DIURNAL AND SUB-DIURNAL VARIATIONS OF THE EARTH ROTATION

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1. INTRODUCTION

The oceanic variability is responsible of most of the variations on polar motion (PM) and on the angular velocity of the Earth in the diurnal and semidiurnal frequency bands . Theoretical evaluations of the ocean tidal effect on PM and UT1 were made by various authors (Gross (1993), Ray et al. (1994), Chao et al. (1996)). The new techniques based on Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS) have recently showned their ability to derive LOD or UT1 and PM with hourly resolutions (IERS TN16, 1994).

Estimation of the diurnal and semidiurnal tidal parameters were made from VLBI analysis by various authors (Sovers et al., 1993; Herring and Dong, 1994; Ma and Gipson 1995; Gipson, 1996) Chao et al. (1996) showed that eight major tides ($Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2$) explain nearly 60% of the total variance in sub-daily polar motion and are responsible for as much as 90% of the sub-daily power of the UT1 variations.

The objective of the present paper is twofold: first to compare different sets of estimates of the coherent tidal oscillations in UT1 and PM on one hand and theoretical ones on the other hand. This was done using both VLBI and GPS series. Secondly, to determine to which extent the atmosphere explains the discrepancy between theory and observations.

2. DATA

Since 1995, the CODE Analysis Center is providing PM and LOD estimates with a one-hour time resolution (Beutler and Rothacher, 1999). Three years of this series (January 2, 1995 - February 14, 1998) were used in this analysis.

In order to calculate the effect of the atmospheric tides on the Earth's rotation we used the 6-hourly series of the effective atmospheric angular momentum (EAAM) computed by NCEP/NCAR reanalysis project (Kalnay et al., 1996).

3. ANALYSIS AND RESULTS

Both the ocean and atmospheric tides are the effects by the luni-solar gravitational forces; the phase φ_j^p of the $j-th$ prograde tide depends on the five fundamental lunisolar arguments (l, l', F, D, Ω). φ_j^p can be written as:

$$\varphi_j^p = a_j l + b_j l' + c_j F + d_j D + e_j \Omega + n_j(GMST + \pi),$$

where a_j, b_j, c_j, d_j, e_j are integer constants, n_j is integer equals to -1 or -2 for diurnal and

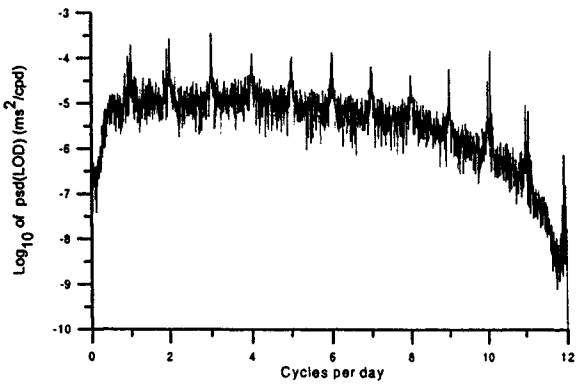

Figure 1: Power spectral density estimates from a seven-point smoothing of the LOD residuals periodogram

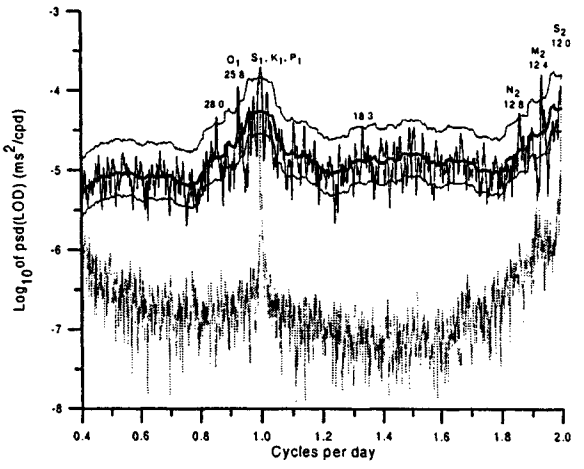

Figure 2: Power spectral density estimates of the LOD residuals (upper graph) and χ_3 (lower graph) periodograms. The bold solid line is highly smoothed surrounded by 95% confidence interval.

semidiurnal waves, respectively, $GMST$ is the Greenwich mean sidereal time. Using this representation the prograde tidal variations in UT1, PM and the AAM χ functions can be expressed as:

$$\begin{aligned} \delta(UT1) &= \sum_j (u_j^{cp}\cos\varphi_j^p + u_j^{sp}\sin\varphi_j^p), \qquad (1) \\ \delta(PM) &= \delta x - i\delta y = -\sum_j (p_j^{cp} + ip_j^{sp})e^{i\varphi_j^p}, \\ \delta\chi &= \chi_1 + i\chi_2 = -\sum_j (\chi_j^{cp} + i\chi_j^{sp})e^{i\varphi_j^p}. \end{aligned}$$

