Balancing, Turning, Saving

Special AOCS Operations to extend the GRACE Mission

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The two GRACE satellites were successfully launched on March 17, 2002 by a Russian Rockot launcher. The main objective of the mission is the measurement of the Earth's gravity field and its time dependencies. It was the first dual-satellite mission operated by GSOC and also the first formation-flying occurring at an altitude below 500 km. The mission is extremely successful from a scientific point of view and the originally envisaged duration of 5 years has more than doubled by now. A follow-on mission is planned by the same partners for 2016 and JPL projects a new generation in the twenties, so there is a strong incentive to prolong GRACE and try to bridge the gap.

A number of special AOCS operations and analyses have evolved over the years in order to extend the mission as long as possible. This encompasses such obvious measures as the minimisation of fuel usage and thruster cycles, but also the continuous optimisation of parameter settings and the balancing of several consumables. Close interaction between the science- and operation- teams is required throughout, because the satellites themselves are part of the experiment.

I. Introduction

The GRACE mission - "**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment" - is a scientific co-operation between the USA and Germany. The two identical satellites were designed and built by Astrium in Germany. All operations are carried out at the German Space Operations Centre (DLR-GSOC), whereas the scientists are from the University of Austin in Texas and the Geoforschungszentrum Potsdam, Germany. The on-board instrument processing unit (IPU) is under the responsibility of JPL (Jet Propulsion Laboratory, USA).
The main scientific goal of the mission is to collect data for creating both static and time-varying Earth gravitational field models of unprecedented accuracy. This is done by measuring relative variations in satellite separation down to 1 μm/sec, using a microwave link between the two spacecraft that are flying on a polar orbit at an altitude of currently ~450 km and that are kept at a distance of 220±50 km. Study of time dependencies, yielding for example the long-term development of polar or glacier ice masses, or of the water masses in the Amazonas basin, gained in importance over the years and is by now the strongest incentive to prolong the mission as long as possible.

The two satellites themselves are the probes in the terrestrial gravity field and thus an integral part of the payload. The determination of the mutual distance is supplemented with accurate measurements of the SuperStar accelerometer on each spacecraft and by information from the USOs (ultra stable oscillator), from the two star cameras, from a GPS receiver and a magnetometer and from the TLEs[3]. Consequently there is a strong interplay

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[3] Two-Line Elements with orbit information of both satellites are daily sent to both, providing each with knowledge of its own and the other's position and velocity – yielding the so-called reference attitude.

between the satellite's payload operations and the attitude control system (AOCS) which also uses (part of) this information. The orbit must be maintained within prescribed limits on distance, eccentricity and inclination for maximal scientific return. GRACE in fact never entered a "routine" phase, but saw continuous optimisations, parameter adjustments and adaptations which are still ongoing.

The unusual character of the mission is illustrated by the dates and the numbers in Table 1. Recommendations contain a description, an incentive, an execution time, parameter settings, as well as commands to be sent to the satellites and these are only written in case of non-standard operations. New star camera parameters, centre-of-mass calibrations, orbit manoeuvres, or battery handling are a few examples. Routine operations, such as the planning of data dumps and station contacts, or the upload of TLEs, or the commands for star camera head switches in case of intrusions, are all handled with a planning tool and do not require a recommendation. Also non-routine, but often returning occurrences such as an IPU reboot, or a restart of the link between the two satellites, lie within the authority of the operators and are handled without recommendations.

Mission phase	Time interval	Days	Recommendations	RI/day
LEOP	17.03.2002 – 28.04.2002	43	454	10.56
Commissioning	29.04.2002 – 15.05.2003	382	381	1.00
Validation	16.05.2003 – 20.05.2006	1101	713	0.65
Observational	21.05.2006 – present	2146	1731	0.81

Table 1. **GRACE satellite operations over the entire mission**. *Note the long duration of the instrument commissioning phase and the fact that there never was a routine phase. Recommendations contain commands or command procedures and comprise non-routine operations only. Their numbers remained at a constant level after LEOP.*

Longevity depends on the continued functionality of hardware components, on orbital height, on the availability of non-replenishable resources and on reliable predictions.
A complete list of failed components and of those with degraded performance can be found in Herman *et al*., 2012. Several factors that limit the lifetime are presented in Section 2. This also contains the estimates for the remaining life of GRACE. The numerous parameter adjustments throughout the mission are subject of Section 3. Note that only those pertaining to AOCS are treated here. An example for another sub-system can be found in Herman *et al*., 2012, where the handling of the degraded batteries is described. A special case of parameter optimisation is presented in Section 4 which describes the balancing of thruster actuations in two axes. The fifth and final Section contains some conclusions and recommendations for the follow-on missions.

II. Lifetime estimates

Prerequisite for a mission extension far beyond the originally planned five years is a careful management of available resources and the balancing of the several effects that limit the lifetime. Some effects can not be controlled of course, but a short discussion will be given here of those that can.

Front-end oxidation
The micro-wave assembly (MWA) handles the K-band ranging signals (K-band at 24 GHz and Ka-band at 32 GHz) that are sent and received by each satellite (Fig. 1). The mount at the front-side implies that the leader must fly backwards. Front-end oxidation by the remnant atmosphere is thus mainly a factor on the follower. The degradation depends upon orbital height and solar activity.

