Space-borne gravimetry: determination of the time variable gravity field

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Abstract. The gravity field of the Earth can be divided into a dominant quasi-static part and several relatively small but significant temporal constituents. Important examples of temporal sources are ocean tides, atmospheric pressure variations, and geophysical signals like those of continental hydrology and ocean bottom pressure variations predicted by the ECCO ocean model. Space-borne gravimetry, such as by the GRACE system, aims at observing temporal changes of the Earth's gravity field, including those induced by continental hydrology. A case study, based on a simulated gravity field retrieval for a 1-year GRACE-type mission, has been conducted to analyze the separability of continental hydrology from other temporal gravity sources.

It has been investigated how typical differences between recent ocean tide models and between global atmospheric pressure variation maps affect the observations (low-low satellite-to-satellite range-rate tracking (SST) and orbital positions from GPS high-low SST) and retrieved gravity field spherical harmonic expansions. In addition, the aliasing of signals predicted by the ECCO model and the effect of low-low SST observation noise and uncertainties in the recovered orbital positions has been analyzed.

It is concluded that large scale features of continental hydrology can be observed by a GRACE-type mission, provided that the low-low SST observations have a precision at the level of 1 μm/s at 1 Hz, and when great care is taken with the gravity field recovery approach.

Key words. low-low satellite-to-satellite tracking, temporal gravity, hydrology, atmosphere, tides, ocean models

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1 Introduction

Satellite Laser ranging (SLR) to satellites such as LAGEOS-1 and -2 has proved the possibility for observing temporal gravity in the very long wavelength domain leading for example to intriguing results for the time evolution of the Earth's oblateness or predominantly the J_2 term (Cox and Chao 2002; Cazenave and Nerem 2002). The CHAMP (launch July 15, 2000, (Reigber et al. 1999)) and GRACE (launch March 17, 2002, (Tapley and Reigber 1999)) satellite missions have opened the possibility for observing temporal gravity from space on a much more detailed scale than ever before and impressive results have already been obtained (Tapley et al. 2004). These results indicated the possibility for observing changes in continental hydrology in very large basins, such as in the Amazone area in South-America. However, results also indicated that great care needs to be taken when modeling other temporal gravity field sources such as ocean tides and changes in the atmospheric mass distribution. In addition, it was found that the gravity field reduction process is very sensitive to the parameterization of the gravity field estimation problem (arc length, empirical accelerations, accelerometer biases and scale factors). It was concluded that SLR tracking remains to be an important asset when analyzing geocenter variations (spherical harmonic degree 1 terms) and changes in J_2, and is a prerequisite for diagnosing possible problems in the processing of CHAMP and GRACE observations taken by the on-board science instruments.

The problem of temporal aliasing of different gravity field sources has been studied extensively,*cf.* (Han et al. 2004) and (Velicogna et al. 2001). We have built a simulation tool around the GEODYN software package (Rowlands et al. 1995) that allows to study the observability and separability of different gravity field sources (static and temporal) for several gravity field mission concepts and scenarios, including CHAMP- and GRACE-type missions, and possible future missions such as GOCE (ESA 1999) and GRACE/GOCE follow-ons. This tool allows a rigorous parameterization of the gravity field estimation problem and long data periods. It has been used for a case study where a one-year GRACE-type mission is defined for observing mass changes due to continental hydrology. The observability is studied in the presence of typical low-low SST observation noise levels and coupling with (errors in the modeling of) other temporal gravity field sources, including atmospheric mass redistributions, ocean tides and mass changes inflicted by ocean bottom pres-

