Geophys. J. Int. (1993) **114**, 341–346

An analysis of tidal variations in the length of day

Dennis D. McCarthy and Brian J. Luzum
US Naval Observatory, Washington, DC 20392, USA

Accepted 1993 January 8. Received 1992 December 1; in original form 1991 March 18

SUMMARY

Observations of the length of day, corrected for the effects of variations in the angular momentum due to changes in wind velocity and atmospheric pressure, ocean-tide heights and currents, and solid-Earth zonal tides, were analysed. The (1992) IERS Standards model for the effects of zonal tides on the Earth's rotation, which includes ocean-tidal effects, adequately accounts for the observations of the high-frequency (periods between one and 30 days) variations in the length of day at the present level of accuracy. A currently unexplained semi-annual variation in the length of day remains, but this may be due to the unmodelled effects of stratospheric winds. The power spectrum of the remaining variations with periods less than 20 days is essentially that of a white-noise process. The amplitudes of the remaining unexplained variations in length of day are less than 30 microseconds.

Key words: Earth's rotation, tides.

1 INTRODUCTION

High-frequency (periods between one and 30 days) variations in the length of day (LOD) are driven by tidal and atmospheric effects, and models dealing with the effects of zonal-solid-Earth tides have been constructed previously (Woolard 1959; Merriam 1980; Yoder, Williams & Park 1981; Wahr, Sasao & Smith 1981; Wahr & Bergen 1986; Dehant 1987). The International Earth Rotation Service (IERS) Standards (McCarthy 1992) lists two sets of corrections for the effects of tides on the rotation of the Earth. One set is used to define the astronomical time scale, UT1R, ΔR, and ωR previously designated by the IERS to be free of the effects of high-frequency zonal Earth tides. Another set incorporates the effect of recently developed ocean-tide models for periods greater than nine days as given by Dickman (1993). This second set is provided as a basis for scientific research and defines the time scale, UT1S, ΔS, and ωS.

The work of Yoder *et al.* (1981) serves as the basis for the IERS Standards (McCarthy 1989, 1992) used in the treatment of astronomical observations of Earth orientation. The models require an assumed value of a transfer function relating variations in tidal potential to the length of day. Nam & Dickman (1990) refer to this as the zonal-response function $\kappa(f_i)$ where f_i represents the frequency of the ith tidal constituent. The effects of the ocean tides are accounted for in Yoder *et al.* (1981) by treating them as equilibrium tides.

Brosche *et al.* (1989), Dickman (1993), and Wünsch & Bußhoff (1992) have estimated the effects of some specific ocean tides on the Earth's rotation using dynamic tide models. Following work done earlier in Baader, Brosche & Hövel (1983), Brosche *et al.* (1989) used hydrodynamical models for the M_2, S_2, N_2, K_1, O_1, P_1, M_f, $M_{f'}$, M_m, and S_{sa} tides to determine the variation of angular momentum due to changes in the ocean heights and currents. These calculations show that the effects on LOD can be on the order of 0.1 ms.

Using the tide models of Dickman (1989, 1990, 1991), Dickman (1993) determined the effects on the Earth's rotation for 32 ocean tidal constituents, including the $2N_2$, N_2, M_2, S_2, K_2, J_1, ψ_1, K_1, P_1, O_1, Q_1, M_9, M_f, $M_{f'}$, M_m, S_m, S_{sa}, S_a, and Nodal tides. Recently, Wünsch & Bußhoff (1992) have provided an improved version of the Brosche *et al.* (1989) results correcting for the fact that the tensor of inertia of the solid Earth is changed by the changing oceanic load.

Observations of the length of the day have been studied previously in order to investigate the adequacy of tidal models (Pil'nik 1970; Guinot 1970, 1974; Djurovic 1976; Hefty 1982; Capitaine & Guinot 1985; Merriam 1985; Luo *et al.* 1987; Newhall, Williams & Dickey 1988; Robertson, Carter & Fallon 1988; Schuh 1988; Pejović & Vondrák 1989; Hefty & Capitaine 1990; Nam & Dickman 1990; Brosche *et al.* 1991). All of these efforts have shown that the effects of zonal tides are evident in the observations and that there appear to be some small anomalies in the observations which cannot be explained fully by current solid-Earth tide models. These apparent anomalies may be due to additional atmospheric and/or oceanic phenomena affecting the Earth's rotation as well as to some inadequacies in the zonal tide model.

