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1 **Observation of the Earth's nutation by the VLBI: how**
2 **accurate is the geophysical signal**

3 **César Gattano · Sébastien B. Lambert ·**
4 **Christian Bizouard**

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7 **Abstract** We compare nutation time series determined by several International
8 VLBI Service for geodesy and astrometry (IVS) analysis centers. These series were
9 made available through the International Earth Rotation and Reference Systems
10 Service (IERS). We adjust the amplitudes of the main nutations, including the free
11 motion associated with the free core nutation (FCN). Then, we discuss the results
12 in terms of physics of the Earth's interior. We find consistent FCN signals in all
13 of the time series, and we provide corrections to IAU 2000A series for a number of
14 nutation terms with realistic errors. It appears that the analysis configuration or
15 the software packages used by each analysis center introduce an error comparable
16 to the amplitude of the prominent corrections. We show that the inconsistencies
17 between series have significant consequences on our understanding of the Earth's
18 deep interior, especially for the free inner core resonance: they induce an uncer-
19 tainty on the FCN period of about 0.5 day, and on the free inner core nutation
20 (FICN) period of more than 1000 days, comparable to the estimated period itself.
21 Though the FCN parameters are not so much affected, a 100% error shows up for
22 the FICN parameters and prevents from geophysical conclusions.

23 **Keywords** VLBI · Earth Rotation · Nutation · Free Core Nutation (FCN) · Free
24 Inner Core Nutation (FICN)

César Gattano
SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC
Univ. Paris 06, LNE
E-mail: cesar.gattano@obspm.fr

Sébastien B. Lambert
SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC
Univ. Paris 06, LNE
E-mail: sebastien.lambert@obspm.fr

Christian Bizouard
SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC
Univ. Paris 06, LNE
E-mail: christian.bizouard@obspm.fr

1 Introduction

Very long baseline radio interferometry (VLBI; Shaffer, 1995) is the only geodetic technique able to measure the nutation of the Earth. The accuracy of the order of 0.1 millisecond of arc (mas) allows researchers to compare the observed nutation with theoretical prediction model for a rigid Earth and, henceforth, constrain geophysical parameters describing the Earth's interior (e.g., Gwinn et al, 1986; Herring et al, 1986, 1991, 2002; Mathews et al, 1991, 1995, 2002; Koot et al, 2008, 2010). Inaccuracies in nutation measurements must therefore be taken into account when developing an Earth model. The identification and the elimination of sources of error in VLBI analysis become crucial for the search of the tiny signature of the free inner core nutation whose resonant period is not clearly determined (Mathews et al, 2002; Koot et al, 2008, 2010) and its excited free motion is thought to be of amplitude smaller than 0.001 mas (Dehant et al, 2005), and thus undetectable in VLBI observations.

Since the 1980s, almost 6000 VLBI 24-h sessions have been scheduled by various space geodesy agencies for monitoring the Earth's rotation as regularly as possible and to determine accurate terrestrial and celestial reference frames. This large amount of data (consisting of about 10 million delays spanning about 35 years) is regularly reanalyzed by several research teams in the framework of VLBI analysis centers (ACs) affiliated to the International VLBI Service for Geodesy and Astrometry (IVS; Nothnagel et al, 2015) and the International Earth Rotation and Reference Systems Service (IERS).

One problem arising with nutation is that one cannot objectively know if one series is more precise than another, i.e., if it better describes the physical phenomenon it is supposed to describe. The reason is that there is no basis of comparison like, e.g., an independent technique or an accurate theoretical predicting model. One can only compare nutation series to other nutation series obtained with a very similar analysis chain. Actually, time series show significant differences at the level of a few tens of microseconds of arc (μas) originating from analysis options or software packages (Tesmer et al, 2007; Heinkelmann and Tesmer, 2013; Gattano et al, 2015a,b). Answering the question which series is the best for geophysical research is an open question, except if some ACs use outdated modeling or evidently bad data analysis procedures.

In this paper, we propose to assess the consistency of nutation time series made available by the IERS. Beyond the statistical overview, we investigate the geophysical signal present in all of the series and made up of mismodeled or unpredictable nutations (Section 2). Section 3 is dedicated to discussing the impact of the inconsistencies on deep Earth interior parameters, namely the resonant frequencies associated with the core and the inner core.

