DIURNAL EXCITATION OF EARTH ROTATION ESTIMATED FROM RECENT GEOPHYSICAL MODELS

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ABSTRACT. Nearly diurnal variations in the atmospheric and nontidal oceanic angular momenta (AAM, OAM) contribute at measurable level to all components of Earth rotation. The estimated contributions to nutation have amplitudes over 0.1 milliarcsecond (mas), while in case of polar motion and UT1 the amplitudes are up to 0.04 mas. However, there are still significant discrepancies between the contributions estimated from different geophysical models as well as between those derived from geophysical models and geodetic data. Here we use a new consistent set of 20-year time series of AAM and OAM based on the ERA-Interim reanalysis fields and the corresponding simulation from the ocean model OMCT, to extract the diurnal component and to estimate the influence on Earth rotation. Results are compared to the earlier estimates using the AAM series from the NCEP-NCAR reanalysis model and the OAM series from the barotropic ocean model, derived by Brzeziński et al. (2004). The estimated geophysical contributions are also compared to the available results derived from the space geodetic observations of Earth rotation.

1. INTRODUCTION

Nearly diurnal variations in distribution of the atmospheric and oceanic masses and in the pattern of winds and ocean currents, associated with the daily cycle in solar heating, change the angular momentum of these two media (AAM, OAM). Diurnal variations of AAM and OAM excite small, below 1 milliarcsecond (mas), but already well detectable variations in all components of Earth rotation including precession-nutation, polar motion and the axial component of rotation expressed by the Universal Time UT1 or changes in the length of day LOD. Understanding this effect is important for modeling global dynamics of the solid Earth and its external fluid layers at daily and subdaily periods. A general description of the perturbations of Earth rotation caused by diurnal thermal tides in the atmosphere and in the oceans was given by Brzeziński et al. (2002), Brzeziński (2008).

Diurnal excitation of Earth rotation can be estimated from the AAM and OAM data only in case when the sampling period of the excitation time series is shorter than 12 hours. This condition is satisfied by most of the AAM series which are available from the International Earth Rotation and Reference Systems Service (IERS) Special Bureau for the Atmosphere (SBA) because the standard sampling interval is 6 hours. Of particular importance are the AAM series derived from the reanalyzes of the Atmospheric Global Circulation Models (AGCM) extending over decades. Unfortunately, all the OAM time series which are available from the IERS Special Bureau for the Oceans (SBO) have daily and longer sampling rates therefore are not useful for studying the diurnal and subdiurnal effects. The OAM series with subdaily resolution are still produced only occasionally and have experimental character.

A first successful attempt to estimate the diurnal component of atmospheric excitation was done by Bizouard et al. (1998) based on the 6-hourly AAM series from the U.S. National Center for Environmental Prediction, National Center for Atmospheric Research (NCEP-NCAR) reanalysis AGCM (Kalnay et al., 1996). They used the approach developed by Brzeziński (1994). By applying the so-called complex demodulation procedure they could extract the diurnal retrograde component of excitation, designated "celestial effective angular momentum" (CEAM) function, which was then used to estimate the atmospheric contribution to nutation. They considered the harmonic components of excitation which contribute to the periodical components of the conventional precession-nutation model, but also devoted much space to the nonharmonic component contributing to the nutation residuals expressed by the time series of the celestial pole offsets. Brzeziński et al. (2002) used the same AAM data and similar methodology to estimate the atmospheric contributions to prograde diurnal and retrograde/prograde semidiurnal components of polar motion, as well as to diurnal and semidiurnal components of UT1/LOD. In case of semidiurnal components, the 6-hourly sampling of AAM did not allow resolving the spectrum therefore only rough overall estimate could be given.

Brzeziński et al. (2004) used a hourly OAM time series spanning 1993.0–2000.5, derived from the barotropic Ocean Global Circulation Model (OGCM), to estimate the non-tidal oceanic contribution to nutation, prograde diurnal and retrograde/prograde semidiurnal polar motion. They also re-estimated the atmospheric contributions over the same 7.5-year period in order to compare them to the oceanic effect and to estimate the aggregated contribution to nutation and polar motion from the dynamically coupled atmosphere-ocean system.