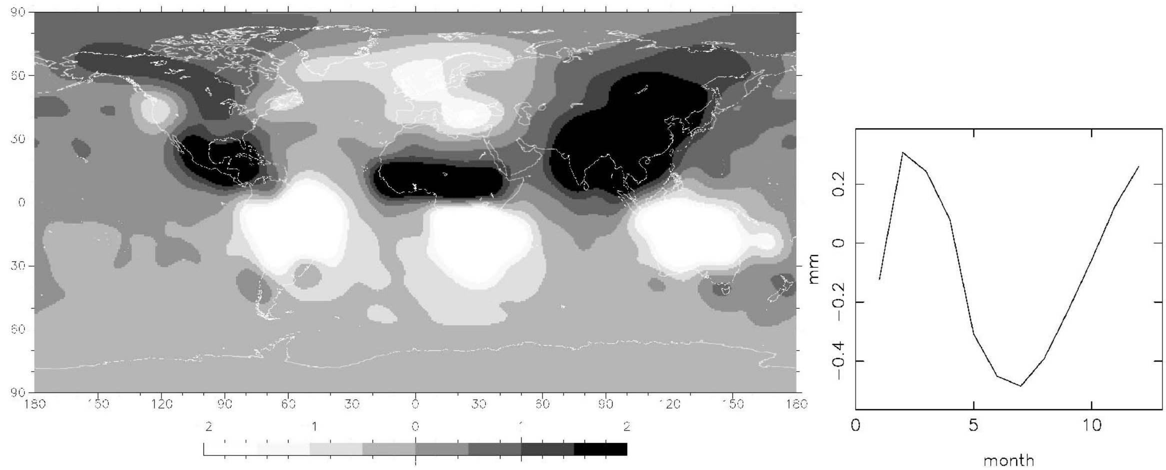

Fig. 1. Dominant mode (EOF) of mass changes due to continental hydrology for 2000 (Fan and van den Dool 2004). Please note the scale of the time pattern is in mm.

sure variations making use of ECCO ocean models (ECCO homepage 2004).

The simulation tool makes use of numerical integration of the equations of motion and variational equations for the estimated gravity field and orbit parameters, and offers the possibility to describe the Earth's gravity field as a sum of a baseline static part and (different) combinations of temporal sources. Currently all sources are represented by spherical harmonic expansions, although also space localized functions such as gravity anomalies and density layers are possible. For the case study to be outlined in the next section, the following models were used:

- Static gravity field model: GGM01S;
- Temporal gravity:
  - Continental hydrology (Fan and van den Dool 2004);
  - Ocean tides: FES99 and GOT99.2b;
  - Atmospheric mass variations: ECMWF and NCEP;
  - Ocean bottom pressure: ECCO.

The real world was modeled by the GGM01S static field (GRACE CSR home page 2004) in combination with GOT99.2b (Ray 1999) ocean tides, ECMWF based atmospheric mass variations, oceanic mass redistribution according to ECCO models, and continental hydrology (Fan and van den Dool 2004). The GGM01S model is a GRACE-based satellite only solution to degree and order 120, but was truncated at degree and order 50 in the case study. The two ocean tide models were derived using different methodologies. GOT99.2b is an empirical model, whereas FES99 makes use of hydrodynamical equations. The temporal background gravity field models were developed complete to degree and order 20 (making in certain cases for example use of Love numbers for converting equivalent water heights to Stokes coefficients, see (Schrama 2003)). Figure 1 displays the dominant mode (first EOF or Empirical Orthogonal Function) of the continental hydrology model in terms of geoid variations for a one year period. This dominant mode represents about 80% of the amplitude, or about 60% of the energy of the total signal. Clearly visible are relatively large fluctuations in the area covering part of the Southern states of the U.S, Mexico and Latin America, the area from the Sahel to South-Africa, the Amazone and Zambesi basins and areas in East-Asia. Also clearly visible is the dominant annual signature (right part of the Figure). The objective of the case study is to investigate whether this signature can be recovered by a GRACE-type mission in the presence of observation errors (low-low SST and GPS-based orbit reconstruction errors), mismodeling of ocean tides (using FES99 as reference model, (Lefèvre et al. 2002)) and atmospheric mass variations (using NCEP reanalysis surface pressure data as reference), and ignoring ECCO predicted gravity changes (see also Table 1). The static gravity field model is assumed to be a long-period averaged solution with negligible errors.

