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Recent Advances in Applications of Geodetic VLBI to Geophysics

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Abstract

This paper presents recent advances in Earth Orientation Parameters (EOP) determination and in their modeling. These advances are related to the increase of the precision of the observation and the implementation of dedicated strategies to better obtain them. The advances are also related to the determination of Earth geophysical parameters from VLBI observations and better modeling of the phenomena within the Earth. Further improvement in the observation precision enhances our understanding of the interior of the Earth. In particular, we examine the coupling mechanisms at the core-mantle boundary: the electromagnetic coupling, the topographic coupling, and the viscous coupling. We also present future developments necessary for a better understanding of the Earth's interior and its orientation parameters.

1. Monitoring the Earth's Orientation using VLBI

A number of improvements have been performed in the networks used for the observation of Earth rotation and orientation parameters. The number of stations has increased, the networks have been extended, and the number of observed sources in each session has been increased. Strategies concerning the processing of the data have been defined (VLBI2010) in order to ensure the best processing of the observation (e.g., Niell et al., 2007). Additionally the realizations of the reference frames (ITRF as well as ICRF) have been improved (Altamimi et al., 2011; Ma et al., 2009). In particular, the axes of the current realization of the ICRF, the ICRF2 (Ma et al., 2009), are defined by a larger set of sources than for the previous ICRF (Ma et al., 1998) covering both hemispheres and stable at the 10 milliarcsecond (mas) level.

The Earth Orientation Parameters time series have become longer and therefore the long period nutations are better determined. The data timespan now allows to drop the first noisy period of observation (before 1995) for the evaluation of the amplitudes of the long period 18.6 year nutation and of all the other shorter ones. The formal errors have become better. The FCN free mode that is visible in the time series of the nutation offsets can be evaluated as a function of time ensuring a better accuracy of the nutation amplitude determination, especially for terms whose frequencies are close to the FCN frequency (e.g., retrograde annual). Figure 1 shows the nutation residuals with respect to the IAU2000 adopted nutation series after evaluation of the FCN free mode.

Whereas VLBI nutation measurements allow for a precise observation of the time-varying amplitude of the FCN free mode, the modeling of this amplitude has never been achieved, due to a very poor knowledge of the excitation mechanism (e.g., Lambert, 2006). As for the FICN, it

