The Annual Retrograde Nutation Variability

C. Gattano, S. Lambert, C. Bizouard

Abstract Very Long Baseline Interferometry is the only technique that can estimate Earth nutations with an accuracy under the milliarcsecond level. With 35 years of geodetic VLBI observations, the principal nutation terms caused by luni-solar tides and geophysical response have been estimated. We focus on the variability. Two of them present very significant amplitude and phase variations: the retrograde Free Core Nutation (FCN) with a period of around 430 days and the Annual Retrograde Nutation (ARN). Despite progress made in global circulation models, the atmospheric and ocean excitation cannot account for that. In particular the ARN shows an amplitude modulation of approximately six years, reminiscent of the six-year geomagnetic oscillation in the Length-of-Day (LOD). As to the latter, we suggest that the nutation term variability may have deep Earth causes, and we estimate an order of magnitude of Earth internal structure parameters to explain this variability.

Keywords Nutation, least-squares adjustment, ARN

1 Introduction

The last approved nutation model, MHB2000 [14], was derived from VLBI data. They have adjusted 1365 luni-solar and planetary terms, associating constant amplitudes and phases with each of them. But this model was unsuccessful in explaining the free core nutation (FCN) that increases by more than 100 µas at some times. This nutation arises from a geophysical response to luni-solar attraction, and it finds its source in the coupling between the fluid outer core and the mantle. This coupling can be of viscous nature, of electromagnetic nature, or due to the topography of the boundary.

Therefore, to estimate correctly the variation of the FCN is important for the understanding of the inner structure of the Earth. Many studies have been published on its estimation, and several models exist: Malkin (2013) [12], Krásná et al. (2013) [10], Belda et al. (2016) [1]. One of them has been selected as reference by the IERS: the Lambert model[1] [16]). These works have in common that they estimate the variability using a window with a width on the order of the FCN period. The proximity of the annual retrograde nutation (ARN) with the FCN can be dangerous because of the beat phenomenon. Given the variability of the FCN and possibly of the ARN, a least-squares adjustment approach may not succeed.

2 Data

We carried out a comparison of several nutation time series provided by different Analysis Centers of the IVS (see Table 1). The nutation time series used in this study are offsets according to the IAU2000A/2006 precession-nutation model [14, 5] in dX, dY parametrization. Despite the divergence between the nutation time series that may be associated with differences in analysis strategies[2], the Analysis Center products are in agreement on the Free Core

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[1] http://syrte.obspm.fr/∼lambert/fcn/notice_fcn.pdf

[2] We do not present an analysis comparison in this study. But if you are interested, you can find all technical files for each IVS so-