The retrograde variations can be obtained using the opposite sign of the tidal phase: $-\varphi^p = \varphi^r$. In the following, we denote the retrograde amplitudes of UT1 and PM as $u_j^{cr}, u_j^{sr}, p_j^{cr}, p_j^{sr}$. We also use the alternative representation for PM:

$$\delta x = \sum_j (A_{xj}\cos\varphi_j + B_{xj}\sin\varphi_j), \qquad (2)$$

$$\delta y = \sum_j (A_{yj}\cos\varphi_j + B_{yj}\sin\varphi_j), \qquad (3)$$

where

$$A_{xj} = -p_j^{cp} - p_j^{cr}, B_{xj} = -p_j^{sp} + p_j^{sr}, A_{yj} = p_j^{sp} + p_j^{sr}, B_{yj} = -p_j^{cp} + p_j^{cr}.$$

Expressions (2-3) do not include the retrograde diurnal components of the PM spectrum because they are not accessible to the GPS. Solutions obtained from VLBI observations do not contain them neither since they are estimated as celestial pole offsets.

In order to estimate the coefficients u_j^{cp}, u_j^{sp}, A_{xj}, B_{xj}, A_{yj}, B_{yj} in eqs.(1-3) from the CODE series for the eight major tides and tide S_1, we removed at first the low-frequency variations.

The estimates of the components u_j^{cp} and u_j^{sp} for UT1 are shown in Table 1 (6^{th} column).

The influence of the atmospheric tides was estimated from the axial atmospheric angular momentum function. The estimates are given in the last column.

Next, we removed the effects of the oceans tides (according to Chao et al, 1996) from the LOD series. The spectra of the residuals is shown in Figures 1. Figure 2 represents LOD residuals (CODE minus ocean model) and function χ_3 from NCEP/NCAR analysis power spectral density

Table 1: The UT1 cosine u^c and sine u^s amplitudes (in $0.1\mu s$). In columns 2,3,4,5 we showed estimates from VLBI observations, as provided by Sovers et al. (1995), Herring and Dong (1994), Ma and Gipson (1994), Gipson (1996). In column 6, the mean of all these estimates is given. In column 7 are the corresponding values of the ocean tide effects, from the model proposed by Chao et al. (1996) and recommended by IERS as standard. In column 8 is given the difference between the mean value of the observed and theoretical ocean tide amplitudes : $\Delta = \bar{u} - u^{ocean}$.

Tide	Sovers	Herring/ Dong	Ma/ Gipson	Gipson	CODE	$\sum u_j/n$	Ocean model	Δ	χ_3
				u^c					
K_2	-9	8	3	7	-12	-0.6 ± 9.3	-3.8	3.2	0
S_2	-4	-1	-12	-8	-7	-6.4 ± 4.2	-4.0	-2.4	?
M_2	-104	-108	-85	-104	-82	-96.6 ± 12.1	-72.0	-24.6	-1
N_2	-23	-16	-44	-19	-19	-24.2 ± 11.3	-15.4	-8.8	0
K_1	35	65	75	90	66	66.2 ± 20.1	86.4	-20.2	-1
P_1	-32	-39	-35	-25	-20	-30.2 ± 7.7	-28.6	-1.6	0
O_1	-135	-173	-156	-133	-111	-141.6 ± 23.7	-121.0	-20.6	0
Q_1	-40	-31	-34	-29	-18	-30.4 ± 8.1	-24.5	-5.9	0
S_1	-	18	6	-4	-18	-0.5 ± 15.3	-	-0.5	-9
				u^s					
K_2	26	37	39	28	15	29.0 ± 9.6	19.6	9.4	0
S_2	52	86	87	80	67	74.4 ± 14.8	75.9	-1.5	?
M_2	149	143	123	154	155	144.8 ± 13.1	161.7	-16.9	-3
N_2	20	28	12	32	34	25.2 ± 9.1	38.0	-12.8	1
K_1	151	178	167	163	157	163.2 ± 10.3	177.1	-13.9	-3
P_1	-64	-59	-54	-53	-69	-59.8 ± 6.8	-51.6	- 8.2	-1
O_1	-166	-162	-168	-177	-137	-162.0 ± 15.0	-160.5	- 1.5	1
Q_1	-53	-44	-39	-48	-44	-45.6 ± 5.2	-50.3	4.7	0
S_1	-	13	19	11	16	14.8 ± 3.5	-	14.8	-5

