ATTITUDE CONTROL FOR GRACE

THE FIRST LOW-FLYING SATELLITE FORMATION

J. Herman[(1)], D. Presti[(1,2)], A. Codazzi[(1)], C. Belle[(3)]

[(1)]German SpaceOperations Centre; DLR-GSOC , 82234 Wessling Germany, E-mail: Jaap.Herman@dlr.de
[(2)]Science Systems – Space & Defence Ltd., at JPL Pasadena,USA, E-mail: Daniel.Presti@jpl.nasa.gov
[(3)] EADS Astrium GmbH, 88039 Friedrichshafen Germany, E-mail:Christian.Belle@astrium.eads.net

ABSTRACT

The GRACE mission - "Gravity Recovery And Climate Experiment" - is a scientific co-operation between the USA and Germany. The two identical spacecraft 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 Texas in Austin and the Geoforschungszentrum Potsdam. The complete on-board science instrumentation is under the responsibility of JPL (Jet Propulsion Laboratory, USA).

The GRACE mission has as primary objective the measurement of the Earth's gravitational field. It is also going to deliver so-called occultation measurements, which are based upon the attenuation of the signals from setting GPS satellites to yield information on the atmosphere.

The twin spacecraft were successfully launched on March 17th 2002 by a Russian Rockot launcher.

GRACE is not only the first dual-satellite mission operated by GSOC, but also the first formation-flying occurring at an altitude below 500 km. The fact that the satellites themselves and their constellation are the scientific experiment, so to speak, poses stringent demands on attitude and orbit control.

The emphasis in this paper is on the aspects of attitude control, leaving the orbit part of AOCS to "flight dynamics" specialists. The principle of attitude control in the several modes is briefly discussed, and the various sensors and actuators are presented. The focus hereby lies on the so-called "science" mode, in which the link between the two satellites is maintained by accurately pointing them at each other.

Shortly after launch the twin spacecraft ceased to be identical and each required and still needs a separate treatment. This is discussed in the last section, together with the solutions installed to guarantee a maximum time in science mode for each of the satellites, thus optimising the scientific return from the formation as a whole.

1. INTRODUCTION

The main scientific goal of the mission is to collect data for creating both static and time-varying Earth gravity 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 about 500 km and that are kept at a distance of 170 - 270 km.

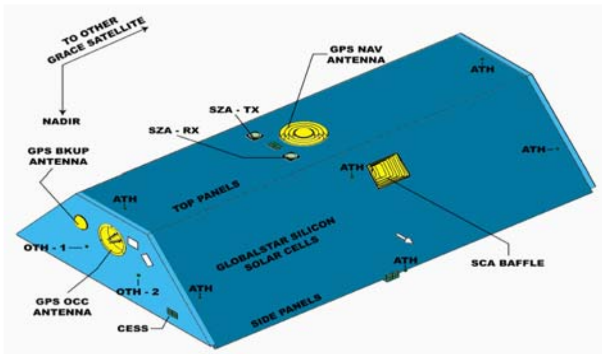

Fig. 1. Outside view of a GRACE satellite

The "payload" consists in a sense of the satellites themselves, which act as small-mass probes in the terrestrial gravitational field. In order to analyse and model the data the scientist use accurate orbit and attitude information, the mutual distance and its rate of change, and the individual spacecraft's accelerations.

Apart from data that are also used by the AOCS (from the star cameras and the GPS; see section 2.1), science also gets inputs from the following dedicated instruments:

- Accelerometer; measuring the s/c accelerations in three axes to very high accuracy (10^{-9}).

- MWA (Microwave Assembly); the RF front-end of the IPU-KBR assembly measuring the distance to the other satellite (10 µm). The calibration of the KBR link and antenna pattern were performed in-orbit and are one of the AOCS tasks.

- USO (Ultra Stable Oscillator); providing frequency reference signals for the MWA and IPU (Instrument Processing Unit).

All the necessary measurements are performed on-board and – with the exception of the orbit determination – are processed completely autonomously.

Gravity maps, which are published each month, are up to 100 times more accurate than previously existing ones. The largest changes in the gravity field of the Earth are due to the movements of stored water in the hydrologic cycle. GRACE measured the weight of up to 10 cm of groundwater accumulations from heavy tropical rains, and even smaller signals caused by changes in ocean circulation, or polar ice movements (Alan Buis/JPL; private communication).

