RECENT ADVANCES IN MODELING THE LUNISOLAR PERTURBATION IN POLAR MOTION CORRESPONDING TO HIGH FREQUENCY NUTATION: REPORT ON THE DISCUSSION OF THE IAU COMMISSION 19 WG ON NUTATION

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ABSTRACT. We give here a brief report on the discussion within the subgroup "Questions regarding subdiurnal nutations" of the IAU Commission 19 Working Group on Nutation. The aim was to establish a model of the polar motion corresponding to high frequency nutation excited by lunisolar perturbation, which could be included in the new IERS Conventions 2000. Such a model was needed for realization of the conventional intermediate pole (CIP) defined by Resolution B1.7 of the XXIVth IAU General Assembly in Manchester. We considered three solutions for the nonrigid Earth: by Mathews and Bretagnon (2002, 2003), by Brzeziński (2001) and Brzeziński and Capitaine (2002), and by Getino *et al.* (2001) and Escapa *et al.* (2002a,b), the last one being restricted to the diurnal component of perturbation. After clarifying several controversial points and introducing the necessary corrections, the maximum difference between these models was found to be within 0.2 microarcseconds (μas) for individual coefficients and 1 μas in the time domain, that is about 0.2% and 1% of the total effect, respectively. The remaining controversy concerning the so-called "indirect contribution" to diurnal waves from triaxiality (almost entirely from that of the core), for which the estimates differed substantially (e.g., from 1 to about 2.5 μas), was left for further research.

1. INTRODUCTION

The IAU Commission 19 Working Group on Nutation chaired by Veronique Dehant was established at the XXIV IAU General Assembly in Manchester, August 2000, as the follow-up of the former Joint IAU/IUGG WG on "Non-rigid Earth Nutation Theory". This group was divided into several subgroups aimed at solving particular problems related to the implementation of the new IAU resolutions. One subgroup, with the first author of the paper (A.B.) as the responsible person, was devoted to "questions regarding subdiurnal nutations". The aim was to establish a model of the polar motion corresponding to high frequency nutation excited by the lunisolar perturbation, for inclusion in the new IERS Conventions 2000. Such a model was needed for realization of the conventional intermediate pole (CIP) defined by Resolution B1.7 of the XXIVth IAU General Assembly (for implementation by the 1st January 2003); see IAU (2001).

The discussion within the subgroup was speeded up after the IERS Workshop on the Implementation of the New IAU Resolutions in Paris, April 2002, when Dennis McCarthy passed on to Veronique Dehant a request for "a user friendly table that could be used to model the high-frequency nutation (periods $<$ 2 days) as polar motion". Between May and July 2002 there was an intensive exchange of e-mails, and 2 circulars were issued. The second circular dated 19 July 2002, contained the proposal of the model which will be described below.

Let us give now a brief physical description of the problem. External lunisolar tidal torques exerted on the Earth cause perturbations of the angular velocity vector. The types of spherical harmonic structures in the Earth's density distribution, and the spherical harmonic components of the lunisolar potential which act on these structures to produce the equatorial component of these torques are detailed in Table 1. The main term comprising the long periodic nutation and precession involves the zonal components $U_{l,0}$ of geopotential, for $l = 1, 2, \ldots$, with the dominant contribution coming from the component of degree $l = 2$. ($U_{l,j}$ stands for the geopotential or Stokes coefficients $C_{l,j}$ and $S_{l,j}$). In addition, there are minor components associated with the departures of the mass distribution from rotational symmetry, expressed by the non-zonal terms of the geopotential: $U_{2,2}$ and $U_{l,j}$ for degrees $l > 2$ and orders $j \neq 0$. A common feature of these terms is that they have quasi-diurnal and subdiurnal periods, as seen from space. An equivalent representation, which is mandated by the recently adopted definition of the conventional intermediate pole (CIP), is obtained by treating this effect as a perturbation of the motion of the pole in the terrestrial frame, that is as polar motion. In this representation the size of perturbation remains unchanged but the periods are different, as can be seen from Table 1.

