SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

THE EARTH'S NUTATION: OBSERVATIONAL AND GEOPHYSICAL ISSUES

S.B. Lambert[1]

Abstract. Since January 2003, the IAU recommends the use of the most precise precession-nutation model of Mathews et al. (2002), referred to as IAU 2000A, in astrometric and geodetic data reduction. The VLBI residuals against this model appear to have a rms around 200 microseconds of arc, yielding that a significant variance is still unexplained. This variance includes both deficiencies in the modeling of the Earth's rotation, including the unpredictable free core nutation, and in the observing and analysis strategy. I will expose several recent results concerning (i) the second order part of the nutation which was partly taken into account in IAU 2000A and has been clarified and accurately computed in a collaboration between P.M. Mathews and myself, (ii) the empirical modeling of the free core nutation and its atmospheric excitation, and (iii) some considerations concerning the fitting of models to VLBI data.

1 Modeling of precession and nutation

The precession-nutation is the motion of the Earth's figure axis seen from a space-fixed reference frame. It is mainly due to the tidal gravitational forcing of the Moon, the Sun and the planets of the Earth's equatorial bulge. Additionally, tidal deformations and loading, mass redistributions within surface geophysical fluids (atmosphere, oceans and continental water) and the free motion of the fluid core participate at a significant level.

Nutation theories are usually based on a geophysical model depending on a small number of parameters describing some physical properties of the Earth, including the Earth's interior. On the one hand, several rigid nutation theories are available (e.g., Roosbeek & Dehant 1998, Bretagnon et al. 1998, Souchay et al. 1999), yielding an internal precision of 0.1 μas. On the other hand, very long baseline interferometry (VLBI) measurements (see Gontier et al., this volume, for a review of geodetic VLBI) give the true nutation amplitudes. Differences between the rigid nutations and their observed couterparts clearly contain the non-rigidity effects and thus bring the possibility to fit the geophysical parameters. These parameters are derived from the linearized equations of the rotation of a multi-layer anelastic Earth: whole Earth and core flatennings, deformability parameters of the mantle and the core-mantle interface, electromagnetic core-mantle and core-inner core couplin! g coefficients.

The IAU 2000A model (Mathews et al. 2002, MHB in the following) has been realized in such a way. The geophysical parameters have been adjusted on a set of amplitudes for 21 well decorrelated frequencies using three different VLBI data sets running from the early 1980's to 2001 (Herring et al. 2002). Comparison of VLBI against MHB yields differences of about 200 μas in rms. Figure 1 (Left) displays the differences against the combined VLBI series made available by the International VLBI Service for Astrometry and Geodesy (IVS), gathering data sets from several VLBI analysis centers. It appears that a slight curvature shows up along with a periodic pattern with variable amplitude. Several effects are likely not taken into account in MHB. The long-term curvature will not be adressed here but is currently under investigation. However, the periodic pattern is the signature of the retrograde free core nutation, a free rotational mode of the Earth's outer core, which excitation! process will be treated in Section 3.

[1] Royal Observatory of Belgium, 3 Avenue Circulaire, Brussels 1180, Belgium

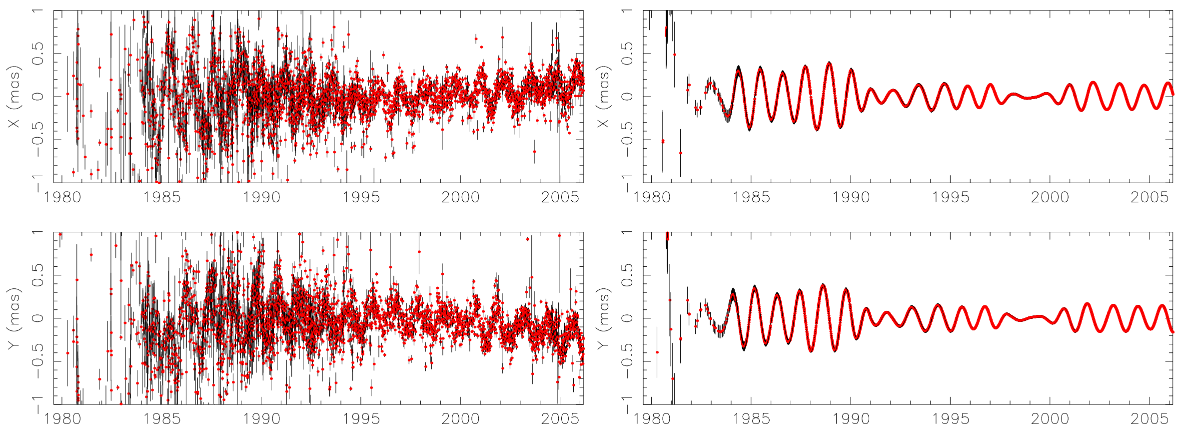

Fig. 1. Left: Differences between nutations estimated from VLBI (IVS combined series) and the IAU 2000A model, projected on the X- and Y-axis of the conventional celestial reference frame. Right: Least-squares fit of the free core nutation on the IVS combined data set.