Technical improvements in the precision of the observations of the Earth's orientation have provided a much-improved set of data with which to investigate such anomalies. In addition, atmospheric angular momentum (AAM) data are now available and may be used in such an analysis in order to determine the possible effect of the atmosphere at tidal frequencies.

2 ASTRONOMICAL OBSERVATIONS

The astronomical observations of the rotation angle UT1–UTC, derived with the procedure described by McCarthy & Luzum (1991), were used to produce astronomical estimates of the length of the day. The combined series of observations was composed of very long baseline interferometry (VLBI), satellite laser ranging (SLR), and lunar laser ranging (LLR) data. Length of day was calculated by differencing the daily values of UT1–UTC to find the length of the day in excess of 86 400 s of atomic time. The data used for this analysis were obtained from MJD 45700 (1984 January 1) through MJD 48621 (1991 December 31). The first MJD was chosen since it appeared that the most accurate astronomical data were available following MJD 45700.

3 ATMOSPHERIC ANGULAR MOMENTUM DATA

Atmospheric angular momentum has been shown to be correlated with the observations of the variations in the length of the day (Rosen & Salstein 1983). Twice-daily values of the total atmospheric angular momentum, including the effects of winds and pressure, were obtained for the same periods of time as the astronomical data from the National Meteorological Center (NMC) through the National Oceanic and Atmospheric Administration (NOAA) Laboratory for Geosciences. These data are in the form of the three components of the atmospheric angular momenta (χ_1, χ_2, χ_3) (Barnes *et al.* 1983). χ_3 is an estimate of the total atmospheric angular momentum component parallel to the direction of the Earth's rotation axis. These values are evaluated from the surface up to 50 mbars of pressure and therefore part of the stratosphere is not included in the data. From the χ_3 values obtained from NMC, estimates of the effect on the length of the day due to the variations on the total atmospheric angular momentum were calculated using the procedure in Barnes *et al.* (1983). Details of the procedure used to calculate these values are given in the report of the IERS Sub-bureau for Atmospheric Angular Momentum in the IERS *Annual Report for 1989*. An inverted barometer oceanic response was assumed in these calculations and the pressure terms were increased by 8 per cent to allow for core decoupling (Nam & Dickman 1990). This resulted in a time series of LOD variations expected only from variations in the atmospheric angular momentum.

4 INDIVIDUALLY MODELLED OCEANIC TIDAL EFFECTS

Following the earlier work in Baader *et al.* (1983) and Brosche *et al.* (1989), Wünsch & Bußhoff (1992) have determined expressions for the effects of certain ocean tidal currents and tidal heights on the Earth's rotation. By taking the derivative of the analytical expression which they give for UT1, an expression for LOD was derived for the fortnightly, the monthly, and the semi-annual tidal terms. This expression could then be used to remove the dynamic oceanic tidal effects from the astronomical LOD series at these particular frequencies. Similarly Dickman (1993) provides estimates of the effects on the length of day of the same tides along with some additional tides which can be compared with observations. This provides the numerical values contained in the IERS Standards (McCarthy 1992) definition of UT1*S*, ΔS and ωS. Both the Dickman (1993) and Wünsch & Bußhoff (1992) models were investigated in this analysis.

5 SPECTRAL ANALYSIS OF THE LOD SERIES

Pertinent coefficients of the tidal variations given in the IERS Standards (McCarthy 1992) were used to remove the effect of the oceans. These values were determined by first multiplying the values of the IERS Standards defining UT1*R*, ΔR and ωR by the ratio of the Love numbers as given by Brosche *et al.* (1989) to obtain the effects due to the zonal solid Earth tides (see Table 1). The effects of the solid-Earth zonal tides as represented by the modified coefficients were then removed from the astronomical LOD data. The oceanic tidal variations determined from Wünsch & Bußhoff (1992) (Table 2) as well as Dickman (1993) (Table 3) were also removed leaving two time series theoretically free from all predicted tidal effects. Use of the Table 3 values along with Table 1 and the remaining coefficients defining UT1*R*, ΔR and ωR is equivalent to the use of UT1*S*, ΔS and ωS (McCarthy 1992).

