OBSERVING AND MODELING LONG-PERIOD TIDAL VARIATIONS IN POLAR MOTION

R.S. GROSS[1], S.R. DICKMAN[2]

[1] Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109, USA
e-mail: Richard.Gross@jpl.nasa.gov

[2] Department of Geological Sciences and Environmental Studies
Binghamton University, Binghamton, NY 13902, USA
e-mail: dickman@binghamton.edu

ABSTRACT. By exchanging angular momentum with the solid Earth, ocean tides cause the Earth's rotation to change. While hydrodynamic tide models have been used to study the effect of ocean tides on polar motion, it is shown here that none of the published models can fully account for the observed variations. An empirical ocean tide model is therefore determined by fitting periodic terms at the tidal frequencies to polar motion excitation observations spanning 1980.0−2010.4 from which atmospheric and non-tidal oceanic effects were removed. While the empirical ocean tide model does fully account for all of the observed tidal power, tests indicate that the model may not have completely converged. So better models of the effects of ocean tides on polar motion are still needed, both dynamical and empirical.

1. INTRODUCTION

Because the long-period tide raising potential is symmetric about the Earth's polar axis it cannot cause an axisymmetric Earth to wobble. But because the oceans are irregularly distributed on the surface of the Earth, ocean tides can and do cause the Earth to wobble. Therefore, observations of the ocean tide-induced wobbles of the Earth can potentially be used to assess the accuracy of ocean tide models. This potential is explored here by comparing models of long-period ocean tidal variations in polar motion excitation to observations. It is shown than none of the currently available dynamic ocean tide models are able to fully account for the observed long-period tidal variations. So following Gross (2009), an empirical model for the effect of the monthly (27.56-day), fortnightly (13.66-day), and termensual (9.13-day) ocean tides on polar motion excitation is determined and its convergence properties examined.

2. OBSERVED TIDAL VARIATIONS IN POLAR MOTION EXCITATION

The observed polar motion excitation series used in this study is that determined from the polar motion and polar motion rate values of the COMB2009 Earth orientation series (Ratcliff and Gross 2010). COMB2009 is a combination of Earth orientation measurements determined from data acquired by the techniques of lunar and satellite laser ranging (LLR and SLR), very long baseline interferometry (VLBI), and the global positioning system (GPS). Because of the corrupting influence on the recovered polar motion rate estimates of errors in the subdaily tide model that is used when reducing the Earth orientation data acquired by these techniques, polar motion rate estimates are generally unreliable and hence were not used when generating COMB2009. Instead, the COMB2009 polar motion rate values were determined numerically from the polar motion measurements as part of the state estimation process of the Kalman filter that was used to generate COMB2009. The polar motion excitation series determined from the COMB2009 polar motion and polar motion rate values consists of daily midnight values spanning 20 January 1962 to 28 May 2010. Figure 1a is a power spectrum of that portion of the COMB2009 polar motion excitation series spanning 25 March 1995 to 28 May 2010. Just visible above the background power is a spectral peak at the prograde fortnightly tidal frequency of +27 cycles per year (cpy).

Removing atmospheric and non-tidal oceanic effects from the observed polar motion excitation observations will lower the level of the background power evident in Figure 1a and enhance the signal-to-noise ratio of the observed tidal signals. Wind and atmospheric surface pressure effects, assuming an inverted