The mission benefits from a launch just after the previous solar maximum and the weak maximum in the current cycle, which means that the increase of the atmospheric scale height is moderate until now. The two satellites were swapped in December 2005 after 1363 days in orbit, at that moment thought to be roughly halfway through the mission. GRACE 1, leader until then, was made follower thus balancing the wear of the front-ends.

Another satellite switch is not contemplated at the moment, although the mission continues for more than 3700 days now. Functionality and temperature behaviour of both front-ends still compare very well and do not make such an action necessary. There is also still fuel enough on-board to carry out an orbit-raise manoeuvre. Again there is no direct need with the satellites still at 450 km and the scientist interested in measurements at lower altitudes also.

Figure 1. Artist impression of the two GRACE satellites. *The MWA supplies the link between the two satellites and is mounted at their front-sides. This means that the leader has to fly backwards to enable payload operations. Obviously the picture shows the situation shortly after launch with both satellites still flying forwards and much closer than the nominal 220 km separation.*

Orbit decay
The current mean altitude of 450 km leads to a prediction for re-entry between early in 2015 to the middle of 2016 depending upon the predicted solar activity (Fig. 2). The expectation of another 3½ years in orbit is enough at the moment to waive the option of spending part of the remaining fuel on an orbit raise manoeuvre. Unexpectedly high solar activity might still change this assessment.

Cold gas fuel
The cold gas system is used to serve both the two 40 mN orbit thrusters as well as the twelve 10 mN attitude thrusters. The fuel remaining in the two tanks can be derived from the known volume and measured pressure and temperature. The on-times, together with the known thruster characteristics yield the fuel expended on orbit and attitude corrections. A third method, dubbed “book-keeping” determines the amount of fuel used between two station contacts assuming a constant conversion factor for the accumulated thruster on-time throughout the mission.

Satellite	**At launch**	**Remaining GN2 fuel**			
	(kg)	TPV (kg)	On-time (kg)	Book-keeping (kg)	Mean
GRACE 1	33.119	13.9	14.5	14.3	14.2±0.2
GRACE 2	33.183	16.0	15.8	16.2	16.0±0.2

Table 2. Remaining cold gas fuel. *The close agreement between the remainder in the tanks (derived from pressure and temperature) and the expenditure by the thrusters (derived from the accumulated on-times) implies that there is no noticeable leakage yet.*

It can be seen from Table 2 that even after ten years the three methods are in excellent agreement and also that an appreciable fraction of the fuel is still available. A realistic estimate of the remaining lifetime, however, must take

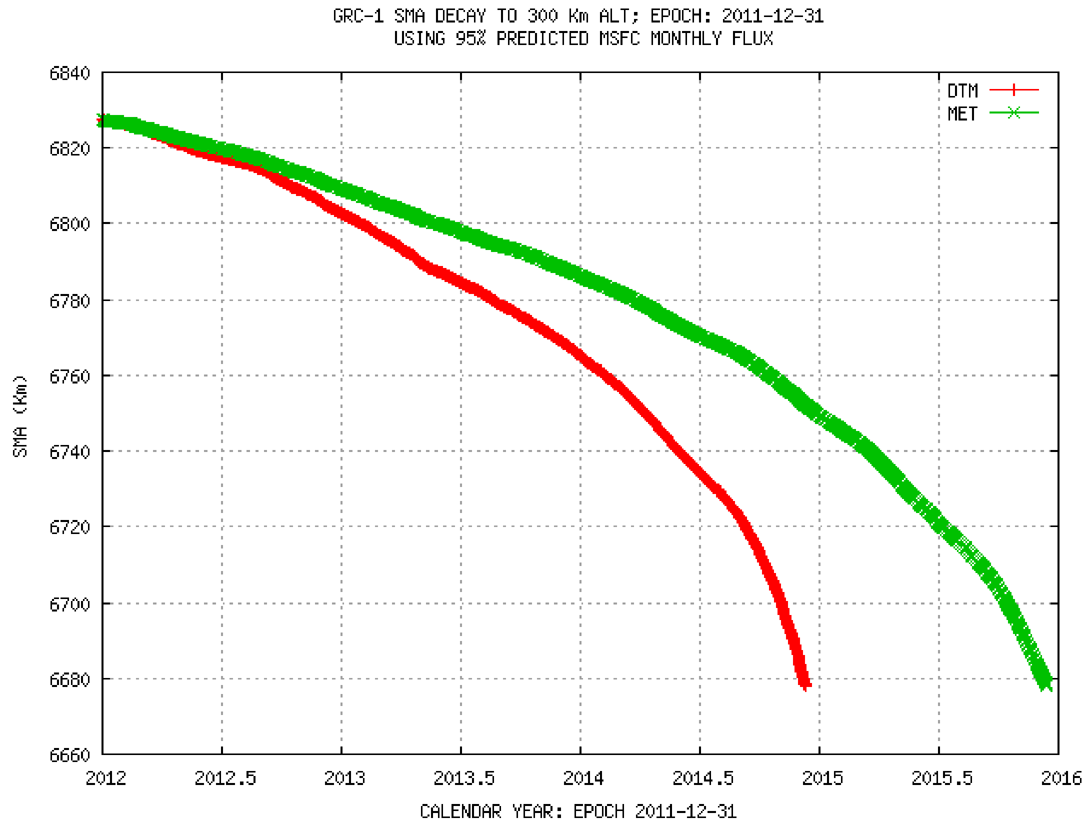

Figure 2. Predicted decay of the semi-major axis (*from the University of Texas, Center for Space Research; website for GRACE operations*).

into account that some fuel will not be usable at the end, that the efficiency slowly decreases and also that seasonal and long-term variations exist.