2 Temporal gravity

The signal and/or model uncertainty size derived from the spherical harmonic expansions of the different gravity field sources is displayed in Figure 2. In fact, for the atmospheric mass variations the signal size is the average of 366 daily spherical harmonic expansions complete to degree and order 20 (in the following referred to as 20x20) using daily pressure fields from the year 1992, for ECCO from 2000, and for continental hydrology the average of 12 monthly 20x20 fields for 2000. It can be seen that the error

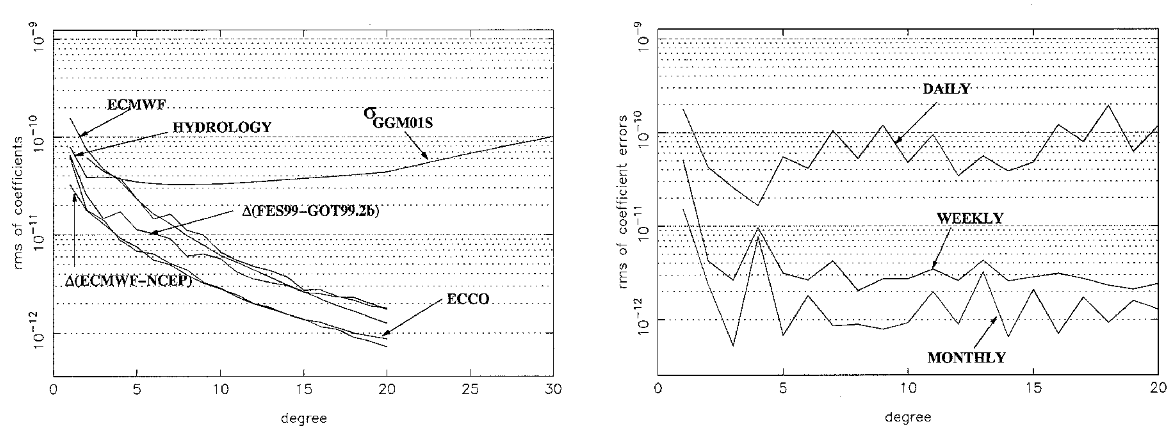

Fig. 2. Magnitude of temporal gravity field sources and model differences, and quality of GGM01S (left), and effect of observation noise on gravity field recovery accuracy for different observation period durations (right). The temporal gravity field sources include ocean tide model differences between FES99 and GOT99.2b, gravity field changes due to atmospheric mass redistributions (total signal according to ECMWF, and differences between ECMWF and NCEP), and gravity field variations due to continental hydrology and ECCO ocean models.

level of GGM01S, which is based on 111 days of GRACE observations, is above the signal size of continental hydrology up to degree 5. However, it is fair to assume that significant improvements will be made as time progresses resulting in more observations and a better understanding of the behavior of the GRACE system. Moreover, the objective is to study temporal gravity, although it is realized that errors in the static gravity field model might affect the recovery of temporal gravity, which is an interesting topic for future research. The signal size of the atmospheric mass variations is of the same order of magnitude as those inflicted by continental hydrology. Assuming that the differences between ECMWF and NCEP atmospheric pressure fields are representative for the accuracy with which atmospheric mass variations can be modeled, Δ(ECMWF-NCEP), continental hydrology can still be observed. The signal predicted by the ECCO model has a size comparable to the differences between the two atmospheric pressure field models and is in fact much below the continental hydrology signal. The uncertainty in ocean tide modeling, reflected by Δ(FES99-GOT99.2b), intersects the continental hydrology signal around spherical harmonic degree 15 (see Figure 2). Based on these results, it may be concluded that an effort is required to further improve ocean tide modeling.

3 Case study

Gravity field recovery simulation experiments have been conducted for a one year period, or 366 days for 2004 (leap year). It has to be noted that some temporal gravity sources that were used in the simulations are for 1992 and 2000 (Section 1). It is fair to assume that these data sets realistically reflect the signal magnitudes and time signatures that can be expected. A GRACE-type mission is selected, consisting of two satellites flying en echelon in 440 km altitude orbits with an inclination of 89° and separation of 200 km. Gravity field models are estimated from low-low SST observations and orbit positions (inertial Cartesian x, y, z coordinates) resolved from the GPS high-low SST observations. The low-low SST observations are sampled at 30-s intervals and Gaussian noise is added with a standard deviation of 0.2 μm/s (equivalent to 1 μm/s at 1 Hz). The orbit coordinates of the two satellites are assumed to have an accuracy of 1 cm (Gaussian) and are sampled at 2-min intervals (Table 1).