estimates. Power law of LOD residuals spectrum is shown by the thick solid line (middle curve). It is surrounded by 95% confidence interval. Spectral peaks at periods of 28.0 hours, 25.8 hours (tide O_1), central peak (combination of tides S_1, K_1, P_1), 18.3 hours, 12.8 hours (N_2), 12.4 hours (M_2) have non-random origin (with 95% probability). According to this estimate of LOD residual spectrum, the semidiurnal atmospheric signal must be detected with a high accuracy level. Unfortunately the estimation of the amplitude of the semidiurnal tide from NCEP data is impossible because of the linmiting 6-hour time-resolution. The spectrum of the residuals for PM (CODE - Oceanic model) is showned on Figure 3; Table 2 gives the PM variations due to the ocean tides obtained from both the GPS and VLBI observations, as provided by Herring and Dong (1994), Ma and Gipson (1994), Gipson (1996). The mean of all these estimates was done. In the last column the tidal oceanic effects, as modeled by Chao et al. (1996), are given.

The differences between observed mean PM variations and theoretical model of Chao et al. (1996) are shown in Table 3.

4. DISCUSSION

The various peaks appearing in the spectra of LOD (Fig. 1) and PM (Fig. 3) are the higher harmonics of the diurnal frequency. One possible explanation is the orbital effects which have typical period of 12 hours. In the AAM series, besides the main terms with frequencies of $1, 2$ cpd connected with S_1 and S_2 tides, other peaks appear with frequencies of $4, 8$ cpd, but their power is very small. Other signals are present with frequencies $3, 5, 7,$ etc. cpd not separable from the noise. The existence of all these harmonics can be predicted by the excitation of the thermal sub-diurnal tides in the atmosphere by the sub-diurnal harmonics of the heating function (Zharov, 1998) but their power is not sufficient to explain the observed residuals with respect tidal oceanic model in CODE series.

For LOD (Figure 2), we remark an increase of power near the semidiurnal frequency band but the power level of χ_3 remains 10 times smaller than those observed by GPS. According to

Table 2: The PM cosine A and sine B amplitudes for x- and y-components (in μas)

Tide	Herring/ Dong		Ma/ Gipson		Gipson		CODE		Mean value		Ocean model	
	A_x	B_x	A_x	B_x	A_x	B_x	A_x	B_x	A_x	B_x	A_x	B_x
	x-component											
K_2	-13	21	-7	21	4	27	-19	51	-9 ± 10	30 ± 14	17	36
S_2	64	111	84	117	85	124	66	125	75 ± 11	119 ± 7	64	145
M_2	9	323	-45	357	-13	331	-45	303	-24 ± 26	329 ± 22	-28	330
N_2	- 3	59	36	89	3	57	-15	47	6 ± 22	63 ± 18	-13	57
K_1	-133	74	-125	38	-129	47	-116	64	-126 ± 7	56 ± 16	-152	78
P_1	49	-35	54	-26	49	-28	60	-25	53 ± 5	-29 ± 5	50	-25
O_1	178	-89	136	-64	133	-69	104	-33	138 ± 31	-64 ± 23	133	-49
Q_1	33	-11	34	-18	34	-11	27	- 8	32 ± 3	-12 ± 4	26	- 6
S_1	-	-	-	-	-	-	-32	-43	-	-		-
	A_y	B_y	A_y	B_y	A_y	B_y	A_y	B_y	A_y	B_y	A_y	B_y
	y-component											
K_2	12	-65	10	-38	5	-27	13	-7	10 ± 4	-34 ± 24	22	-18
S_2	87	-69	95	-69	93	-64	91	-64	92 ± 3	-67 ± 3	87	-59
M_2	208	-12	213	-15	215	-20	201	-43	209 ± 6	-23 ± 14	196	-37
N_2	35	-21	28	-13	27	-7	35	-9	31 ± 4	-13 ± 6	33	-11
K_1	- 74	-133	- 38	-125	- 47	-129	- 64	-116	-56 ± 16	-126 ± 7	- 78	-152
P_1	35	49	26	54	28	49	25	60	29 ± 5	53 ± 5	25	50
O_1	89	178	64	136	69	133	33	104	64 ± 23	138 ± 31	49	133
Q_1	11	33	18	34	11	34	8	27	12 ± 4	32 ± 4	6	26
S_1	-	-	-	-	-	-	43	-32	-	-	-	-

Table 3: Difference between observed PM variations and ocean tidal model (Chao et al, 1996). Unit is μas)

