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NEW GFZ EFFECTIVE ANGULAR MOMENTUM EXCITATION FUNCTIONS AND THEIR IMPACT ON NUTATION

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ABSTRACT

Recently the Earth System Modelling Group of GeoForschungsZentrum (ESMGFZ) in Potsdam started producing a new series of Effective Angular Momentum Excitation Functions (EAM). As a novelty, the data is given in 3-hour resolution for the influence of the atmosphere and dynamic ocean, and 1-day resolution for terrestrial hydrosphere and barystatic sea-level changes. In addition to this, IERS recently started publishing their new series of C04 solution for Earth Orientation Parameters (EOP), based on new combination of all observations and ITRF2014 terrestrial frame. We use the ESMGFZ data to numerically integrate Brzeziński's broad-band Liouville equations in celestial frame and compare the results with IERS C04 solution for celestial pole offsets in the interval 1986.0-2018.4. Alternatively, we also add a possible influence of unevenly distributed Geomagnetic jerks (GMJ). In the process of integration we look for the best-fitting parameters (period T, Q-factor) of Free Core Nutation (FCN). It is demonstrated that the fit between integrated and observed values is much better when compared with our previous solutions, based on older models of geophysical excitations. The fit is improved significantly when GMJ quasi-impulse effect is included. The best fit is obtained for atmospheric, oceanic and GMJ excitations, the preferred parameters of FCN being $T = 429.53 \pm 0.04d,\ Q = 21600 \pm 200$. We also estimate new value for empirical prograde MHB Sun-synchronous correction $\mathrm{SSC}_{new} = (0.1045 + 0.0193\mathrm{i})\mathrm{e}^{\mathrm{i}l'}$.

1. INTRODUCTION

In our previous works (Ron et al., 2014; Vondrák and Ron, 2010, 2015, 2016, 2017) we studied the influence of geophysical effects in nutation. To this end, we used numerical integration of Brzeziński's broad-band Liouville equations (Brzeziński, 1994) and different sources of excitations by the atmosphere (NCEP/NCAR, MERRA, ERA) and ocean (ECCO, OMCT). In our most recent paper (Vondrák and Ron, 2017) we proposed a new method of determining the parameters (period T, Q-factor) of Free Core Nutation that is not part of the IAU 2000 model of nutation, and therefore present in observed celestial pole offsets (CPO). We were able to demonstrate in all these papers that including a modeled effect of geomagnetic jerks (GMJ, sudden changes of second time derivative of the intensity of Earth's geomagnetic field) always improves the fit of integrated CPO to the observed values. In our previous study (Vondrák and Ron, 2015) we tested how much the influence of GMJ changes when the epochs of modeled excitations are shifted by ±100 days with respect to GMJ epochs. We found that the best fit is obtained if GMJ epochs are used. Here we continue the study with the most recent model of geophysical excitations, prepared in GeoForschungsZentrum in Potsdam (GFZ) that are based on ECMWF data for the atmosphere and on Max Planck-Institute for Meteorology Ocean Model (MPIOM, Jungclaus et al., 2013) for the ocean. International Earth Rotation and Reference Systems Service (IERS) also recently improved their combined daily solution of Earth Orientation Parameters IERS EOP 14C04 (referred to as C04 in the following), so we are using namely this series to check the validity of our integrations. Here we tacitly assume that the C04 accuracy is much better than the accuracy of AAM/OAM integrated series, and can be taken as a ground-truth. These new series (i.e., both ESMGFZ and C04) enable us to better study the effects of geophysical excitations in nutation, to compare the results with our previous studies made with NCEP/NCAR (Salstein, 2005) and ERA/OMCT (Dobslaw et al., 2010) excitations, and to derive period T and Q-factor of FCN. T is related to the flattening of Earth's fluid core and electromagnetic coupling between the core and mantle, and Q is related to visco-elastic properties of the Earth and is responsible for the damping of free motion (the smaller is its value, the faster is the damping).