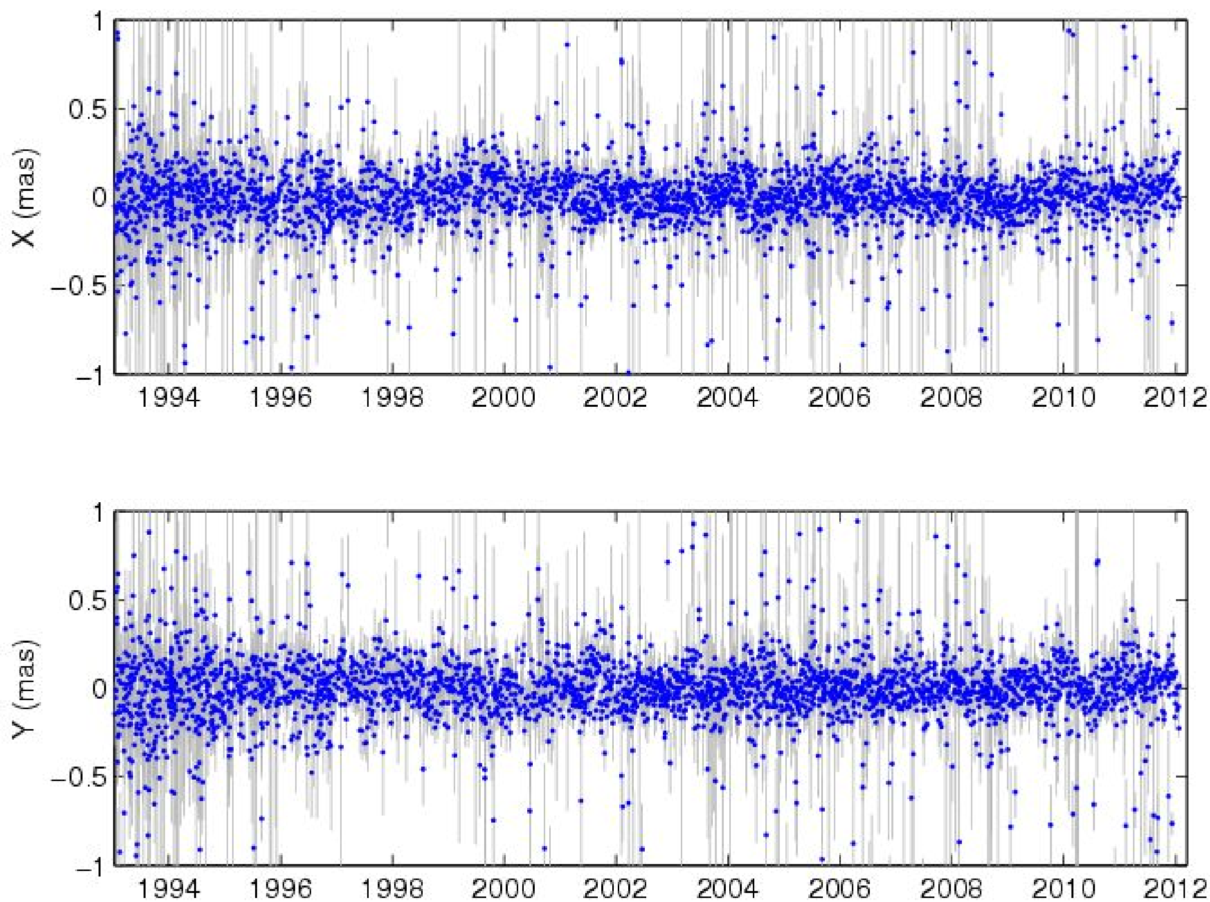

Figure 1. Nutation offsets with respect to the IAU2000 adopted nutation model.

has not yet been observed directly. The knowledge on these mode frequencies and dissipations is coming from their effects on the forced nutation.

2. Insights into the Earth's Interior from VLBI Data

2.1. Physical Properties of the Core-Mantle Boundary

VLBI observations allow for the estimation of a coupling constant characterizing the strength of the mechanical coupling at the CMB, as well as the total energy dissipated through the coupling. As the strength and dissipation involved in the coupling depend directly on CMB physical properties, the estimated coupling constant can be used to infer constraints on these properties (e.g., Mathews et al., 2002, Koot et al., 2010). Several constraints have been obtained depending on the coupling mechanism considered. If the observed dissipation is assumed to result from a purely electromagnetic (EM) coupling at the CMB, then the coupling constant can be explained by an RMS strength of the magnetic field at the CMB of the order of 0.7 mT, if the electrical conductivity of the outer core and of the lowermost mantle is fixed to 5×10^5 S m^{-1} (Buffett et al., 2002, Koot et al., 2010). For lower values of the conductivities, the RMS strength of the field must be higher. From observations of the surface magnetic field, the large scale components of the field (spherical harmonic degrees smaller than 14) at the CMB are known to have an RMS strength of the order of 0.3 mT. Therefore, nutation observations suggest that a large part of the energy of the magnetic field at the CMB is contained in the small scale components (harmonic degrees larger than 14), which are unobservable at the Earth's surface.

Another interpretation of the observed coupling constant has been obtained relying on a visco-magnetic coupling at the CMB (Mathews and Guo, 2005, Deleplace and Cardin, 2006, Koot et al., 2010), but these studies show that the viscous torque becomes significant only for values of the outer core viscosity of the order of 10^{-2} m^2 s^{-1}. However, these values are in disagreement with inferences obtained from other sources (such as laboratory experiments on iron alloys at high pressure and temperature and theoretical 'ab initio' computations, see Rutter et al., 2002, Alfè et al., 2000), even if the viscosity is assumed to be an effective eddy viscosity due to turbulent motions (Buffett and Christensen, 2007). For realistic values of the outer core viscosity (i.e., lower than 10^{-4} m^2 s^{-1}), the viscous coupling does not contribute significantly to the observed dissipation.

Recently, another mechanism has been proposed to explain the observed coupling constant at the CMB. This mechanism is a variant of the EM coupling that requires the existence of a light elements stratification at the top of the core and of a topography at the CMB (Buffett, 2010a). If the stratification at the top of the core is strong (with a buoyancy frequency $N = 0.09$ s^{-1}), this mechanism is able to explain the observed dissipation with an RMS strength of the magnetic field at the CMB of 0.5 mT, with a lowermost mantle conductivity of 10^3 S m^{-1} and a CMB topography with a height of 120 m and horizontal length scale of 10^5 m.