	K_2	S_2	M_2	N_2	K_1	P_1	O_1	Q_1	S_1
A_x	-26	11	4	19	26	3	5	6	-32
B_x	- 6	-26	-1	6	-22	-4	-15	-6	-43
A_y	-12	5	13	-2	22	4	15	6	43
B_y	-16	- 8	14	-2	26	3	5	6	-32

the results shown in Table 1 there is a systematic difference between observations and theoretical ocean tides. It means that some unknown processes, not linked to atmospheric tides, were nor taken into account. The explanation is probably the mismodeling of the ocean tides. We assume that the amplification of the tides M_2, N_2, O_1 due to the coincidence of their frequencies with those of the normal modes of the oceans (Sündermann, 1982) could improve the agreement between both the observations and the model. As stated previously, non-tidal signals exist in the spectrum of the LOD residuals (Fig.2). The term with a period of 28.0 hours can be connected with normal mode of the world ocean with a period of 28.7 hours. The reality of this signal is confirmed by independent analysis of VLBI data (Titov, 1999). The origin of the large discrepancy of the K_1 amplitudes is still unknown. power near the sub-diurnal frequencies. Most powerful The amplitude of this questionable.

The comparison of the LOD variations from CODE analysis with ocean tidal model is shown on Figure 4 for two time intervals. Variance of residuals (observation minus model) is equals to $\sigma = 0.12$ ms for the first one (MJD 49990-50005) and to $\sigma = 0.19$ for the second one (MJD 50255-50270) intervals. Significant scatter of residuals exceeding 3σ is observed during the period ranging from MJD 50262 to 50268. A similar effect is observed for PM variations too. It is one example when over one week the amplitude of LOD and PM variations is significantly increasing with respect to the model. The atmosphere cannot be responsible for such an effect because the variations of χ_3 function 10 times smaller.

According to Table 3 the largest discrepancies between PM and tidal estimates are observed for K_1 ($34\mu as$ in amplitude) and S_1 ($45\mu as$ in amplitude) and K_2 tides. Here again, these

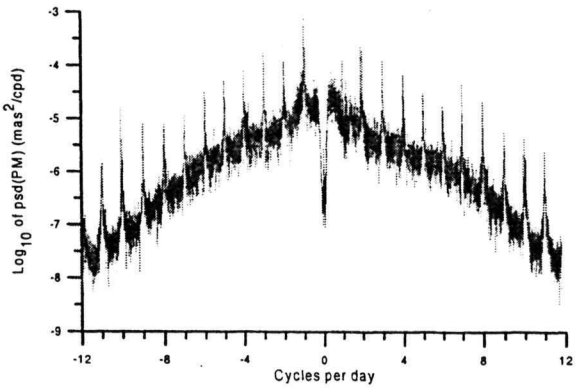

Figure 3: Power spectral density estimates from a seven-point smoothing of the PM residuals periodogram.

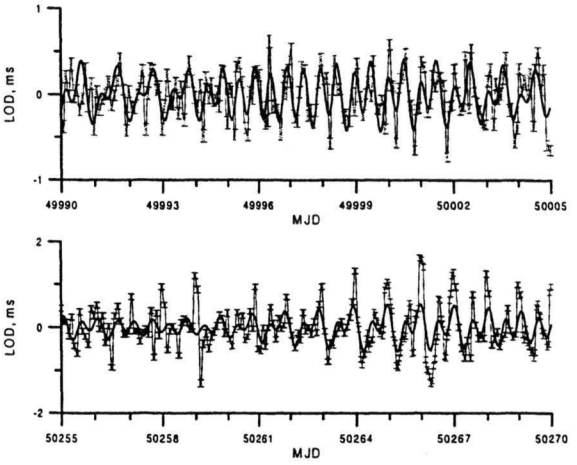

Figure 4: LOD estimates from CODE analysis and ocean tidal model for different intervals

atmospheric effects are not sufficient, since they do not exceed $10\mu as$ (Petrov, 1998; Brzezinsky and Bizouard, 2000).

The agreement of the mean value of amplitudes of $M_2, N_2, O1$ tides with theoretical values is fair but the scatter of the amplitudes in different series is large. It could be explained by the variable amplification of these tides.

5. CONCLUSION

The tidal coherent waves in UT1 and PM were estimated from GPS CODE series. The values obtained for UT1 are consistent with those deduced from VLBI observation, with discrepancies within 1 μs, except for tides of K_1, O_1 for which the discrepancies exceed 2 μs. We have shown that almost all tidal coherent waves of UT1 (especially K_1, O_1, M_2, N_2) exceed their prediction from oceanic tidal model. The atmospheric effect is ten time smaller, and can not explain such a discrepancy. One possible explanation is the coincidence of the frequencies of the tides $M_2, N_2, O1$ with the frequencies of the normal modes of the world ocean. More generally, this systematic difference shows that another effect has to be taken into account.

Similar conclusion can be given for PM variations. The largest difference in amplitude between observations and model is found for K_1, S_1, K_2 tides. No explanation could be given.

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