HIGH FREQUENCY ATMOSPHERIC EXCITATION OF EARTH ROTATION

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1. INTRODUCTION

Recent determinations of the Earth orientation parameters by the space geodetic measurements revealed rapid variations in Earth rotation. These variations are at least partly driven by the fluctuations of the atmospheric angular momentum. Two types of atmospheric excitations are observed at short periods extending from several days down to 12 hours. First type is a set of tidal waves, principally of thermal origin, appearing at diurnal and semidiurnal frequencies. Second group comprises pseudoharmonic variations due to the free modes in global atmospheric circulation, such as Rossby-Haurwitz waves ψ_3^1 and ψ_1^1 with periods of about 10 and 1.2 days. The corresponding variations in Earth rotation are much smaller than the seasonal effects of atmospheric origin, nevertheless are important when taking into account the current accuracy level of monitoring changes in Earth rotation.

In this paper which is an extension of our earlier study (Petrov *et al.*, 1998), we investigate such excitations from the point of view of both theoretical modeling and observational evidence based on the available time series of the *atmospheric angular momentum* (AAM). We give a general description of the atmospheric excitation of Earth rotation and review main features of the high frequency AAM variations. Then we perform spectral analysis of the homogeneous 4-times daily AAM series based on the recent reanalysis data. Finally we estimate from the AAM data the high frequency atmospheric influences on polar motion and on the length of day variation.

2. GENERAL DESCRIPTION

Perturbations in Earth rotation are conventionally split up into the equatorial component, *polar motion*, and the axial component which is expressed either as changes in the *length of day* (l.o.d.) or as the *universal time* UT1 variation. Atmospheric excitation appears in all 3 components of the Earth's rotation vector. It has been proven that the atmosphere is a dominating driving agent at periods from weeks up to about 2 years, with a particularly strong seasonal signal; see (Eubanks, 1993) for review. At diurnal and semidiurnal periods the atmospheric excitation is in most cases much weaker than the corresponding oceanic excitation, nevertheless is non-negligible in view of the current observational accuracy and the expected future requirements.

There are two different methods of modeling atmospheric influences on Earth rotation. The first one, commonly referred to as the torque approach, consists in computation of the atmospheric torque upon the solid Earth, while the second one, the angular momentum approach, is based on the angular momentum balance between the solid Earth and the overlying atmosphere; see e.g. (Wahr, 1982) for theoretical background. These two approaches are equivalent from the first principles therefore, when properly implemented in computations, should give similar results. This is in fact the case at low frequencies, but there are still significant differences, up to one order of magnitude, at diurnal retrograde frequencies corresponding to nutation; compare e.g. recent estimates by Bizouard *et al.* (1998) and Gegout *et al.* (1998).

In the angular momentum approach, which is applied in this paper, the excitation is expressed by the AAM function $\vec{\chi}$ introduced by Barnes *et al.* (1983), which has been initially corrected for the elastic rotational and loading deformations of the Earth. The AAM consists of the matter (pressure) term $\vec{\chi}^p$ which can be estimated from the routine surface pressure observations, and the motion (wind) term $\vec{\chi}^w$ depending on the wind velocities at various heights above the surface of the Earth. The excitation by the pressure term is additionally modified by the oceanic response to the atmospheric forcing. At periods longer than weeks the simple so-called *inverted barometer* (IB) approximation for the ocean response seems to be appropriate (Wahr, 1982), but at shorter periods the oceanic response becomes highly non-equilibrium and no adequate dynamical models are available so far.

Atmospheric excitation of polar motion can be expressed by the following "broad band" Liouville equation derived by Brzeziński (1994)

$$(\partial_t - i\sigma_c)(\partial_t - i\sigma_f)\, p = -i\sigma_c[(\partial_t - i\sigma_f)(\chi^p + \chi^w) + (\partial_t - i\sigma_c)(a_p\chi^p + a_w\chi^w)] \qquad (1)$$

in which ∂_t denotes the time derivative operator, $i = \sqrt{-1}$ is imaginary unit, $p = x - iy$ stands for polar motion expressed as complex quantity and $\chi = \chi_1 + i\chi_2$ is the corresponding equatorial AAM function, σ_c, σ_f are the *Chandler wobble* (CW) and the *free core nutation* (FCN) angular frequencies of resonance, and $a_p = 9.2 \times 10^{-2}, a_w = 5.5 \times 10^{-4}$ are dimensionless constants.