Next, the LOD series (both astronomical LOD and the AAM series) were filtered using a Gaussian high-pass filter configured to remove effects with periods greater than 365 days. This was done in order to minimize any errors due to low-frequency systematic errors in the AAM data. The effects of the filtered atmospheric angular momentum were then subtracted from the filtered, astronomical LOD data corrected for tidal effects, leaving two data sets presumably free from the variations in the length of the day caused by both tides and atmosphere.

No significant differences were found in the appearance of the spectra of the LOD series corrected with either the coefficients of Tables 2 or 3. Thus, no significant difference in the fit of either the Dickman (1993) or Wünsch & Bußhoff (1992) models was found. Both appear to fit the data equally well, the only difference being that the Dickman model treats more tides. Figs 1, 2 and 3 show the amplitude spectra of the LOD series, uncorrected as well as corrected for the atmospheric and oceanic contributions (using the UT1*S* coefficients of Table 3). The ranges of the horizontal axes for the first two graphs were chosen to highlight the principal high-frequency tidal terms with fortnightly and monthly periods.

The plots show several interesting features. First, removing the effects of AAM from the LOD shows little effect in the amplitude spectrum at very high frequencies. In particular, there is virtually no difference between spectra

Table 1. Effect of solid-Earth tides. Δ is length of day and ω rotational speed. Units for UT1-UT1R_s are 10^{-4} s, for $\Delta - \Delta R_s$, 10^{-5} s, and for $\omega - \omega R_s$, 10^{-14} rad/s.

ARGUMENT*					PERIOD	UT1-UT1R$_s$ Coefficient of Argument		Δ-ΔR$_s$ Coefficient of Argument		ω-ωR$_s$	
l	l′	F	D	Ω	Days	sin	cos	cos	sin	cos	sin
1	0	2	0	1	9.12	-0.35	-	2.4	-	- 2.1	-
1	0	2	0	2	9.13	-0.85	-	5.8	-	- 5.0	-
0	0	2	0	1	13.63	-2.75	-	12.7	-	-10.7	-
0	0	2	0	2	13.66	-6.64	-	30.5	-	-25.8	-
0	0	2	0	0	14.77	-0.62	-	2.6	-	- 2.2	-
1	0	0	0	0	27.56	-7.07	-	16.1	-	-13.6	-
-1	0	0	2	0	31.81	-1.56	-	3.1	-	- 2.6	-
0	0	2	-2	2	182.62	-41.28	-	14.2	-	-12.0	-
0	1	0	0	0	365.26	-13.14	-	2.2	-	- 1.9	-

* l = 134°96 + 13°064993(MJD-51544.5) = mean anomaly of the Moon
l′ = 357°53 + 0°985600(MJD-51544.5) = mean anomaly of the Sun
F = 93°27 + 13°229350(MJD-51544.5) = L-Ω; L= mean longitude of the Moon
D = 297°85 + 12°190749(MJD-51544.5) = mean elongation of the Moon from the Sun
Ω = 125°04 - 0°052954(MJD-51544.5) = mean longitude of the ascending node of the Moon

Table 2. Effect of zonal tides due to oceans only from Wünsch & Bußhoff (1989). Δ is length of day and ω rotational speed. The units are as given in Table 1.

ARGUMENT					PERIOD	UT1-UT1R$_o$ Coefficient of Argument		Δ-ΔR$_o$ Coefficient of Argument		ω-ωR$_o$	
l	l′	F	D	Ω	Days	sin	cos	cos	sin	cos	sin
0	0	2	0	1	13.63	-0.29	0.12	1.3	0.6	-1.1	-0.5
0	0	2	0	2	13.66	-0.70	0.29	3.2	1.3	-2.7	-1.1
1	0	0	0	0	27.56	-0.87	0.21	2.0	0.5	-1.7	-0.4
0	0	2	-2	2	182.62	-5.57	0.23	1.9	0.1	-1.6	-0.1

Table 3. Effect of zonal tides due to oceans only from Dickman (1993). Δ is length of day and ω rotational speed. The units are given in Table 1.