Table 1. Definition of case study: truth, reference and error models.

Truth model	
static gravity field:	GGM01S
continental hydrology:	Fan & Dool, 2004
ocean tides:	GOT99.2b
ocean bottom pressure:	ECCO
atmospheric pressure:	ECMWF
Reference model	
static gravity field:	GGM01S
continental hydrology:	none
ocean tides:	FES99
ocean bottom pressure:	none
atmospheric pressure:	NCEP
Observation errors (Gaussian)	
low-low SST:	$\sigma = 0.2$ μm/s @ 30-s
orbit coordinates:	$\sigma(x, y, z) = 1$ cm @ 2-min

The one-year simulated observation data set is divided into daily periods and for each day normal equations are computed for a 20x20 spherical harmonic gravity field model (including degree 1 terms) and for epoch state vectors for the two satellites ($2 \times 6 = 12$ unknowns per day, each state vector consisting of 3 position and 3 velocity coordinates). It is fair to assume that above degree 20, the temporal gravity field signals have a very low signal magnitude (Figure 2) and it is also assumed that a high-accuracy, higher resolution background model is available for the static gravity field (in this case the 50x50 truncated GGM01S model). However, for future more advanced and precise gravity field missions, the simulations can be extended to (much) higher degrees, requiring extensive (but feasible) computer resources. The daily normal equations can be combined to obtain gravity field solutions for different period lengths. For example, a weekly solution is obtained by combining 7 daily normal equations solving for 84 (7×12) epoch state vector unknowns and one 20x20 gravity field spherical harmonic expansion.

4 Results

Before conducting the gravity field recovery in the presence of all error sources according to Table 1, the effect of different temporal gravity field sources on the low-low SST range-rate observations was assessed. The signal Root-Mean-Square (RMS) of the low-low SST range-rate observations is typically around 20 cm/s, and is dominated by the J_2 term. For all 366 days, the RMS is computed by estimating only the 12 (2×6) epoch state vector parameters. Finally, the RMS of the 366 daily RMS values is displayed in Table 2. Continental hydrology causes an RMS signal of about 0.18 μm/s, compared to 0.14 μm/s for the FES99/GOT99.2b ocean tide model differences, 0.43 μm/s for atmospheric mass variations predicted by ECMWF pressure fields, 0.22 μm/s for the differences between ECMWF and NCEP, and 0.10 μm/s for mass variations induced by the ECCO model. These numbers indicate that atmospheric mass variations need to be accurately modeled, that ocean tide model uncertainties compete with the continental hydrology signal and that the ECCO model results in relatively small low-low SST range-rate perturbations.

In a second step, the separate effect of observation errors on the achievable gravity field recovery error was assessed by generating 366 daily, 52 weekly and 12 monthly solutions. The annual averages of the degree RMS values of spherical harmonic coefficient errors is displayed in Figure 2. It can be seen that for weekly and monthly solutions the errors are below the continental hydrology signal, but that this is not the case for daily solutions (which can be anticipated considering that the satellites complete 16 orbital revolutions per day, but that a 20x20 model is solved for; in all cases no regularization was applied). The dominant error mode (EOF analysis) of the daily gravity field solutions in term of geoid is displayed in Figure 3 displaying a pattern commensurate with the daily ground tracks of the satellite pair. A similar pattern was predicted by an EOF analysis of the dominant eigenvectors of the daily inverses of the normal equations.

Table 2. RMS of low-low SST observation residuals (30-s sampling) due to different temporal gravity field sources (366 daily arcs)

Source	RMS (μm/s)
Continental hydrology:	0.179
Tide model differences:	0.142
Atmosphere: ECMWF	0.432
Atmosphere: ECMWF-NCEP	0.227
ECCO	0.101