An example is given in Fig. 3 for GRACE 1, which has 1.8 kg less fuel left than GRACE 2. The red and green lines show the total and remaining lifetime based upon all mission data. This includes effects of the LEOP and early commissioning phase, which explains why the curves rise at the beginning. The expectancy for the mission duration levelled off at ~16.8 years, meaning that the prediction is now quite reliable. A small decrease can be observed at the very end, however, which is caused by clearly higher than average expenditure over the last year. The cause is the number of additional yaw manoeuvres that have to be made to keep the battery alive (see Herman *et al.*, 2012).
The decrease of the thrusters' efficiency is determined from the on-time required per attitude pulse. This is now ~3% more on average than at the beginning of the mission. Thus an expectancy of six more years is too optimistic, but the mission goal of 2016 can easily be attained.

Fig. 3 shows two more curves that corroborate this conclusion. A more reliable prediction is obtained when the usage over the last 322 days only is extrapolated (322d corresponds to the precession period of the GRACE orbit in the inertial frame; brown line). The yellow line shows a prediction on basis of the last 100 days. Here a seasonal variation is observed with the life expectancy dependant upon which star camera is used as prime (indicated by the lilac and blue lines at the bottom). The orbit precession necessitates a switch every 161 days. The performance of SCA#2 on the –y-side of the satellite is clearly better and leads to more optimistic lifetime predictions. Considerable differences are observed during the first years of the mission, but presently all three methods (total mission, last 322d and last 100d) have converged and predict a remaining life of almost six years.

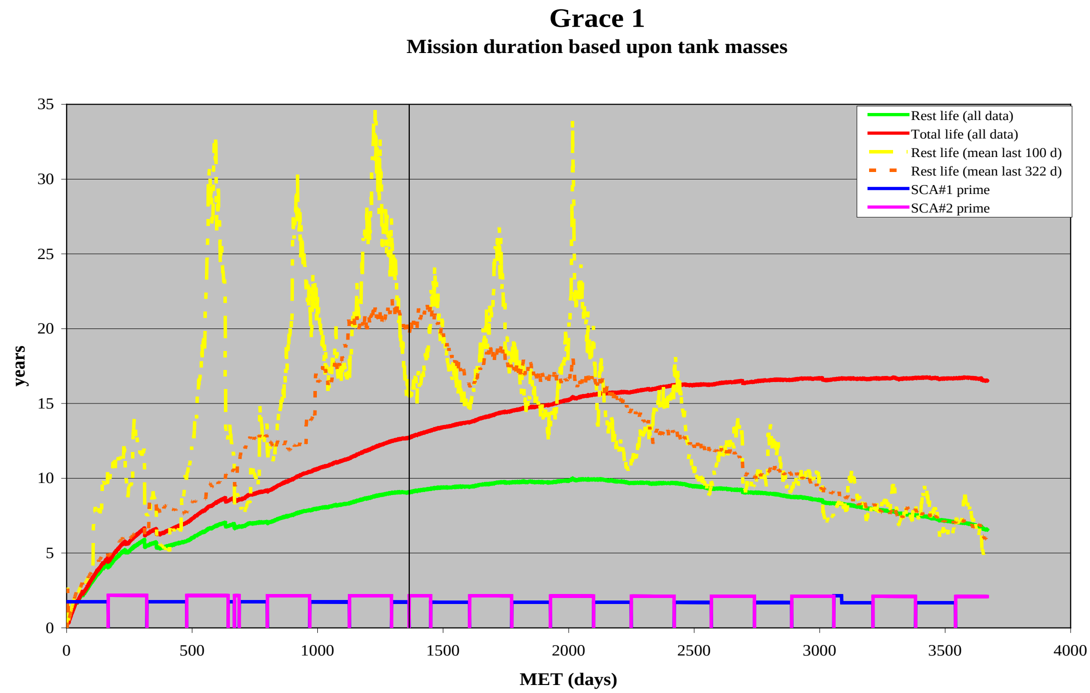

Figure 3. Lifetime estimates for GRACE 1 based upon fuel expenditure. *The vertical line shows the time of the satellite swap. The abscissa shows mission elapsed time (MET since 17.03.2002). See text for further details.*