ARGUMENT*					PERIOD	UT1-UT1R$_o$ Coefficient of Argument		Δ-ΔR$_o$ Coefficient of Argument		ω-ωR$_o$	
l	l′	F	D	Ω	Days	sin	cos	cos	sin	cos	sin
1	0	2	0	1	9.12	-0.05	0.01	0.3	0.1	-0.3	-0.1
1	0	2	0	2	9.13	-0.13	0.03	0.9	0.2	-0.8	-0.2
0	0	2	0	1	13.63	-0.45	0.09	2.1	0.4	-1.8	-0.4
0	0	2	0	2	13.66	-1.09	0.21	5.0	1.0	-4.2	-0.8
0	0	2	0	0	14.77	-0.10	0.02	0.4	0.1	-0.4	-0.1
1	0	0	0	0	27.56	-1.26	0.12	2.9	0.3	-2.4	-0.2
-1	0	0	2	0	31.81	-0.28	0.02	0.6	0.0	-0.5	0.0
0	0	2	-2	2	182.62	-7.56	0.11	2.6	0.0	-2.2	0.0
0	1	0	0	0	365.26	-2.41	0.02	0.4	0.0	-0.4	0.0

with AAM removed or retained for periods less than 10 days except for a slightly higher noise level in the 'corrected' time series. Fig. 4, which displays both spectra together, makes this clearer. There are at least two possible causes for this. The smoothing of the AAM data by the NMC might be such that it eliminates traces of AAM signal with periods less than 10 days, or systematic errors in the data may be contributing to the lack of correlation. Aliasing of the semi-diurnal or diurnal ocean tides into lower-frequency spectral peaks is possible, but this possibility could be eliminated if an ocean-tide model were used in the reduction of the astronomical observations used in the formation of the LOD time series.

The spectra also show that some of the peaks in the observational LOD series corrected using the IERS Standards zonal-tides model are due to the AAM data. In particular, the peaks at 14.77 and 27.56 days virtually disappear into the noise when the effects of the AAM are removed. It is also interesting to see that there is no evidence for a significant 13.69-day variation as reported in Capitaine & Guinot (1985) from their analysis of UT1 data.

The anomalously large corrections indicated for the period of 182 days could have several explanations. The most probable of these is the exclusion of the stratospheric winds in the AAM data. As reported by Rosen & Salstein (1985), and Rosen, Salstein & Wood (1990), the

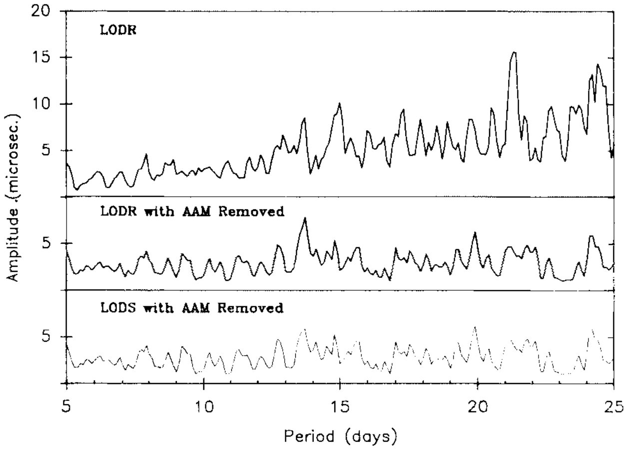

Figure 1. Amplitude spectrum of (1) LOD*R* determined astronomically, (2) LOD*R* with the effects of AAM removed, and (3) LOD*S* with the effects of AAM removed for periods between 5 and 25 days.

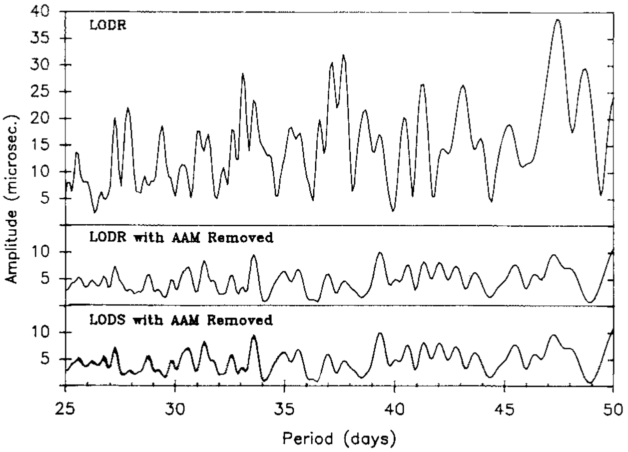

Figure 2. Amplitude spectrum of (1) LOD*R* determined astronomically, (2) LOD*R* with the effects of AAM removed, and (3) LOD*S* with the effects of AAM removed for periods between 25 and 50 days.