2.2. Physical Properties of the Inner Core Boundary

Due to the amplification of the amplitude of long period forced nutations (the Bradley 18.6 year nutations) and of the large semi-annual prograde nutation by the FICN normal mode, VLBI nutation observations allow for the estimation of a coupling constant at the ICB, characterizing the strength and energy dissipation of the mechanical coupling at this boundary. If the observed dissipation is due only to an EM coupling, this would require a magnetic field at the ICB with an RMS strength of the order of 7 mT, for an electrical conductivity of the outer and inner cores of 5×10^5 S m^{-1} (Buffett et al., 2002). However, such a strong magnetic field seems to be in disagreement with geodynamo models and observations of fast torsional oscillations in the core, which both suggest an ICB magnetic field of the order of 2-3 mT (Christensen and Aubert, 2006; Gillet et al., 2010). Consequently, part of the observed dissipation probably comes from another dissipative mechanism. For realistic values of the outer core viscosity, the viscous coupling is not able to explain a significant part of the observed dissipation (Mathews and Guo 2005; Koot et al., 2010). Other alternative mechanisms have been proposed to explain the observed dissipation. First, the dissipation could come from Ohmic dissipation in the outer core, arising from the stretching of magnetic field lines in the outer core by shear layers induced by the precessing inner core (Buffett, 2010b). This mechanism could explain the observed dissipation with a magnetic field in the core of the order of 2.5 mT. Alternatively, part of the dissipation could come from the viscous relaxation of the inner core (Koot and Dumberry, 2011). This mechanism is significant for inner core viscosities of the order of 10^{14} Pa s. The remaining dissipation due to EM coupling could then be explained by a magnetic field between 4.5 and 6.5 mT.

3. Refining Present Models of the Earth's Rotation

3.1. Present Models

The geophysical interpretation of VLBI data relies on our ability to identify meaningful geophysical signatures in nutation time series and thus to accurately model the Earth's nutation. Detailed explanations on the modeling of the Earth's nutation can be found in Dehant and Mathews (2007).

Nowadays, the Earth's response (rotation variations and deformation) to the luni-solar attraction (and to a minor extent to the attraction of the other planets of the solar system) is computed following a two-step procedure: first, nutation time series are precisely computed for an equivalent rigid Earth from celestial mechanics; then, these series are corrected to account for the actual, non-rigid interior of the Earth (given as radial profiles, e.g. of the density, the shear modulus and the bulk modulus) by multiplication with the so-called Earth nutation transfer function for each tidal frequency.

There are two ways to compute the nutation transfer function. One can compute the Earth's response to the tidal forcing locally at every particle, solving for the particle infinitesimal displacement by integrating the equations of continuum mechanics from the center up to the surface. This is done in an ellipsoidal rotating Earth (Wahr, 1981; Dehant, 1987). Nutations (due to tesseral tides) correspond to global toroidal degree-1 order-1 displacements and rotation rate variations (due to zonal tides) correspond to global toroidal degree-1 order-0 displacements; both of them cannot occur without additional tidal deformation. Another method to compute the nutation transfer function is to compute the Earth's response to the tidal forcing globally for every layer inside the Earth. This will solve the angular momentum balance equation for the wobbles of the whole Earth and of the inner core, outer core, and mantle, considering coupling mechanisms between adjacent layers at the ICB (inner core boundary) and CMB (core-mantle boundary). The coupling mechanisms usually considered are the pressure torque (due to the flattening of the core boundaries), the gravitational torque, the electromagnetic torque, and the viscous torque. These approaches are detailed in Dehant and Mathews (2007).

The currently adopted nutation model (IAU2000 nutation model) is based on the angular momentum balance equation approach in which the physical parameters are determined from VLBI data or computed from realistic physical properties of the Earth (Mathews et al., 2002). As the observation accuracy has been improved since then, these parameters can be better determined and therewith improve our knowledge of the Earth's interior (Koot et al., 2010).

To refine the geophysical interpretation of VLBI data, we should also refine the adopted nutation model and make it as realistic as possible. The model may be improved at different levels, for example by incorporating the topographic torque, by self-consistently considering the Earth's non-hydrostatic flattening, and by refining the description of atmospheric and oceanic contributions to nutations.

