Proceedings of the IX Bulgarian-Serbian Astronomical Conference: Astroinformatics (IX BSACA) Sofia, Bulgaria, July 2-4, 2014,
Editors: M. K. Tsvetkov, M. S. Dimitrijević, O. Kounchev, D. Jevremović and K. Tsvetkova
Publl. Astron. Soc. "Rudjer Bošković" No 15, 2015, 127-135

ATMOSPHERIC, OCEANIC AND GEOMAGNETIC EXCITATION OF NUTATION

CYRIL RON[1], JAN VONDRÁK[1] and YAVOR CHAPANOV[2]

[1]*Astronomical Institute, Academy of Sciences of the Czech Republic Prague, Czech Republic*
E-mail: ron@asu.cas.cz, vondrak@ig.cas.cz
[2]*National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Sofia, Bulgaria*
E-mail: astro@bas.bg

Abstract. We tested the hypothesis of Malkin (2013), who recently demonstrated that the observed changes of Free Core Nutation parameters (phase, amplitude) occur near the epochs of geomagnetic jerks (rapid changes of the secular variations of geomagnetic field). We found that if the numerical integration of Brzezinski broad-band Liouville equations of atmospheric/oceanic excitations is re-initialized at the epochs of geomagnetic jerks, the agreement between the integrated and observed celestial pole offsets is improved (Vondrák & Ron 2014). Nevertheless, this approach assumes that the influence of geomagnetic jerks leads to a stepwise change in the position of celestial pole, which is physically not acceptable. Therefore we introduce a simple continuous excitation function that hypothetically describes the influence of geomagnetic jerks, and leads to rapid but continuous changes of pole position. The results of numerical integration of atmospheric/oceanic excitations plus this newly introduced excitation are then compared with the observed celestial pole offsets, and prove that the agreement is improved significantly.

1. INTRODUCTION

Atmospheric and oceanic excitations play dominant role in polar motion and rotational velocity of the Earth. As we demonstrated in our paper Vondrák & Ron (2010), thanks to the new precession/nutation model IAU2000/2006 (Matthews et al. 2002; Capitaine et al. 2003) used after 2003, their small but non-negligible effect can be detected also in nutation. The effects of geophysical excitations in nutation, i.e. the quasi-periodic motion of Earth's axis of rotation in space, especially at annual and semi-annual frequencies, are caused by quasi-diurnal changes of angular momentum functions of the atmosphere and oceans, expressed in terrestrial frame. Therefore, high-resolution data are needed. Fortunately, the atmospheric/oceanic data with 6-hour steps are available, from different agencies, which enable these studies to be made. However, this effect was found to be different for different sources of atmospheric/oceanic angular momentum functions (Ron et al. 2011; Vondrák & Ron 2014). Better agreement with Very Long Baseline Interferometry (VLBI)-based celestial pole offsets (CPO) was achieved for the atmospheric/oceanic data from U.S. agency (NCEP + ECCO) than from the European one (ERA + OMCT). Very recently Malkin (2013) implied that the observed rapid changes of Free Core Nutation (FCN) amplitude and phase were probably related to the epochs of geomagnetic jerks. Therefore we tested this possibility by re-initializing numerical integration at these epochs to see if the agreement between the observed and excited CPO is improved. Preliminary results are presented by Ron et al. (2014) and Vondrák & Ron (2014). The present paper continues in these efforts, namely by applying additional excitations at the geomagnetic jerk epochs. This approach has more physical basement than the simple re-initialization of the numerical integration used in the our last papers.