2. ATTITUDE CONTROL

The AOCS (Attitude and Orbit Control System) uses sensors to measure the attitude and actuators to correct it, if the measurement shows this to be necessary. The accompanying algorithms were designed by Space Systems/Loral (USA) and coded by EADS Astrium.

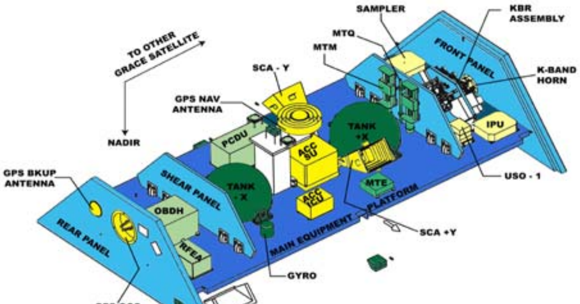

Fig. 2. Inside structure of a GRACE satellite

The scientific requirements put high demands on the AOCS, which are fully met on both spacecraft. For example, fuel use and thruster activity were kept so low until now, that currently the expected mission duration is at least 3 years longer than the minimum requirement of 5 years. The redundancy in sensors and actuators, as well as a high flexibility in the on-board software, guarantee smooth operations with a high scientific return. As is typical for a scientific mission, however, one is not content with "good", but tries for the "optimum", meaning that the AOCS hard- and software is being optimised continuously in a regime well above the mission requirements.

2.1 Sensors

The following sensors are used by the AOCS alone. Data collection and handling is done by the OBDH (on-board computer).

- CESS (Coarse Earth and Sun Sensors); one head on each of the six sides of the satellite. The resulting Earth-vector has an accuracy of ~5-10°, the Sun-vector ~3-6° (there is a dependence upon orbit geometry).

- Magnetometer; measurements of the magnetic field are used in conjunction with the CESS in safe mode and for the commanding of the torque rods in fine pointing mode.

- IMU (Inertial Measurement Unit); an optical gyro, measuring the spacecraft's rates in all three axes.

Some sensors are not only used by the AOCS but also by the scientists. Their data are collected and handled by the IPU, before being handed down to the OBDH to be used by the AOCS.

- SCA (Star Camera Assembly); 2 cameras with a field of view of ±7° by ±9.5° for stars. Data from both are collected at a rate of 1Hz and are used by the science team. The one looking away from the Sun is also used by the AOCS. The determination of the boresights with respect to the spacecraft's frame (K-frame related to the KBR assembly; see section 1.) was performed in-orbit and is one of the AOCS tasks. The consistency of both cameras is <0.1 mrad.

- GPS receiver (one main and two back-up antennae); data are used by the AOCS directly, but also to make off-line orbit determinations. The resulting high-precision orbit predictions are re-sent to the satellites each day in the form of so-called two-line elements (TLE's). The occultation experiment uses measurements from the trailing spacecraft tracking setting GPS satellites through the Earth's atmosphere.

2.2 Actuators

The actuators for attitude control are

- three magnetic torque rods, which use the Lorentz force generated by a current in the terrestrial magnetic field. Although at the flight altitude the field is of the order of 10 nT only, the resulting torque in general is large enough to control the spacecraft.

However, at four places in the orbit the field lines are parallel to the required torque for one of the axes (the roll axis near the equator and the yaw axis around the poles). There, and also in case the torquers alone don't suffice, attitude control uses

- 2x6 thrusters located near the edges of the spacecraft. The GN2 cold gas system has two independent branches that are used simultaneously, but are completely redundant.

The cold gas system also drives

- the two OC thrusters for orbit control. Both are located at the rear of the satellite and can be used in conjunction or separately. About 2 – 3 manoeuvres per year are necessary to keep the formation within the prescribed distance range of 170 – 270 km.

2.3 The AOCS Modes

The operational modes of the satellites are named after the objectives and the pointing accuracy. The modes using the star camera for attitude information are called "fine pointing", those using the CESS "coarse pointing".