2 Data analysis

We considered solutions provided by nine IVS ACs plus three combinations (Fig. 1). They are listed in Table 1. All individual series are publicly available and documented at the IVS data centers¹ or at the institution web sites. The IVS combination is based on a weighted average of pre-reduced normal equations (Böckmann

¹ <ftp://ivscg.gsfc.nasa.gov/pub/vlbi>

et al, 2007). The IERS EOP 08 C 04 produced at the IERS Earth Orientation Center is based on a smoothing of the IVS combination, interpolated to a 1-day interval and densified by some individual series (Bizouard and Gambis, 2009). Bulletin A delivered by the IERS Rapid Service/Prediction Center is built up from combination of both IVS combination and individual series.

The precise identification of the causes of the differences between series is out of the scope of this paper: such an identification cannot be done by a comparison of a posteriori solutions but would need extensive tests and comparisons between software packages. We therefore do not detail the strategies adopted by each AC, but we refer the reader to the technical documents mentioned above. Nevertheless, one must keep in mind that there are several prominent sources of error limiting the accuracy of VLBI nutation series. First, one must consider software issues including the inversion method: though Calc/Solve and VieVS (Böhm et al, 2012) use classical weighted least-squares, OCCAM (Titov et al, 2004) implements Kalman filtering. The software packages differ in to what level state-of-the-art modelling (Petit and Luzum, 2010) is realized. Second, the number of processed sessions, and thereby the number of observations that constrain the global parameters like radio source or station coordinates, varies drastically from one series to another. Although most of the IVS ACs are now processing as many sessions as possible, the possible bad influence of regional networks or sessions not designed for EOP measurement should be addressed. Third, the instability of the targeted radio sources can generate a noise in EOP of a few tens of μas (Dehant et al, 2003; Feissel-Vernier, 2003; Feissel-Vernier et al, 2005, 2006). The adequate analysis strategy to minimize this noise is still an open question. For instance, although most of the IVS ACs now use the ICRF2 (Fey et al, 2015), some operational solutions are still based on ICRF1 (Ma et al, 1998), whose accuracy and stability are worse by factors of 5 and 2, respectively. To finish with, an important factor limiting the accuracy of VLBI products is the station-dependent correlated noise associated with clocks and troposphere modeling errors in absence of covariance error model (Gipson, 2007; Romero-Wolf et al, 2012). As the number of observations increases, the correlated noise becomes dominant with respect to the thermal noise that tends to zero on average. The impact of this effect partly depends on the troposphere wet delay, gradient, and clock offsets estimation intervals, as well as the choice of the mapping functions (Böhm et al, 2006).

Most of time series contain offsets to the IAU 2000A nutation model, based on the model of Mathews et al (2002), also referred to as MHB in the following. These offsets of about 0.2 mas in rms are attributed to various unmodeled or mismodeled geophysical effects (Dehant et al, 2003) as well as a noise-like signal due to imperfections of the analysis strategy. The majority of the series are also referred to the IAU 2006 precession (Capitaine et al, 2003). We corrected series based on older references so that all our series represent differences to the precession-nutation model consisting of the IAU 2006 precession and the IAU 2000A nutation.

We modeled the series by (i) a set of corrections to the main nutation amplitudes (circular terms with known astronomical frequencies and phases and unknown constant amplitudes), (ii) corrections to precession rate and constant biases due to a misorientation of the celestial reference frame, and (iii) a retrograde circular term accounting for the free core nutation (FCN) whose variability and unpredictability is discussed in several studies on the light of the various possible excitation sources accounted for by different existing atmospheric and oceanic

118 models as well as triggering by geomagnetic jerks (Herring et al, 2002; Shirai et al,
 119 2005; Lambert, 2006; Vondrak and Ron, 2009; Malkin, 2013; Vondrák and Ron,
 120 2016). For item (i), we chose the 21 prograde and retrograde nutations used by
 121 the MHB authors to fit their geophysical model. For (iii), the adjustment of the
 122 FCN amplitude was done using a running window. The FCN period was fixed to
 123 the MHB value (-430.21 days). The window width was set to 6.7 years in order
 124 to ensure the demodulation of the FCN and the annual retrograde nutation. We
 125 therefore have an overlap of data so that the annual values of the FCN amplitude
 126 are not independent. However, the overlap allows us to record interannual ampli-
 127 tude variations and constitutes a good compromise between time and frequency
 128 resolution. The obtained FCN amplitudes (Fig. 2) are all consistent within error
 129 bars and comparable to those raised by other studies (Herring et al, 2002; Lam-
 130 bert, 2006; Malkin, 2007; Vondrak and Ron, 2009; Krásná et al, 2013; Chao and
 131 Hsieh, 2015; Belda et al, 2016). The FCN amplitudes adjusted by Malkin (2007)
 132 are shown in the figure. They appear globally consistent with ours. Deviations can
 133 be explained by the different adjustment strategy: Malkin (2007) used a different
 134 input series (smoothed IVS combined series) and adjusted the FCN amplitude
 135 on a 400-d interval running by step of one day. Note that we do not show the
 136 comparison with the IERS model (Petit and Luzum, 2010) since the derivation
 137 method is extremely close to our scheme and the results do not exhibit noticeable
 138 differences.