The transfer function of eq.(1) is rather complicated due to the presence of 2 sharp peaks expressing the CW and FCN resonances and 1 notch resulting from the coupling between these resonances (see (Brzeziński, 1994, p. 164) for discussion), therefore comparisons between geodetic and geophysical estimates is difficult, particularly in the time domain. A simplified version of this equation is obtained after neglecting the FCN resonance, which is equivalent to the assumption $a_p = a_w = 0$:

$$(\partial_t - i\sigma_c)\, p = -i\sigma_c(\chi^p + \chi^w). \qquad (2)$$

This is the classical low-frequency approximation of the polar motion equation (Brzeziński, 1992), but it can also be applied at high frequencies with exception of the nutation (that means diurnal retrograde) band; see (Brzeziński, 1994) and (Petrov, 1998) for argumentation. Note that in eq.(2) χ^p, χ^w are equivalent driving agents of polar motion, but this is no longer the case in the vicinity of the FCN resonance, as expressed by the last term of eq.(1).

Atmospheric excitation of the axial component of Earth rotation is expressed by the following equation

$$\delta\lambda/\lambda_o = -\chi_3, \qquad (3)$$

in which $\delta\lambda$ denotes increment of l.o.d. from its mean value $\lambda_o = 2\pi/\Omega$, and Ω is the mean angular velocity of diurnal sidereal rotation. This equation is considerably simpler than the equation of polar motion, eq.(1) or eq.(2), because the transfer function is constant therefore the comparisons between geodetic and geophysical estimates are very simple both in the time domain and in the frequency domain.

3. AAM VARIATIONS: MAIN FEATURES

The equatorial component of the high frequency atmospheric excitation comprises two groups, namely a set of the tidal waves appearing at diurnal and semidiurnal periods, and a number of the broad band oscillations associated with the atmospheric normal modes. Atmospheric tides are principally of thermal origin but the gravitational contributions are probably non-negligible. The diurnal retrograde (that means migrating clockwise, from the East to the West) tidal waves in the equatorial AAM contributing to the precession/nutation, were investigated extensively in our recent paper (Bizouard *et al.*, 1998). It is commonly believed that diurnal/semidiurnal atmospheric excitations are weaker than the corresponding oceanic effect,

with the only one exclusion, namely the Sun-fixed S_1 tide contributing to the annual prograde nutation.

Two sets of the atmospheric normal modes which are important for Earth rotation are the retrograde rotational waves ψ_n^m, the Rossby-Haurwitz waves (toroidal modes), and the retrograde and prograde gravity modes ξ_n^m (spheroidal modes). Among them only ψ_1^1, ψ_3^1 and ξ_2^1 modes will couple with polar motion and only ξ_2^0 will couple with the l.o.d. changes (Eubanks, 1991). The ψ_3^1 mode with retrograde period of about 10 days was first detected in the AAM data by Brzeziński (1987) and also observed in the polar motion data with the amplitude of the order of 1 mas (Eubanks *et al.*, 1988). The ψ_1^1 mode with retrograde period of about 1.2 days has been detected in the AAM data and should cause polar motion of the order of 30 μas (Eubanks, 1991). The ξ_2^1 mode with predicted period of 0.61 days (*ibid.*), has not received observational evidence so far.

As concern the axial component of excitation, the atmospheric effects within the frequency range of interest, i.e. between 1 cycle in several days and one cycle in 12 hours, are confined to the diurnal and semidiurnal tidal waves which are expected to be much weaker than the corresponding oceanic influences.

