NEXT DECIMAL FOR NUTATION MODELING

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1. INTRODUCTION AND PRESENT SITUATION CONCERNING THE NUTATION MODELING

The nutation model adopted by the IAU and the IUGG in 2000/2003 has been elaborated on the basis of the model MHB2000, a work of Mathews et al. (2002), and the rigid Earth nutation REN2000 of Souchay et al. (1999). The differences between the very Long Baseline Interferometry (VLBI) observations and the theory are at the milliarcsecond (mas) level in the time domain. Consequently, the next decimal for modeling is at the sub-centimeter level in pole position. The adopted model is based on a seismic model for the rheological properties inside the Earth from which the deformations are computed, and the Liouville equations are derived for a three-layered Earth for computing the nutational motions. There is an elastic inner core, a liquid outer core, and an inelastic mantle. The three layers are flattened and the Earth has a uniform rotation, which is used to compute the flattening of the inner core in hydrostatic equilibrium. Deviation from the hydrostatic equilibrium is considered for the core flattening and the global Earth dynamical flattening. The ocean tides, the mantle inelasticity, and a constant atmospheric contribution to the prograde annual nutation are considered. MHB2000 has been built from a fit of some geophysical parameters on the VLBI observations. The rigid Earth nutation model REN2000 accounts for the luni-solar gravitational attraction on Earth, the direct and indirect effects of the planets, the coupling effect induced by J_2 (the so-called J_2-tilt effect), the second order terms related to the Earth precession-nutation effects on the nutations. The new model is the result of the convolution of the Earth transfer function and these rigid Earth nutations, and considers in addition, the ocean tide and atmospheric contributions. It brings the theory close to the observations. Nevertheless, when compared to the observations, remaining residuals appear at the level of the mas.

2. IMPROVEMENT IN THE EXPRESSION OF THE OBSERVATION VARIABLES

Previously and for the adopted model, the nutation variables used were $\Delta\psi$ and $\Delta\epsilon$, the so-called nutation in longitude and in obliquity respectively. However, due to the new adopted procedure to pass from the terrestrial frame to the celestial frame, based on the adopted Non Rotating Origin scheme, one uses the variables X and Y (see Capitaine et al., 1986, 2003, and Capitaine, 2005, this issue). For this reason, Folgueira et al. (2005, this issue) and Souchay et al. (2005, this issue), have examined a new formulation for the Earth Rotation Parameters (ERP). They have established and integrated the equation of the Earth rotation using the ERP as defined by the IAU in 2000, using (X, Y). They have construct the relation that shows the equivalence between the use of $\Delta\psi$ and $\Delta\epsilon$ and the use of (X, Y).

3. IMPROVEMENTS IN OBSERVATION AND IN FITTING PROCEDURE OF THE GEOPHYSICAL PARAMETERS

Fey (2005, this issue) has mentioned the improvement in technology of VLBI observations and of their treatment, in the modeling of the phenomena which must be considered to improve the residuals such as the tropospheric corrections. Additional improvement in coverage of the sky and the increase of the number of stations participating in the networks, allows a better geometry of the VLBI networks. Titov (2005, this issue, se also Feissel-Vernier, 2003) also mentioned the corruption from source instabilities, and proposes a selection procedure. Charlot (2005, this issue) addressed as well the problems related to the source structure and showed the improvement from their knowledge.

The geophysical parameters such as the global Earth flattening, the core flattening, the dissipation at the Core-Mantle Boundary (CMB) and at the Inner Core Boundary (ICB), are generally fitted using the nutation amplitudes and phases in the frequency domain. However, this does not allow to account for the noise in the data, which is a function of time. Additionally, some of the corrections such as the atmospheric effects on nutation are not constant with time when considering each frequency component. They are better represented in the time domain. For this reason, Koot et al. (2005, this issue) have used a Bayesian approach to fit the parameters. This method is very promising.

4. IMPROVEMENT IN THE COUPLING MECHANISM AT CMB

The coupling mechanisms which could play a role in Earth rotation are the following:

1. the so-called inertial coupling related to the gravitational interaction between the flattened three layers of the Earth,
2. the gravitational coupling between the mass anomalies in the mantle and in the core,
3. the electromagnetic coupling,
4. the viscous coupling, and
5. the topographic coupling.