2. METHOD USED

The excitations of the Earth rotation in the celestial reference frame (nutation) by atmosphere and ocean were studied using Brzezinski (1994) broad-band Liouville equations

$$\begin{aligned} \ddot{P} & -i(\sigma'_C + \sigma'_f)\dot{P} - \sigma'_C\sigma'_f P = -\sigma_C \Big\{\sigma'_f(\chi'_p + \chi'_w) + \\ & \sigma'_C(a_p\chi'_p + a_w\chi'_w) + i[(1+a_p)\dot{\chi}'_p + (1+a_w)\dot{\chi}'_w]\Big\} \end{aligned} \quad (1)$$

where $P = dX + idY$ is excited motion of Earth's spin axis in celestial frame (CRF), $\sigma'_C = 6.32000 + 0.00237i$, $\sigma'_f = -0.0146011 + 0.0001533i$ (in radians per sidereal day) are the complex Chandler and FCN frequencies in celestial frame, respectively, $\sigma_C = 0.01962 + 0.00237i$ in the complex Chandler frequency in terrestrial frame and $a_p = 9.509 \times 10^{-2}$, $a_w = 5.4809 \times 10^{-4}$ are dimensionless constants. χ'_p and χ'_w are the angular momentum excitation functions (presure and wind) in the celestial frame. To solve the second order differential equation (1) we apply substitutions

$$\begin{aligned} y_1 &= P, \quad \text{and} \\ y_2 &= \dot{P} - i\sigma'_C P, \end{aligned}$$

and get two first-order differential equations

$$\begin{aligned} \dot{y_1} &= i\sigma'_C y_1 + y_2 \\ \dot{y_2} &= i\sigma'_f y_2 - \sigma_C \left\{\sigma'_f(\chi'_p + \chi'_w) + \sigma'_C(a_p\chi'_p + a_w\chi'_w) + \right. \\ & \left. +i[(1+a_p)\dot{\chi}'_p + (1+a_w)\dot{\chi}'_w]\right\} \end{aligned} \quad (2)$$

To be able to integrate the system (2) we set the initial values P_0, $\dot{P}_0$ constrained so that the free Chandlerian term (with quasi-diurnal period in celestial frame) vanishes. The initial values are closely connected to the phase and amplitude of the integrated series. The final choice of P_0 was made by repeating integration with different values P_0 to fit the integrated motion to VLBI observations so that reaches a minimum rms differences, and the numerical integration was performed using the Runge-Kutta 4th order in 6h steps (Press et al. 1992).

In our previous studies Ron et al. (2013) and Vondrák & Ron (2014), we looked for additional excitations to explain the inconsistency in phases of observed CPO and integrated series. The best agreement has been found for the geomagnetic jerks (or secular geomagnetic variation impulse) that are relatively sudden changes in the second time derivative of the Earth's magnetic field. More informations on geomagnetic jerks can be found in Olsen & Mandea (2007).

We found the double ramp function as the closest one. We tested the behaviour of the double ramp function using the integration with simulated schematic excitation, which is shown in Fig. 1.

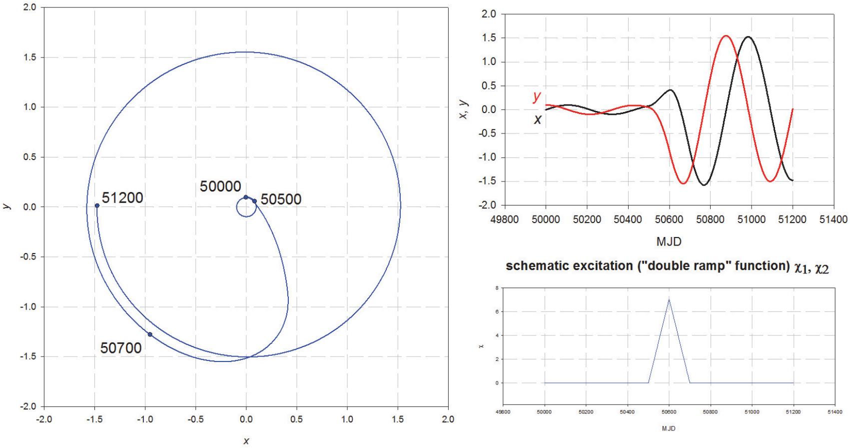

Figure 1: The integration with the simulated schematic excitation function.