4. AAM VARIATIONS: DATA ANALYSIS

In the computations reported here we used a 40-years homogeneous series of the 4-times daily AAM estimates (Salstein and Rosen, 1997) computed on the basis of results of the U.S. National Center for Environmental Prediction (NCEP) / U.S. National Center for Atmospheric Research (NCAR) reanalysis project (Kalnay *et al.*, 1996), spanning the period from 1958.0 to 1997.7. The input data contains 2 versions of the pressure term, the one which is not corrected for the ocean response, designated below χ^p, and the other one with the inverted barometer correction, designated χ^p+ IB.

We started the analysis from estimating the overall power spectra of the input AAM series by the maximum entropy method (Brzeziński, 1995). Then we extracted diurnal/semidiurnal components of the AAM by the so-called complex demodulation procedure (see e.g. (Bizouard *et al.*, 1998) for description) and studied them in details. Finally, the corresponding amplitudes in polar motion and l.o.d. were estimated by convolving the integrated AAM power spectrum with the theoretical transfer function, and then compared to the corresponding oceanic contributions taken from the IERS Conventions (McCarthy, 1996).

From the inspection of the overall AAM power spectra shown in Fig. 1 we can conclude what follows.

Equatorial component. These are mixed power spectra with sharp peaks at seasonal, diurnal and semidiurnal frequencies superimposed on the background continuous spectra. Power spectrum of the pressure term is approximately symmetrical with respect to zero frequency, while the wind term is mostly retrograde: from the integration we estimate that 95% of its power is at retrograde frequencies and as much as 80% of the power is concentrated within the diurnal retrograde band alone. For periods shorter than about 3 days, the wind term has similar power as the pressure term at prograde frequencies and much higher power at retrograde frequencies; for longer periods the pressure term is prevailing. The IB correction reduce significantly the continuous power spectrum of the pressure term and introduce new features, such as a broad peak at the frequency ± 1.3 cycles/day. All the expected normal modes, ψ_1^1, ψ_3^1 and ξ_2^1, are clearly visible in the equatorial AAM functions. An interesting common feature of the 3 spectra is a sharp peak at the retrograde O_1 frequency, which provides important verification of the AAM functions; see (Petrov, 1998) for explanation.

Axial component. Similarly as for the equatorial component, we have mixed power spectra with sharp peaks at seasonal, diurnal and semidiurnal frequencies superimposed on the background