Here we will estimate the diurnal atmospheric and nontidal oceanic contributions to precession-nutation, prograde polar motion and UT1/LOD, using a new consistent set of 20-year excitation time series produced by the IERS Associated Product Centre Deutsches GeoForschungsZentrum (GFZ) Potsdam, Germany (courtesy of Henryk Dobslaw). Amplitudes of the main harmonic terms will be compared to the earlier results of Brzeziński et al. (2004). We will also compare the estimated geophysical perturbations of Earth rotation to the determinations from the space geodetic observations.

2. DATA ANALYSIS

We used in the analysis a new set of geophysical excitation series: AAM, OAM and the hydrological angular momentum (HAM). The AAM series is based on the ERA Interim re-analysis from the European Center for Medium Weather Forecasts (ECMWF) (Uppala et al., 2008) with $1°\times1°$ regular grids and 37 vertical pressure levels. The HAM estimate is computed from output of the hydrological model LSDM (Dill, 2008) with $0.5°\times0.5°$ spatial resolution. The model is forced by precipitation, evaporation and 2m-temperatures. The OAM series is computed from the Ocean Model for Circulation and Tides (OMCT) (Dobslaw and Thomas, 2007). Discretized on a regular $1.875°\times$ $1.875°$ grid with 13 vertical layers, the model is forced by wind stress, atmospheric pressure, 2m-temperatures, and freshwater fluxes from both atmosphere and continental hydrosphere. Further details about these data sets and the underlying models can be found in (Dobslaw et al., 2010) and the references therein. We note only here that the new set of geophysical excitation series is consistent in a sense of mass conservation in the corresponding models.

We ignore in our analysis the HAM series because of its daily sampling rate. More generally, it is expected that the contribution of HAM can be important in the excitation balance of Earth rotation at seasonal frequencies but is negligible at high frequencies including diurnal and subdiurnal bands. The AAM and OAM series span the period between 1989.0 and 2009.0 with 6-hourly sampling which is sufficiently short for resolving the diurnal frequency band. The pressure term of AAM is given with the inverted barometer (IB) correction and the OAM series is referred to the IB ocean model. Consequently, the aggregated atmospheric and oceanic influence on Earth rotation is expressed just by the sum AAM+OAM. This representation of new AAM and OAM series is also consistent with that of the series used by Brzeziński et al. (2004) which enables direct comparisons of the estimated contributions to Earth rotation.

We process all terms of the AAM and OAM series in a similar way as Brzeziński et al. (2004) and by applying the procedure described in details by Brzeziński (2000) and Brzeziński et al. (2004). First, we express the axial component of excitation χ_3 in the units of LOD. Next, we compute the complex demodulate of the equatorial component of excitation $\chi = \chi_1 + i\chi_2$, with $i = \sqrt{-1}$ being the imaginary unit, at frequencies $-\Omega$ (contributing to nutation) and $+\Omega$ (contributing to prograde diurnal polar motion), and of the axial component χ_3 at frequency $+\Omega$. Here Ω denotes the diurnal sidereal frequency equal to 1 cycle per sidereal day (cpsd). Each demodulated series is then smoothed by a Gaussian low-pass filter with full width at half maximum equal to 10 days and re-sampled at equidistant 5-days intervals. That gives 1457 data points starting from modified Julian date (MJD) 47540.0.

The demodulated series are spectrally analyzed by applying the maximum entropy method (MEM) algorithm developed by Brzeziński (1995). The demodulated series and the corresponding power spectral density (PSD) functions are shown in Figures 1, 2 and 3. Note that the demodulated series are different than the original once, in particular that of χ_3 is the complex quantity. On the other hand, the PSD functions have only been shifted along the frequency axis in such a way that the demodulation frequency becomes 0. The tidal code used to label the spectral lines in the PSD plots of Figures 1 to 3 refers to the original AAM and OAM series, with the superscripts "$-/+$" denoting the retrograde/prograde variations.

Finally, we estimate for each of the demodulated series the best least-squares fit of the model which is a sum of the first order polynomial and the complex sinusoids with periods ±1 year, $\pm1/2$ year and

Table 1: Main periodical components of the atmospheric and nontidal oceanic contributions to nutation. VLBI estimate is taken from the MHB 2000 model (Mathews et al., 2002). Units are μas.