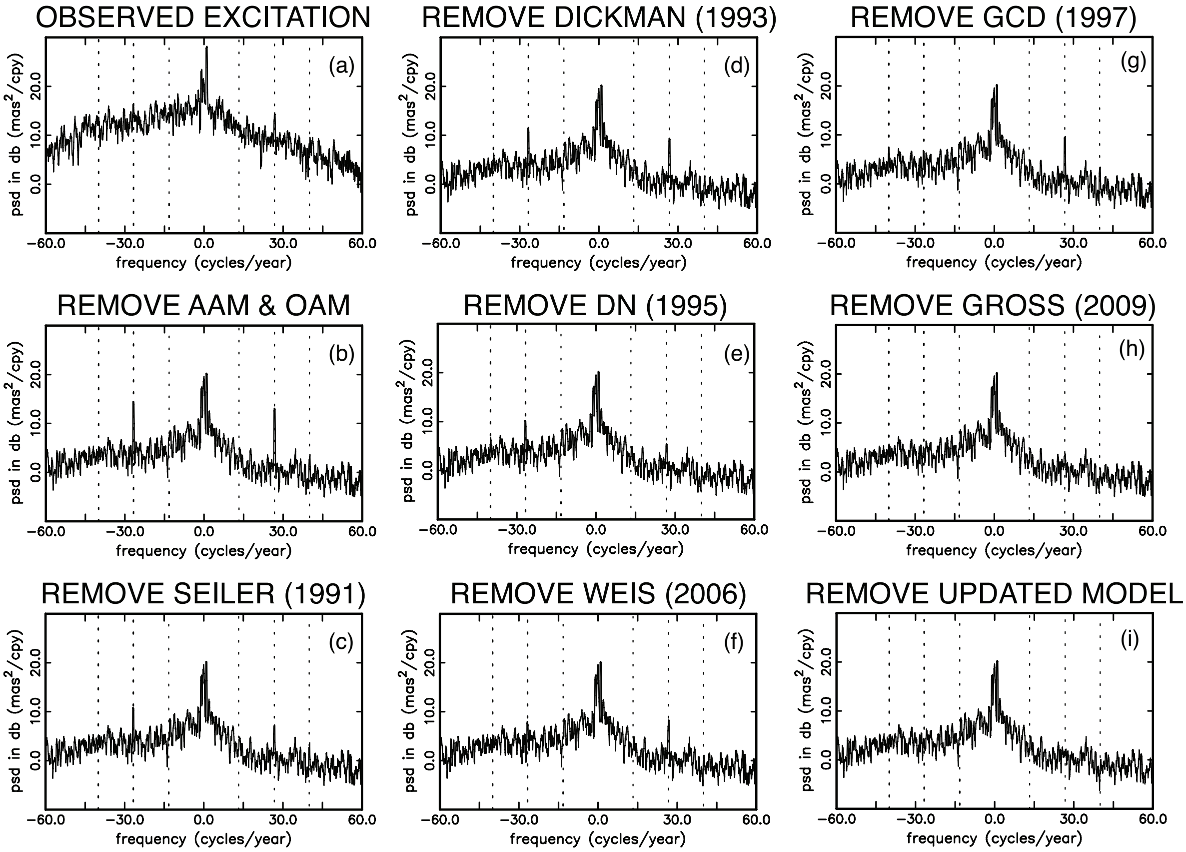

Figure 1: Power spectral density (psd) estimates in decibels (db) computed by the multitaper method from time series spanning 25 March 1995 to 28 May 2010 of the: (a) observed COMB2009 polar motion excitation functions; (b) residual excitation functions formed by removing atmospheric and non-tidal oceanic effects from the observations; (c) residual excitation functions formed by additionally removing the dynamical ocean tide model of Seiler (1991) as reported by Gross (1993); (d) residual excitation functions formed by instead removing the dynamical ocean tide model of Dickman (1993) as reported by Gross et al. (1997); (e) residual excitation functions formed by instead removing the dynamical ocean tide model of Dickman and Nam (1995) as reported by Dickman and Gross (2010); (f) residual excitation functions formed by instead removing the dynamical ocean tide model of Weis (2006) as reported by Gross (2009); (g) residual excitation functions formed by instead removing the empirical ocean tide model of Gross et al. (1997); (h) residual excitation functions formed by instead removing the empirical ocean tide model of Gross (2009); and (i) residual excitation functions formed by instead removing the empirical ocean tide model determined here. Vertical dashed lines indicate the prograde and retrograde frequencies of the monthly (±13 cpy), fortnightly (±27 cpy), and termensual (±40 cpy) tidal terms. The retrograde component of polar motion excitation is represented by negative frequencies, the prograde component by positive frequencies.