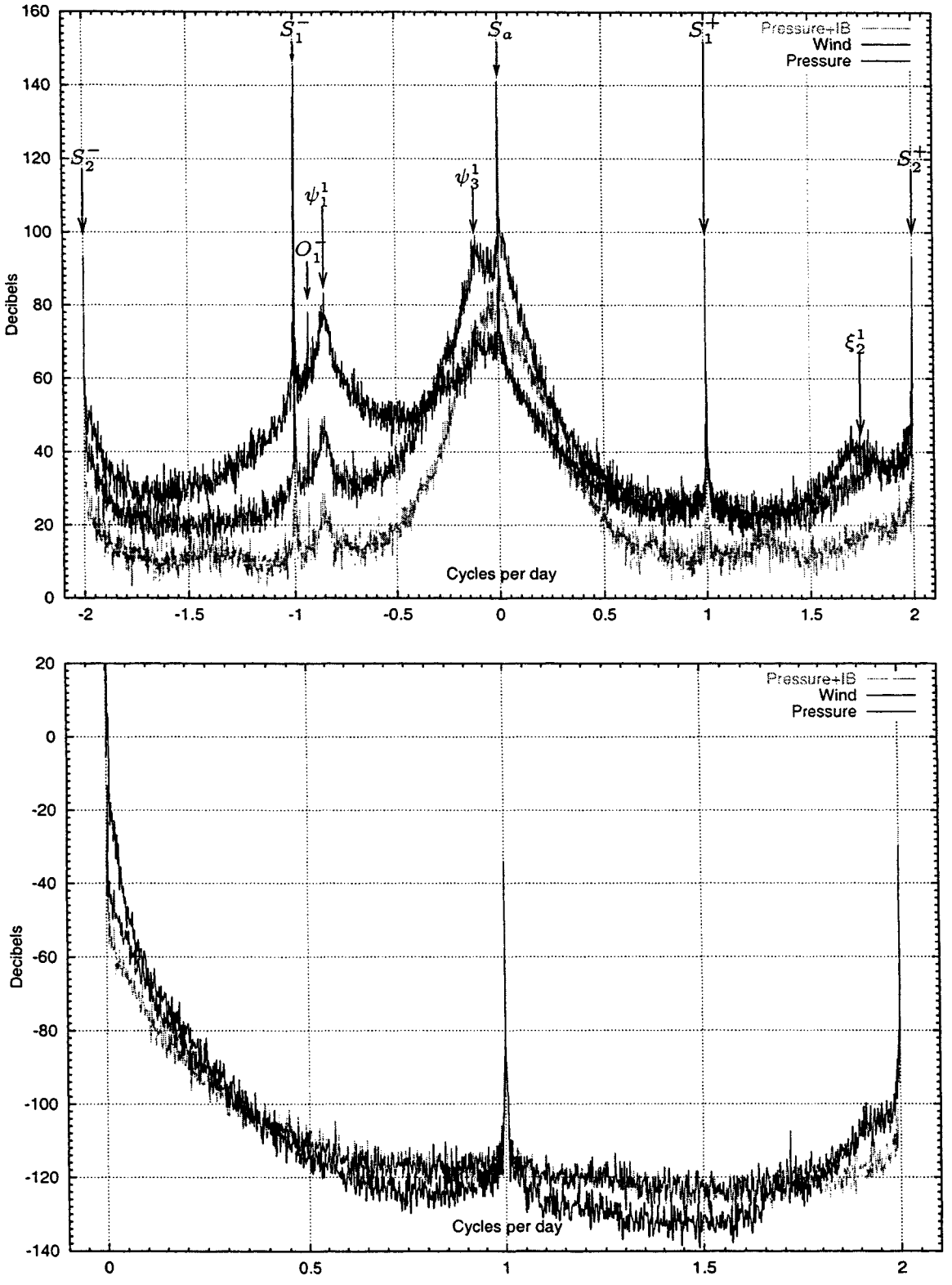

Figure 1: *Overall maximum entropy method power spectra of the NCEP/NCAR reanalysis AAM series, equatorial component (upper diagram) and axial component (lower diagram).*

Table 1.

Diurnal/semidiurnal atmospheric tides in polar motion, μas

	Prograde		Retrograde	
	in phase	out of phase	in phase	out of phase
S_1	−5.2	4.9	−16.6	−88.7
P_1	0.6	−1.2	−2.0	−41.1
K_1	1.4	0.7	51.2	85.8
ψ_1	−0.5	0.5	108.7	−43.5
S_2	−2.8	0.6	2.8	−0.6

Diurnal/semidiurnal atmospheric tides in LOD, μs

	LOD		UT1-UTC	
	in phase	out of phase	in phase	out of phase
S_1	1.2	−3.1	−0.5	−0.2
S_2	0.0	−6.0	−0.5	0.0

NOTE: Diurnal retrograde component of polar motion corresponds to nutation. The 'in phase'/'out of phase' convention is the same as described in details by Bizouard *et al.* (1998).