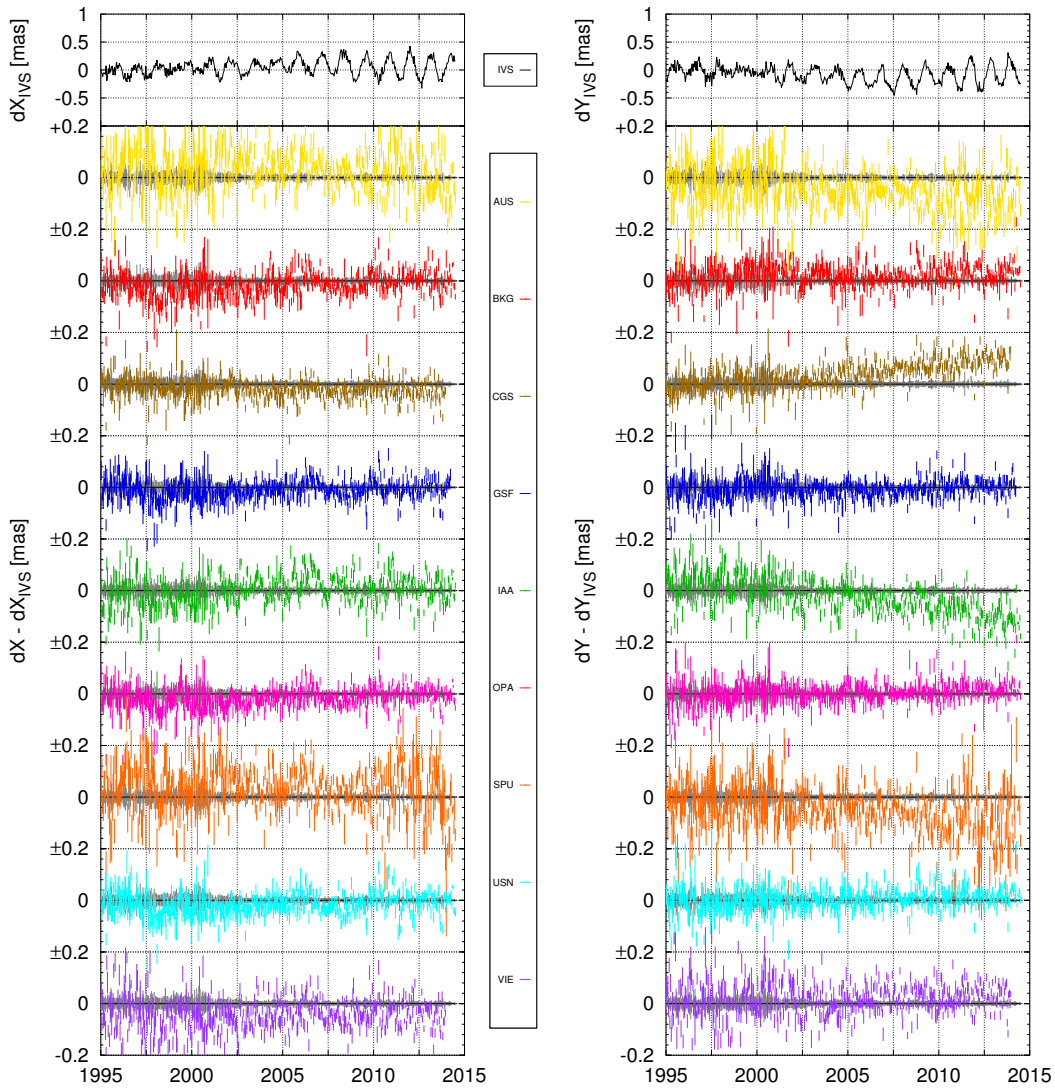

Fig. 1 Comparison of dX,dY from several IVS Analysis Centers with respect to the IVS combination solution.

Nutation (FCN) and the Annual Retrograde Nutation (ARN) products and their variability at the level of about 30 µas.

3 Analysis

Earth nutations can be of luni-solar(-planetary) origin, e.g., the Annual Retrograde Nutation (ARN), or can be a response of the Earth structure, from inner core to superficial fluid layers, to external gravitational perturbation and show up at different frequencies that the latter one, as is the case for FCN. It is common to state that the luni-solar nutations are constant in amplitude, phase, and frequency, whereas those produced by geophysical response are known to be variable in amplitude and phase (e.g., Lambert model [16]) and in frequency (e.g., Gubanov 2010 [8]).

In this study, we suppressed the hypothesis of constance for the luni-solar nutation, especially for the ARN, and we adjusted it simultaneously with the FCN

lution in one of three primary IVS Data Centers (CDDIS, BKG, OPAR) or see Gattano et al. [7].

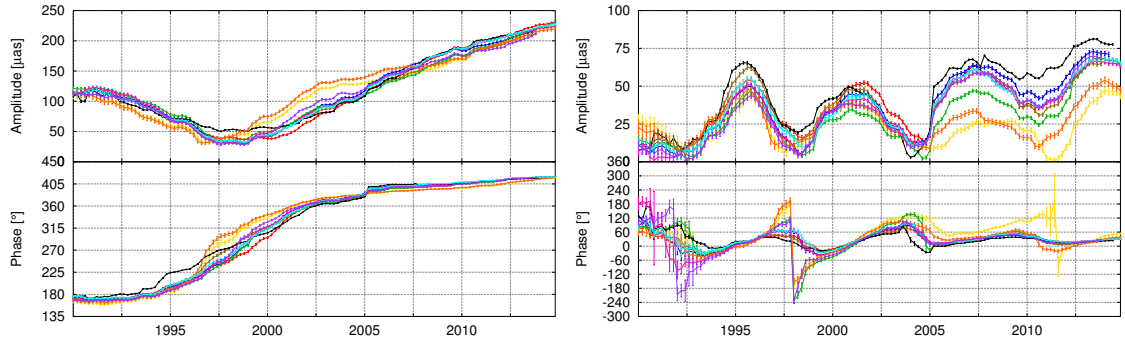

Fig. 2 Free Core Nutation and Annual Retrograde Nutation simultaneous adjustments using a seven-year sliding window least-squares approach.

Table 1 Nutation time series of several IVS Analysis Centers.

Solution	Analysis Center
aus00007	Geoscience Australia, Canberra
bkg00014	Bundesamt für Kartographie und Geodäsie, Leipzig, Germany
cgs2014a	Centro di Geodesia Spaziale, Matera, Italy
gsf2014a	NASA Goddard Space Flight Center (GSFC), Greenbelt, MD, USA
iaa2007a	Institute of Applied Astronomy, Saint Petersburg, Russia
opa2015a	Paris Observatory, France
spu00004	Saint-Petersburg University, Russia
usn2015a	United States Naval Observatory (USNO), Washington, DC
vieeop13	Vienna University of Technology, Austria
ivs14q2X	IVS Combination Center, Germany