barometer response of the oceans to the surface pressure variations, were removed from the polar motion excitation observations using atmospheric angular momentum values computed from products of the National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis project by the International Earth Rotation and Reference Systems Service (IERS) Global Geophysical Fluids Center (GGFC) Special Bureau for the Atmosphere (Salstein 2003). Current and oceanic bottom-pressure effects were removed from the polar motion excitation observations using oceanic angular momenta values computed by the IERS GGFC Special Bureau for the Oceans (Gross 2003) from products of the kf080 data assimilating version of the oceanic general circulation model run at the Jet Propulsion Laboratory (JPL) as part of their participation in the Estimating the Circulation and Climate of the Oceans (ECCO) consortium (Stammer et al. 2002). Figure 1b shows the power spectrum of the observed polar motion excitation series from which atmospheric and non-tidal oceanic effects have been removed. As can be seen, peaks at both the retrograde and prograde fortnightly tidal frequencies of ±27 cpy are now both very prominent, and a small peak at the prograde termensual frequency of $+40$ cpy is now also visible.

3. DYNAMICAL OCEAN TIDE MODELS

One of the first dynamical ocean tide models to be used to study ocean tidal effects on the Earth's rotation was that of Brosche (1982), later updated by Seiler (1991). Figure 1c is a spectrum of the result of removing the Seiler (1991) long-period ocean tide model as reported by Gross (1993) from the residual polar motion excitation series whose spectrum is shown in Figure 1b. As can be seen, while the amplitudes of the fortnightly tides at ± 27 cpy are reduced, there is still some residual power evident at these frequencies. And since the Seiler (1991) model includes only the fortnightly, monthly, and semi-annual long-period tides, the peak at the prograde termensual frequency of $+40$ cpy is left unchanged.

Dickman (1993) used his spherical harmonic ocean tide model to study the effect of 10 long-period tidal constituents on the Earth's rotation, including the fortnightly and termensual tides. Figure 1d shows the effect of removing the Dickman (1993) ocean tide model as reported by Gross et al. (1997) from the residual polar motion excitation series whose spectrum is shown in Figure 1b. While the Dickman (1993) model eliminates the observed power at the prograde termensual tidal frequency, it reduces but does not eliminate the observed power at the fortnightly tidal frequencies.

Dickman and Nam (1995) revised the Dickman (1993) tide model by altering the values of the frictional parameters used in the model. The bottom friction and lateral turbulent dissipation parameters in the revised model were determined by maximizing the agreement between the model and the observations at the fortnightly tidal frequency. Figure 1e shows the effect of removing the Dickman and Nam (1995) ocean tide model as reported by Dickman and Gross (2010) from the residual polar motion excitation series whose spectrum is shown in Figure 1b. Like the Dickman (1993) model, the Dickman and Nam (1995) model eliminates the observed power at the prograde termensual tidal frequency. And while the Dickman and Nam (1995) model accounts for more of the observed fortnightly tidal power than does the Dickman (1993) model, it does not completely eliminate it.

Most recently, Weis (2006) developed a high-resolution, global ocean tide model and used it to study the effects of 12 long-period tidal constituents on the Earth's rotation, including the fortnightly and termensual tides. Figure 1f shows the effect of removing the Weis (2006) ocean tide model as reported by Gross (2009) from the residual polar motion excitation series whose spectrum is shown in Figure 1b. Like the Dickman (1993) and Dickman and Nam (1995) tide models, the Weis (2006) model completely accounts for the observed prograde termensual tidal power. And while it accounts for more of the observed retrograde fortnightly tidal power than do the Seiler (1991), Dickman (1993), and Dickman and Nam (1995) models, it accounts for less of the observed prograde fortnightly tidal power than do either the Seiler (1991) or the Dickman and Nam (1995) models.