The first coupling mechanism, the inertial coupling, has been considered in the adopted model and thus does not need further improvement. The second coupling has been shown to be negligible by Defraigne et al. (1996). The electromagnetic coupling has already been considered for a part in MHB2000. At diurnal timescale, there exists a large relative motion of the core with respect to the mantle (see Figure 1). This motion is associated with the nutations and is particular important for nutations near the resonance at the Free Core Nutation (FCN). The magnetic field lines are following the global motion in the main part of the layer but there is a shearing of the magnetic field due to the relative rotations (see Figure 1). This interaction is not only considered at the CMB between the mantle and the fluid outer core, but also at the ICB, between the fluid outer core and the solid inner core. The magnetic field considered in the model has two components: (1) the most important part of the field, i.e. the dipole part, and (2) a uniform field representing the remaining contributions. In a recent paper, Delaplace and Cardin (2005) have recomputed the electromagnetic coupling for a global field developed in spherical harmonics. They of course used the recent values of the field as determined from the recent satellite missions.

In parallel, Huang et al. (2004, and 2006 in preparation) consider the coupling between the deformation equation and the induction equation. They have added a Lorentz force in the motion equation and considered the induction equation relating the magnetic field and the velocity field in the core. This is an ongoing very promising work.

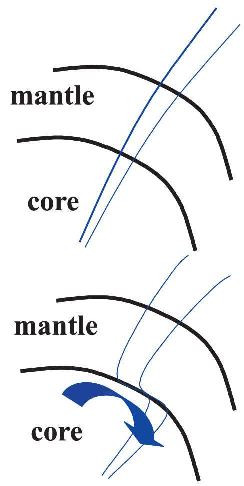

Figure 1: Magnetic field lines with and without the diurnal differential nutation of the core with respect to the mantle.

Topographic coupling must be considered in the future nutation models. It consists of considering the fluid pressure effects on the CMB topography (see Figure 2). Wu and Wahr (1997) have considered the topographic coupling and have analytically developed the torque acting on the core-mantle boundary. This needs to be evaluated in the light of new topography from seismologic tomography.

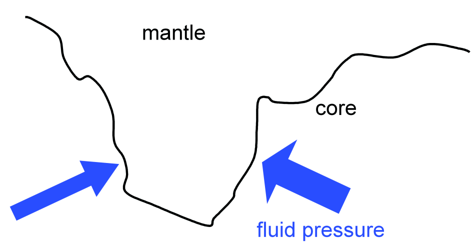

Figure 2: Representation of the topographic torque induced by the fluid pressure acting at the CMB.

Viscous coupling has been shown to be very small. However, the existence of an effective viscosity (Brito et al., 2004) has been discovered from laboratory experiment. For that reason, viscous coupling is not considered as negligible any more. Mathews and Guo (2005), on the one hand, and Deleplace and Cardin (2005), on the other hand, have computed the effects of this coupling mechanism between the core and the mantle and its influence on nutation (see Figure 3 for a representation of this coupling mechanism).

Concerning the coupling mechanisms at ICB, electromagnetic and viscous coupling must be considered, but no topographic coupling is evaluated because the inner core is considered to be

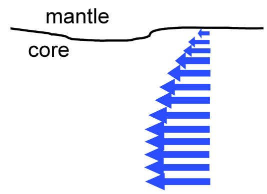

Figure 3: Viscous coupling between the core and the mantle.

in hydrostatic equilibrium.

5. CONSIDERATION OF THE INNER CORE VISCOSITY

Greff et al. (2000 and 2002) have considered the viscosity of the inner core in the computation of the nutations. They investigated the perturbations induced by the nearly-diurnal luni-solar tidal potential considering the effects of the magnetic friction at the inner core boundary (ICB) and considering the inner core viscosity. They showed that VLBI observations of the in-phase and out-of-phase components of some nutations can give information on the viscosity of the inner core and on the amplitude of the radial component of the magnetic field at the ICB. The effects are generally very small but at the level of the nutation observation precision. Generally speaking the electromagnetic field must be even larger when the inner core viscosity is considered than without considering the inner core viscosity. There is one exception to the generally small effect of the inner core viscosity: the effect on the 18.6 year nutation. The amplification due to the long period of this nutation can lead to a variation of the amplitude, induced by different viscosity and friction parameters, of a few tenths of milliarcsecond, well above the VLBI precision. In the model MHB2000, Mathews et al. (2002) do not account for the inner core viscosity but do consider the electromagnetic coupling at the CMB and ICB. They have modeled the non-elastic behaviour of the inner core with frequency dependent rheological parameters (they consider a frequency-to-the power-law for the rheology). This does not cover the whole range of viscosity possibilities but must be considered as a first step. Considering a Maxwell body rheology allows Greff et al. (2000 and 2002) to describe a completely solid inner core, a completely fluid behaviour, and all the intermediate states of the inner core rheology. This has allowed them to examine the behaviour of the forced nutations as a function of the different possible ranges of the electromagnetic frictional coupling constant as well as of the inner core viscosity.

