Ocean tides in GRACE gravimetry.

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Abstract. The GRACE mission will map the Earth's gravity fields and its variations with unprecedented accuracy during its 5-year lifetime. Unless ocean tide signals and their load upon the solid earth are removed from the GRACE data, their long period aliases obscure more subtle climate signals which GRACE aims at. The difference between two existing ocean tide models can be used as an estimate of current tidal model error for the M_2, S_2, K_1, and O_1 constituents. When compared with the expected accuracy of the GRACE system, both expressed as spherical harmonic degree variances, we find that the current ocean tide models are not accurate enough to correct GRACE data at harmonic degrees lower that 35. The accumulated tidal errors may affect the GRACE data up to harmonic degree 56. To study the temporal characteristics of the ocean tidal constituents when sampled by GRACE, approximate alias frequencies were derived assuming a sampling of half a sidereal day. Those results show that the ocean tide errors will not cancel in the GRACE monthly averaged temporal gravity fields. The S_2 and the K_2 terms have alias frequencies much longer than 30 days, so they remain almost unreduced in the monthly averages. A simple experiment demonstrate that the potential of using GRACE data for improving the ocean tide models may reduce the total errors of the models from 2.2 cm to 0.55 cm.

Keywords: GRACE satellite mission, ocean tides, gravity.

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1 Introduction

The GRACE mission will accurately map variations in the Earth's gravity field over its 5-year lifetime [*Tapley*, 1997; *Bettadpur et al.*, 1999]. It will provide scientists from all over the world with an efficient way to map the Earth's gravity fields with unprecedented accuracy. The results from this mission will yield crucial information about the distribution and flow of mass within the Earth and it's surroundings. The gravity variations that GRACE will study include: changes due to surface and deep currents in the ocean; runoff and ground water storage on land masses; exchanges between ice sheets or glaciers and the oceans; and variations of mass within the Earth [*Wahr et al.*, 1998]. To reach these goals it is important to eliminate the effects of ocean tides on the estimated gravity field. Hence, an evaluation of the quality of existing models is important.

Hence, analyses of these effects and evaluation of their quality may be important. Previous studies have shown that ocean tides are important to consider and that the ocean tide models are not accurate enough to correct GRACE gravity fields fully at lower harmonic degrees [*Knudsen et al.*, 2000, and *Ray et al.*, 2001]. The analysis needs to be repeated using the most accurate ocean tide models. Furthermore, the results of the previous analysis indicate that ocean tides, e.g. the S_2 term, will not cancel out in the monthly averaged gravity fields due to the sampling characteristics of GRACE [*Knudsen et al.*, 2000].

In this analysis procedure for correction of GRACE gravity fields for effects by ocean tides are revised. The accuracies of the M_2, S_2, K_1, and O_1 ocean tide constituents of the most recent and highly accurate models NAO99 [*Matsumoto et al.*, 2000] and CSR4.0 [*Eanes and Bettadpur*, 1995] are assessed using spherical harmonic functions and the expected error degree variances for GRACE [*Bettadpur*, personal communication]. The sampling characteristics are revised and alias frequencies associate

(Figure 1). The M_2, S_2, K_1, and the O_1 constituents are significant up to harmonic degrees 33, 29, 24, and 22 respectively. The sum of the tidal errors from all four constituents accumulated by harmonic degree is shown in Figure 2 together with the accumulated error of GRACE. Above harmonic degree 40 the accumulated error of the tidal constituents reaches a value of about 1 micro Gal and intersects the increasing accumulated GRACE error at harmonic degree 56.

4 Tidal errors in GRACE monthly averages

The errors described in this study will affect the single measurements of GRACE. How the errors will affect GRACE products (e.g. models of monthly averaged temporal gravity fields) depend on the sampling frequency of GRACE, which depends on the orbit configuration for GRACE. The GRACE orbit is expected to be very stable in the inertial system due to its high inclination, i=89.5° [e.g. *Kaula*, 1966]. Hence, the solar tides may appear as a signal with an alias frequency close to annual or semiannual cycles. Subsequently, the errors in the models of the solar tides will not be averaged out over 30 day intervals.