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2. INPUT DATA

We use the data covering the interval 1986.0 – 2018.4. They are as follows:

- Celestial pole offsets $\mathrm{d}X$, $\mathrm{d}Y$ (i.e., differences between observed pole position in space and its position given by IAU 2000A model of nutation) from IERS combined solution C04, given with 1-day resolution. All data exceeding 1 mas were removed, and the series were then filtered to contain only periods between 10 and 6000 days, using the filter by Vondrák (1977). Shorter periods are supposed to be noise, longer ones caused by other than geophysical fluids. We use these values in complex form, $P = \mathrm{d}X + \mathrm{i}\mathrm{d}Y$ in which we leave the Sun-synchronous correction (SSC) applied by Mathews et al. (2002). In contrast to our previous expectation that this empirical prograde annual term is due to geophysical excitation, we found (Vondrák and Ron, 2017) that it is not the case – SSC alone yields better results than excitations by the atmosphere and ocean.
- ESMGFZ excitations (Dobslaw and Dill, 2018) by the atmosphere and dynamic ocean (only their equatorial components χ_1, χ_2 that are capable of affecting nutation). These values being given in terrestrial frame, they require to be transformed into celestial frame. To do so, we use a simple formula $\chi' = -\chi^{\mathrm{i}\phi}$, in which $\chi = \chi_1 + \mathrm{i}\chi_2$ denotes the complex equatorial component of the excitation in terrestrial frame, χ' the same in celestial frame and ϕ the Greenwich sidereal time. This procedure transforms the periods in prograde quasi-daily range (in terrestrial frame) into long-periodic one (in celestial frame). Thus, sub-daily excitations in terrestrial frame are required to calculate the effect in nutation. Consequently, only the atmospheric and oceanic excitations (having 3-hour resolution) can be used. The other two (hydrosphere and sea level changes) are not sufficiently variable at sub-daily time-scales, and therefore disregarded. The transformed data are eventually smoothed to suppress noise with periods shorter than 10 days.
- Only the eight epochs of GMJ as published by different authors: 1991.0, 1994.0, 1999.0, and 2007.5 (Malkin, 2013), 2003.5, 2004.7 (Olsen and Mandea, 2008; Mandea et al., 2010), 2011.0 (Chulliat and Maus, 2014), and 2014.0 (Brown et al., 2016) are used. The corresponding excitations, centered at these epochs, are modeled by quasi-impulse bell-shaped functions (see next section).

3. METHOD USED

Here we roughly follow the same procedures described in our previous studies, with some minor modifications. Only a shortened description is given below, the reader can find more details in (Vondrák and Ron, 2017). A combination of direct and indirect approach is used to estimate the best-fitting values of period T and Q-factor of FCN. To this end, we use numerical integration of Brzeziński's broad-band Liouville differential equations in celestial frame, in complex form (Brzeziński, 1994):

$$\begin{aligned}\ddot{P} - \mathrm{i}(\sigma'_c + \sigma'_f)\dot{P} - \sigma'_c\sigma'_f P &= -\sigma_c\Big\{\sigma'_f\left(\chi'_p + \chi'_w\right) \\ &+ \sigma'_c\left(a_p\chi'_p + a_w\chi'_w\right) \\ &+ \mathrm{i}\left[(1+a_p)\dot{\chi}'_p + (1+a_w)\dot{\chi}'_w\right]\Big\},\end{aligned} \tag{1}$$

in which $P = \mathrm{d}X + \mathrm{i}\mathrm{d}Y$ denotes the motion of celestial pole due to excitations, σ_c, σ'_c are Chandler frequencies in terrestrial and celestial frame, respectively, σ'_f is the FCN frequency in celestial frame. All frequencies are expressed in radians per day. χ'_p and χ'_w are excitations (in celestial frame) due to pressure (matter) and wind (motion), respectively. Numerical constants $a_p = 9.200 \times 10^{-2}$, $a_w = 2.628 \times 10^{-4}$ are those recommended by Koot and de Viron (2011), the relation between frequency of FCN and its parameters T, Q is

$$\sigma'_f = -\frac{2\pi}{T}\left[1 - \frac{\mathrm{i}(1+1.00273T)}{2Q}\right] \tag{2}$$

Since the exact mechanism of transferring GMJ to changes of Earth orientation remains unknown, we are not able to compute these changes from the known GMJ directly. Instead, we model it by using an impulse-like, bell-shaped functions, 200 days long and centered at GMJ epochs t_0, whose complex amplitude a is estimated to obtain the best fit to observations:

$$\chi'_{GMJ} = \frac{a}{2}\left[1 + \cos\frac{2\pi(t-t_0)}{200}\right]. \tag{3}$$