Table 1: Summary of the lunisolar perturbations responsible for the equatorial component of Earth rotation. Only those components for which the total effect reaches the level of 0.1 μas are shown. In the first column, $U_{l,j}$ stands for the Stokes coefficients $C_{l,j}$, $S_{l,j}$ of degree l and order j, and $u_{l,j}$ in the next column represents the tidal potential of degree l and order j, expressed as the series of spectral terms with coefficients $A_{l,j,s}$, $s = 1, 2, 3, \ldots$. The last column shows the sum of the absolute values af all amplitudes greater than 0.01 μas.

Geo-potential	Tidal potential	Nutation	Polar motion	Sum of all amplitudes (μas)
$U_{l,0}$ for $l = 2, 3, \ldots$	$u_{l,1}$	long periodic	retrograde diurnal	nutation $> 10^7$ + precession
$U_{3,1}$	$u_{3,0}$	prograde diurnal	long periodic	91.3
$U_{4,1}$	$u_{4,0}$			periodic 1.0 + drift 5.1 μas/yr
$U_{2,2}$	$u_{2,1}$	prograde semidiurnal	prograde diurnal	51.6
$U_{3,2}$	$u_{3,1}$			0.2
$U_{3,3}$	$u_{3,2}$	prograde terdiurnal	prograde semidiurnal	0.1
$U_{3,1}$	$u_{3,2}$	retrograde diurnal	retrograde semidiurnal	0.8
$U_{3,2}$	$u_{3,3}$	retrograde semidiurnal	retrograde terdiurnal	0.1

To our knowledge, the subdiurnal nutations, or to be more precise, the prograde semidiurnal terms associated with the triaxiality of the Earth's figure expressed by $U_{2,2}$, were considered first by Kinoshita (1977) in his nutation theory for the rigid Earth. He arrived at the conclusion that such terms "have no appreciable effect on the rotational motion of the Earth" which was true indeed given the cut-off level of $0.0001''$ that he adopted for the amplitudes . The first estimation for the nonrigid Earth was reported by Chao *et al.* (1991), and corrected later by Chao *et al.* (1996). They considered this effect as a perturbation of the pole as viewed from the terrestrial frame, and designated it as "prograde diurnal libration in polar motion". Chao *et al.* (1991) neglected the potential terms of higher degree because the lunisolar torques diminish rapidly with l. This argument was correct but overlooked an important fact that in the case of the long periodic equatorial torques associated with the $U_{3,1}$ and $U_{4,1}$ terms of geopotential, an enhancement due to proximity to the Chandler resonance compensates the decrease of the magnitude of the torque and the corresponding polar motion is even larger than the diurnal libration; see Table 1 for the estimated magnitudes.

A more complete spectrum of the subdiurnal nutation was estimated as a part of the recent rigid Earth nutation theories, SMART97 (Bretagnon *et al.*, 1998), REN2000 (Souchay *et al.*, 1999), and RDAN97 (Roosbeek,1999); see also (Folgueira *et al.*, 2001) for comparison of these three theories.

Here we will compare the available estimates for the nonrigid Earth and describe the model which was submitted for publication in the IERS Conventions 2000.

2. MAIN POINTS OF DISCUSSION

2.1. *Solutions for the nonrigid Earth*

We considered 3 solutions for the polar motion due to lunisolar perturbation, each of them assuming a 2-layer structural model of the Earth consisting of an elastic mantle and a liquid core.

– The model developed by Brzeziński (2001) and Brzeziński and Capitaine (2002), further referred to as BC. The equation of polar motion was derived from the Liouville equation under a simple assumption that the core is not coupled to the mantle. The dissipative processes in the mantle and on the Earth were taken into account by allowing the Chandler frequency to be complex, with its parameters determined from the observations of polar motion. The external forcing was expressed by the tide-generating potential (TGP) catalogue HW95 of Hartmann and Wenzel (1995).