4. EMPIRICAL OCEAN TIDE MODELS

Figure 1 shows that none of the dynamical ocean tide models discussed here are able to fully account for the observed fortnightly tidal power. Recognizing this, a number of studies have developed empirical tide models by least-squares fitting periodic terms at the tidal frequencies to polar motion observations. For example, Gross et al. (1997) determined an empirical ocean tide model by fitting a mean, trend, seasonal, and periodic terms at the monthly, fortnightly, and termensual tidal frequencies to polar motion excitation observations from which atmospheric effects had been removed. Figure 1g shows the effect of removing the Gross et al. (1997) empirical ocean tide model from the residual polar motion excitation series whose spectrum is shown in Figure 1b. As can be seen, while the Gross et al. (1997) model does a good job of removing the observed retrograde fortnightly tidal power, it does not completely remove either the observed prograde fortnightly or the observed prograde termensual tidal power.

When determining their model, Gross et al. (1997) included separate periodic terms for the two principal fortnightly tides (*Mf* and *mf*) and the two principal termensual tides (*Mtm* and *mtm*). Since the frequencies of the two principal fortnightly tides differ by only 1/18.6 cpy, as do the frequencies of the two principal termensual tides, the oceans and hence the Earth's rotation should have the same relative response to the tidal potential at these two nearby frequencies. That is, the phase of the two principal fortnightly tidal terms in polar motion excitation should be the same and the ratio of their amplitudes should be the same as the ratio of the amplitudes of these two terms in the tidal potential. However, Gross et al. (1997) found that their results for the two principal fortnightly tidal terms did not have this property, nor did their results for the two principal termensual terms. This inconsistency in their empirical tide model may explain why it does not fully explain the prograde fortnightly and prograde termensual tidal power that is observed during 25 March 1995 to 28 May 2010 (Figure 1g). So