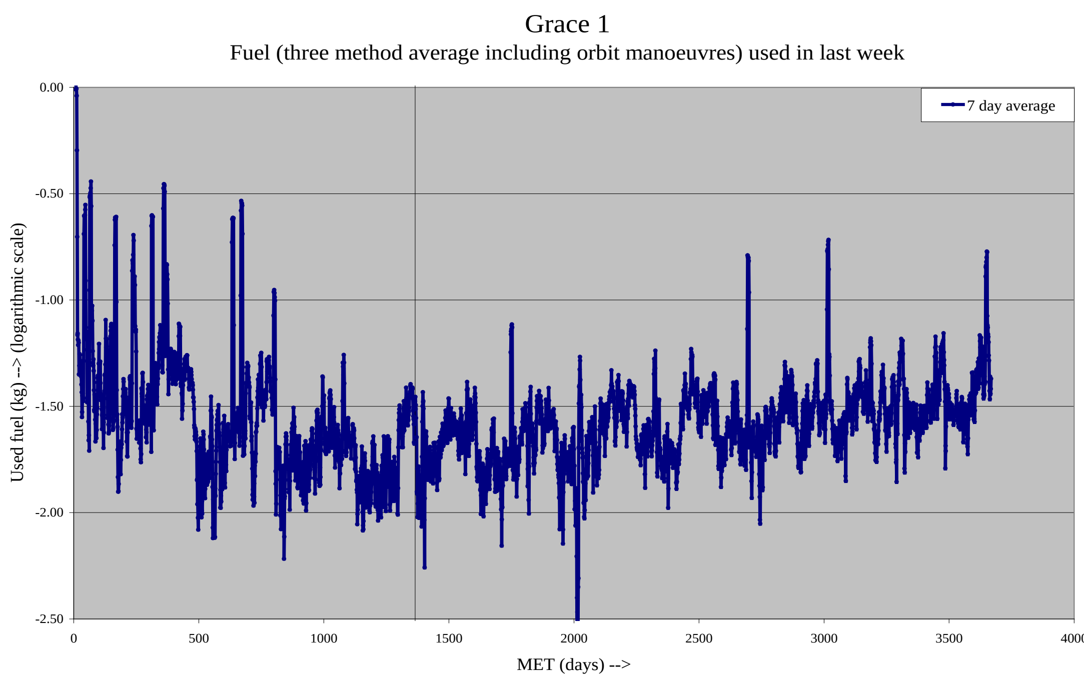

Figure 4. Fuel usage per week over the entire mission. *Optimisation during the first part of the mission with MET<1000 resulted in a clear improvement in average expenditure. The slow rise after the swap manoeuvre (vertical line) is caused by the gradual performance degradation of the star cameras. The 322d period that is visible in the data reflects the seasonal changes of the prime star camera. The single peaks are due to either safe mode, or special operations such as orbit manoeuvres or slews.*

There will be a somewhat more detailed discussion on the optimisation of star camera performance in the next Section.

GRACE 1 has 1.8 kg less fuel left than GRACE 2. Also, the depletion of the two tanks is not exactly equal. Currently there is a difference of ~100 grams between the two tanks on GRACE 1 and ~300 grams on GRACE 2. All orbit correction manoeuvres are therefore made on GRACE 2 and the last eight manoeuvres used only one thruster and hence only fuel from the tank with most mass left. Finally, it would be possible to restore the balance between the tanks in case the difference grows too large by opening the connecting solenoid valve.

Thruster cycles

Attitude corrections are made with three magnetic torque rods (with a double coil for redundancy) assisted by twelve 10 mN thrusters. Magnetic authority to correct deviations in pitch is given over the entire orbit, but roll errors can only be corrected in the vicinity of the poles and yaw deviations only near the equator. The number of thruster cycles in the roll- and yaw- channels is much higher therefore than in pitch (*Cf.* left and right hand scales in Fig. 5).
The maximum number of actuations for a single thruster does not have a hard limit, but the manufacturer guaranteed the functionality up to one million cycles and tests have been performed up to $2\ 10^6$ (project internal information). The yaw thrusters on GRACE 1 recently reached the guaranteed million. Neither these nor any of the other attitude thrusters on both satellites shows any problems so far[4].