– The model of Mathews and Bretagnon (2002, 2003), further referred to as MB. This is based on a modification of the dynamical equations of Sasao *et al.* (1980) for the whole Earth and for the core, which take into account the coupling between the mantle and the liquid core. In addition, MB accounted for mantle anelasticity by introducing its frequency-dependent model. The TGP development RATGP95 of Roosbeek (1996) provided the forcing function in this estimation.

– The model developed by Getino *et al.* (2001) and Escapa *et al.* (2002a,b), further referred to as GFE, by applying the Hamiltonian formalism. The forcing was expressed by the perturbing potential estimated by Kinoshita (1977). So far, this theory has been confined only to the prograde quasidiurnal terms of the polar motion.

We were aware of the fact that there was one more solution for the nonrigid Earth, derived by Molodensky and Groten (2001), but we did not receive from the authors the parameters of the solution in the form enabling direct comparison with other results.

2.2. *Cut-off level*

Participants of the discussion agreed that the cut-off level 0.5 μas for the requested model of polar motion was consistent with other models submitted already for the IERS Conventions, while at the same time being sufficient for bringing out the details of the solution. After merging each pair of prograde and retrograde long periodic waves with the same period into a single elliptical wave, the model (Table 2) is found to contains 15 long periodic terms, a linear drift, and 10 prograde quasi diurnal terms representing circular waves.

2.3. *Arguments of the model*

In each term of the polar motion, the x and y coordinates of the pole are expressed as a linear combination of $\sin(arg)$ and $\cos(arg)$, where arg is an integer combination of the six astronomical arguments. Five of them are the well-known Delaunay fundamental arguments l_m, l_s, F, D, Ω which are used in the nutation theories, while the sixth one χ expresses the diurnal sidereal

Table 2: Polar motion of the nonrigid Earth due to tidal gravitation. Estimates, taken from (Mathews and Bretagnon, 2003), are based on the geopotential model JGM3, the tide generating potential RATGP95 and disregard the triaxiality of the core. Adopted cut-off level is 0.5 μas on the amplitude defined as the square root of the sin and cos coefficients of x_p or y_p, whichever is larger. The Earth's rotation angle is expressed by χ = GMST + π. The order of the tidal potential is expressed by the first digit of the Doodson number which equals the coefficient of χ.