To study this in more detail, alias frequencies of the eight largest tidal constituents were computed [e.g. *Knudsen*, 1994]. As sampling interval half a sidereal day (0.4986 days) was assumed. This corresponds to a sampling of the gravity field at both ascending and descending tracks, which will be relevant except for areas near the poles. The GRACE satellite will fly in a non-repeating orbit that complicates the definition of alias frequencies, since the sampling wi where □ and □ are the variances of the signal and the error respectively.

The results of the estimation experiment are shown in Figure 3. As expected, the aposteriori error degree variances are smaller that the GRACE error degree variances. The accumulated variances are shown in Figure 4 and show that the total errors in the gravity has decreased from 0.96 to 0.24 micro gal, which corresponds to a reduction in the errors in the tides from 2.2 to 0.55 cm. Hence, the a substantial improvement of the tide models may be obtained in the future using data from GRACE. However, the results of this experiment are highly optimistic, since no other errors have been considered in the estimation.

6 Discussion

The results show that latest generation of the ocean tide models are not being accurate enough to correct GRACE data at wavelengths corresponding to harmonic degrees 1-40 fully. Furthermore, the results of this analysis show that the ocean tide errors will not cancel in the GRACE monthly averaged temporal gravity fields at those wavelengths. Analysis of the alias frequencies of the tidal constituents show that the S_2 term and the K_2 term have alias frequencies much longer than 30 days, so that they remain almost unreduced in monthly averages. Furthermore, K_2 will introduce an error in determination of the static gravity field.

At harmonic degrees lower that 20 sea level signals as low as one millimeter will be significant in the GRACE temporal gravity fields. Hence, errors in both the ocean tide models and the loading models need to be considered. Spatial and temporal changes in the ocean water density may also be significant. On the other hand, the GRACE mission provide a new opportunity to improve the ocean tide models, which in turn will improve the modeling of the distribution and flow of mass within the Earth and it's surroundings.

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Table 1. Expected accumulated error of GRACE expressed as free air anomalies in micro Gal together with corresponding change in sea level height in centimeters.

Table 2. Tidal frequencies and preliminary alias frequencies assuming a sampling frequency of 0.498634 days in days. Also relative magnitude of tidal signal averaged over one month.

Constituent	Frequency	Alias	Averaged
M_2	0.5175	13.7	0.093
S_2	0.5000	182.5	0.955
N_2	0.5274	9.1	0.082
K_2	0.4986	∞	1.000
K_1	0.9973	0.9973	0.010
O_1	1.0758	1.0758	0.001
P_1	1.0028	1.0028	0.001
Q_1	1.1195	1.1195	0.001

Figure 1. Error degree variances of the M_2, S_2, K_1, and O_1 tidal models compared with the accuracies of GRACE.

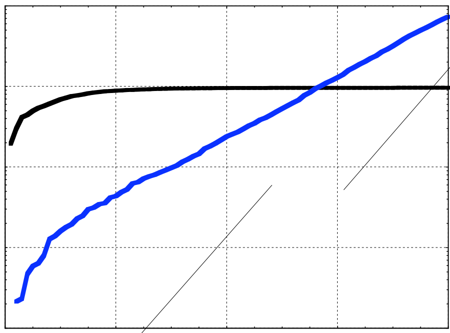

Figure 2. Accumulated error degree variances of the combined M_2, S_2, K_1, and O_1 tidal models compared with the accuracies of GRACE. The sum of the four constituents has a RSM of 2.2 cm.

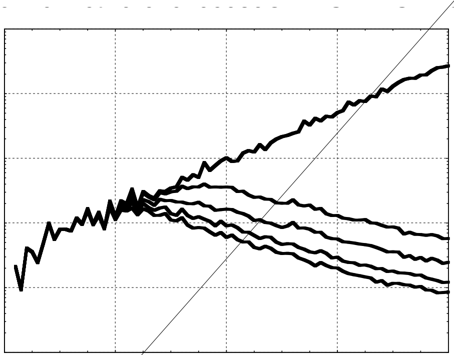

Figure 3. Error degree variances of the optimally improved M_2, S_2, K_1, and O_1 tidal models compared with the accuracies of GRACE.