Based on the previous results, it was decided to generate a time series of 52 weekly (or 52 7-day) gravity field solutions in the presence of all error sources listed in Table 1. Again, an EOF analysis was conducted. Figure 4 clearly reveals the dominant mode caused by errors in the recovery of degree 1 terms, which are heavily correlated with the 2×6 epoch state vector. It is obvious that the continental hydrology signal (Figure 1) is completely obscured by this mode. This error mode can again be predicted by error propagation, and thus seems to indicate an inherent weakness in the gravity field recovery approach (which might be solved by adding certain types of tracking data to other satellites, such as SLR tracking of LAGEOS-1/2). It was also found that the FES99 and GOT99.2b ocean tide model differences cause relatively large perturbations in the degree one gravity field terms indicating the need for co-estimation of tide model terms and/or independent tide model improvement. However, generating a second series of weekly gravity field solutions without solving for the degree one terms results in a dominant mode as displayed in Figure 5, clearly revealing the most important features of the continental hydrology signal (Figure 1). Striking differences can be observed in the Antarctic region, which can be attributed to large differences between the ECMWF and NCEP atmospheric pressure fields. Although the time signature is rather noisy, it displays a clear annual period comparable to the true annual pattern. It was found that this noisy behavior is reduced significantly when making monthly gravity field solutions.

It is interesting to compare as well the fourth EOF of the case where the gravity degree 1 terms (3 coefficients leading to possibly 3 dominant EOFs) are

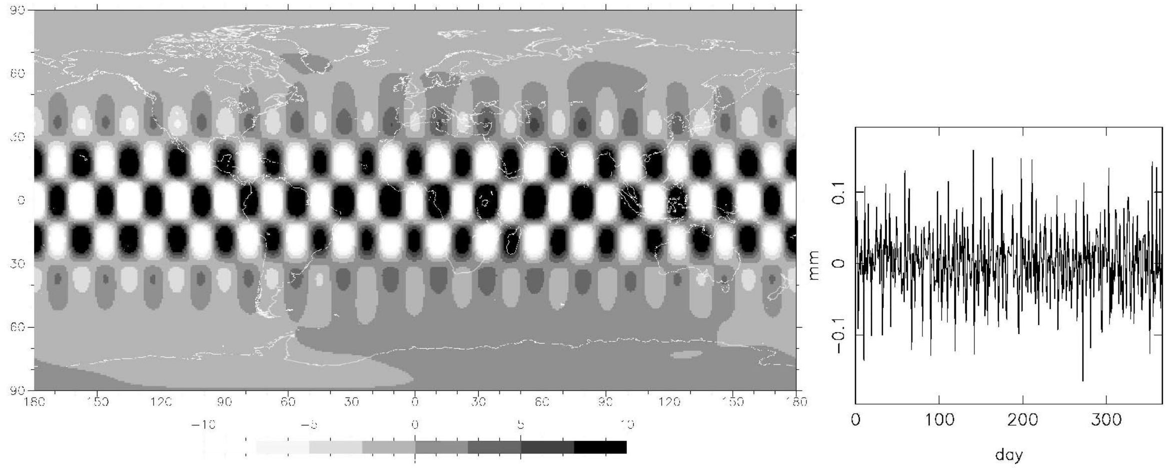

Fig. 3. Dominant mode (EOF) of recovered daily gravity field solutions with only observation noise switched on.