Geo-	Tidal potential		Fundamental arguments						Period	PMx (μas)		PMy (μas)	
pot.	Doodson	deg.	χ	l_m	l_s	F	D	Ω	(days)	sin	cos	sin	cos
$U_{4,1}$	055.565	4	0	0	0	0	0	−1	6798.3837	−0.03	0.63	−0.05	−0.55
$U_{3,1}$	055.645	3	0	−1	0	1	0	2	6159.1355	1.46	0.00	−0.18	0.11
$U_{3,1}$	055.655	3	0	−1	0	1	0	1	3231.4956	−28.53	−0.23	3.42	−3.86
$U_{3,1}$	055.665	3	0	−1	0	1	0	0	2190.3501	−4.65	−0.08	0.55	−0.92
$U_{3,1}$	056.444	3	0	1	1	−1	0	0	438.35990	−0.69	0.15	−0.15	−0.68
$U_{3,1}$	056.454	3	0	1	1	−1	0	−1	411.80661	0.99	0.26	−0.25	1.04
$U_{3,1}$	056.555	3	0	0	0	1	−1	1	365.24219	1.19	0.21	−0.19	1.40
$U_{3,1}$	057.455	3	0	1	0	1	−2	1	193.55971	1.30	0.37	−0.17	2.91
$U_{3,1}$	065.545	3	0	0	0	1	0	2	27.431826	−0.05	−0.21	0.01	−1.68
$U_{3,1}$	065.555	3	0	0	0	1	0	1	27.321582	0.89	3.97	−0.11	32.39
$U_{3,1}$	065.565	3	0	0	0	1	0	0	27.212221	0.14	0.62	−0.02	5.09
$U_{3,1}$	073.655	3	0	−1	0	1	2	1	14.698136	−0.02	0.07	0.00	0.56
$U_{3,1}$	075.455	3	0	1	0	1	0	1	13.718786	−0.11	0.33	0.01	2.66
$U_{3,1}$	085.555	3	0	0	0	3	0	3	9.1071941	−0.08	0.11	0.01	0.88
$U_{3,1}$	085.565	3	0	0	0	3	0	2	9.0950103	−0.05	0.07	0.01	0.55
$U_{2,2}$	135.645	2	1	−1	0	−2	0	−1	1.1196992	−0.44	0.25	−0.25	−0.44
$U_{2,2}$	135.655	2	1	−1	0	−2	0	−2	1.1195149	−2.31	1.32	−1.32	−2.31
$U_{2,2}$	137.455	2	1	1	0	−2	−2	−2	1.1134606	−0.44	0.25	−0.25	−0.44
$U_{2,2}$	145.545	2	1	0	0	−2	0	−1	1.0759762	−2.14	1.23	−1.23	−2.14
$U_{2,2}$	145.555	2	1	0	0	−2	0	−2	1.0758059	−11.36	6.52	−6.52	−11.36
$U_{2,2}$	155.655	2	1	−1	0	0	0	0	1.0347187	0.84	−0.48	0.48	0.84
$U_{2,2}$	163.555	2	1	0	0	−2	2	−2	1.0027454	−4.76	2.73	−2.73	−4.76
$U_{2,2}$	165.555	2	1	0	0	0	0	0	0.9972696	14.27	−8.19	8.19	14.27
$U_{2,2}$	165.565	2	1	0	0	0	0	−1	0.9971233	1.93	−1.11	1.11	1.93
$U_{2,2}$	175.455	2	1	1	0	0	0	0	0.9624365	0.76	−0.43	0.43	0.76
Rate of secular polar motion (μas/yr) due to the zero frequency tide													
$U_{4,1}$	055.555	4	0	0	0	0	0	0			−3.80		−4.31

rotation of the Earth. We agreed that a proper choice for χ, which is consistent with the recent developments of the TGP, is χ = GMST + π, where GMST stands for the Greenwich mean sidereal time.

2.4. *Flattening terms in the TGP developments*

By flattening terms, we mean here the terms in the lunar/solar potential which arise from incremental acceleration of the Moon/Sun relative to the Earth because of the contribution from the Earth's flattening to the geopotential. The TGP developments used in the solutions BC and MB, that is, HW95 (downloaded from the website http://www.gik.uni-karlsruhe.de/ wenzel/hw95/) and RATGP95 (courtesy of Fabian Roosbeek), contain terms representing the flattening effect. These terms appear in the HW95 tables as $u_{3,0}$ terms, hence according to Table 1 should contribute to the long periodic part of the solution, while in RATGP95 these are the first-order degree terms which do not perturb polar motion. This inconsistency caused a systematic difference of about 0.5% in the amplitudes of the long periodic polar motion, hence reaching a detectable level for the largest waves shown in Table 2. However we found that the paper of Hartmann and Wenzel (1995) shows only degree 1 terms in the flattening contribution to the

Table 3: Comparison of the 3 solutions for polar motion of the nonrigid Earth due to tidal gravitation, derived by Brzeziński and Capitaine (2002) – BC, by Getino, Ferrándiz and Escapa (2001) – GFE, and by Mathews and Bretagnon (2003) – MB. All solutions are based on the assumption of rotational symmetry of the core.