139 Our fitting method is based on least-squares with weights taken as the inverse
 140 of the squared errors given in the series. These errors are derived from least-squares
 141 estimation propagated from delay weights and constraints applied at various stages
 142 of the analysis to source and station positions, clocks and troposphere parameters.
 143 Delay weights have been defined in a preliminary analysis (not processed by us but
 144 by special IVS ACs) as a combination of a formal uncertainty of the ionosphere
 145 group delays at X and S-band and a station-dependent uncertainty determined
 146 such that the chi-squared of the residuals within each session is close to unity. For
 147 each VLBI session, the error associated with nutation is therefore consistent with
 148 the standard deviation of delay residuals. However, the fit of the above model
 149 to time series leaves reasonably flat residuals with χ^2 significantly larger than
 150 unity, suggesting that errors are underestimated. Because they use a larger number
 151 of observations, large network sessions can produce small errors. However, there
 152 exists systematics between sessions due to, e.g., changing network or target source
 153 geometry. For white noise residuals, these discrepancies should be explained by
 154 the errors, so that the rms of the scaled residuals (or, equivalently, the χ^2) should
 155 be close to unity, which is not the case. To remedy this inconsistency, we included
 156 an iterative recalibration of errors by a scale factor s and an error floor f in our
 157 fitting algorithm so that our final estimates achieve (i) a minimum sum of squared
 158 differences between observations and model and (ii) a standard deviation of the
 159 residuals consistent with the errors (Herring et al, 1991, 2002). The recalibrated
 160 error σ_{rec} is such that $\sigma_{\text{rec}}^2 = (s\sigma)^2 + f^2$.

161 Corrections to precession rate and bias are displayed in Table 2. Formal un-
 162 certainties are typically 0.005 mas for bias and 0.05 mas/yr for precession rate.
 163 Although most of precession rates are in agreement within one sigma, five series
 164 present significantly different values. The reason is unclear but should be investi-
 165 gated because it could lead to misinterpretation of the measured precession rate
 166 in terms of Earth's flattening.

167 Error floors and scale factors are displayed in Table 2 with the postfit rms
 168 (i.e., the signal unexplained by corrected nutations and FCN). Our analysis yields
 169 an averaged error floor of 0.074 mas, an averaged scale factor of 1.47, and an
 170 averaged median error of 0.157 mas. There is no clear dependence on the software
 171 package although the solutions obtained with Calc/Solve tend to show a slightly
 172 smaller scale factor: on average, the scale factor for Calc/Solve solutions is 1.42,
 173 while it is 1.83 for other software packages. However, this tendency is not true for
 174 noise floors and median errors. One important remark arising from Table 2 is that
 175 the IVS combined series present the smallest postfit rms, scale factor and median
 176 error. This indicates that the combined series is actually more accurate than the
 177 individual contributions, and therefore more reliable for geophysical studies.

178 3 Discussion

179 The observed corrections to IAU 2000A nutation amplitudes are displayed in Ta-
 180 ble 3. Though corrections were obtained independently for each series, the table
 181 does not display all the results but only the median amplitudes of the individual
 182 corrections, the highest range (difference between the maximum and minimum val-
 183 ues), and median errors. Doing so, we aim at pointing out the differences between
 184 amplitudes obtained from different series rather than the amplitudes themselves.

