clearly distinguish between BCRS and GCRS.

Aoki and Kinoshita (1983) considered a combined form of 3 rotations, using the parameters $\psi_A + \Delta\psi_1$, $\omega_A + \Delta\epsilon_1$ and $\chi + \Delta\chi$, the two first ones including precession and nutation referred to the fixed ecliptic (see Fig 4) which can easily be referred to the GCRS.

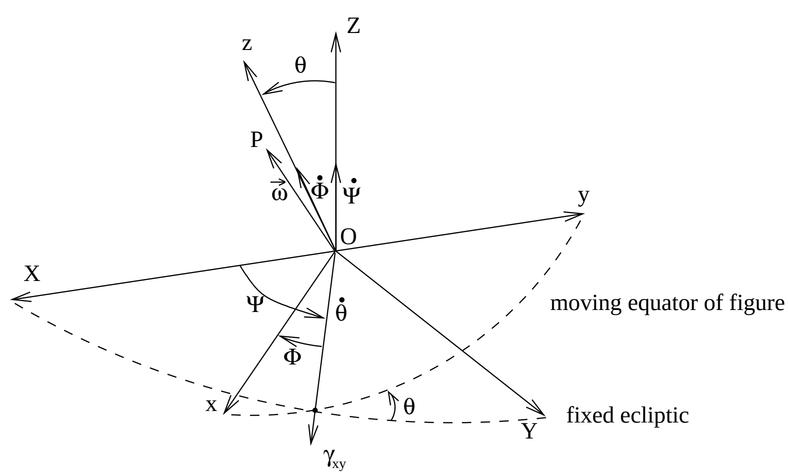

Figure 2: Euler's angles between terrestrial and celestial systems and the angular velocity vector $\vec{\omega}$

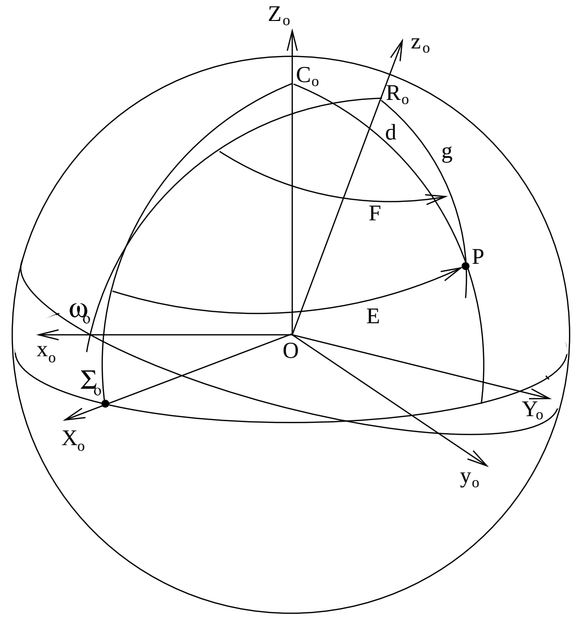

Figure 3: The coordinates of the pole P in the CRS and the TRS

Williams (1994) also proposed a restricted number of parameters in order to minimize the number of rotations by combining the rotations for precession and nutation, but the angles considered in longitude and obliquity are referred to the ecliptic of date.

The coordinates of the CIP in the GCRS (Capitaine 1990, Capitaine *et al.* 2000), $X = sind \cos E$ and $Y = sind \sin E$ (see Figure 3), are the direction cosines (wrt GCRS) of the vector directed to the CIP (designated by P on the Figure). They include precession, nutation, the coupling effects between precession and nutation and the offsets ξ_o, η_o, $d\alpha_0$ of the precession-nutation models at J2000 wrt the pole and equatorial origin of the GCRS. These quantities, which appear in a symmetrical form to the coordinates of P in the ITRS, are easily associated with the use of the NRO. It is interesting to note that the use of celestial coordinates of the mean celestial pole of date had already been proposed by Fabri (1980) for replacing the classical precession angles.

Fukushima (1994) proposed the use of the magnitude components of the angular momentum vector, $\overrightarrow{G}$, in the GCRS (XYZ) and in the ITRS (ABC) and the longitude of A-axis measured from X-axis along the great circle perpendicular to the angular momentum of date. The orientation matrix from the ITRS to the GCRS is thus generated by five successive rotations and the corresponding origin on the moving equator is the intersection of the zero-line meridian of the GCRS relative to the plane perpendicular to the angular momentum axis.

Mathews & Herring (2000) proposed to use the celestial coordinates of the z-axis of the TRS, which is similar to Euler’s angles between GCRS and ITRS, replacing angles by coordinates.

A comparison of the parameters considered above shows that Euler’s angles, or equivalently the celestial coordinates of the z-axis of the TRS, which reduce to 3 the number of EOP, do not use any intermediate pole and consequently include both high frequency and low frequency components of the motion of the Earth’s axis of figure wrt the GCRS. On the contrary, the position of the CIP in the GCRS, which combines precession and nutation, separates the celestial components from the terrestrial ones using an intermediate pole (the CIP) in order to facilitate the estimation of the parameters from observations. The use of the angular momentum vector, whereas it is very useful for a dynamical approach of Earth’s rotation, cannot easily be linked to the observations. Other proposed EOP are not referred to a fixed plane and do not thus take benefit of the properties of the GCRS.