Excit. term	Brzeziński et al., 2004 in-phase	Brzeziński et al., 2004 out-of-phase	This study in-phase	This study out-of-phase
	excitation: ψ_1^- component, nutation: retrograde annual			
A presIB	51.8 ±27.2	51.3 ±27.2	50.5 ±6.4	−43.6 ±6.4
A wind	6.9 ±2.3	9.2 ±2.3	7.2 ±1.7	2.6 ±1.7
O mass	3.1 ±39.9	124.0 ±39.9	−5.3 ±31.1	8.9 ±31.1
O veloc.	−0.6 ±0.7	0.8 ±0.7	0.2 ±0.3	1.5 ±0.3
A-IB+O	**61.2 ±48.3**	**185.3 ±48.3**	**52.6 ±31.8**	**−30.6 ±31.8**
	excitation: S_1^- component, nutation: prograde annual			
A presIB	−40.8 ±2.1	−44.0 ±2.1	27.7 ±0.4	−53.2 ±0.4
A wind	−7.1 ±0.7	−26.9 ±0.7	−2.4 ±0.5	−21.1 ±0.5
O mass	−68.6 ±4.3	−22.3 ±4.3	39.8 ±1.7	−6.4 ±1.7
O veloc.	3.4 ±0.3	−2.9 ±0.3	−4.5 ±0.2	−3.2 ±0.2
A-IB+O	**−113.1 ±4.8**	**−96.1 ±4.8**	**+60.6 ±1.8**	**−83.9 ±2.8**
VLBI	10.4	−108.2	10.4	−108.2
	excitation: P_1^- component, nutation: prograde semiannual			
A presIB	−11.3 ±0.9	4.7 ±0.9	4.7 ±0.3	−17.7 ±0.3
A wind	−6.2 ±0.6	−38.9 ±0.6	−12.9 ±0.6	−43.1 ±0.5
O mass	16.4 ±2.7	2.2 ±2.7	37.4 ±1.3	6.8 ±1.2
O veloc.	−0.6 ±0.2	0.1 ±0.2	−0.7 ±0.2	2.1 ±0.2
A-IB+O	**−1.7 ±2.9**	**−31.9 ±2.9**	**31.5 ±1.5**	**−51.9 ±1.3**

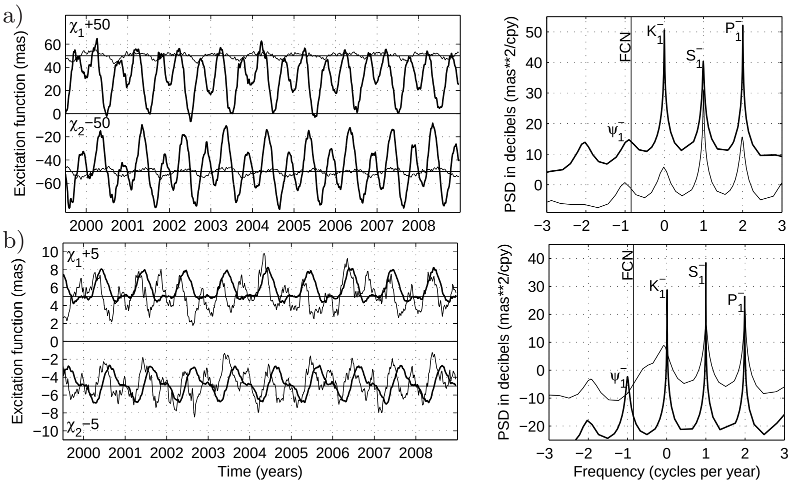

Figure 1: Equatorial effective angular momentum functions of the atmosphere (AAM – thick line) and ocean (OAM – thin line) demodulated at frequency −1 cpsd: a) motion term, b) mass term. On the right-hand side shown are the MEM power spectra estimated over the entire 20-year period. Period of analysis 1989.0–2009.0.

±1/3 year. Such a model comprises all terms which could be detected by the spectral analysis, on the other hand each component of the model has a physical explanation either as being excited by the S_1 thermal tide, or as expressing its seasonal modulations, annual – (K_1, P_1), semiannual – (ψ_1, π_1). The estimated parameters are convolved with the theoretical transfer function (Brzeziński, 1994) in order to estimate the corresponding terms of nutation, polar motion and UT1/LOD.