3.2. Topographic Coupling

In the nutation model adopted by the IAU in 2000, the only topographic feature which is considered in the nutation computation is the flattening of the CMB and the hydrostatic flattening of ICB. In reality however, the CMB shape is bumped. The seismologists provide us with values of the shape expressed in terms of spherical harmonics (Forte et al., 1994; Boschi and Dziewonski, 2000; Ishii and Tromp, 2001; Simmons et al., 2009; Soldati et al., 2012). Wu and Wahr (1997) have computed the effects of the topography on the nutation and length-of-day (LOD) and Dehant et al. (2012) have considered this approach for an analytical computation in parallel with a numerical estimation of the effects. Wu and Wahr have in particular shown that some of the topography coefficients induce large contributions in the response of the Earth. We can wonder why only some of the topography coefficients are more important than others. With a close look into the equations used to compute topographic effects on the fluid motion, Dehant et al. (2012) have shown that (for a simplified case of incompressible fluid) the incremental velocity due to the topography corresponds to resonance with inertial modes. Some of these modes have their frequency close to a tidal frequency of nutation, which is then enhanced. This might induce observable effects that may be important enough to be seen at the present level of accuracy in the observed nutation amplitudes. In practice, the strategy for computing the effect of the topography on nutations is the following: (1) establish the motion equations and boundary conditions in the fluid, separating the Navier-Stokes equation into a part related to the classical approach and a part related to additional inertial modes, (2) compute analytically/numerically the solutions, (3) obtain the dynamic pressure as a function of the physical parameters, and (4) determine the topographic torque. This can be performed in a completely analytical approach or a numerical approach. This is ongoing work that is very promising in view of the level of the nutation contributions for a particular topography (at the milliarcsecond level). Part of the work has been published in proceedings of conferences (see Dehant et al., 2008; 2012a; 2012b).

3.3. Flattening and Non-hydrostaticity

In the current conventional model of the Earth's rotation (IAU2000), interior properties relevant to rotation are summarized in a set of parameters. Poorly known parameters are estimated so as to best match VLBI data. Other parameters are computed for a simplified, spherical, non-rotating, hydrostatically pre-stressed Earth model, thus neglecting the Earth's flattening, rotation, and non-hydrostaticity. These characteristics should be considered in a refined nutation model.

While the former conventional model of the Earth's rotation (IAU1980) did fully consider the Earth's polar flattening and rotation (Wahr, 1981), it disregarded non-hydrostaticity, which however affects the FCN period (Gwinn et al., 1986). A full consideration of the Earth's non-hydrostatic flattening is therefore necessary and can be achieved by extending Wahr's model to a non-hydrostatically pre-stressed Earth. The non-hydrostatic, roughly triaxial shape of the Earth is maintained by mantle convection and can be obtained from a geodynamic model of mantle flow constrained by lateral density heterogeneities derived from tomography (e.g., Defraigne et al., 1996).

3.4. Atmosphere and Oceans

In addition to the gravitationally-driven nutations, torques applied on the Earth by the ocean and atmosphere also induce nutations, with amplitudes smaller by several orders of magnitude. In the adopted model, the effect of the ocean tides contributions are taken into account, as well as the non-tidal atmospheric effects on the prograde annual nutation. The non-tidal atmospheric effects on the other terms are not taken into account. However, using several reanalyses of atmospheric general circulation models (GCM), Koot and de Viron (2011) have shown that these effects could be safely neglected in the nutation model, as they are sufficiently small to not affect the estimation of Earth's interior parameters from nutation observations. As a perspective, contributions coming from the non-tidal ocean should also be estimated but this would require ocean GCM with a good precision in the diurnal frequency band.

4. Outlook

It is often asked to the theoreticians developing nutations what would be the best strategy for obtaining better nutation theory and better knowledge on the interior of the Earth. We would like to stress that the most important nutations for the determination of the interior parameters such as the free nutation periods and damping are the prograde and retrograde annual nutations and the prograde and retrograde 18.6 year Bradley nutations. Therefore we acknowledge the present effort for the continuation of long-term observation of nutation. In parallel, further refinements of the theoretical models should be achieved, in order to take the most out of the available observations.

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