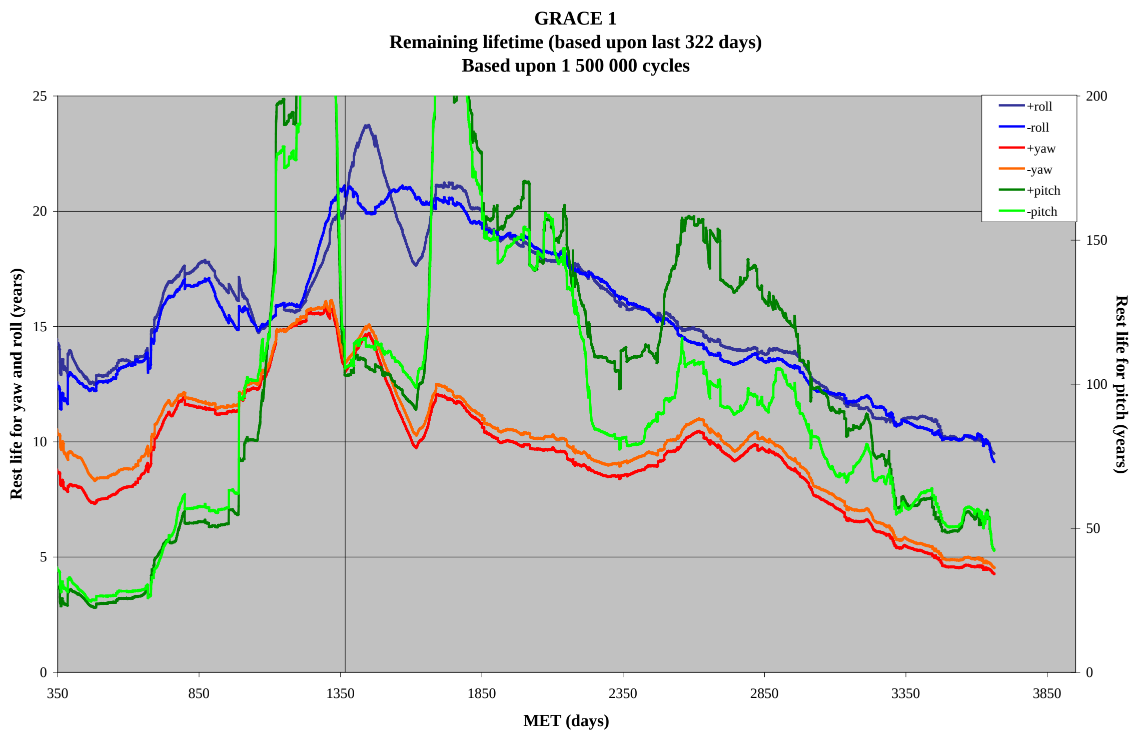

Figure 5. Estimation of the remaining lifetime of the several attitude thrusters. *The calculation is based upon the assumption that 1½ million cycles is the maximum. The factor of ten difference between roll (blue lines) and yaw (red/orange) on the one hand (left scale) and pitch on the other (green lines; right hand scale) is explained by the relative orientation of the orbit and of the magnetic field. The clearly visible difference in life expectancy between roll- and yaw- thrusters prompted extensive mitigation measures to be initiated (see discussion in Section IV).*

[4] Analysis of long-term thruster behaviour seems to indicate a small leak on one of the –roll thrusters on GRACE 2. The loss amounts to less than 1% of the daily expenditure, or <30 grams per year, negligible in view of the 1.8 kg difference between the two satellites (Table 2).

An estimation of the thuster lifetime is therefore made under the somewhat arbitrary assumption that the maximum number of cycles will be 1.5 10^6 (see Fig 5).
Again results for GRACE 1 only are shown, because the expectancies on GRACE 2 are somewhat higher. The worst channel is +yaw which has an expectancy of less than five years. However, this is still amply sufficient to attain the mission goals. There is of course no guarantee that a given thruster will continue fully functional, but the AOCS still has the full redundancy of 2x3 torque rods, 2x6 attitude thrusters and 2 orbit thrusters available. The cold-gas systems also is equipped with two separate branches and tanks, which still can be connected if need arises.

III. Parameter adjustments

21% of the AOCS parameters have been adjusted over the years, several of them even manifold. The star camera alignments provide an obvious example, but also the strength of the magnetic control as compared to that of the attitude thrusters was tuned a number of times during the first years. Both star cameras now run with a 1 Hz sampling rate, which was not foreseen originally. The magnetic field measurements turned out to be too noisy to the liking of the scientists and were therefore smoothed with the on-board field model. Later in the mission a servo-loop was installed, whereby the measurements of the magnetometers are corrected for the disturbances by the currents commanded to the torque rods. The influences of attitude control and of changes in AOCS parameter settings on the scientific results have been subject of detailed study (see e.g. Bandikova *et al*., 2010). Numerous other parameters, threshold and filter settings were also optimised, but a complete discussion lies outside the scope of this paper.

A few of the recurrent measurements and adjustments are briefly presented here. The balancing of yaw- and roll-thruster actuations will be discussed in more detailed in the next Section.

Calibration of the KBR-link
Settings for the link between the two satellites were calibrated in orbit several times by measuring the beam pattern. This is done by moving each satellite in turn ±2° in yaw and pitch and measuring the attenuation. Detailed results can be found in Wang (2003).

Determination of the centre of gravity
The centre of mass (CoM) of each satellite changes during the mission, mainly due to the imbalance between the two fuel tanks. It is measured twice per 322 day period at specific longitude and latitude locations, when the satellite is in full-sun orbit. Attitude errors are first minimised by decreasing the dead bands by a factor of ten. Then autonomous attitude control is *de facto* disabled by suddenly increasing the dead bands by a factor of hundred. A periodic attitude variation is introduced by sending exactly defined currents through the torque rods, for example in the vicinity of the equator to get an oscillation in yaw direction. Likewise a roll oscillation is initiated near the North Pole and for the pitch axis measurements at both locations are done (see e.g. Wang, 2003).
The measured deviations of the CoM can be compensated by moving a trim mass[5] along each of the three axes.

An example is shown for the roll axis on GRACE 1 in Fig. 6 which is taken from the JPL website (GRACE Science Working Team). The tracking model (blue line) takes the differential depletion of the two fuel tanks into account, as well as the actual position of the trim masses.

Star cameras
The performance of the cameras is a major factor to the quality of the science data. The manufacturer DTU (Technical University of Denmark) has been involved in their optimisation throughout the mission (see e.g. Jørgensen, 1999).
The bore sights lie in the spacecraft's y-z-plane with a nadir offset of ±45° (the baffle of the camera on the –y-side of the satellites is just visible at the top of the solar panels in Fig. 1). Data of both heads are collected with 1 Hz sampling and handled by the IPU, but only data from the prime camera are forwarded to the AOCS. Prime camera for attitude control is the one that looks away from the Sun. There is no autonomous switch-over in case of blinding.

[5] Each of the three trim masses weighs 4.8 kg and can be moved over maximally 5 cm along a rod by a stepper motor at increments of 2.5 μm.

This means that twice in the 322 day precession period the prime has to be changed. Switches to the secondary camera are commanded in case of Moon intrusions, provided there is no Sun blinding at that moment.