6. PRECESSION CONSTANT

The precession constant can be deduced from the precession and nutation observation after correction of the non luni-solar contribution to precession. It is proportional to the differences of the moments of inertia of the whole Earth or the so-called dynamical flattening of the Earth. This parameter also enters in the principal nutation amplitudes. A fitting on the observation of precession and of nutation for this parameter has therefore been done by Mathews et al. (2002). A readjustment of the precession is discussed in Capitaine et al. (2003) and in Hilton (this issue). In their paper, Capitaine et al. (2003) discuss precession models consistent with the IAU2000A precession-nutation (i.e. MHB2000, provided by Mathews et al. 2002) and provide a range of expressions that implement them. They have developed new expressions for the motion of the ecliptic with respect to the fixed ecliptic using the developments from Simon et al. (1994) and Williams (1994) and with improved constants fitted to the most recent numerical planetary ephemerides. The final precession model, designated by P03, is a possible replacement for the precession component of IAU2000A, considering the improved dynamical consistency and a better basis for future improvement.

G. Bourda in her thesis (2004) has considered the coupling between J_2 and the precession constant as based on same geophysical parameters, and their time variation. The possibility to have time variation of the precession constant is considered in the P03 solution of Capitaine et al. (2003).

7. SECOND ORDER EFFECTS

The next step for nutation is the consideration of all second order effects that have been neglected in MHB2000. Dehant and Mathews are examining these terms for their book (in preparation). I only provide here a non exhaustive list of what can be expected.

1. Second order effects due to Liouville equations developed up to the second order in the wobbles: the Liouville equations contain linear terms in the wobble amplitudes m_i and the moment of inertia components c_{ij} and first order in the small quantities such as the dynamical flattenings of the whole Earth and of the core or the so-called compliances (directly related to deformability). Second order terms in the small quantities and in m_i, in particular the coupling between m_3 and m_1, m_2, must be considered.

2. Poincaré motion is considered in the liquid core. This is a strong approximation that certainly must be studied. One possibility is to consider second order of the core relative angular momentum due to second order in Poincaré motion.

3. The geometrical flattening was considered as equal to the dynamical flattening, which is not the case as the Earth is not in hydrostatic equilibrium.

4. The torques acting at the fluid core-mantle boundary involve the normal to the surface, which is expressed at the first order and should be extended as well.

5. The expression of the initial products of inertia for the whole Earth can be considered at second order.

6. Second order effects due to triaxiality can be considered. One finds already some work in that direction in the literature. Zharkov and Molodensky (1996), Gonzalez and Getino (1997), Van Hoolst and Dehant (2002) have also examined these effects and in particular have estimated the changes in the normal modes such as the Chandler Wobble.

7. The second order in C_{nm} S_{nm} (coefficients of the Earth gravitational potential) contributions to the external torque are related to additional gravitational interaction with respect to the classical interaction between the ellipsoidal Earth (J_2-part of the Earth gravity) and the celestial bodies (the Moon, the Sun, and the other planets). These effects induce non-retrograde-diurnal contributions as well in the terrestrial frame (see Bretagnon and Mathews, 2003, see also Lambert and Mathews, 2006).

8. Additional contributions to the torque acting on the Earth from the gravitational interaction between the external celestial bodies and the tidally deformed Earth (Lambert and Mathews, 2006).

9. Effect of coupling between the gravitational potential acting on an Earth which has tides (Lambert and Mathews, 2006).

8. EFFECT OF THE GEOPHYSICAL FLUIDS

The most important contribution of which the computation must be improved is the effect of the atmosphere, the ocean, and possibly the hydrosphere.

A few remarks need to be done at this level:

1. These contributions are not constant with time. They contain seasonal modulations, but the amplitudes of the sine and/or cosine of the seasonal period are not constant with time.

2. The computation from the angular momentum approach are not yet perfect as based on not enough sampling in the time domain for representing diurnal contribution.

3. Although the torque approach for computing the response of the Earth to the loading and attraction of the geophysical fluids provides very nice insight on the physical mechanisms of transfer of angular momentum, it is less precise than the angular momentum approach.