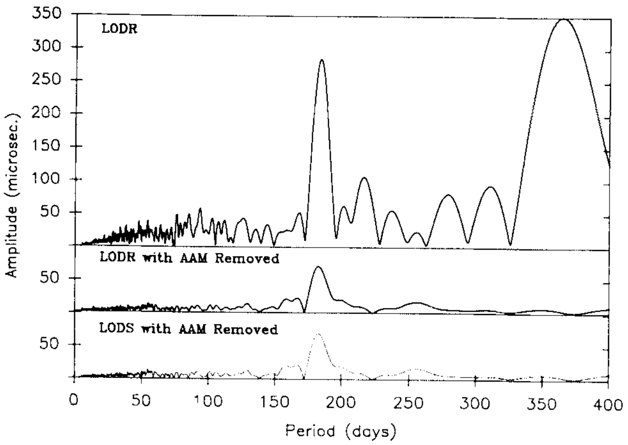

Figure 3. Amplitude spectrum of (1) LOD determined astronomically, (2) LOD*R* with the effects of AAM removed, and (3) LOD*S* with the effects of AAM removed for periods between 3 and 400 days.

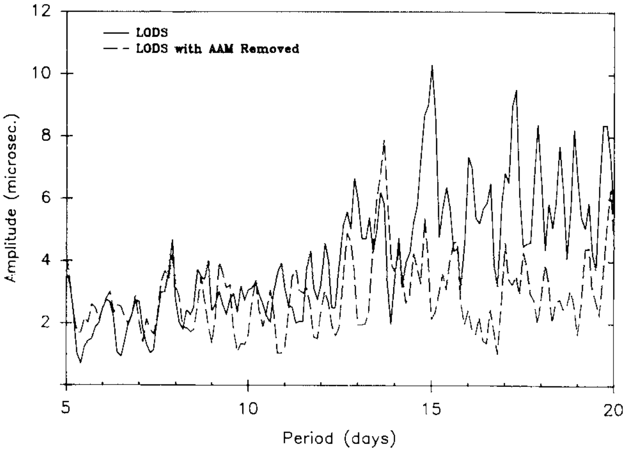

Figure 4. Amplitude spectrum of the LOD inferred from AAM superimposed on the amplitude spectrum of the astronomical LOD.

stratospheric winds account for much of the discrepancy between the astronomical LOD series and the AAM LOD series. Other possible explanations are changes in global sea level, redistribution of ground water (Rosen & Salstein 1985; Rosen *et al.* 1990), and wind-driven ocean currents (Christou 1990).

The heavily smoothed amplitude spectrum of the variations in the length of day that remain after removal of the effects of AAM and ocean tides, as well as an empirical 180-day variation, is seen in Fig. 5. The overall spectral index, α, characterizing the behaviour of the spectral power, S, with frequency, f, by

$$S \propto f^{\alpha},$$

is found to be -0.52 for periods less than 400 days long. The spectrum would also indicate that the remaining variations in the length of day can be considered essentially as a white-noise process ($\alpha = 0$) for periods less than 20 days and a flicker-noise process ($\alpha = -1$) for lower frequencies. The spectrum shows that variations with periods less than 180 days and greater than 3 days in LOD having amplitudes greater than 0.02 milliseconds appear to be accounted for by current models and theories.

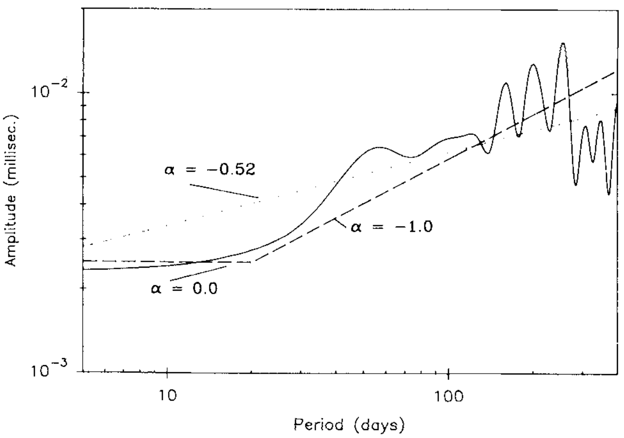

Figure 5. Smoothed amplitude spectrum of variations in the length of day. The dashed lines are plots of Amplitude = Period $^{\alpha/2}$.