Results of estimation are shown in Tables 1, 2 and 3. In case of nutation (Table 1) we apply the same convention for representation of the in-phase and out-of-phase coefficients of the circular nutation terms as Bizouard et al. (1998), which may differ from the conventions applied by other investigators. For instance, Mathews et al. (2002) described each circular term of nutation by the pair of coefficients (real, imaginary) which are exactly opposite in sign to our pair (in-phase, out-of-phase). In case of prograde diurnal polar motion $p = x_p - iy_p$ (Table 2) the parametrization is

$$x_p = x^{sin}\sin(arg) + x^{cos}\cos(arg),$$
$$y_p = y^{sin}\sin(arg) + y^{cos}\cos(arg),$$

and in case of diurnal UT1 variation (Table 3)

$$\mathrm{UT1} = \mathrm{UT1}^{sin}\sin(arg) + \mathrm{UT1}^{cos}\cos(arg),$$

where the argument is expressed as $arg = (\mathrm{GMST} + \pi) + k_1 l_m + k_2 l_s + k_3 F + k_4 D + k_5 \hat{\Omega}$, and l_m, l_s, F, D, $\hat{\Omega}$ are the fundamental arguments used in the nutation theory; GMST denotes Greenwich mean sidereal time, and $k_1, \ldots, k_5$ is a set of integer coefficients identifying the quasi-harmonic component of perturbation. Table 2 shows only the coefficients x^{sin} and x^{cos} because for the prograde harmonics of polar motion the following relationships hold $y^{sin} = -x^{cos}$, $y^{cos} = x^{sin}$.

The estimated coefficients of the main periodical components of perturbation are compared in the tables to the results of Brzeziński et al. (2004). Note that the last paper was entirely devoted to the equatorial components of Earth rotation, hence when comparing the UT1/LOD results in Table 3 the reference (Brzeziński et al., 2004) means only the same excitation data sets while the estimated coefficients are published here for the first time. We shown also in the tables the coefficients estimated from the Very

Long Baseline Interferometry (VLBI) measurements of Earth rotation. This is done for only one term of perturbation corresponding to the S_1 term of excitation. The reason, discussed by Brzeziński (2008), is that the other diurnal terms are dominated by the ocean tide contributions and the uncertainty of their amplitudes is at the same level as the nontidal contributions expressed by AAM and OAM. Finally, we note that several other estimates of the perturbation by the S_1 tide, including those from the alternative reanalysis AAM data, from the operational AAM series and from the hydrodynamic ocean model of Ray and Egbert (2004), can be found in (Brzeziński, 2008).

3. RESULTS AND CONCLUSIONS

Analysis of a new set of 20-year time series of atmospheric and nontidal ocean angular momenta confirmed several features which could be either deduced from the physics or detected from earlier investigations using alternative data sets. The spectral structure of excitation is similar in all three cases considered: it consists of the S_1 component driven by the thermal (radiational) atmospheric tide and its side lobes shifted in frequency by ±1 and ±2 cycles per year. The side lobes are caused by seasonal modulations of the S_1 tide. In case of the retrograde diurnal equatorial component of excitation contributing to nutation, there is much greater power in the wind term of AAM than in the pressure term. However, this discrepancy of power is largely counterbalanced by the opposite discrepancy of the transfer coefficients used to convert the amplitudes of geophysical excitation to the amplitudes of nutation. Spectral analysis of the residuals obtained after removal of the polynomial-harmonic model (not shown here) revealed that in all three cases the S_1 term of diurnal excitation contains the random component which could not be expressed by the harmonic model. A proper representation of this component is in the time domain therefore the atmospheric-oceanic excitation considered here needs to be monitored on regular basis.

From the comparison with earlier results of Brzeziński et al. (2004) and with the VLBI estimate it can be seen a rough agreement in size of the estimated atmospheric and nontidal oceanic contributions to nutation, diurnal polar motion and diurnal UT1/LOD variation, nevertheless the differences are in most cases

Table 2: Main periodical components of the atmospheric and nontidal oceanic contributions to prograde diurnal polar motion. VLBI estimates are taken from (Gipson, 1996) – G96, and from (Bolotin and Brzeziński, 2006) – BB06. Units are μas.