Several software changes were made in the IPU to enhance the camera performance, first of all one to allow the simultaneous 1 Hz sampling on both heads. The trade-off between invalid measurements, that will be discarded automatically, and acceptable noise was also object of s/w changes. The IMU was originally foreseen to bridge such gaps, but this had to be revised because it is defunct on GRACE 1 and not used anymore on GRACE 2 due to power constraints (see Herman et al., 2012). Four times per 322 day period images are made (two on each head) to determine the number of "hot pixels", spurious bright points that slowly fade again. Interestingly their numbers appear to be decreasing with time, which is beneficial to the noise level of the measurements.

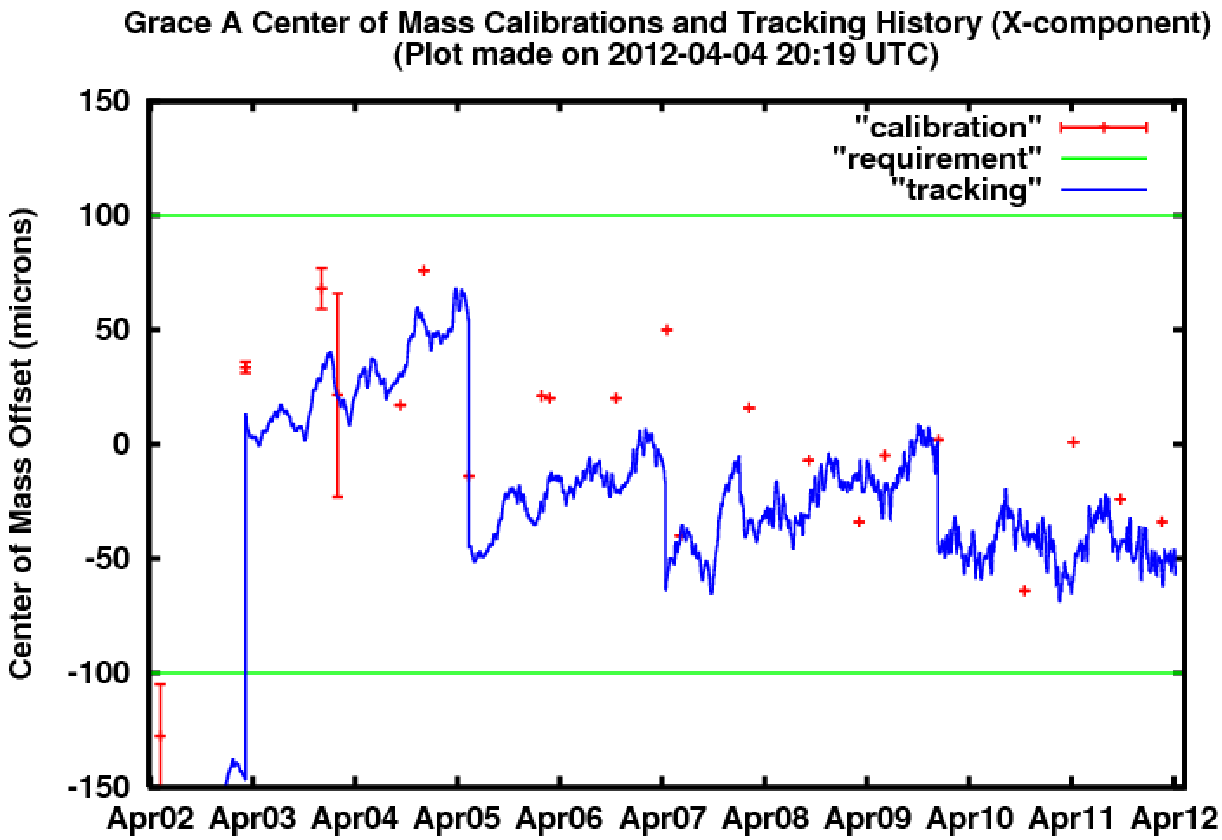

Figure 6. Results of the CoM calibrations in the roll axis. *The in-orbit measurements (red symbols) are compared with a tracking model based upon the differential depletion of the two fuel tanks (JPL website for GRACE monitoring).*

Aging leads to an inexorable deterioration (see Fig. 4). However, the negative influence of several external factors can be mitigated by the appropriate choice of parameter combinations or by optimum planning. E.g. stray light from the Sun or the Moon was minimised by enlarging the exclusion zones, in practice meaning longer use of the secondary camera in case of Moon intrusions, but only if further away from the Sun than originally foreseen. Adaptation of the dynamical range also relates to this.

The precession of the orbit implies that there is a secular variation of the star density in the camera's field of view (FOV). The limiting magnitude and the threshold above background noise are parameters adjusted in this case. Occasionally there are periods of several weeks that for part of the orbit the FOV is directed towards one of the galactic poles. The star density becomes so low, that parameter optimisation as described above (which must hold for the *full* orbit) is insufficient and gaps of several minutes long appear during which no attitude control is performed. The discontinuities, large attitude errors and hence enhanced fuel consumption are mitigated by switching to the secondary head if possible. This is only done however if the FOV of the secondary camera is far enough away from the Sun and the Moon. A recent instance of this strategy reduced in March/April 2012 the number of invalid points from 5% to 0% at the same time decreasing fuel expenditure from 12 to 6 grams/day.

A discussion of further parameter adjustments, such as camera focal length, kappa-values, or central pixel value, lies outside the scope of this paper (those interested are referred to Jørgensen, 1999).