2 Torque on the tidal redistribution

A class of effects only partly taken into account in MHB is due to the action of the degree 2 external and centrifugal potentials on the deformations induced by these potentials. They will be referred to as second-order effects in the following for obvious reasons, since computations of the nutations consider ordinarily the first-order effects, namely, the torque exerted by the tesseral tidal potential on the ellipsoidal Earth, plus the inertial effects of the deformations produced by the tesseral and centrifugal potentials associated with wobbles induced by the tesseral potential. The torque is thus computed on the static shape of the Earth, while the much smaller torque resulting from the action of the potential on the variations induced by the potential in the shape of the Earth is missing.

Several studies have investigated the second-order effects on the Earth's nutation due to the action of the tesseral potential on the time dependent increments to the Earth's flattening produced by the zonal potential (e.g., Souchay & Folgueira 1999 for an elastic Earth, MHB and Lambert & Capitaine (2004) for a deformable Earth with fluid core, also including an ocean). All these studies yielded significant effects at the level of 200 μas, that clearly should be investigated.

Lambert & Mathews (2006) investigated the effects resulting from the coupling of each part of the degree 2 potential (tesseral, zonal and sectorial) to deformations due to other parts of the potential. It is clear that the net effect is very small as a result of reciprocal cancellations: the effects of the tesseral potential on zonal deformations are nearly canceled out by the reciprocal effects of the zonal potential on tesseral deformations. In the same way, the effects of the tesseral potential on sectorial tides are almost canceled out by the effects of the sectorial potential on tesseral tides. The reasons for incomplete cancellation are that (i) the value of the deformability parameter κ of the mantle differs for tides of different orders (0,1,2) even for a nondissipative Earth, and (ii) for an anelastic Earth with oceans, the contributions from these to κ are not only frequency dependent (with a different dependence in different frequency bands) but als! o complex, meaning that the response to tidal forcing is out of phase with the forcing. The net effect on the nutation reaches -35 μas on the 18.6-yr nutation in longitude and comes mainly from the oceanic tides. The total effect on the precession is of the same order of magnitude (0.1 mas/cy) in longitude and in obliquity.

3 The free core nutation

Retrograde free core nutation (RFCN) is a free rotational mode of the Earth, associated with the ellipsoidal liquid core rotating inside the visco-elastic mantle. The signature of this free mode on the Earth's figure axis observed from a space-fixed reference frame is a retrograde motion (opposite to the Earth's rotation), with an amplitude varying between 50 and 300 μas and with a period estimated at -430.23 sidereal days (Herring et al. 2002) with a variable phase. A least-squares fit on this oscillation in the observed nutation is displayed on

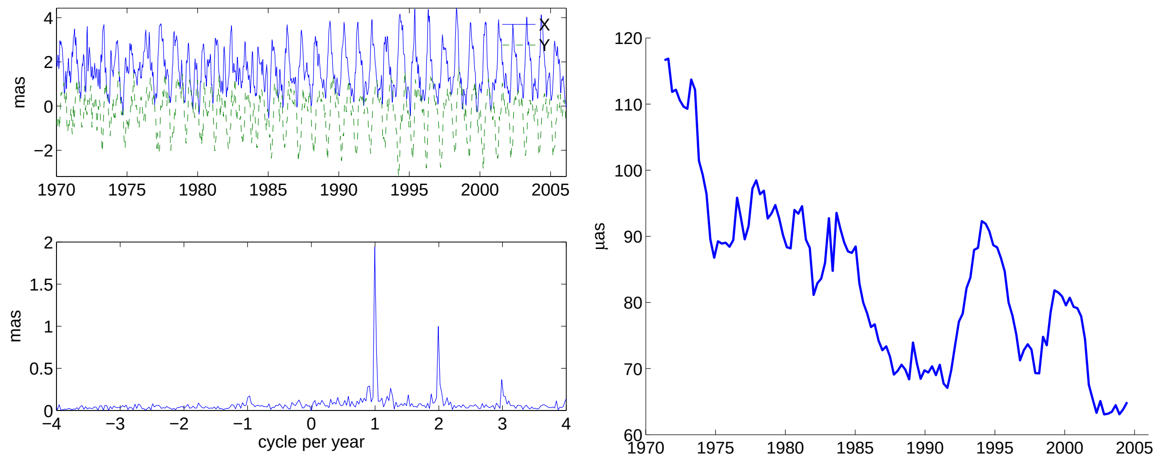

Fig. 2. Left: Time series and complex spectrum of the celestial atmospheric angular momentum (NCEP/NCAR Reanalysis). Right: Predicted amplitude of the free core nutation (Lambert 2006).

Fig. 1 (Right).