Excitation term	Brzeziński et al., 2004		This study	
	x-sin	x-cos	x-sin	x-cos
	P_1^+ component, period 1.0027454 day			
A presIB	0.3 ±0.1	0.8 ±0.1	0.1 ±0.1	−0.6 ±0.1
A wind	−0.5 ±0.2	0.3 ±0.2	0.0 ±0.1	2.2 ±0.1
O mass	−1.0 ±0.3	−1.4 ±0.3	−3.0 ±0.1	−0.1 ±0.1
O veloc.	1.3 ±0.2	0.3 ±0.2	2.6 ±0.1	−0.3 ±0.1
A-IB+O	**0.1 ±0.4**	**0.0 ±0.4**	**−0.3 ±0.2**	**1.2 ±0.2**
	S_1^+ component, period 0.9999999 day			
A presIB	−0.7 ±0.1	−3.8 ±0.1	−3.2 ±0.1	0.6 ±0.1
A wind	5.2 ±0.1	−0.1 ±0.1	1.9 ±0.1	2.7 ±0.1
O mass	7.2 ±0.3	−3.5 ±0.3	4.0 ±0.1	0.1 ±0.1
O veloc.	−3.4 ±0.3	4.0 ±0.3	−0.8 ±0.1	−0.1 ±0.1
A-IB+O	**8.3 ±0.4**	**−3.4 ±0.4**	**1.9 ±0.2**	**3.3 ±0.2**
VLBI – G96	7	−28	7	−28
VLBI – BB06	27	−13	27	−13
	K_1^+ component, period 0.9972696 day			
A presIB	−0.5 ±0.1	−0.2 ±0.1	0.1 ±0.1	0.4 ±0.1
A wind	0.4 ±0.2	−0.2 ±0.2	0.1 ±0.1	−0.6 ±0.1
O mass	0.9 ±0.4	1.2 ±0.4	2.5 ±0.1	1.8 ±0.1
O veloc.	−0.9 ±0.3	−0.3 ±0.3	−1.9 ±0.1	−0.2 ±0.1
A-IB+O	**−0.1 ±0.5**	**0.5 ±0.5**	**0.8 ±0.2**	**1.4 ±0.2**

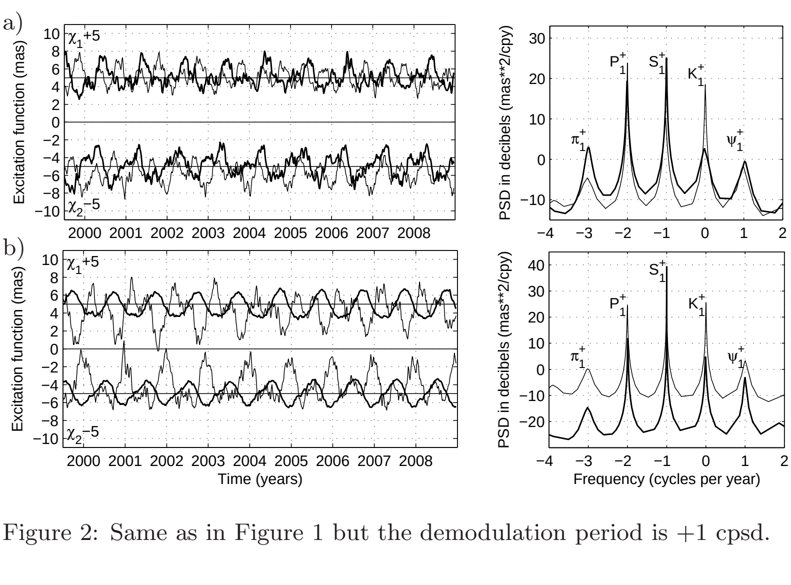

Figure 2: Same as in Figure 1 but the demodulation period is +1 cpsd.

Table 3: Main periodical components of the atmospheric and nontidal oceanic contributions to diurnal UT1 variation. VLBI estimates are taken from (Gipson, 1996) – G96, and from (Bolotin and Brzeziński, 2006) – BB06. Units are μas. (Note: 1 μs of UT1 corresponds to 15 μas.)