Dead Bands

Attitude control is performed with fixed dead bands for roll, pitch and yaw errors. Reactions depend upon attitude *and* rate deviations and are adaptive; i.e. if a first correction was too small, a second will be slightly larger, a third even larger or smaller again etc. The originally planned DB values proved somewhat too small during LEOP and settings of 3 mrad for roll and pitch and 4 mrad for yaw were used for several years in science mode. This is roughly a factor of 10 larger than the noise of the star camera measurements (axis dependent though!). A growing dichotomy between the numbers of actuations in the yaw- and roll-channels prompted extensive in-orbit tests and mitigation measures from mid 2007 onwards. This will be discussed in more detail in the next section.

IV. Thruster balancing

Fig. 5 shows that before the satellite swap in 2006 the life expectancies of the roll- and yaw- thrusters were relatively similar with a difference of less than half a year. A year later, around MET 1800, the difference had increased to more than eight years! This was a point of concern, although the maximum number of thruster actuations is not a real hard limit.

The nearly polar orbit with an inclination of 89° means that attitude corrections in roll direction can be performed primarily by the magnetic torque rods in a reach of approximately ±30° around the poles. Corrections in yaw direction can be done with the torque rods in a similar range around the equator. Ideal geometry for the Lorentz force is when field and rod are both perpendicular to the direction of the desired correction. Perfect conditions are found nowhere and the deviation will increase with increasing latitude difference. Corrections are therefore typically made by commanding currents through two torque rods implying a spill-over in the other axis. It is thus theoretically possible to transfer thruster activity from the roll- into the yaw- channel or *vice versa*.

First in-orbit tests were made in July and August 2007. The roll dead bands were decreased from 3 mrad to 2.94 and 2.88 mrad, respectively. Data for each setting were collected for a full week without any disturbances such as Moon intrusions and with a calibration period on the default dead band in between. The results were inconclusive, however. Actuations in yaw direction did decrease, but those in roll direction increased disproportionally.

The second try was to keep the roll dead band fixed and to gradually increase the yaw dead band with steps of 0.08 mrad. Each new setting was tested in orbit for seven full days on both satellites simultaneously, always followed by a calibration period on the default settings that was at least as long. Intervals with Moon intrusions, camera switches, or other AOCS activities were avoided altogether. Consequently, test series stretched over several months due to these restrictions.

The first five steps (yaw DB from 4.0 to 4.4 mrad) were measured from July to October 2007. Results were analysed by building the harmonic mean for the ratio yaw over roll actuations over each test and calibration period. A clear decrease of this ratio with increasing yaw DB was found (see the first five points in Fig. 7) confirming the desired transfer of yaw actuations into the roll channel. At the end of the tests it was decided to set the yaw DB to a new default value of 4.4 mrad (October 2007; see Table 2).

A second series of tests was conducted in the first half of 2008, now increasing the yaw DB from 4.4 to 4.8 mrad again in steps of 0.08 mrad. The ratio of yaw over roll actuations was found to decrease further still (second set of five points in Fig. 7). Combination with the earlier results is not straightforward, because in the meantime the regular change of prime star camera had taken place. Several yaw DB settings were therefore measured twice with either of the cameras used for attitude control. These comprise the settings at 4.40, 4.48, 4.56 and 4.80 mrad and for GRACE 1 only also at 5.4 mrad (see Fig. 7). Only one double measurement was used to scale all and as can be seen from Fig. 7 this leads to consistent results throughout. In June 2007 the yaw DB was set to 4.8 mrad, because in the meantime it had become clear that the accuracy of scientific results was not affected by the larger tolerance.

The beneficial effect can be clearly seen in Fig. 5. Whereas the life expectancy of the yaw thrusters had become more than eight years less than that of the roll thrusters around MET 1850, some three years later around MET 2850 the difference had decreased to about three years. This situation with a reasonable balance between the yaw- and roll- thruster firings and with comparable life time estimates has been maintained since then.

Date of implementation	GRACE 1	GRACE 2
	Default yaw DB (mrad)	Default yaw DB (mrad)
26.03.2002	4.0	4.0
24.10.2007	4.4	4.4
26.06.2008	4.8	4.8
03.01.2012	5.4	5.2

Table 2. **Changes in settings for the yaw dead band in science mode**. *New settings are permanently used after the listed dates*.

The difference in life expectancy continued to exist, however. Also, the number of yaw thruster actuations increased over the last couple of years due to special operations made necessary by the weakness of the batteries (see Herman *et al*., 2012). Further increase of the yaw DB was expected to continue the transfer of actuations, but this could not be tested in orbit immediately. The algorithm specifications for the AOCS software set a limit of 5 mrad for the dead bands in combination with the other parameter settings used in science mode. It first had to be ascertained therefore that higher values would not lead to problems in the attitude control system.

In the mean time, Macala *et al*. (2011) investigated simulated attitude behaviour as a function of yaw DB up to values of 10 mrad. They confirmed that the transfer of yaw actuations into the roll channel continues unabated up to the highest values. The total number of thruster actuations (yaw and roll combined) showed a clear minimum around a yaw DB of 6 mrad. A perfect balance between the two directions was found at a value of 6.25 mrad.

Several more tests were therefore made near the end of 2011, as soon as it was ascertained that larger DB values would not lead to software problems. Again, the theoretical expectation was confirmed and the ratio of yaw over roll thruster actuations continued to decrease with larger yaw DB. A ratio of one, i.e. balance between yaw- and roll-thruster firings, was found to occur at slightly lower values in orbit than predicted in the simulations. Figure 7 shows that for GRACE 1 the balance occurs at 5.4 and for GRACE 2 around 5.2 mrad. These values were then implemented in January 2012 and have since been used as default for the yaw dead band.