185 Corrections relevant to most important nutations for geophysical applications
 186 are displayed in the upper panels of Fig. 3. The retrograde 18.6-yr nutation shows
 187 the highest range and standard deviation. This was expected since, in addition to
 188 the fact that the observing time only integrates two periods, this term is strongly
 189 influenced by the first decade of VLBI observations when VLBI sessions were not
 190 as dense as nowadays and realized through weaker networks. The impact of such
 191 differences on further estimates of geophysical parameters can be evaluated by
 192 considering the frequency-domain MHB transfer function linking the rigid Earth
 193 nutation (REN) series (Souchay et al, 1999) to non-rigid series. After adding up
 194 the values of Table 3 to the corresponding IAU 2000A amplitudes, we removed the
 195 nonlinear and sun-synchronous contributions of Table 7 of the MHB paper and
 196 derived the ratio to the REN series. Then, we adjusted the values of the FCN and
 197 FICN complex frequencies (see, e.g., Eq. (42) of MHB). We used MHB values as a
 198 priori parameters and followed a classical nonlinear iterative least-squares scheme
 199 that converges after a few iterations (Mathews et al, 2002).

200 Whisker plots of FCN and FICN periods and quality factors are shown in the
 201 lower panels of Fig. 3 where the real period P and the damping factor Q are such
 202 that the complex resonant frequency σ reads $(1/P)(1 - i/2Q)$. Solution iaa2007a
 203 returned an unexpectedly high FICN period close to 9000 days with a similarly
 204 higher uncertainty. Nevertheless, we arranged the scale relevant to this parameter
 205 so that one can better appreciate the differences between other solutions. We found
 206 that the FCN period stays within one half day with uncertainties of ~ 0.2 day. The
 207 quality factor remains roughly between 16000 and 18000, in agreement with Rosat
 208 and Lambert (2009) obtained by a similar method, with uncertainties between 600
 209 and 900. For both the FCN period and the quality factor, the dispersion of the
 210 results associated with the AC is of the order of the median uncertainty, so that one
 211 can reasonably claim that the analysis strategy does not significantly perturb the
 212 estimates of this geophysical parameter. The situation is different for the FICN.

213 Even excluding iaa2007a, the FICN period ranges an interval of the order of the
214 period itself (~ 1300 days), indicating that this parameter is particularly sensitive
215 to the analysis strategy.

216 4 Conclusion

217 In this study, we analyzed various available nutation series provided by different
218 analysis in terms of nutation amplitude. The results emphasizes that the analysis
219 strategy does not have a significant influence on the estimates of the FCN pa-
220 rameters but does have one on the FICN parameters. Such a large dispersion can
221 make the detection of the FICN by VLBI questionable. It is therefore urgent to
222 investigate thoroughly the sources of error in VLBI analysis, especially for deriv-
223 ing nutation offsets that give important insight into the Earth's interior. It is clear
224 that providing as many series as possible with different softwares and strategies
225 is useful for the scientific community only if the submission of the series to the
226 international services (IVS, IERS) is followed by a rigorous assessment of their
227 quality for scientific use. The assessment method has still to be discussed, as well
228 as the combination schemes that are supposed to wipe out the defects of individual
229 data sets and return series optimized for scientific exploitation.