The problem is solved in two variants. The first and simpler one does not consider *GMJ*. Thus, only the initial pole position P_0 and parameters T, Q are looked for, such that the best fit of numerical integration of Eq. (1) to observations, in least-squares sense, is achieved. In the second variant we make numerical integration with additional modeled GMJ excitations, so we estimate eight more unknowns, complex amplitudes a of Eq. (3) for each GMJ epoch. However, the observed CPO are referred to IAU 2000 model of nutation, which is based on the values $T = 430.21\mathrm{d}, Q = 20000$. If the parameters T, Q, for which the integration is done, differ from these, the celestial pole offsets must be changed. To this end, we use MHB transfer function by Mathews et al. (2002) that expresses frequency-dependent ratio between amplitude of non-rigid and rigid Earth nutation term, given in complex form as

$$T_{MHB}(\sigma) = \frac{e_r-\sigma}{e_r+1} N_0 \left[1 + (1+\sigma)\left(Q_0 + \sum_{j=1}^{4} \frac{Q_j}{\sigma - s_j}\right)\right]. \tag{4}$$

Here σ denotes the frequency of a nutation term, e_r dynamical ellipticity of the rigid Earth, N_0, Q_j are complex numerical constants, and s_j are complex resonance frequencies. All frequencies are expressed in cycles per sidereal day. The most important resonance is given by s_2, corresponding to retrograde FCN. It is related to σ'_f of Eq. (1) by the expression $s_2 = \sigma'_f/\Omega - 1$, in which $\Omega = 6.30038$ rad/day is the mean speed of Earth's rotation. If this frequency is changed, the complex amplitudes of all nutation terms also change. Here we limit ourselves to the change of only five retrograde nutation terms (with periods 365.26, 182.62, 121.75, 27.55 and 13.66 days) that are most affected by FCN resonance; the rest can be neglected.

Unlike in paper (Vondrák and Ron, 2017) we choose a faster procedure by successive approximations to make the least-squares estimation. We do not integrate Eq. (1) for many combinations of parameters *T*, *Q* as before. Instead, we choose some initial values of FCN parameters *T*, *Q,* recalculate CPO correspondingly, find the best-fitting initial pole position P_0 (and amplitudes of GMJ excitation in second variant) and during the process of integration we also calculate numerically partial derivatives of the pole position with respect to estimated unknown FCN parameters. They are then used to form observation equations and normal equations whose solution yields the improved values of the unknowns. If they differ from the initial ones significantly, we use these as new initial values and repeat whole procedure until convergence is achieved.

4. RESULTS AND DISCUSSION

In our recent study (Vondrák and Ron, 2017) we proved that better fit is obtained when empirical prograde annual Sun-Synchronous Correction, introduced by Mathews et al. (2002), is kept in the nutation model, even if geophysical excitations are considered. Even SSC alone, without any additional geophysical excitation, yielded better result. From this follows the conclusion that prograde annual SSC is evidently due to other influence than geophysical excitation by the atmosphere and ocean (the excitation by hydrosphere and sea-level changes cannot be tested because they are given in GFZ model with 1-day resolution, and their transformation from terrestrial into celestial frame yields no long-periodic signal). Here we test the importance of SSC again, and calculate the numerical integration of Eq. (1) with atmospheric and oceanic excitations, in the following variants:

- With and without SSC;
- With and without GMJ.

Table 1 Complex amplitudes of GMJ excitations [mas]

Epoch	ESMGFZ A+O		ESMGFZ A+O+SSC	
	Re	Im	Re	Im
1991.0	-2.57	-0.52	-2.53	-0.60
1994.0	0.03	0.73	0.03	0.61
1999.0	-3.32	-1.40	-3.33	-1.44
2003.5	1.27	-1.20	1.00	-0.95
2004.7	0.65	-0.65	0.85	-1.01
2007.5	0.06	1.10	0.06	1.07
2011.0	-2.52	-0.55	-2.40	-0.70
2014.0	-0.69	-1.54	-0.70	-1.63

The estimated values of the accompanied complex amplitudes of GMJ excitations (in milliarcseconds) are displayed in Table 1. Their magnitude is comparable to atmospheric/oceanic excitations. We can see that using SSC influences these values only marginally.