V. Conclusion

It could be shown that resources on both GRACE satellites are still sufficient to prolong the mission until at least 2016, the year that a follow-on mission is planned. Extensive parameter adjustments and dedicated operational efforts are used to mitigate the effects of some imbalances that were found to exist in e.g. fuel expenditure or thruster firings.

An easier and quicker way to determine the centre of mass of the satellites would certainly be valuable for the follow-on mission, because calibrations take twelve hours now. Interruptions of attitude control either due to resets of the instrument processor or due to invalid measurements should be minimised in order to enhance overall performance and to decrease fuel expenditure. This could be accomplished by higher redundancy (e.g. an extra star tracker, or IMU), or by delivery to AOCS of data from the secondary star camera also. The prime star camera should be set on board and switches in case of intrusions or other problems should be made autonomously. This would not only improve overall performance but also alleviate operational effort.

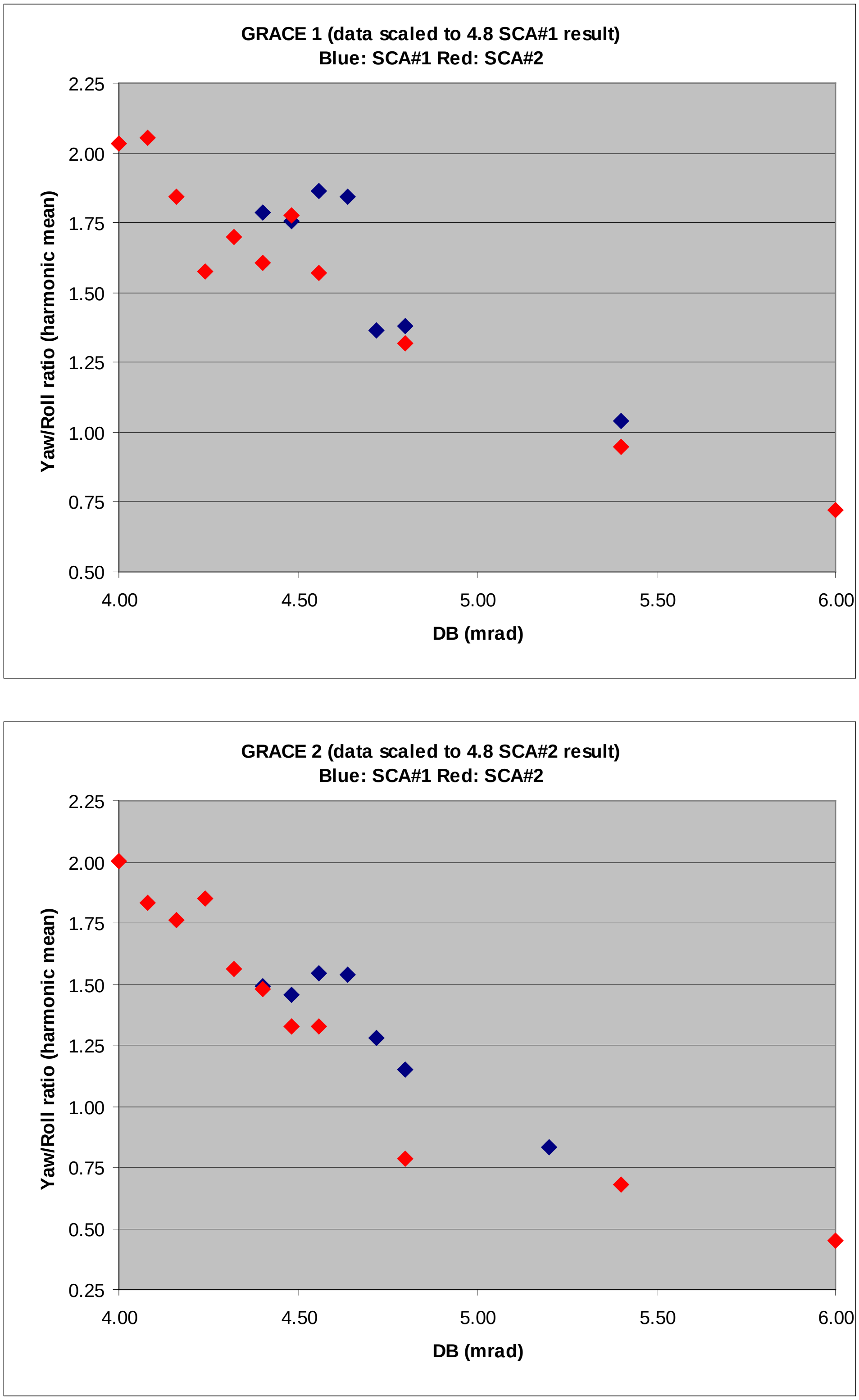

Figure 7. The ratio of yaw over roll thruster actuations as a function of yaw dead band. *Each point represents the results of a seven day campaign. Data measured with different star cameras as prime have been scaled to fit (see text for full details).*

Acknowledgements

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JPL GRACE Science Working Team: website http://podaac.jpl.nasa.gov (further extension for GRACE monitor /grace_mon is password protected; please contact JPL)