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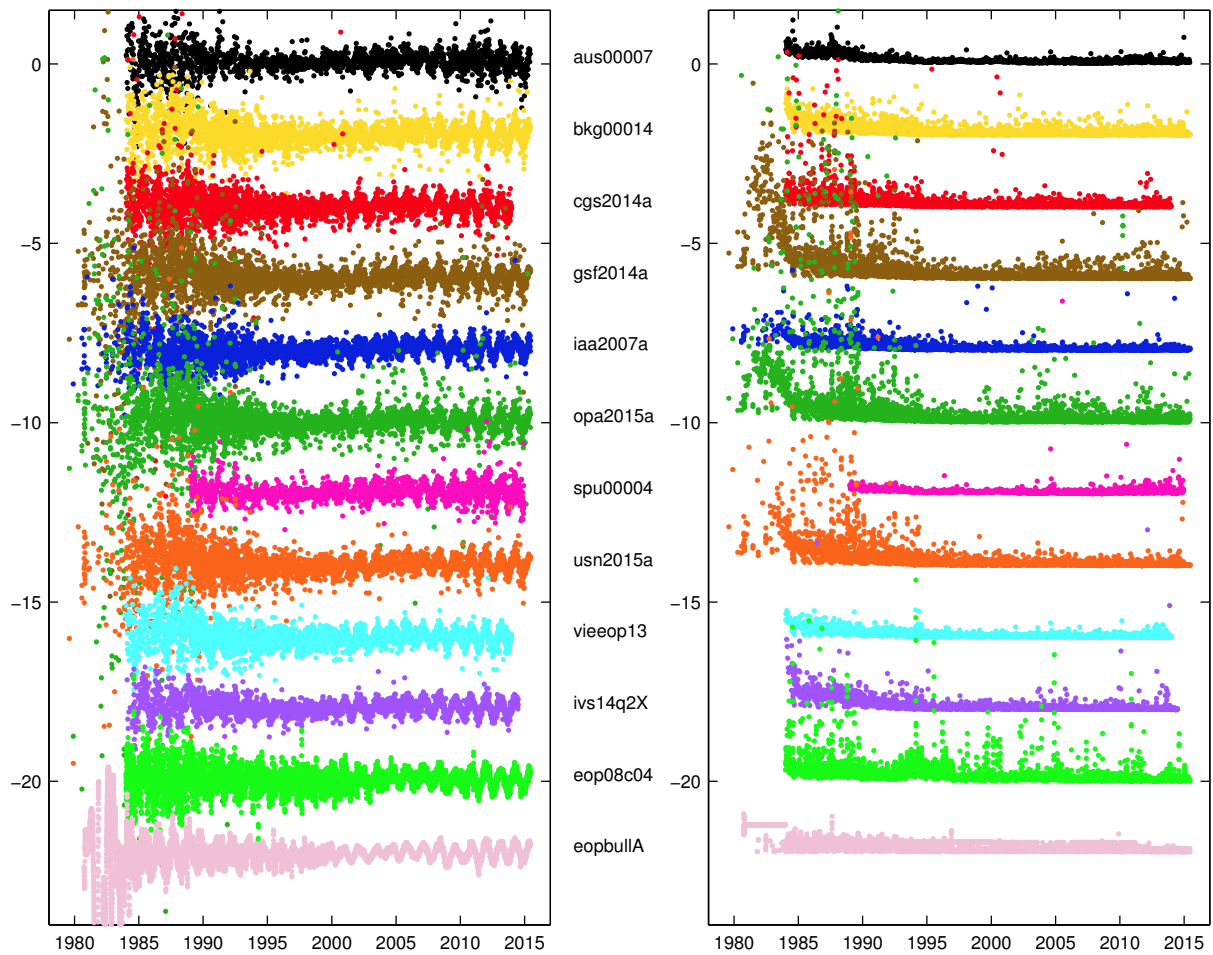


Fig. 1 (Left) Nutation series available from the IVS and the IERS and (Right) their respective errors. Y-axes are labeled in mas. For clarity purposes, the series have been shifted by steps of 2 mas and only the X-component is represented. The Y-component shows a similar behavior.

Table 1 Identifiers of the nutation time series corresponding to the IVS solution code (except for eop08c04 and eopbullA which name have been chosen by the authors), hosting institute of the IVS ACs, number of processed sessions (i.e., length of the series), and time span.

Analysis center & Software package			Sessions	Span
aus00007	Geoscience Australia, Canberra	OCCAM	2469	1984.0–2015.4
bkg00014	Bundesamt für Kartographie und Geodäsie, Leipzig, Germany	Calc/Solve	4615	1984.0–2015.4
cgs2014a	Centro di Geodesia Spaziale, Matera, Italy	Calc/Solve	4743	1984.0–2013.9
gsf2014a	NASA Goddard Space Flight Center (GSFC), Greenbelt, MD	Calc/Solve	5360	1979.5–2015.4
iaa2007a	Institute of Applied Astronomy, Saint Petersburg, Russia	OCCAM	4391	1979.9–2015.4
opa2015a	Paris Observatory, France	Calc/Solve	5671	1979.5–2015.4
spu00004	Saint-Petersburg University, Russia	OCCAM	2067	1989.0–2014.9
usn2015a	United States Naval Observatory (USNO), Washington, DC	Calc/Solve	4842	1979.5–2015.4
vieeop13	Vienna University of Technologies, Austria	VieVS	3768	1984.0–2014.0
ivs14q2X	IVS Combination Center, Germany	-	3403	1984.0–2014.4
eop08c04	IERS Earth Orientation Center, Paris Observatory, France	-	11487	1983.9–2015.4
eopbullA	IERS Rapid Service/Prediction Center, Washington, DC	-	12681	1980.7–2015.4

Table 2 Bias b (mas) and corrections to precession rate p (mas/yr), postfit rms r (mas) of the residuals after the fit of the annual values of the FCN amplitude and the corrections to IAU 2000A nutation amplitudes, noise floor f (mas), scale factor s , and median error m (mas) of the series.