Table 2 displays the summary of the results and its comparison with the results, obtained recently by Vondrák and Ron (2017) without and with original $\mathrm{SSC}_{MHB} = (0.1082 + 0.0104\mathrm{i})\mathrm{e}^{\mathrm{i}l'}$, where l' denotes the mean anomaly of the Sun. In case when SSC is used, we estimate its improved value, leading to the best fit of integration to observation. It is calculated simply as the adjusted value of prograde annual term in the residuals (observed minus integrated CPO values). Our new estimation does not differ very much from the original one: $\mathrm{SSC}_{new} = (0.1045 + 0.0193\mathrm{i})\mathrm{e}^{\mathrm{i}l'}$. It should be noted that the present results with GFZ excitations (first two rows) covers slightly longer time interval (1986.0-2018.4) than our previous results in the last three rows (1986.0-2016.0).

It is clear that SSC improves the fit (compare rows 1 and 2), but even more significant improvement is achieved when GMJ effect is added. GFZ excitations yield better results than our previous solutions with NCEP IB and ERA/OMCT, especially when GMJ effect is included. Our preferred result, obtained with GFZ atmosphere + ocean + SSC_{new}, is marked in bold. The results of integration, given in the first row of Table 1, are depicted graphically in Figures 1 (without GMJ) and 2 (with GMJ).

If we compare Figures 1 and 2, we immediately see the difference. Figure 1, without GMJ effects, displays large discrepancies between integration and observations, both in amplitude and phase. These discrepancies almost completely disappear in Figure 2; impulse-like GMJ excitations, introduced around the epochs marked with arrows, evidently improve the fit significantly. Please also notice that the values of observed celestial pole offsets (dotted series) are slightly different in both figures. The

Table 2 Results of FCN period T and Q-factor, obtained with GFZ excitations by the atmosphere (A) and ocean (O), both without and with GMJ effect included. Root-mean-square fit (rms) between integrated and observed values (in mas) is also shown. For comparison, results that we obtained recently (Vondrák and Ron, 2017), are given in the last three rows.

excitation	without GMJ			with GMJ		
	T	Q	rms	T	Q	rms
GFZ A+O+SSC$_{new}$	429.87±0.08	19100±300	0.415	**429.53±0.04**	**21600±200**	**0.199**
GFZ A+O	429.87±0.08	19100±300	0.431	429.54±0.04	21500±200	0.226
NCEP IB	430.23±0.05	21800±300	0.267	430.16±0.04	21400±200	0.218
ERA/OMCT	430.23±0.08	18700±300	0.422	429.96±0.05	19800±200	0.242
SSC$_{MHB}$	430.37±0.05	19300±200	0.259	430.28±0.04	19500±200	0.204