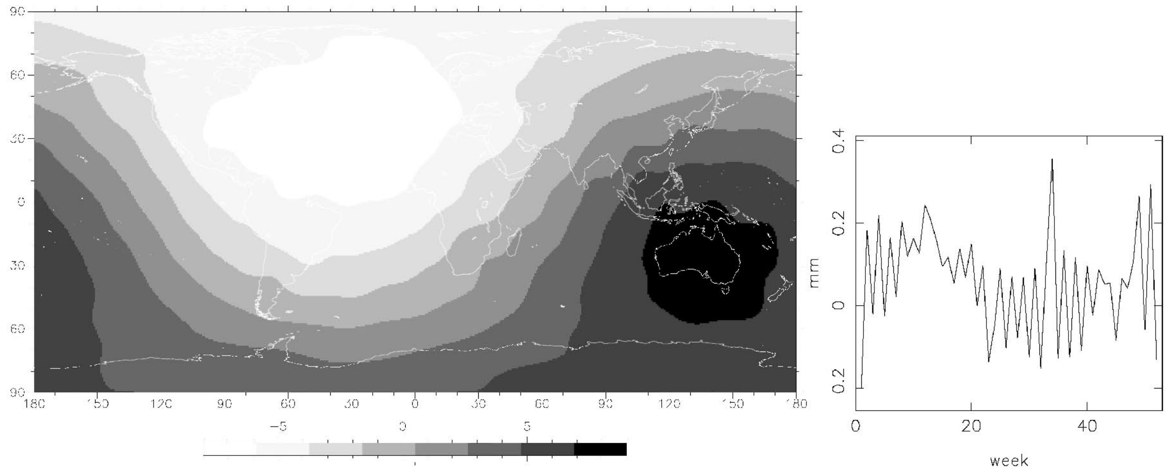

Fig. 4. Dominant mode (EOF) of recovered weekly gravity field solutions with all error sources switched on (degree one terms included).

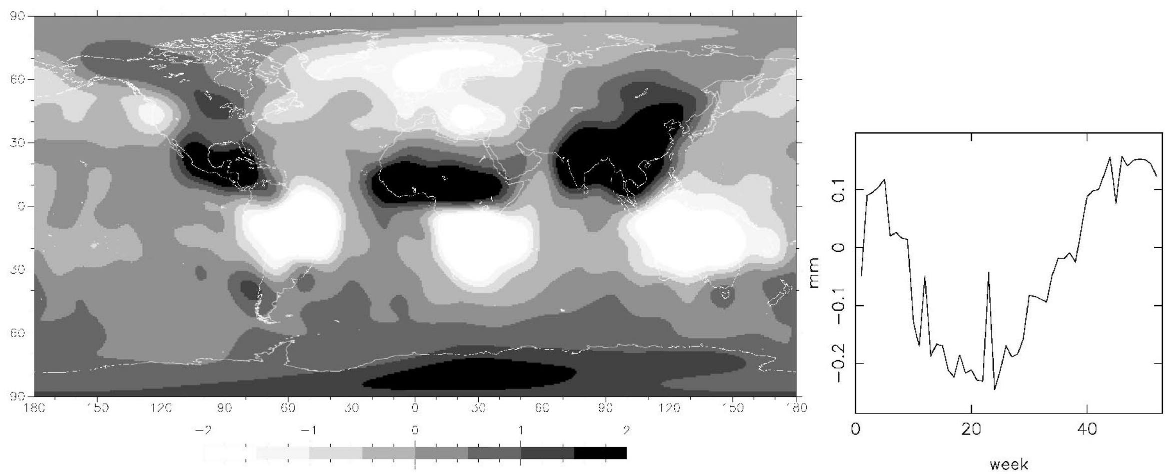

Fig. 5. Dominant mode (EOF) of recovered weekly gravity field solutions with all error sources switched on (degree one terms ignored).

estimated with the first EOF as displayed in Figure 4. It was found that these EOFs compare very well: the correlation is bigger than 90%.

5 Conclusions

Temporal gravity field variations such as induced by continental hydrology is observable with GRACE-type missions.

Great care needs to be taken with the parameterization of the gravity field recovery. First of all, the arc length and the combined estimation of non-gravitational (for example satellite epoch state vectors) and gravitational parameters needs to be carefully defined and investigated. Second, the period for which gravity field solutions are to be generated needs to be balanced with the required precision, temporal and spatial resolution levels.

It was found that the degree one terms can be seriously affected by uncertainties in ocean tide models. Also, there are indications that degree one terms are weakly observable by the investigated mission concept in combination with the adopted gravity field recovery approach. For overcoming this weakness, continued high-quality SLR tracking is instrumental and will in combination with GRACE-type observations guarantee high-precision temporal gravity modeling from the very long to the medium wavelength domain (degree 1 - 20).

The low-low SST observations need to have a high precision level, of the order of 1 μm/s at 1 Hz. In order to be able to observe continental hydrology, mass variations due to ocean tides and atmosphere need to be modeled with great precision.

Finally, it can be concluded that a tool has been implemented that can be used for gravity field mission analysis, opening the possibility to assess in a closed-loop the effect of observation noise, satellite configuration, mismodeling of (combinations of) gravity field sources and gravity field recovery reduction approach and parameterization.

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