The excitation mechanism of the RFCN is still an open question (Dehant et al. 2003). Several studies have shown evidence of a source of excitation in the surface geophysical fluids (atmosphere, oceans). The RFCN is comparable to the Chandler wobble, another free rotational mode of the Earth, occurring with a period of 433 days in the Earth-fixed reference frame. Gross (2000) showed that combined atmospheric and ocean bottom pressure variations could excite the Chandler wobble. Similarly, the long-term modulation of the diurnal signal in geophysical fluids could drive the amplitude variability and the phase changes of the free core nutation.

In Lambert (2006), I developped a formalism based on Brzeziński's (1994) equations, linking the amplitude of the space motion of the Earth's figure axis to the atmospheric excitation based on the assumption that the atmospheric excitation can be modeled by a white noise. I used meteorological data (atmospheric pressure and winds), provided on a regular basis by several agencies. The 6-hour time resolution of some of these data sets allows one to explore the diurnal and sub-diurnal signal likely able to contribute to the RFCN excitation. (Conversely, the diurnal signal becomes long-periodic when seen from a space-fixed reference frame. See Fig. 2, where the atmospheric angular momentum functions are rotated by GMST.) The study showed that, globally, the atmospheric contribution to the RFCN accounts for half of the observed RFCN amplitude. However, the time variability of the RFCN signal, as observed by VLBI, is not explained by the time-varying noise in the atmosphere (see Fig. 2). The variations of the latter are too weak and not statistically significant considering the uncertainty attached to the atmospheric data in the diurnal band. Improvements are thus needed in atmospheric modeling to enforce the reliability of the atmospheric data at diurnal frequencies. Until this is achieved, the physical link between the observed RFCN and its atmospheric excitation, especially concerning its time variability, will remain unclear. Further research is also necessary to extend the study to other geophysical fluid layers. A lack of oceanic data in the diurnal band does not allow one to investigate their effects on the RFCN, although they are expected to be significant.

4 On the side of VLBI

When studying the Earth's nutation, one cannot evade instrumental issues. VLBI ties the observing stations (fixed on the crust) to compact extragalactic radio sources (e.g., quasars, BL Lac, AGN) which consistute the current best realization of an inertial (celestial) reference frame (CRF). There therefore exists a balance between the realization of the Earth orientation and the realization of the celestial frame. Any error on the determination of one will result in an error on the determination of the other. Until these errors are identified, there exists a risk of misinterpretation.

The choice of the CRF is one of these potential sources of error. A constraint of no-net rotation is applied on a subset of radio sources which constitutes the CRF. Ma et al. (1998), in the frame of an IAU working group, selected 212 defining sources building so the International Celestial Reference Frame (ICRF), presenting at this time a stability at the level of 20 μas. The ICRF was derived on the basis of all VLBI observations since the late 1970's. Since then, Earth orientation data are derived in VLBI operational analysis using the constraint. About 8 years later, the number of observations has increased by a factor of 2, and the question of finding a more stable set of radio sources is open.

Actually, evolutions in the radio source structures (jets) significantly modify the position of the radio center. Feissel-Vernier (2003), using various stability criteria, derived a CRF more stable than the ICRF. Feissel-Vernier et al. (2006) showed that applying the no-net rotation constraint to this new CRF could change significantly estimates of the precession-nutation amplitudes. One can understand that such a result has crucial implications in geophysics (see Section 1 of this paper). Researches are currently performed in this sense at the Paris Observatory (see Gontier et al., this volume).

The network (shape of the interferometer, capabilities of the dishes, geographical location of the observing sites) has also an influence on the Earth orientation data determination. Although this influence is significant on polar motion and UT1 (Lambert & Gontier 2006), the effect on nutation and precession remains marginal.

5 Conclusion and perspectives

Although the current modeling of the precession-nutation is very accurate and satisfying on a geophysical and astronomical point of view, several questions still need to be addressed. The main signal showing up in the unmodeled observed nutation is the signature of the free rotational mode of the fluid outer core. The excitation process of this free core nutation has been shown to be mainly atmospheric, but the time variability of its amplitude and phase remains unclear and should be re-examined with better meteorological and ocenic data. The choice of the celestial reference frame is also a crucial point for future VLBI analyses and is currently under investigation. A last point concerns the method used to fit the geophysical parameters in VLBI data. A recent work by Koot et al. (2006), using a Bayesian estimation in the time domain, showed that some geophysical parameters were more sensitive to the VLBI analysis strategy (that appears through different VLBI data sets worke! d out by different VLBI analysis centers) and to various assumptions made on the nature of the noise.

Understanding the Earth's nutation, including the effects of surface geophysical fluids, is a challenging question for a large community. Except geophysical or astronomical applications, fundamental operational applications exist like the short term Earth orientation prediction at the International Earth Rotation and Reference Systems Service (IERS), a crucial activity for high precision positioning or civilian and military navigation.

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