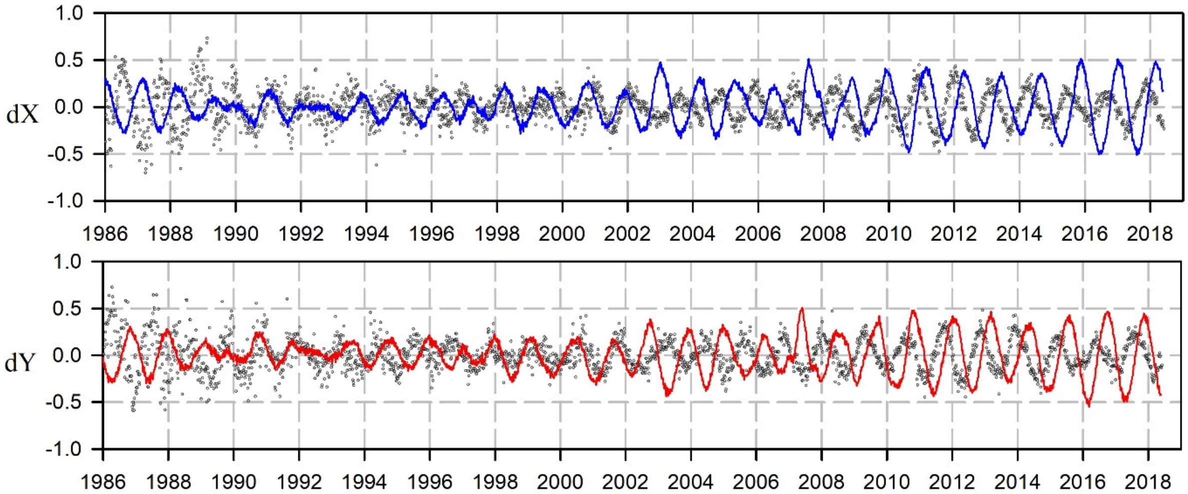

Fig. 1 Integrated (full line) and observed (dots) celestial pole offsets. Excitation by atmosphere and ocean only, as well as new estimation of SSC are used.

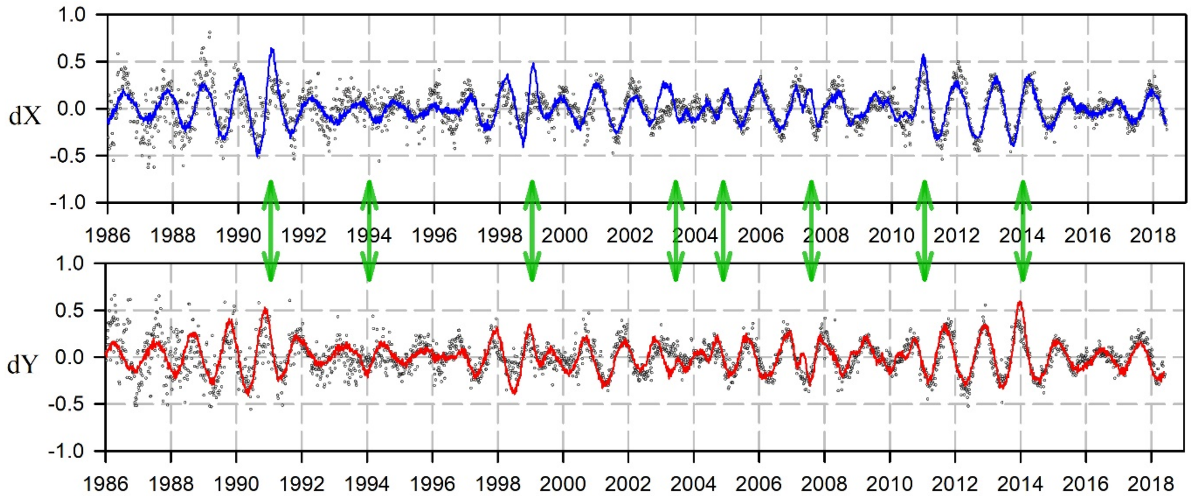

Fig. 2 Integrated (full line) and observed (dots) celestial pole offsets. Excitation by atmosphere, ocean and GMJ, as well as new estimation of SSC are used. GMJ epochs are marked by arrows.

differences are due to the fact that they correspond to different values of FCN parameters (see the first line of Table 2), as described in Section 3.

5. CONCLUSIONS

We test the most recent model of geophysical excitations, provided by ESMGFZ in Potsdam to derive the FCN parameters (period, Q-factor). To this end, we use the method that we proposed earlier (Vondrák and Ron, 2017) with some modifications and the data in interval 1986.0-2018.4. The excitations by hydrosphere and sea-level changes are useless for nutation, being given in terrestrial frame in 1-day steps. Thus, we use only atmospheric and oceanic excitations in this study. Following our previous findings, we keep the MHB empirical prograde Sun-synchronous correction with annual period in the nutation model. We confirm again that its inclusion yields better fit to the observed celestial pole offsets also with the new ESMGFZ geophysical excitations. Significant improvement brings the use of modeled GMJ effect, so that the best of all our solutions is achieved for the combination of ESMGFZ atmosphere + ocean + GMJ + SSC. Our preferred values of FCN parameters are $T = 429.53 \pm 0.04d, Q = 21600 \pm 200$, and our new estimation of SSC is $\mathrm{SSC}_{new} = (0.1045 + 0.0193\mathrm{i})\mathrm{e}^{\mathrm{i}l'}$.

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