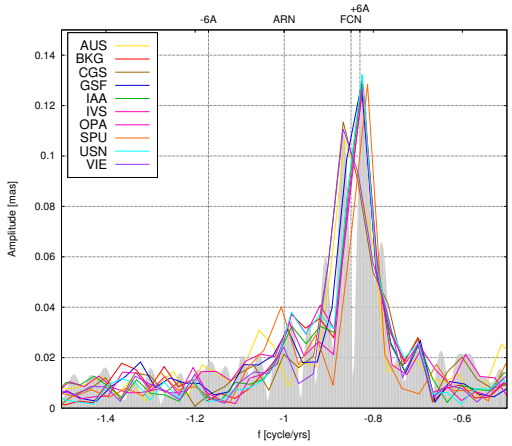

Fig. 3 Spectrum comparison of the IVS nutation time series around the annual retrograde range. The gray area shows the oversampled spectrum of the IVS, to investigate the details of the spectrum.

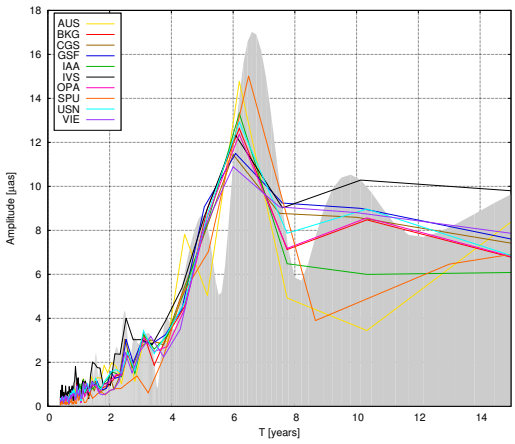

Fig. 4 Spectrum comparison of the ARN least-squares adjustment of the IVS nutation time series. The gray area shows the oversampled spectrum of the IVS, to investigate the details of the spectrum.

by means of a seven-year sliding window in a least-squares approach, to ensure the demodulation due to the beat, and decayed every 0.2 year. The rigid Earth model [18] predicts an amplitude of 24 mas, amplified by a factor ≈ 1.3 in the non-rigid Earth model [14]. Our analysis of the ARN products of the IVS Analysis Centers clearly shows a periodical modulation with a period of about six years and an intensity of about 20 µas, confirmed when we look at the spectrum (Figure 4).

Can this variability be an artefact from our analysis? Indeed, the sum of two periodic signals, one at the ARN period and the other at the FCN period, leads to a single modulated signal with a modulation period of 6.62 years, suspiciously close to the period of the

peak in Figure 4. In the spectral domain, if the ARN is truly modulated in amplitude with a six-year period, the spectrum should present two symmetric peaks around the ARN frequency: one at the right place of the FCN and thus invisible because of the dominance of the latter, one on the other side. By studying the spectrum of several IVS solutions (Figure 3), we see no evidence of such a second peak around −313 days (−1.17 cycle/year in frequency), even if we see a dissymmetry of the FCN pattern, amplified by about 20 µas at the right place where the ARN modulation peak should be. But the surroundings also show that fluctuations are also at the level of 20 µas, and the amplitude modulation we see in the least-squares adjustment would be hidden in those fluctuations. So it is difficult to conclude anything from the spectral domain.

Following the IVS General Meeting we tested our least-squares adjustment approach on artificial data and tried to recover the FCN and ARN amplitude variations from the constructed dX, dY series. We cannot show the results in this paper, but we can give the preliminary conclusions. The least-squares adjustment is perfect in the case of constant nutation. But when we make the ARN and/or the FCN vary, things are more complicated. When the FCN varies, which is a known fact nowadays, some pseudo-oscillations of about five to six years appear, even if the ARN is constant. Furthermore, if the ARN truly varies at these periods, it creates a false signal of about three years in the FCN, when adjusting it using a smaller width window. For example, in a recent study [1], a comparison of various FCN models adjusted with a window size in the range of the FCN period is presented. In their amplitude series, we see some bumps of several years width that can be an effect of an ARN variation. Another work [13] uses a similar algorithm associating these features to geomagnetic jerks whereas it can just be an effect of an ARN variation that has been missed.

Currently, it is still unclear to us what happened between the FCN and the ARN, but it seems that the least-squares adjustment is not suitable for a correct estimation of both of them.