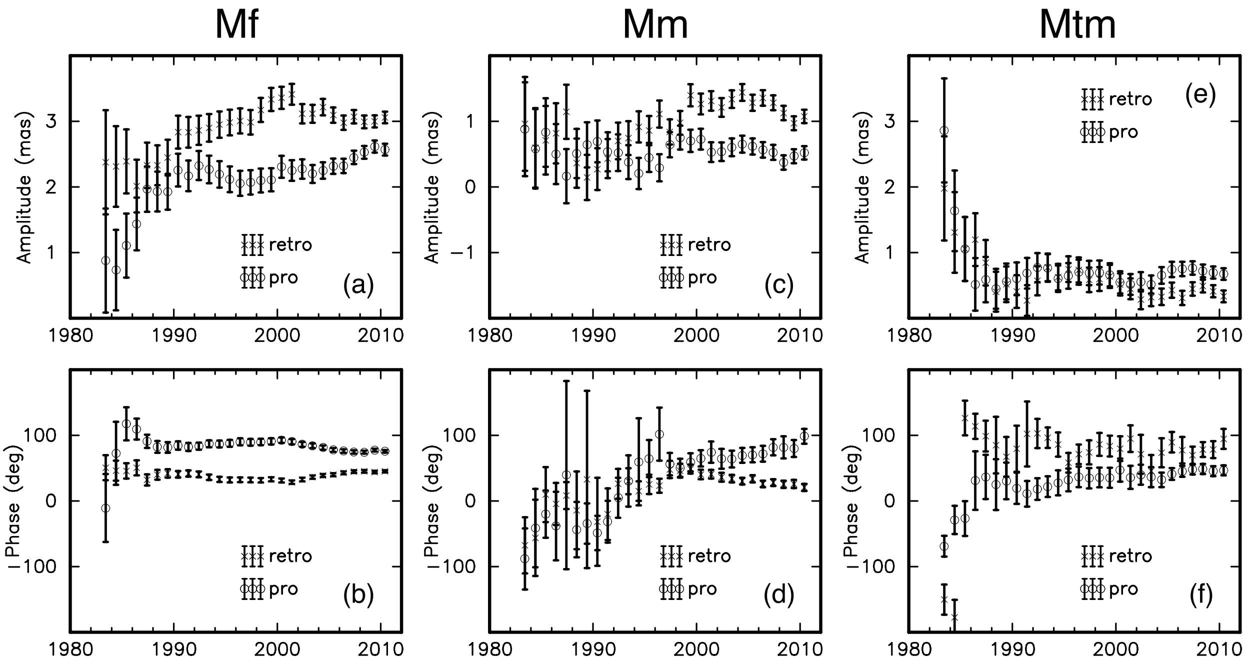

Figure 2: Test of the convergence of the updated empirical ocean tide model determined here. The amplitudes (a, c, e) in milliarcseconds (mas) and phases (b, d, f) in degrees (deg) of the retrograde (retro, crosses) and prograde (pro, circles) components of the fortnightly *Mf*, monthly *Mm*, and termensual *Mtm* tidal terms are plotted as a function of the epoch of the last measurement included in the fit. The ±1-sigma formal uncertainties of the recovered amplitudes and phases are indicated by the error bars.

Gross (2009) determined an empirical ocean tide model by constraining the phases of the two principal fortnightly tidal terms to be the same and constraining their relative amplitudes to be the same as that of the tidal potential. Similar constraints were applied to the two principal termensual tidal terms. Figure 1h shows the effect of removing the Gross (2009) empirical ocean tide model from the residual polar motion excitation series whose spectrum is shown in Figure 1b. This empirical model, which was determined by fitting observations spanning 2 January 1980 to 8 September 2006, is seen to fully account for the fortnightly and termensual tidal power that is observed during 25 March 1995 to 28 May 2010.

By studying the convergence properties of his empirical tide model, Gross (2009) became concerned that it had not converged because the amplitudes and phases of the recovered fortnightly tidal terms continued to change as additional observations were included in the fit. So a new empirical ocean tide model was determined here by taking the same approach as Gross (2009) but by fitting observations spanning 2 January 1980 to 28 May 2010, an additional 3.7 years. The coefficients of this updated empirical tide model are given in Table 1 (the entries labeled "This paper") along with the coefficients of the Dickman (1993), Dickman and Nam (1995), and Weis (2006) dynamical ocean tide models and of the Gross (2009) empirical ocean tide model. Figure 1i shows the effect of removing the updated Gross (2009) empirical ocean tide model from the residual polar motion excitation series whose spectrum is shown in Figure 1b. Like the Gross (2009) empirical tide model, the updated model determined here also fully accounts for the fortnightly and termensual tidal power that is observed during 25 March 1995 to 28 May 2010. But also like the Gross (2009) empirical tide model, the updated model may still not have converged because the amplitudes and phases of the recovered tidal terms continue to change as additional data is included in the fit, particularly for the monthly tide (see Figure 2).