We fix the the central epochs of additional excitations around geomagnetic jerks epochs: 1991.0, 1994.0, 1999.0, 2003.5, 2004.7, and 2007.5 taken from Malkin (2014) and take into account that the geomagnetic jerks last typically several months. We fix the length of an excitation to 200 days. The complex amplitudes of the excitations were estimated to lead to the best rms fit to observed celestial pole offsets. We also tested if the excitations is preceeding, delaying or corresponding to the geomagnetic jerk epochs. The values[1] of the rms and correlations are displayed in Tab. 1. The best agreement was found just for the epochs of the geomagnetic jerks.

Table 1. The values of rms of the residuals between observed celestial pole offsets and integrated series of AAM functions with the additional excitations in the epochs preceeding and delaying 100 days the geomagnetic jerk epochs.

epoch of GMJ +	rms [mas]	correlation
−100d	0.211	0.578
0d	0.196	0.632
+100d	0.213	0.570

[1] These values were obtained from slightly shorter interval and do not correspond to the presented solution.

3. DATA USED

3. 1. THE CELESTIAL POLE OFFSETS

There exist many solutions provided by different VLBI analysis centers, but, Malkin (2012) demonstrated that IVS series may be preferable for applications of FCN models. We used the celestial pole offsets from IVS combined solution `ivs13q4X.eops` (Schlüter & Behrend 2007) covering the interval 1989.0-2014.0. The coordinates dX and dY are given in unequally spaced intervals (typically 1-7 days long), sometimes with outliers. We cleaned the data by removing CPO > 1mas. The empirical Sun-synchronous correction has been added to the IAU2000 nutation model (Matthews et al. 2002) to account the influence of atmosphere into the theoretical model. In order the observed CPO can be compared with the atmosheric contribution we added the Sun-synchronous correction $(0.1082 + 0.0104i)e^{il'}$ (in mas), where l' is the mean anomaly of Sun, to the complex CPO values. The data were then filtered (Vondrák 1977) to retain only periods between 60 and 6000 days. Finally the series were interpolated at regular 10-day intervals and both the observed and filtered ones are shown in Fig. 2.

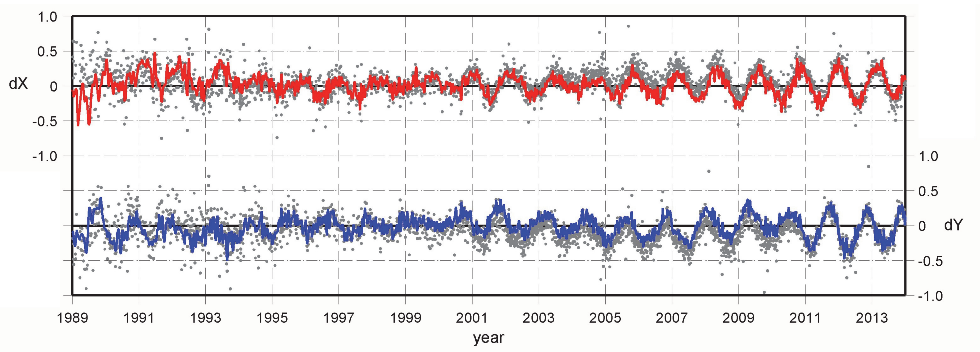

Figure 2: IVS Celestial pole offsets dX (up) and dY (bottom) in mas. The observed values (dots) and then filtered so that the periods are longer than 60d and shorter than 6000d (lines).

3. 2. ATMOSPHERIC ANGULAR MOMENTUM

There are two different series of Atmospheric Angular Momentum (AAM) available on the website of the IERS. First the European Centre for Medium-Range Weather Forecasts (ECMWF) that produced a reanalysis ERA40 on the time interval 1958–2001 and after 2001 is producing solutions ERAInterim, that are provisional solutions before a new global reanalysis. The corresponding oceanic angular momentum based on the model OMCT is produced continuosly by Dobslaw et al. (2010). The second series are produced by Atmospheric and Environmental Research, USA. That are NCEP/NCAR reanalysis prepared yearly in the time interval 1948–present. Unfortunately, there is no model of oceanic angular momentum available for the whole period of our interest (1989–2014). The pressure term of AAM function with the inverted barometer correction, that is provided by NCEP/NCAR Data Center as well, can serve alternatively as a simple model of oceanic response on the pressure changes (Wunsch & Stammer 1997).