3.3 Comparison between Old and New EOP

The position of the CIP in the GCRS, of which use is recommended by Resolution B1.8, can be expressed by the direction cosines $X = \sin d \cos E$ and $Y \sin d \sin E$ (see Figures 3 and 5), which can be related to the combined classical angles for precession and nutation (see Figure 4) by (Capitaine 1990) :

$$X = \bar{X} + \xi_o - d\alpha_0 \bar{Y}; \quad Y = \bar{Y} + \eta_o + d\alpha_0 \bar{X} \ , \ (1)$$

with :

$$\begin{aligned} \bar{X} &= \sin(\omega_A + \Delta\epsilon_1)\sin(\psi_A + \Delta\psi_1) \\ \bar{Y} &= -\sin\epsilon_o\cos(\omega_A + \Delta\epsilon_1) + \cos\epsilon_o\sin(\omega_A + \Delta\epsilon_1)\cos(\psi_A + \Delta\psi_1) \ , \ (2) \end{aligned}$$

$\bar{X}$ and $\bar{Y}$ being the coordinates of the CIP in the mean equatorial frame at J2000 and the relation (1) being given at the first order in the offsets quantities at J2000, ξ_o, η_o and α_0. These quantities can be developed at a microarcsecond accuracy as a polynomial form of t plus a series of Poisson terms, valid over an interval of several centuries (Capitaine *et al.* 2000).

The new EOP, as adopted by the IAU (Resolution B1.8) in consistency with the ICRS, abandon the current parameters and formulation in the FK5 System which combine the motions of the equator and the ecliptic wrt the ICRS. The new parameters X and Y include both precession and nutation and refer directly to the GCRS. They use the intermediate reference system of the CIP, which allows to clearly separate high frequency and low frequency motions. The Earth’s angle of rotation is no more reckoned from the true equinox, but from the NRO (Guinot 1979), which is an unavoidable origin to separate the precession-nutation from Earth’s rotation.

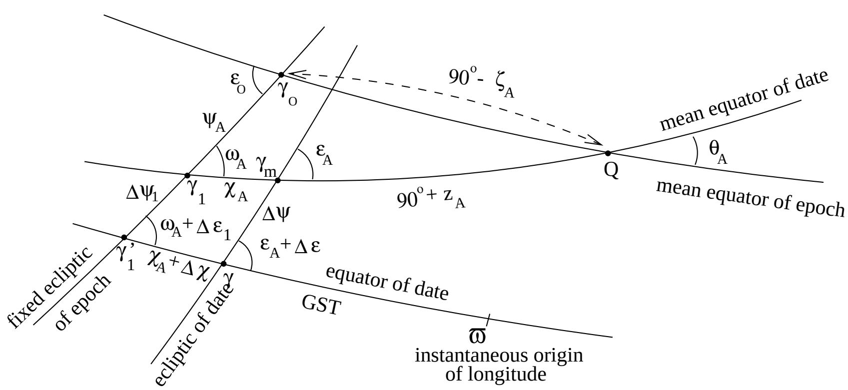

Figure 4: Earth orientation parameters (precession, nutation, GST) in the FK5

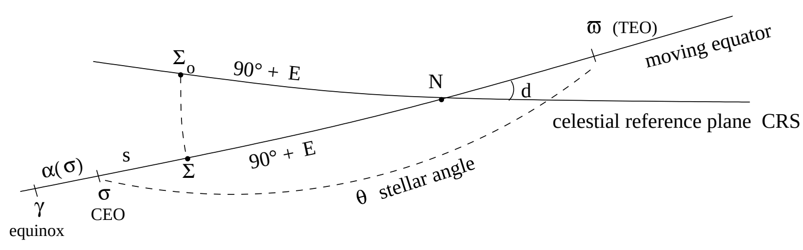

Figure 5: Earth orientation parameters (E, d, θ) (see (1)) referred to the GCRS

This reduces to 5 the parameters for the transformation between ITRS and GCRS (see Figure 3): two (E, d) (or X and Y) for the position of the CIP in the GCRS (instead of 6 current precession and nutation angles), two (F, g) (or polar coordinates u and$-v$) for the position of the CIP in the ITRS and one for the Earth's angle of rotation.

In order to refer the Earth Rotation Angle (ERA) to the NRO (designated by CEO in the GCRS and TEO in the ITRS, respectively), as required by Resolution B1.8, the angle of position of the CEO (resp. TEO) in the GCRS (resp. ITRS) has also to be provided; it is given by the quantity s (see Figure 5) (resp. s'). This can be expressed by a development as function of time (Capitaine *et al.* 2000). The relationship between the ERA (also called the “stellar angle” θ) and UT1 is linear and ensures the continuity in phase and rate of UT1 with the value obtained by the conventional relationship between Greenwich Mean Sidereal Time (GMST) and UT1 (Aoki *et al.* 1982). Such a linearity represents a significant improvement in the definition of UT1.

4 Acknowledgements

The subgroup T5 untitled “Computational consequences” of the IAU Working Group ICRS has been in charge of this issue from 1997 to 2000. I thank here all the contributors to the work of this subgroup (http://danof.obspm.fr/T5.html) which played a significant role for the adoption of the IAU 2000 Resolutions B1.7 and B1.8.

The T5 membership was : N. Capitaine (Chair, France), V. Dehant (Belgium), A.-M. Gontier (France), B. Kolaczek (Poland), J. Kovalevsky (France), J. Lieske (USA), C. Ma (USA), D.D McCarthy (USA), O. Sovers (USA), J. Vondrak (Czech. Republic). Other contributors to the discussion have been : C. Bizouard (France), P. Bretagnon (France), A. Brzezinski (Poland), S. Loyer (France), P. Mathews (India), M. Rothacher (Germany), H. Schuh (Germany), Y. Yatskiv (Ukraine).

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