Table 1: Long-Period Ocean Tidal Variations in Polar Motion Excitation

Tide Model	Tidal Argument					Period	Prograde		Retrograde	
	l	l'	F	D	Ω	(days)	amp (μas)	phase (degrees)	amp (μas)	phase (degrees)
mtm										
Dickman (1993)	1	0	2	0	1	9.12	130.38	72.73	213.45	15.05
Dickman & Nam (1995)	1	0	2	0	1	9.12	205.83	67.21	269.95	21.17
Weis (2006)	1	0	2	0	1	9.12	248.17	−21.16	182.26	−137.16
Gross (2009)	1	0	2	0	1	9.12	180.15	51.26	80.18	−26.98
This paper	1	0	2	0	1	9.12	278.91	46.69	138.08	94.61
Mtm										
Dickman (1993)	1	0	2	0	2	9.13	315.24	72.89	517.67	15.17
Dickman & Nam (1995)	1	0	2	0	2	9.13	497.59	67.27	652.59	21.14
Weis (2006)	1	0	2	0	2	9.13	857.20	35.84	535.91	102.84
Gross (2009)	1	0	2	0	2	9.13	434.55	51.26	193.41	−26.98
This paper	1	0	2	0	2	9.13	672.76	46.69	333.05	94.61
mf										
Dickman (1993)	0	0	2	0	1	13.63	521.36	99.93	713.09	7.85
Dickman & Nam (1995)	0	0	2	0	1	13.63	841.32	88.42	1002.12	13.15
Weis (2006)	0	0	2	0	1	13.63	887.43	25.83	766.26	82.84
Gross (2009)	0	0	2	0	1	13.63	880.22	73.88	1205.93	39.27
This paper	0	0	2	0	1	13.63	1065.30	75.78	1268.09	45.16
Mf										
Dickman (1993)	0	0	2	0	2	13.66	1257.22	100.08	1716.11	7.82
Dickman & Nam (1995)	0	0	2	0	2	13.66	2028.73	88.53	2414.94	13.11
Weis (2006)	0	0	2	0	2	13.66	3071.79	47.83	3107.14	70.84
Gross (2009)	0	0	2	0	2	13.66	2123.44	73.88	2909.16	39.27
This paper	0	0	2	0	2	13.66	2569.90	75.78	3059.11	45.16
MSf										
Dickman (1993)	0	0	0	2	0	14.77	105.46	105.26	135.32	6.21
Dickman & Nam (1995)	0	0	0	2	0	14.77	168.13	92.70	194.74	11.60
Weis (2006)	0	0	0	2	0	14.77	474.74	134.83	422.74	−13.15
Mm										
Dickman (1993)	1	0	0	0	0	27.56	465.13	135.86	283.75	−6.50
Dickman & Nam (1995)	1	0	0	0	0	27.56	643.61	123.13	520.16	−1.06
Weis (2006)	1	0	0	0	0	27.56	681.12	102.83	838.55	8.85
Gross (2009)	1	0	0	0	0	27.56	567.37	68.42	1391.36	34.62
This paper	1	0	0	0	0	27.56	520.12	98.49	1075.23	20.63
MSm										
Dickman (1993)	−1	0	0	2	0	31.81	83.17	140.41	39.25	−10.77
Dickman & Nam (1995)	−1	0	0	2	0	31.81	111.62	128.72	79.23	−4.36
Weis (2006)	−1	0	0	2	0	31.81	134.44	102.83	161.31	5.85
Ssa										
Dickman (1993)	0	0	2	−2	2	182.62	107.85	162.21	397.94	172.16
Dickman & Nam (1995)	0	0	2	−2	2	182.62	118.56	159.42	336.32	175.46
Weis (2006)	0	0	2	−2	2	182.62	55.97	−59.28	399.43	−28.11
Sa										
Dickman (1993)	0	1	0	0	0	365.26	3.15	163.17	355.33	169.47
Dickman & Nam (1995)	0	1	0	0	0	365.26	3.33	161.60	332.53	170.51
Weis (2006)	0	1	0	0	0	365.26	26.39	−32.02	39.64	−80.09
Mn										
Dickman (1993)	0	0	0	0	1	−6798	221.54	167.34	174.03	167.12
Dickman & Nam (1995)	0	0	0	0	1	−6798	221.43	166.88	175.07	166.68

amp, amplitude; μas, microarcseconds; see Gross (2009) for definition of tabulated amplitudes & phases

5. SUMMARY

The Earth's rotation responds to changes in the tidal height and also, because the tides are not in equilibrium, to changes in the tidal currents. While many hydrodynamic models of the ocean tides exist, relatively few include both the tidal height and the tidal current components that are needed for Earth rotation studies. Those that do and that have been used previously to study the effects of ocean tides on polar motion have been examined here to test the degree to which they can explain the tidal variations that are observed to occur during 25 March 1995 to 28 May 2010. Since none of them can fully account for the observed tidal variations, an updated empirical model for the effects of long-period ocean tides on polar motion excitation was determined by fitting periodic terms at the tidal frequencies to observations spanning 2 January 1980 to 28 May 2010 from which atmospheric and non-tidal oceanic effects had been removed. While this empirical model does fully account for the tidal variations that are observed to occur during 25 March 1995 to 28 May 2010 (the time spanned by the second half of the data used to determine the empirical tide model), tests indicate that at least some of the tidal terms have not yet converged. So better models of the effects of ocean tides on polar motion are still needed, both dynamical and empirical.

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