	b_X	b_Y	p_X	p_Y	r_X	r_Y	f	s	m
aus00007	0.068	-0.111	0.152	-0.512	0.159	0.162	0.066	2.00	0.173
bkg00014	0.029	-0.060	0.149	-0.103	0.146	0.145	0.083	1.46	0.151
cgs2014a	0.025	-0.065	0.018	0.469	0.134	0.141	0.071	1.74	0.153
gsf2014a	0.033	-0.087	0.115	-0.102	0.131	0.129	0.067	1.28	0.147
iaa2007a	0.027	-0.065	0.583	-0.501	0.138	0.145	0.083	1.60	0.143
opa2015a	0.025	-0.078	0.166	-0.092	0.140	0.135	0.060	1.40	0.180
spu00004	0.072	-0.105	0.058	-0.714	0.150	0.148	0.072	1.85	0.158
usn2015a	0.026	-0.078	0.128	-0.054	0.130	0.128	0.069	1.23	0.139
vieeop13	-0.005	-0.065	0.135	0.067	0.148	0.150	0.080	1.87	0.152
ivs14q2X	0.048	-0.076	0.073	-0.197	0.119	0.124	0.098	0.84	0.109
eop08c04	0.041	-0.084	0.131	-0.008	0.141	0.150	0.077	1.24	0.162
eopbullA	-0.026	-0.093	0.424	-0.452	0.166	0.157	0.067	1.08	0.218

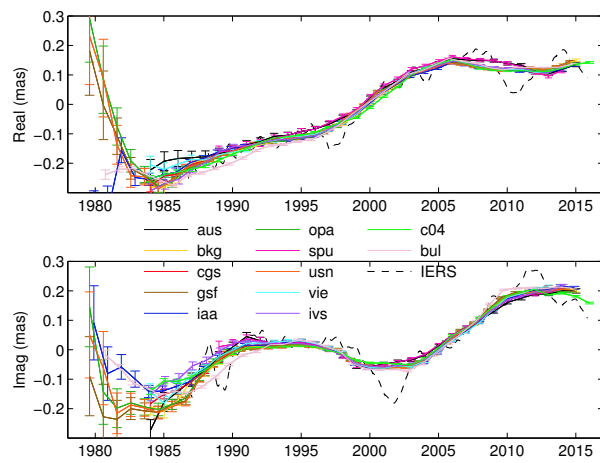


Fig. 2 (Top) Real and (Bottom) imaginary parts of the amplitude of the annual values of the FCN amplitude obtained from the analysis of the nutation time series. The color code follows the Fig. 1.

Table 3 Median amplitudes of the correction to IAU 2000A adjusted to the nutation time series, highest difference between values (Range), and median standard deviation. Unit is μas .