Period	BC − MB				GFE − MB			
(days)	PMx (μas)		PMy (μas)		PMx (μas)		PMy (μas)	
	sin	cos	sin	cos	sin	cos	sin	cos
6798.3837	0.00	−0.01	0.01	0.00				
6159.1355	−0.01	0.01	0.01	−0.01				
3231.4956	0.14	−0.21	−0.04	0.06				
2190.3501	0.02	−0.03	0.00	0.01				
438.35990	−0.13	−0.05	0.05	−0.13				
411.80661	−0.05	−0.08	0.08	−0.05				
365.24219	−0.03	−0.02	0.03	−0.02				
193.55971	−0.02	−0.01	0.01	−0.02				
27.431826	0.00	0.00	0.00	0.00				
27.321582	−0.03	−0.01	0.00	−0.01				
27.212221	−0.01	0.00	0.00	0.00				
14.698136	0.00	0.00	0.00	−0.01				
13.718786	0.00	0.00	0.00	0.00				
9.1071941	0.00	0.00	0.00	0.01				
9.0950103	0.00	0.00	0.00	0.00				
$\sum$|ampl|	0.44	0.43	0.23	0.33				
1.1196992	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.1195149	−0.02	0.02	−0.02	−0.02	0.00	0.01	−0.01	0.00
1.1134606	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.0759762	−0.02	0.01	−0.01	−0.02	−0.01	0.00	0.00	−0.01
1.0758059	−0.09	0.05	−0.05	−0.09	−0.03	0.02	−0.02	−0.03
1.0347187	0.01	−0.01	0.01	0.01	0.00	0.00	0.00	0.00
1.0027454	−0.03	0.02	−0.02	−0.03	−0.01	0.01	−0.01	−0.01
0.9972696	0.10	−0.06	0.06	0.10	0.03	−0.02	0.02	0.03
0.9971233	0.02	−0.01	0.01	0.02	0.01	0.00	0.00	0.01
0.9624365	0.00	−0.01	0.01	0.00	0.00	−0.01	0.01	0.00
$\sum$|ampl|	0.29	0.19	0.19	0.29	0.09	0.07	0.07	0.09
Rate of secular polar motion (μas/yr) due to the zero frequency tide								
		0.01		0.02				

potential, in agreement with Roosbeek (1996). Therefore we omitted the $u_{3,0}$ flattening terms in the final computations.

2.5. *Indirect effect of the triaxiality*

This effect, first considered by Escapa et al. (2002) and further developed by Mathews and Bretagnon (2003), is caused by the coupling produced between the diurnal prograde and retrograde wobbles by triaxiality terms in the angular momentum of the whole Earth and of its fluid core. Its contribution to the diurnal prograde terms of the model considered here can be significant due to the FCN-related resonance in the retrograde wobbles, but is small (below 0.1 μas) if the core is rotationally symmetric. Unfortunately, there was a significant discrepancy, up to a factor of 2.5 or even more, between estimates of the indirect effect obtained by Escapa *et al.* (2002a,b) and by Mathews and Bretagnon (2003), (about 2.5 μas versus 1 μas for the largest contribution, when it is assumed that $A_c/B_c = A/B$, where A, B are principal equatorial moments of inertia of the whole Earth, and A_c, B_c are the corresponding quantities for the core alone); see (Escapa *et al.*, this volume) for further details and comparisons. This was the main controversy of the discussion which needs to be resolved by further study.

2.6. *Assumptions about the model*

We decided to provide for the IERS Conventions 2000 the model based on the assumption that the core is rotationally symmetric ($A_c = B_c$). There were two reasons for that:

– The triaxiality of the core, which is expressed by the equatorial moments of inertia A_c, B_c, can only be estimated from the geophysical determinations of the core-mantle boundary topography. However,comparison between different geophysical models (Brzeziński and Capitaine, 2002) shows large differences which suggests that it is too early to give preference to any of them. Such opinion was shared by Veronique Dehant (private communication) who headed that time the IERS Special Bureau for the Core.

– As stated in Sec. 2.5, there is no agreed set of values for the "indirect contributions" from the core triaxiality coefficient A_c/B_c. This problem requires further study. On the other hand, when disregarding the triaxiality of the core, the three sets of coefficients become very similar as can be seen from comparison shown in Table 3.