Table 4. Estimated zonal-response function (f_i) found from the analysis of the LOD data. The errors listed are formal one-sigma error estimates.

Band Period (days)	Tidal Periods (days)	Amplitude	phase (deg.)
9.12	9.12 9.13	0.300 ±0.008	-3.45 ±1.60
13.96	13.63 13.66 13.78 14.77	0.306 ±0.001	-1.38 ±0.24
29.68	27.56 31.81	0.315 ±0.003	-0.66 ±0.58
365.26	365.26	0.310 ±0.024	2.69 ±4.41

6 ZONAL RESPONSE FUNCTION

To investigate the theoretical tidal amplitudes and phases, solutions were made for corrections to the zonal response function $\kappa(f_i)$ for each tidal frequency. The observed astronomical LOD series was corrected for AAM, and solid Earth and ocean tides using the values of Dickman (1993) as shown in Table 3 and which define the UT1*S* and LOD*S* systems. A separate solution was made for the nine-day tides using a time series uncorrected for AAM since, as seen above, AAM appears to have little connection to the observed LOD series at this frequency. A simple simultaneous least-squares analysis of the amplitudes and phases is inadequate because of high correlations between the solutions of closely spaced tides. Corrections to $\kappa(f_i)$ were held constant for the frequency bands shown in Table 4. Using this procedure, a simultaneous non-linear least-squares solution was performed for the 10 largest tides. These results are summarized in Table 4. Fig. 6 shows the plot of the amplitudes of the observationally determined zonal-response function and Fig. 7 shows the plot of the phases. The tables and plots do not show the semi-annual correction since it is clear that the effect seen in the spectrum is too large to be due to a remaining solid Earth or ocean tide. It is more likely to be due to the atmosphere and, therefore, it has been deleted. Also plotted are the results expected from the theory of Nam & Dickman (1990).

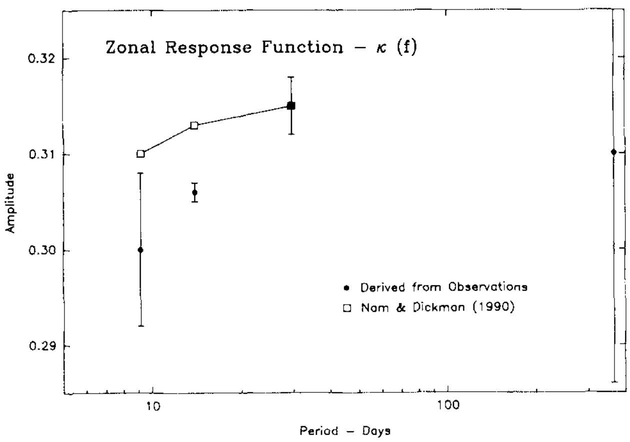

Figure 6. Observational estimates of $\kappa(f_i)$ amplitudes.

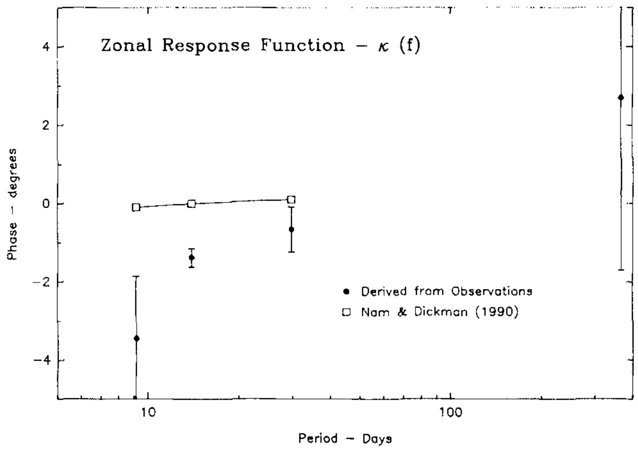

Figure 7. Observational estimates of $\kappa(f_i)$ phases.