Excitation term	Brzeziński et al., 2004		This study	
	UT1-sin	UT1-cos	UT1-sin	UT1-cos
	P_1 component, period 1.0027454 day			
A presIB	2.2 ±0.3	−0.6 ±0.1	−0.4 ±0.1	0.5 ±0.1
A wind	−1.5 ±0.2	−1.7 ±0.2	0.6 ±0.1	−6.4 ±0.5
O mass	−0.6 ±0.3	0.0 ±0.1	22.5 ±0.3	−21.8 ±0.3
O veloc.	1.4 ±0.1	2.5 ±0.2	0.0 ±0.1	1.1 ±0.1
A-IB+O	**1.5 ±0.5**	**0.3 ±0.3**	**22.7 ±0.3**	**−26.6 ±0.6**
	S_1 component, period 0.9999999 day			
A presIB	0.9 ±0.1	−4.6 ±0.3	−7.5 ±0.1	1.5 ±0.1
A wind	14.4 ±0.2	−3.4 ±0.1	1.2 ±0.5	0.3 ±0.1
O mass	−5.3 ±0.2	−2.5 ±0.1	6.3 ±0.4	1.0 ±0.1
O veloc.	−7.4 ±0.2	5.0 ±0.1	−10.8 ±0.1	8.0 ±0.1
A-IB+O	**2.6 ±0.4**	**−5.6 ±0.3**	**−10.7 ±0.7**	**10.9 ±0.2**
VLBI – G96	−32	17	−32	17
VLBI – BB06	−25	7	−25	7
	K_1 component, period 0.9972696 day			
A presIB	−0.8 ±0.4	0.5 ±0.3	0.3 ±0.1	−0.7 ±0.1
A wind	2.7 ±0.3	−0.5 ±0.2	−0.2 ±0.3	−3.0 ±0.4
O mass	0.5 ±0.3	0.9 ±0.3	19.0 ±0.2	−28.2 ±0.2
O veloc.	−0.7 ±0.2	0.2 ±0.2	1.2 ±0.1	−0.3 ±0.1
A-IB+O	**1.7 ±0.6**	**1.0 ±0.5**	**20.3 ±0.4**	**−32.2 ±0.5**

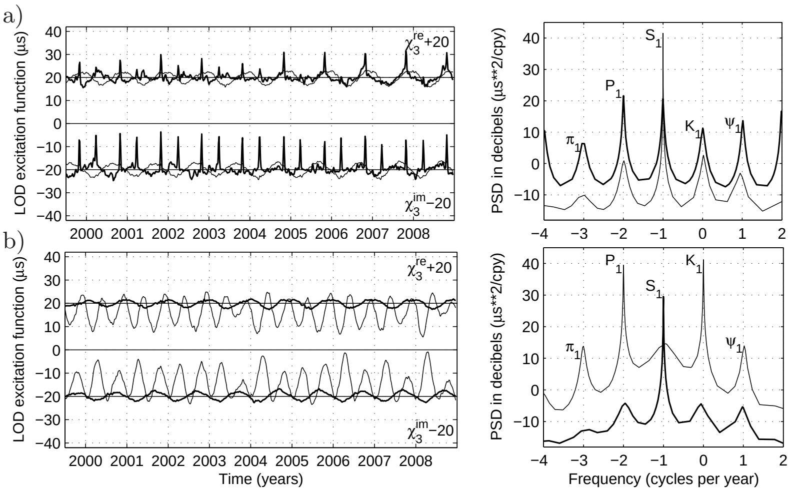

Figure 3: Same as in Figure 1 but for the axial component of excitation and the demodulation period of +1 cpsd.

still significantly larger than the estimated formal uncertainties. In case of the prograde annual nutation, which is the only nutation component where comparison of AAM and OAM with the VLBI estimate is possible, there is considerable improvement of agreement between the model and observation in the in-phase amplitude but a slight increase of discrepancy in the out-of-phase amplitude. For prograde diurnal polar motion the estimated geophysical contribution is at the level of only 4 μas, which is 2 times less than found previously. The amplitude of the S_1^+ component is almost 10 times smaller than estimated from VLBI observations. This large discrepancy between the modeled and observed amplitudes, noted already in previous works, clearly needs further investigations. In case of diurnal UT1/LOD variation the estimated geophysical contribution to the S_1 component is at the level of 10 μas, about 2 times larger than in the previous estimation but still 3 times less than derived from VLBI data. Another feature is the large size of the side lobes P_1 and K_1 of the OAM mass term and the anomalous behavior of the AAM wind term, not seen in the previous data.

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