Our previous studies based on atmospheric/oceanic angular momemtum function of European meteorological Center ECMWF ERA40 and on the ocean model OMCT showed relatively worse agreement in comparison with the NCEP/NCAR data (Vondrák & Ron, 2014). That is why we only used the NCEP/NCAR data in this study.

The time series of AAM χ (complex values) were transformed from the terrestrial frame to the celestial frame by using the complex decomposition at retrograde diurnal frequency $\chi' = -\chi e^{i\Phi}$, Φ is the Greenwich sidereal time.

Because we are interested in the long-periodic motion that is comparable with nutation, we applied the smoothing (Vondrák 1977) to remove periods shorter than 10 days and at the same time calculated their time derivatives needed for integration. The time series of the NCEP/NCAR atmospheric excitations corrected for inverted barometer after demodulation is displayed in Fig. 3. The dimensionless values of χ_1, χ_2 are given in units of 10^{-8}. The wind terms, which are much larger than pressure term, have in resulting integration lower influence because of two-order smaller value of the constatnt coefficient a_w mentioned above. The pressure term is better seen in Figures 4 and 5.

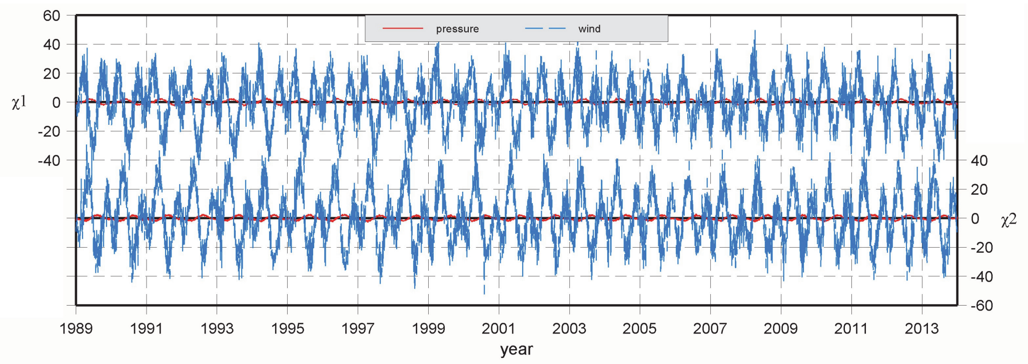

Figure 3: NCEP excitations pressure and wind terms. Pressure with the inverted barometer correction.

4. RESULTS

The IVS solution of CPO corrected for the sun-synchronous correction is compared with geophysically excited motion of celestial pole obtained by numerical integration of Eq. (2). To obtain the best fit to CPO values, the integration was repeated with different initial values for the first interval, i.e., from the beginning of the series in 1989 up to the first epoch of geomagnetic jerk 1991 and then were searched the complex values of the additional excitations for each interval between the successive geomagnetic jerks.

The integrated CPO obtained with NCEP excitations without and with the inverted barometer correction are graphically depicted in Figures 4 and 5, respectively.