Figures 6 and 7 indicate that the observationally determined amplitude of $\kappa(f_i)$ may be less than that expected from the theory of Nam & Dickman (1990) and that there may be a larger than expected phase dependence on frequency. However, the errors indicated by the error bars in the figures make definitive statements about the nature of these differences difficult to make.

7 CONCLUSION

The IERS Standards (McCarthy 1992) corrections applied to obtain UT1*S* and LOD*S*, adequately model the variation in LOD to the level of accuracy of the observations. The apparent effect of AAM on the astronomically determined LOD is found to be much less at the highest frequencies than at lower frequencies. For periods shorter than 10 days there appears to be essentially no correlation between AAM and LOD. With future improvements in the accuracy of the Earth-orientation series and in the AAM series, this conclusion might change. The apparent lack of correlation at high frequencies is particularly interesting in view of attempts to use AAM in the prediction of UT1–UTC. If the high-frequency effects of AAM on UT1 are negligible, its contributions to the prediction of UT1 is questionable.

The spectral peak at 182 days suggests a large correction in both amplitude and phase, but this may be explained by the current exclusion of the upper stratosphere in the atmospheric data. The high-frequency variations in LOD with amplitudes greater than 0.02 milliseconds now seem to be accounted for by current models and theories. Lower frequency variations with much larger amplitudes still pose a challenging problem.

An observational estimation of the zonal-response function $\kappa(f_i)$ has been determined and compared with theoretical values of Nam & Dickman (1990). This indicates that improvements may be required in the $\kappa(f_i)$ derived in their work.

8 ACKNOWLEDGMENTS

It is a pleasure to thank Dr Brent Archinal and Mr Marshall Eubanks for their helpful discussions in preparing this document. We also wish to acknowledge the suggestions of Dr Steve Dickman and an unknown referee.

9 REFERENCES

Baader, H.-R., Brosche, P. & Hövel, W., 1983. Ocean Tides and Periodic Variations of the Earth's Rotation, *J. Geophys.*, **52,** 140–142.

Barnes, R. T. H., Hide, R., White, A. A. & Wilson, C. A., 1983. Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, *Proc. R. Soc. Lond.*, A, **387,** 31–73.

Brosche, P., Seiler, U., Sündermann, J. & Wünsch, J., 1989. Periodic changes in the Earth's rotation due to oceanic tides, *Astr. Astrophys.*, **220,** 318–320.

Brosche, P., Wünsch, J., Campbell, J. & Schuh, H., 1991. Ocean tide effects in universal time detected by VLBI, *Astr. Astrophys.*, **245,** 676–682.

Capitaine, N. & Guinot, B., 1985. Anomalies of some tidal waves of UT1, *Geophys. J. R. astr. Soc.*, **81,** 563–568.

Christou, N. T., 1990. On the Space-Time Ocean Current Variability and Its Effects on the Length of Day, *PhD dissertation*, Department of Surveying Engineering Technical Report No. 148, University of New Brunswick, Fredericton, New Brunswick, Canada.

Dehant, V., 1987. Tidal parameters for an inelastic Earth, *Phys. Earth planet. Inter.*, **49,** 97–116.

Dickman, S., 1989. A complete spherical harmonic approach to luni-solar tides, *Geophys. J.*, **99,** 457–468.

Dickman, S., 1990. Experiments in tidal mass conservation *Geophys. J.*, **102,** 257–262.

Dickman, S., 1991. Ocean tides for satellite geodesy, *Mar. Geod.*, **14,** 21–56.

Dickman, S. R., 1993. Dynamic ocean-tide effects on the Earth's rotation, *Geophys. J. Int.*, **112,** 448–470.

Djurovic, D., 1976. Determination du nombre de Love et du facteur affectant les observations du temps universal, *Astr. Astrophys.*, **47,** 325–332.

Guinot, B., 1970. Short-period terms in universal time, *Astr. Astrophys.*, **8,** 26–28.

Guinot, B., 1974. A determination of the Love number *k* from the periodic waves of UT1, *Astr. Astrophys.*, **36,** 1–4.