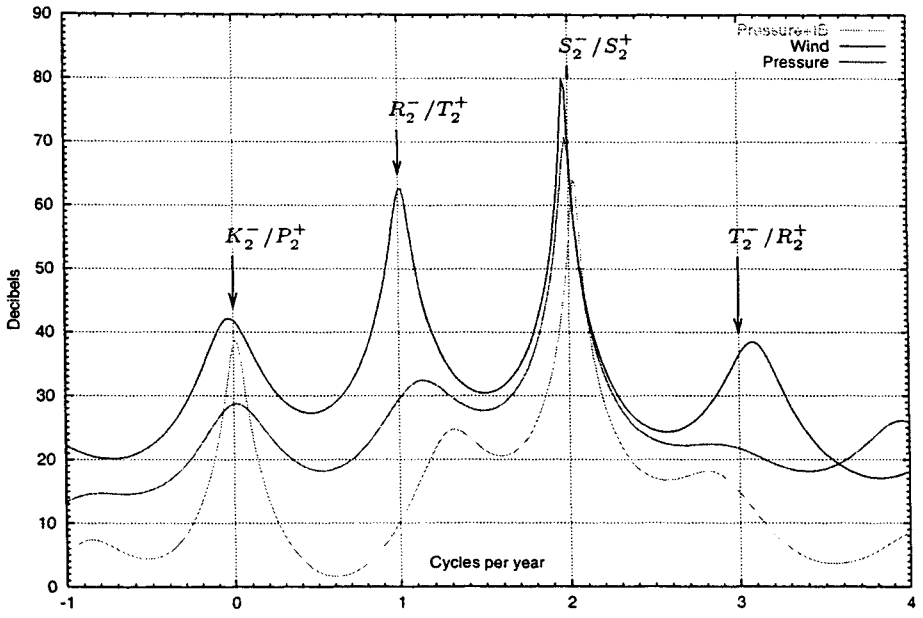

Figure 2: *Power spectra of equatorial AAM series in semidiurnal retrograde band (frequency* 0 *corresponds to* −2 *cycles per day in Fig. 1).*

continuous spectra. It can be observed a strong increase of power towards zero frequency, the 40-50 day peak can only be seen in the wind term. At periods shorter than about 1 week, the wind and pressure terms have similar power; at longer periods the wind term is prevailing.

Let us now investigate in a more detailed way different terms of the equatorial component of the AAM function.

Semidiurnal variations (Fig. 2, Tab. 1). Detailed spectral analysis is not possible with the 6-hourly estimates because the Nyquist limits are just inside this band, in particular such analysis cannot discriminate between prograde and retrograde oscillations (that is the reason why only the retrograde component is shown in Fig. 2). The estimated total atmospheric effect in polar motion is only about 3 μas, that is 2 orders lower than the oceanic effect; cf. Table 8.4 of the IERS Conventions (McCarthy, 1996).

Diurnal retrograde variations (Tab. 1; for the plot of the power spectra see Fig. 1 of Bizouard *et al.* (1998)). This spectral band corresponding to nutation has been investigated in details by Bizouard *et al.* (1998), therefore we recall here only briefly some important conclusions. To

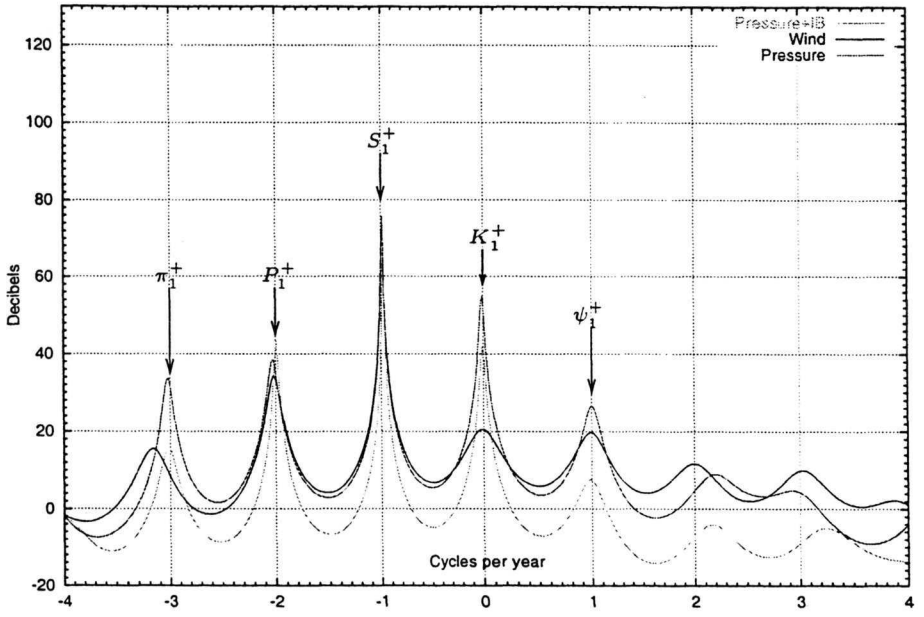

Figure 3: *Power spectra of equatorial AAM series in diurnal prograde band (frequency* 0 *corresponds to* 1 *cycle per day in Fig. 1).*