2.7. *Comparison of different estimates*

The 3 solutions for the nonrigid Earth, computed under the assumption of rotational symmetry of the core ($A_c = B_c$), are compared in Table 3. There can be observed an almost perfect agreement between the solutions MB and GFE. A slightly larger difference is between the solutions MB and BC, up to 0.2 μas in terms of the individual amplitudes, and about 1 μas in the time domain. This difference comes almost entirely from modeling of the nonrigid Earth response, because a similar comparison done for the rigid Earth (not shown here) yielded almost perfect agreement. The largest differences are for the terms with periods 8.85 years, 438 days, 412 days, and are caused by the fact that in the MB estimation the parameters of the Chandler resonance, the period and the quality factor, were frequency-dependent while in the solution BC these parameters were kept fixed. In the case of diurnal terms, the differences are caused by other features of the models, mostly by the omission in the solution BC of the indirect effect of the triaxiality.

2.8. *Comparison with oceanic and atmospheric contributions*

At prograde diurnal frequencies, the lunisolar perturbations in polar motion are superimposed on the variations excited by the ocean tides and the atmospheric tides. From Table 4 it can be seen that the atmospheric contribution is comparable in magnitude to the lunisolar effect but its power distribution among diurnal frequencies is different. The largest term with the amplitude of about 7 μas has a period of 1 solar day corresponding to the S_1 tide. This term has no counterpart in Table 2 and the corresponding ocean tide contribution is several times

Table 4: Prograde diurnal polar motion excited by the oceanic tides (Chao *et al.*, 1996) and by the atmospheric tides (Brzeziński and Petrov, 2000). Amplitudes are in μas and periods are in days.

Fundamental arguments						Tidal	Terrestrial	Oceanic				Atmospheric			
								PMx		PMy		PMx		PMy	
χ	l_m	l_s	F	D	Ω	code	period	sin	cos	sin	cos	sin	cos	sin	cos
1	−1	0	−2	0	−2	Q_1	1.1195149	6.2	26.3	−26.3	6.2				
1	0	0	−2	0	−2	O_1	1.0758059	48.8	132.9	−132.9	48.8				
1	0	0	−2	2	−2	P_1	1.0027454	26.1	51.2	−51.2	26.1	−0.6	1.2	−1.2	−0.6
1	0	−1	0	0	0	S_1	1.0000000	−0.6	−1.2	1.2	−0.6	5.2	−4.9	4.9	5.2
1	0	0	0	0	0	K_1	0.9972696	−77.5	−151.7	151.7	−77.5	−1.4	−0.7	0.7	−1.4
1	0	1	0	0	0	ψ_1	0.9945541	−0.6	−1.2	1.2	−0.6	0.5	−0.5	0.5	0.5

smaller, therefore there exists at least a potential chance that this atmospheric wave will be detected in the observations of polar motion. In case of the oceanic perturbations the situation is more difficult. Comparison of Table 4 with Table 2 shows that the ocean tide contributions are systematically about 10 times larger and differ in phase by about 90°. It is unlikely that the model of the dominant ocean-driven polar motion is sufficiently accurate for separating this effect from the direct influence of the tidal gravitation.

3. CONCLUSIONS

We presented here a report on the discussion within the subgroup "Questions regarding subdiurnal nutations" of the IAU Commission 19 Working Group on Nutation. The aim was to establish a model of the lunisolar perturbation in polar motion corresponding to high frequency nutation, which could be included in the new IERS Conventions 2000. We considered three different solutions for the nonrigid Earth comprising the solid mantle and the liquid core. Under the assumption of the rotational symmetry of the core, the difference between these solutions was found to be no greater than 0.2 μas in terms of the individual coefficients of the harmonic development and about 1 μas in the time domain, that is about 0.2% and 1% of the total effect. The remaining controversy which requires further research, is a question how the "indirect contributions" to the diurnal waves depend on the core triaxiality coefficient A_c/B_c. There seems to be little chance that this controversy will be solved in the near future on the basis of the measurements of polar motion, because for that one needs predictions for the dominant ocean tide contribution which are good at least at the 1 μas level.

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