Period (days)	Median amplitude		Range		Median error	
	Real	Imag	Real	Imag	Real	Imag
-6798.38	35.5	-28.7	47.4	17.6	2.2	2.2
6798.38	22.4	-32.8	18.9	18.3	2.2	2.2
-3399.19	4.5	-9.4	15.8	11.7	2.1	2.1
3399.19	11.3	-5.2	10.8	24.0	2.1	2.1
-1615.75	-2.0	-8.1	17.8	9.3	2.1	2.1
1615.75	0.9	-9.1	12.2	6.7	2.1	2.1
-1305.48	0.6	8.2	13.4	10.0	2.1	2.1
1305.48	0.0	4.4	11.8	12.8	2.1	2.1
-1095.18	-1.1	1.1	10.7	10.5	2.0	2.0
1095.18	-3.3	-1.2	9.5	9.2	2.0	2.0
-386.00	-1.2	-1.4	12.5	7.7	2.0	2.0
386.00	-4.3	1.9	10.6	11.7	2.0	2.0
-365.26	27.5	5.6	9.4	18.6	2.1	2.1
365.26	-3.8	-0.9	15.8	21.6	2.1	2.1
-346.64	-13.3	4.7	16.6	10.6	2.2	2.2
346.64	-2.2	2.2	6.8	8.7	2.2	2.2
-182.62	-15.2	4.2	8.5	6.6	2.0	2.0
182.62	7.5	-2.8	14.0	12.5	2.0	2.0
-121.75	-3.7	2.2	4.8	5.6	2.0	2.0
121.75	3.1	-0.2	6.4	10.8	2.0	2.0
-31.81	-1.0	-2.7	9.5	6.2	2.0	2.0
31.81	-1.4	1.4	6.0	6.4	2.0	2.0
-27.55	-16.2	-8.3	8.3	6.9	2.0	2.0
27.55	-0.7	-1.6	5.3	5.3	2.0	2.0
-23.94	-2.2	0.3	3.6	3.3	2.0	2.0
23.94	-2.4	-1.3	7.3	3.7	2.0	2.0
-14.77	-2.3	3.5	9.8	6.6	2.0	2.0
14.77	-1.6	0.4	3.4	6.6	2.0	2.0
-13.78	-0.6	-1.6	4.4	8.9	2.0	2.0
13.78	-0.6	0.1	4.0	10.2	2.0	2.0
-13.66	-11.2	-10.0	10.9	7.1	2.0	2.0
13.66	-6.0	11.6	17.4	22.6	2.0	2.0
-9.56	0.6	-0.9	5.4	3.0	2.0	2.0
9.56	1.1	-0.8	7.0	8.5	2.0	2.0
-9.13	-3.5	-0.1	6.0	4.8	2.0	2.0
9.13	-1.5	2.7	5.7	14.3	2.0	2.0
-9.12	1.1	0.8	9.5	9.3	2.0	2.0
9.12	-0.5	-1.4	8.3	12.1	2.0	2.0
-7.10	-1.8	-1.0	6.2	8.8	2.0	2.0
7.10	-2.8	6.5	11.8	10.7	2.0	2.0
-6.86	-2.6	-2.5	7.3	13.1	2.2	2.2
6.86	1.8	-0.4	6.9	5.7	2.2	2.2

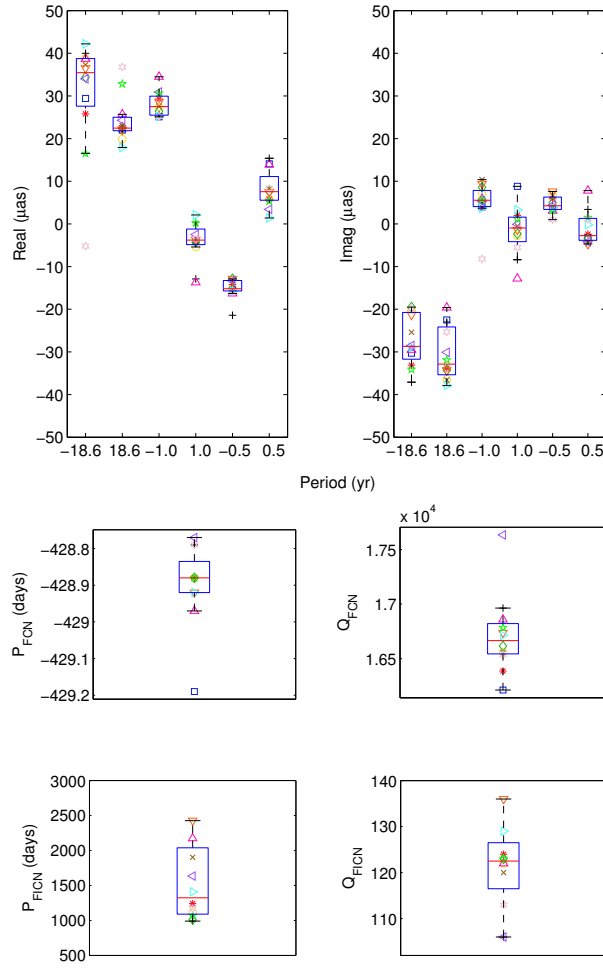


Fig. 3 Top panels: estimated corrections to the IAU 2000A amplitudes of the ± 18.6 , annual, and semi-annual nutations. Bottom panels: periods and quality factors of the FCN and FICN estimated from previous nutation amplitudes. The size of the whiskers corresponds to the standard deviation of the estimates from the various solutions. The horizontal red line represents the median value. The color code follows Fig. 1. Plus sign: aus00007; Circle: bkg00014; Asterisk: cgs2014a; Cross: gsf2014a; Square: iaa2007a; Diamond: opa2015a; Upward-pointing triangle: spu00004; Downward-pointing triangle: usn2015a; Right-pointing triangle: viceop13; Left-pointing triangle: ivs14q2X; Pentagram: eop08c04; Hexagram: eopbullA.