the observable level, atmosphere contributes to the nutation constituents with periods +1 yr (77 μas), −1 yr (53 μas), +1/2 yr (45 μas) and constant offset of the celestial pole ($\delta\psi \sin\epsilon_o = -86$ μas, $\delta\epsilon = 77$ μas), corresponding to the atmospheric tides S_1, ψ_1, P_1 and K_1, respectively. Dominating contribution is from the pressure variations; only the 1/2 yr prograde nutation is driven mostly by the wind term. Striking correlation between the variability of the VLBI nutation amplitudes and the atmospheric contribution provides a strong indication that the estimated effect is real. Observed degradation of correlation with VLBI data when the IB correction is applied confirms earlier claims that this correction is not adequate at nearly diurnal frequencies.

Diurnal prograde variations (Fig. 3, Tab. 1). Power spectrum of the pressure term has similar shape as in the nutation band (cf. Fig. 1 of Bizouard *et al.* (1998)), but the corresponding polar motion has an amplitude of about 7 μas only. The power of the wind term is about 40 decibels below that at diurnal retrograde frequencies (cf. *ibid.*), as could be expected from general considerations.

Atmospheric normal modes (Fig. 1, Tab. 2). The ψ_1^1 retrograde mode is similar in all 3 time series, but the strongest peak is in the wind term χ^w. The ψ_3^1 mode is similar in χ^p and χ^w, though much stronger in the first case; the IB correction seems to smooth it out to a certain extent and move some power to the prograde frequencies. The ξ_2^1 mode is manifested as a broad peak at prograde period of 0.6 days only slightly arising from the continuous background, nevertheless is visible in all spectra; the strongest one is in the wind term χ^w. We modeled all the 3 atmospheric normal modes as pseudoharmonic oscillations and estimated their parameters: central periods T, the quality factors Q and the mean amplitude of the corresponding polar motion (Tab. 2). Numerical experiment described by Petrov and Brzeziński (1996) demonstrated that when taking into account the model of the ψ_3^1 oscillation in processing polar motion data, the residuals became less correlated which results in improving the whole estimation.

Let us now discuss briefly the axial component of the AAM function. The detailed power spectra in the diurnal and semidiurnal frequency bands show similar features as in the case of the equatorial component presented so far, therefore will be not shown here. The main

Table 2. Atmospheric normal modes in polar motion

	Period, d	Mean amplitude, μas			Quality factor
		Press.	Press.+IB	Wind	
ψ_3^1	8.3	537	199	147	5
ψ_1^1	1.2	2	1	30	10
ξ_2^1	0.6	2	1	2	-

atmospheric contribution (Tab. 1) is from the S_1 tide: 3.3 μs in LOD and 0.5 μs in UT1, and from the S_2 tide: 6.0 μs in LOD and 0.5 μs in UT1. These effects are significantly smaller than diurnal and semidiurnal oceanic contributions given in Table 8.3 of the IERS Conventions (McCarthy, 1996).

5. SUMMARY AND DISCUSSION

Diurnal and semidiurnal atmospheric tides contribute below 10 μas to polar motion and below 1 μs to UT1, that is by about 2 orders of magnitude less than the corresponding oceanic influence. A more significant and well observable atmospheric effect on nutation is of the order of 100 μas. Atmospheric normal modes ψ_1^1, ψ_3^1 and ξ_2^1 are clearly visible in all power spectra of the equatorial AAM data. Their contributions to polar motion are of the order of 1 mas, 30 μas and 3 μas, respectively. The ξ_2^1 gravity mode which has not been observed so far, has only prograde component. Simple numerical experiment demonstrated that including atmospheric normal modes in modeling polar motion can improve the estimation procedure. Finally we like to caution that the estimated high frequency atmospheric effects on Earth rotation remain uncertain as long as we have no adequate dynamical model of the ocean response to the atmospheric forcing.

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