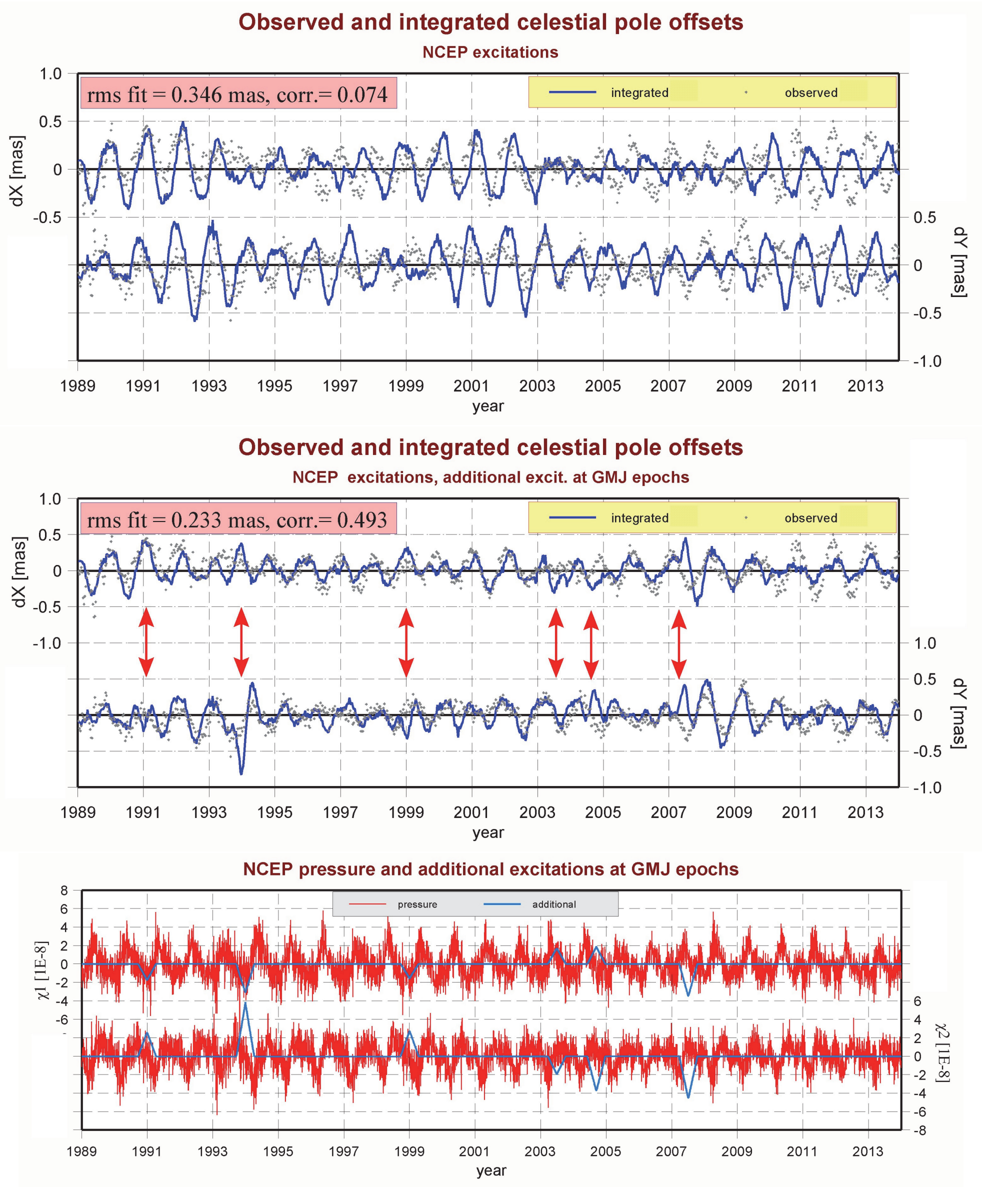

Figure 4: Top: Observed and integrated CPO obtained with NCEP excitations without inverted barometer correction. Middle: the same with the added geomanetic excitations. Bottom: The added geomagnetic exciations together with the pressure term.