In Figure 4, we provide the wavelet transform of the atmospheric angular momentum contribution to nutation and the residuals between the VLBI observations and the MHB2000 model.

From this figure one can see that there is much more power in the nutation residuals than in the atmosphere angular momentum. This leaves some rooms for the ocean and hydrological contributions. Particular efforts have been recently done on the FCN excitation and the FICN excitation.

Concerning the FCN excitation, many Descartes Fellows are working on it as this is an important limitation of MHB2000 model. On the other hand, the residuals that are seen in a period range between 500 and 1000 days also intrigued the scientists. They are presented in Figure 5.

The large residuals that were seen in the nutation and were not yet explained by MHB2000 were believed to be related to an excitation of the FICN. However, a white noise excitation of this mode does not provide amplitude high enough to explain this (Dehant et al., 2005). The reality must be found in the network configuration (see Feissel-Vernier and Ma, 2005).

9. CONCLUSIONS

The new adopted nutation model is precise at a couple of centimeter level at the Earth surface. The advance in analytical, numerical, and observational works will therefore have to understand the physics and to consider all the contributions at the millimeter levels. We have here summarized a few steps in these directions. They are addressing the coupling mechanisms at the core-mantle boundary and at the inner core boundary, all the second order effects that are necessary to be included, and the geophysical fluid contributions. The Advisory Board of the Descartes Nutation Prize has therefore selected proposals in these directions. The new Descartes Nutation Fellows are listed her below. The theme of their research is also provided.

1. 'Dynamical Flattening and Geophysical Fluids Combinationt' (with a GGOS flag), Laura Fernández, 6 months, working with Harald Schuh at Technical University of Vienna;

2. 'Relations between the EOP and the variations of the Earth gravity field, through the inertia tensor', (with a GGOS flag), Géraldine Bourda, 6 months, working with Harald Schuh at Technical University of Vienna;

3. 'Investigation of excitations of nutation from geophysical fluids', Yonghong Zhou, 6 months, working with David Salstein at AER (Atmospheric and Environmental Research), USA;

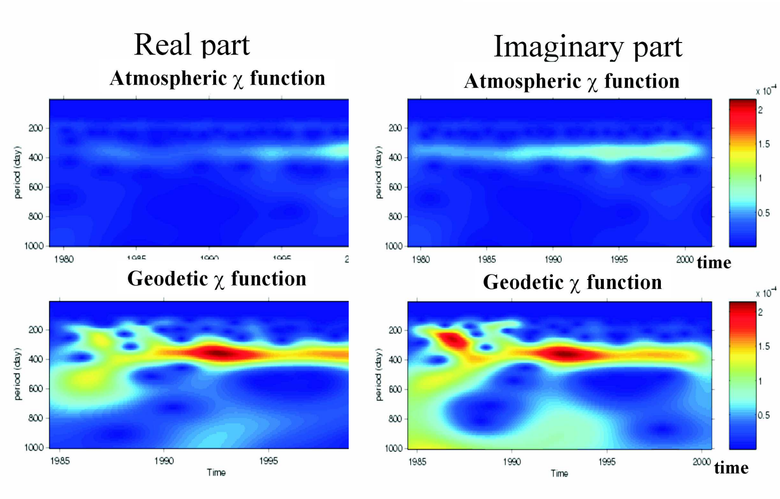

Figure 4: Real part (left) and imaginary part (right) of the atmosphere angular momentum (top graphics) and the geodetic observed residuals (bottom graphics).

4. ‘Modeling and prediction of the FCN; Study of the atmospheric and non-tidal oceanic effects on nutationť, Maciej Kalarus, 6 months, working with Harald Schuh at Technical University of Vienna (3 months) and with Tom Johnson at US Naval Observatory, USA (3 months);

5. ‘Modeling atmospheric and oceanic contribution to nutation’, Sergei Bolotin, 6 months, working with Aleksander Brzeziński at Space Research Center in Poland;

6. ‘Study of the FCN and subdaily variability of polar motion and length of day’, Maria Kudryashova, working with Aleksander Brzeziński at Space Research Center in Poland;

7. ‘Coupling and new nutation model from observation’, Laurence Koot, 2 months, working with Veronique Dehant, at Royal Observatory of Belgium;

8. ‘Advances in the integration of the equations of the Earth’s rotation in the framework of the new parameters adopted by the IAU 2000 Resolutions’, Marta Folgueira, 6 months, working with Nicole Capitaine at Paris Observatory, France;