Hefty, J., 1982. Love number *k* determined from astronomical observations of the Earth's rotation, *Bull. astr. Inst., Czech.*, **33,** 84–88.

Hefty, J. & Capitaine, N., 1990. The fortnightly and monthly zonal tides in the Earth's rotation from 1962 to 1988, *Geophys. J. Int.*, **103,** 219–231.

International Earth Rotation Service (IERS), *Annual Report for 1989*, Observatorie de Paris, Paris.

Luo, S., Zheng, D., Robertson, D. S. & Carter, W. E., 1987. Short-period variations in the length of day: atmospheric angular momentum and tidal components, *J. geophys. Res.*, **92,** 11657–11661.

McCarthy, D. D., 1989. *IERS Standards*, IERS Technical Note 3, Observatorie de Paris, Paris.

McCarthy, D. D., 1992. *IERS Standards*, IERS Technical Note 13, Observatoire de Paris, Paris.

McCarthy, D. & Luzum, B., 1991. Combination of precise observations of the orientation of the Earth, *Bull. Geod.*, **65,** 22–27.

Merriam, J. B., 1980. Zonal tides and changes in the length of day, *Geophys. J. R. astr. Soc.*, **62,** 551–561.

Merriam, J. B., 1985. Lageos and UT measurements of long-period Earth tides and mantle *Q*, *J. geophys. Res.*, **90,** 9423–9430.

Nam, Y. S. & Dickman, S. R., 1990. Effects of dynamic long-period ocean tides on changes in the Earth's rotation rate, *J. geophys. Res.*, **95,** 6751–6757.

Newhall, X. X., Williams, J. G. & Dickey, J. O., 1988. Earth rotation for Lunar Laser Ranging, in *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*, pp. 159–164A, eds Babcock, A. & Wilkins, G., D. Reidel, Dordrecht.

Pejović, N. & Vondrák, J., 1989. Atmospheric excitation of the Earth's rotation: comparison of the spectrum of the length-of-day and axial component of the angular momentum function of the atmosphere, *Bull. Astr. Inst. Czech.*, **40,** 382–393.

Pil'nik, G. P., 1970. A correlation analysis of the Earth tides and nutation, *Astr. Zh.*, **47,** 1308–1323.

Robertson, D. S., Carter, W. E. & Fallon, F. W., 1988. Earth rotation from the IRIS project, in *The Impact of VLBI on Astrophysics and Geophysics*, pp. 391–400, eds Reid, M. J. & Moran, J. M., Kluwer, Dordrecht.

Rosen, R. D. & Salstein, D. A., 1983. Variations in atmospheric angular momentum on global and regional scales and the length of day, *J. geophys. Res.*, **88,** 5451–5470.

Rosen, R. D. & Salstein, D. A., 1985. Contribution of stratospheric winds to annual and semi-annual fluctuations in atmospheric angular momentum and the length of day, *J. geophys. Res.*, **90,** 8033–8041.

Rosen, R. D., Salstein, D. A. & Wood, T. M., 1990. Discrepancies in the Earth-Atmosphere Angular Momentum Budget, *J. geophys. Res.*, **95,** 265–279.

Schuh, H., 1988. Analysis of UT1 determinations by VLBI within project IRIS, in *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*, pp. 171–180, eds Babcock, A. & Wilkins, G., D. Reidel, Dordrecht.

Wahr, J. & Bergen, Z., 1986. The effects of mantle anelasticity on nutations, Earth tides, and tidal variations in rotation rate, *Geophys. J. R. astr. Soc.*, **87,** 633–688.

Wahr, J. M., Sasao, T. & Smith, M. L., 1981. Effect of the fluid core on changes in the length of day due to long-period tides, *Geophys. J. R. astr. Soc.*, **64,** 635–650.

Woolard, E. W., 1959. Inequalities in mean solar time from tidal variations in the rotation of the Earth, *Astr. J.*, **64,** 140–142.

Wünsch, J. & Bußhoff, J., 1992. Improved observations of periodic UT1 variations caused by ocean tides, *Astr. Astrophys*, **366,** 588–591.

Yoder, C. F., Williams, J. G. & Parke, M. E., 1981. Tidal variations of Earth rotation, *J. geophys. Res.*, **86,** 881–891.