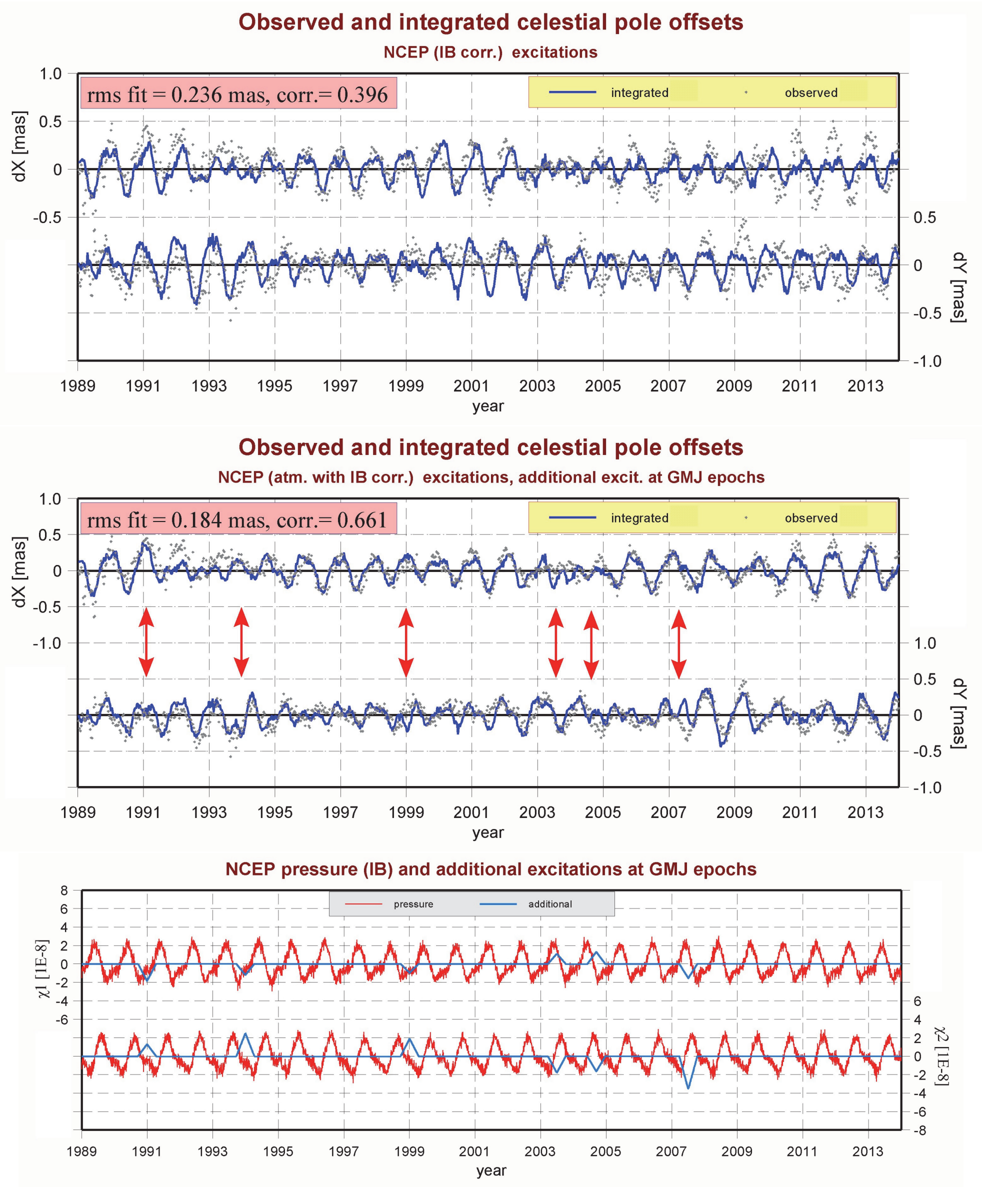

Figure 5: Top: Observed and integrated CPO obtained with NCEP excitations with the inverted barometer correction. Middle: the same with the added geomanetic excitations. Bottom: The added geomagnetic exciations (in blue) together with the pressure term (red).

The application of the additional exitations in the epochs of geomagnetic jerks to the NCEP atmospheric exciation functions with the inverted barometer correction improves the agreement of the integrated CPO with the observed CPO significantly as it is seen from Tab. 2.