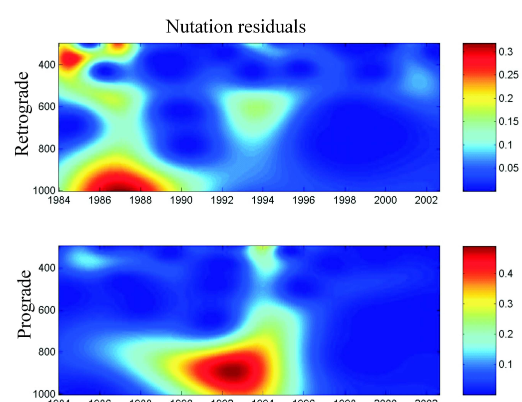

Figure 5: Nutation residuals (VLBI-MHB2000).

9. ‘Geophysical effects of considering the new solutions for the Earth’s rotation in the framework of the new parameters adopted by the IAU 2000 Resolutions’, Marta Folgueira, 3 months, working with Veronique Dehant at Royal Observatory of Belgium;

10. ‘Future of nutation from combination between GPS and GALILEO’, Kristyna Snajdrova, 1.5 year, working with Harald Schuh at Technical University of Vienna (in collaboration with Veronique Dehant at Royal Observatory of Belgium);

11. ‘Computation of the coupling mechanisms at the core-mantle boundary from a finite element approach; geodynamo model integration for the electromagnetic coupling’, Laurent Métivier, 6 month from Descartes Prize and 6 months from a GSFC grant, working 3 months with Véronique Dehant at the Royal Observatory of Belgium and 9 months with Weijia Kuang at Goddard Space Flight Center, USA.

REFERENCES

Bourda G., 2004, “Terrestre et variations du champ de gravité : étude et apport des missions CHAMP et GRACE.”, PhD thesis, Observatoire de Paris, France.

Brito D., Aurnou J., and Cardin P., 2004, “Turbulent viscosity measurements relevant to planetary core mantle dynamics.”, Phys. Earth planet. Inter. 141(1), pp. 3-8.

Capitaine N., Guinot B., and Souchay J., 1986, “A non-rotating origin on the instantaneous equator: definition, properties and use.”, Celest. Mech. 39, pp. 283-307.

Capitaine N., Wallace P., and Chapront J., 2003, “Expressions for IAU2000 precession quantities.”, A&A 412, pp. 567-586.

Defraigne P., Dehant V., and Wahr J.M., 1996, “Internal loading of an homogeneous compressible Earth with phase boundaries.”, Geophys. J. Int. 125, pp. 173-192.

Dehant V., de Viron O., Greff-Lefftz M., 2005, “Atmospheric and oceanic excitation of the rotation of a three-layer Earth.”, A&A 438, pp. 1149-1161, DOI: 10.1051/0004-6361:20042210.

Deleplace B. and Cardin P., 2006, “Viscous and Electromagnetic Coupling at the Core Mantle Boundary.”, Geophys. J. Int. in press.

Feissel-Vernier M. and Ma C., 2003, “Selecting stable extragalactic compact radio sources from the permanent astrogeodetic VLBI program.”, A&A 403, 105.

Feissel-Vernier M., 2003, “Selecting stable extragalactic compact radio sources for the maintenance of the ICRF axes.”, in: proc. 4th IVS workshop, Paris, France.

Getino J., Gonzalez A.-B., and Escapa A., 1997, “The rotation of a non-rigid, non-symmetrical Earth II: free nutations and dissipative effects.”, Celest. Mech. Dyn. Astr. 76(1), pp. 1-21.

Greff-Lefftz M., Legros H., and Dehant V., 2000, “Influence of the inner core viscosity on the rotational eigenmodes of the Earth.”, Phys. Earth planet. Inter. 122, pp. 187-204.

Greff-Lefftz M., Dehant V., and Legros H., 2002, “Effect of inner core viscosity on gravity changes and spatial nutations induced by luni-solar tides.”, Phys. Earth planet. Inter. 129(1-2), pp. 31-41.

Huang C., Dehant V., and Liao X., 2004, “The explicit equations of infinitesimal elastic-gravitational motion in the rotating, slightly elliptical fluid outer core of the Earth.”, Geophys. J. Int. 157(2), pp. 831-837, DOI: 10.1111/j.1365-246X.2004.02238.x.

Lambert S. and Mathews P.M., 2006, “Second order torque on the tidal redistribution and the Earth’s rotation.”, A&A submitted.