4 Geophysical Interpretation

Whether the retrograde annual nutation is variable in amplitude may have consequences for our understanding of the Earth's deep interior. Mechanisms driving such a variability would be searched at the surface of the Earth or inside the Earth. Surface fluids, especially the atmosphere which dominates at the diurnal frequencies, exert a variable torque on the Earth. Nevertheless, in absence of reliable or consistent data sets, it is today difficult to make conclusions about their contribution (see, e.g., [6, 11]). Inside the Earth, the main source of excitation is the tidally (or electromagnetically) driven core flow interacting at the core-mantle boundary (CMB) and the inner core boundary (ICB). The core flow is tied to the walls of the cavity by viscous, topographic, or electromagnetic couplings. The former occur when, e.g., the fluid is trapped in incursions of the CMB in the mantle. The latter comes up if there is a thin metallic layer at the base of the mantle that can be permeated by the toroidal magnetic field [17, 2, 3]. Another source of excitation is the gravitational coupling between the inner-core and the mantle (e.g., [4, 3, 15]). Recently, a six-year oscillation detected in the length-of-day (LOD) was possibly accounted for by a combination of the above mechanisms [15], while Holme & de Viron [9] suggested that observed jumps in the LOD were direct signatures of geomagnetic jerks.

In the diurnal band, the amplitude of the nutation is mainly governed by the FCN resonance occurring near −430 days. The resonant frequency is

$$\sigma_{\mathrm{FCN}} = -\Omega - \Omega \frac{A}{A_{\mathrm{m}}} \left(e_{\mathrm{f}} - \beta + K_{\mathrm{CMB}} + \frac{A_{\mathrm{s}}}{A_{\mathrm{f}}} K_{\mathrm{ICB}} \right),$$

where A, $A_{\mathrm{m,f,s}}$ are the mean moment of inertia of the whole Earth, the mantle, the fluid outer core, and the solid inner core, respectively; e_{f} is the core flattening; β is a compliance expressing the deformation at the surface when a pressure is applied to the CMB; and $K_{\mathrm{CMB,ICB}}$ are coupling constants at the CMB and the ICB (see Mathews et al. 2002). Note that K_{CMB} is directly proportional to the radial component of the magnetic field at the CMB.

We used the transfer function of Mathews et al. (2002) to constrain a possible departure of the global constant $K_{\mathrm{CMB}} + A_{\mathrm{s}}/A_{\mathrm{f}} K_{\mathrm{ICB}}$ with respect to the model and allowing the observed variability of the annual retrograde nutation. Results are reported in Figure 5. The coupling constant remains within $\sim 10^{-6}$ which is actually the order of magnitude of the uncertainty given by Mathews et al. (2002) for

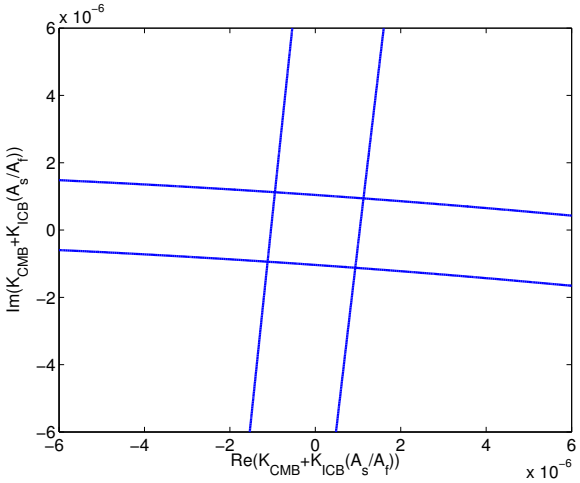

Fig. 5 The region where the global coupling constant $K_{\mathrm{CMB}} + A_{\mathrm{s}}/A_{\mathrm{f}} K_{\mathrm{ICB}}$ can vary to account for the observed variability of the retrograde annual nutation.

$\mathrm{Im}K_{\mathrm{CMB}}$ but smaller than the uncertainty for K_{ICB}. Such a change would push the FCN period by a few hours only, which is hardly detectable by direct observation of the free motion or indirect determination of the resonance through VLBI or superconducting gravimeter data (e.g., Rosat & Lambert 2009).

5 Conclusions

We decided to suppress the hypothesis of the constance of the luni-solar nutation, especially for the Annual Retrograde Nutation (ARN). We used dX, dY data from several IVS Analysis Centers and adjusted for FCN and ARN simultaneously using a seven-year sliding window least-squares adjustment approach. The result for the ARN was to find a variation of a six-year period in the amplitude and phase time series.

But the configuration is complicated here because of the proximity of the frequencies between ARN and FCN. A modulation phenomenon arises from this closeness and impacts the least-squares algorithm. Testing this algorithm on artificial data reveals that the periodic signal we see in ARN, but also some periodic features we can see in FCN in the literature (e.g., [1, 13]), could be a contamination of the variability of one or the other. Spectral analysis is also not conclusive about the trueness of the ARN variability.

Furthermore, the study of the geophysical consequence of such a variability, in the inner structure of the Earth, reveals changes in parameters that are actually on the order of magnitude of the error bars given by the current reference model of Mathews et al. [14]. This means that we have to clarify the situation between FCN and ARN from the data, and the least-squares adjustment may become useless and should be replaced by a more refined technique.

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