Table 2. The rms fits and the correlations between integrated and observed CPO

Series	without		with additional exc	
	rms [mas]	corr.	rms[mas]	corr.
NCEP without IB	0.346	0.074	0.233	0.493
NCEP with IB	0.236	0.396	0.184	0.661

5. CONCLUSIONS

In our previous work (Vondrák & Ron 2014) we detected considerable differences between ERA40 and ERAinterim the wind term in AAM data about 30% relative difference in amplitude of the semi-annual wind term. NCEP solution with the inverted barometer correction leads to better agreement than with the ERA series and therefore we used only the NCEP solution in this study. Geophysical excitations yield significant contribution to nutation, of the order of 0.1mas. The influence of motion (wind) terms is one order of magnitude smaller than that of matter (pressure) terms. The application of the pressure term of AAM function with the inverted barometer correction, that implies a simple ocean model, improved the correlation between the observed and integrated CPO series in relation to the case when the the pressure term of AAM function without the inverted barometer correction is used. The application of schematic additional excitations at geomagnetic jerk epochs improves the agreement of integrated pole position with VLBI observations even more.

Acknowledgements

This research was financially supported by the grant No. 13-15943S "Geophysical excitations in the motion of Earth's axis of rotation", awarded by the Grant Agency of the Czech Republic. The support given to C.R. and J.V. by Bulgarian Academy of Sciences to participate the IXth Bulgarian-Serbian Astronomical Conference held in Sofia is appreciated.

References

Brzeziński, A.: 1994, Polar motion excitation by variations of the effective angular momentum function: II. Extended Model, *Manuscripta Geodaetica*, **19**, 157.

Capitaine, N., Wallace, P. T. and Chapront, J.: 2003, Expressions for IAU 2000 precession quantities. *Astron. and Astrophys.*, **412**, 567.

Dobslaw, H., Dill, R., Grotzsch, A., Brzeziński, A. and Thomas, M.: 2010, Seasonal polar motion excitation from numerical models of atmosphere, ocean, and continental hydrosphere, *J. Geophys. Res.*, **115**, B10406, doi: 10.1029/2009JB007127.

Malkin, Z.: 2012, Celestial pole offsets: From initial analysis to end user. *Proc. IVS 2012 General Meeting*, 375.

Malkin, Z.: 2013, Free core nutation and geomagnetic jerks, *Journal of Geodynamics*, **72**, 53.

Mathews, P.M., Herring, T.A. and Buffett, B.A.: 2002, Modeling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earths interior, *J. Geophys. Res. (Solid Earth)*, **107(B4)**, doi:10.1029/2001JB000390.

Olsen, N. and Mandea M.: 2007, Investigation of a secular variation impulse using satellite data: The 2003 geomagnetic jerk. *Earth and Planetary Science Letters*, **255**, 94.

Press, W.H., Teukolsky, S.A., Vetterling, W.T and Flannery, B.P.: 1992, "Numerical Recipes in Fortran 77. The Art of Scientific Computing", 2nd Edition, Cambridge University Press, 993 p.

Ron, C., Vondrák, J. and Štefka, V.: 2011, Comparison of the various atmospheric and oceanic angular momentum series, In Proc. Journées 2010 Systèmes de référence spatio-temporels, ed. N. Capitaine, Observatoire de Paris, 221.

Ron, C., Vondrák, J. and Chapanov, Ya.: 2014, Free core nutation – possible causes of changes of its phase and amplitude, In Proc. Journées 2013 Systèmes de référence spatio-temporels, ed. N. Capitaine, Observatoire de Paris, in press.

Schlüter, W. and Behrend, D.: 2007, The International VLBI Service for Geodesy and Astrometry (IVS): Current capabilities and future prospects. *J. Geod.*, **81**, 379.

Vondrák, J.: 1977, Problem of smoothing of observational data II, *Bull. Astron. Inst. Czechosl.*, **28**, 84.

Vondrák, J. and Ron, C.: 2010, Study of atmospheric and oceanic excitations in the motion of Earths spin axis in space. *Acta Geodyn. Geomater.*, **7**, No. 1, 19.

Vondrák, J. and Ron, C.: 2014, Geophysical Excitation of nutation – comparison of different models, *Acta Geodyn. Geomater.*, **11**, No. 3, 193.

Wunsch, C. and Stammer, D.: 1997, Atmospheric loading and the oceanic "inverted barometer" effect. *Reviews of Geophysics*, **35**, 79. doi: 10.1029/96RG03037