- Fine pointing mode (FPM); attitude deadbands 3-4 mrad (~0.2°), subdivided into
    - science mode (SM) and back-up science mode (BSM)
    - attitude hold mode (AHM) and back-up attitude hold mode (BAHM)

BAHM and BSM were originally devised as back-up modes with slightly larger deadbands in case one of the two star cameras would fail. Now that both SCA's are working well on both spacecraft, these modes are used as an equivalent to AHM and SM -- using the same deadbands -- with the IMU in the control loop to minimise the influence of star camera noise.

- Coarse pointing or safe mode (CPM); attitude deadbands 150 –200 mrad (~9° - 11°), subdivided into
    - a mode using CESS and IMU (CICPM)
    - a mode using CESS and magnetometer (CMCPM), which is to be used only if the IMU is not available. Both safe modes have three sub-modes:
        - rate damping; attitude uncontrolled, but rates are minimised
        - Earth orientation; z-axis of the satellite nadir pointing
        - Yaw steering; z-axis of the satellite nadir pointing and the Sun kept in the y-z plane (thus ensuring illumination of the side solar panels)

The attitude control in each of the modes will be briefly discussed.

2.3.1 (B)SM – (Backup) Science Mode

In order to do science the satellites must "see" each other. The leading satellite flies with a 180° yaw bias, thus enabling transmission and reception of the K-band signals. An arbitrary offset can in principle be added in each direction. This option is in (B)SM only used for the roll and pitch axes during a calibration of the K-band antenna pattern. The mutual distance is kept at 220±50 km, which leads to a continuous small pitch bias of ~-1°.

Small differences in the osculating orbital elements and the slowly varying mutual distance imply that the desired attitude is not a constant. Therefore, each day the latest result of the orbit determinations for both satellites are up-loaded to both satellites. This enables the instantaneous on-board computation of the desired, or "reference" attitude. The spacecraft are then controlled within narrow deadbands around this reference attitude, whereby the actual attitude is measured by one of the two star cameras.

Any corrective action is first of all directed to the magnetic torquers, using the measured magnetic field to compute the available Lorentz force for that particular position in the orbit. If the action from the torque rods is insufficient, the remnant will be delivered by the thrusters. These apply an adaptive strategy, whereby the length of a pulse depends upon the strength and the result of the preceding one(s).

The expenditure of not-renewable resources is thus minimised and after 2½ years of mission it averages about 2 – 3 grams/day (~33 kg of GN2 was available at launch).

Several safety measures are in place in order to guarantee uninterrupted science mode.

- in case of short star camera outages, the IMU takes over. The last measured valid attitude is extrapolated with the IMU rates.
- in case of longer, expected star camera outages, e.g. blinding by the Sun or the Moon, a switch to the

secondary camera is performed. The alignments of the SCA's were calibrated in orbit with respect to the K-band frame and are consistent to within 0.1 mrad. If switching is impossible, e.g. in case of simultaneous intrusions in both cameras, the IMU takes over again. However, only a maximum "outtime" of 710 sec is allowed before a transition into one of the safe modes occurs.

- if the measurement of the magnetic field is erroneous or falls outside a certain specified range, an automatic switch to the on-board field model is made.

- persistent outages or limit violations of required products (e.g. star camera, reference attitude, GPS, or CESS data) lead to a transition into safe mode. In case the wrong, or missing products become available once again and are of good quality, the AOCS is configured such that an automatic recovery into one of the FPM's takes place (preferably science mode, but if the reference attitude is still missing the transition will be to attitude hold mode).

At the moment of writing, 900 days after launch, science data were collected for more than 80% of the time (i.e. with *both* spacecraft in (B)SM; each satellite individually was >85% of the time in science mode).

Several settings for the ratio of thruster to torquer action have been tried out. On one hand thruster activity should be minimised – thereby balancing the number of firings and fuel expenditure --, but on the other hand the commanded torquer currents should be small enough to prevent undesirable cross-coupling with the magnetometer measurements.

A lot of effort was put into the optimisation of the instrument processing unit (IPU), for which already three complete new s/w versions have been uploaded to the spacecraft. Improvements included several aspects of data handling and the alleviation of some unexpected numerical problems, additional wishes from the science team – e.g. a 1 Hz sampling rate on both star cameras simultaneously – and the possibility of individual adjustment of the SCA's.

2.3.2 (B)AHM – (Backup) Attitude Hold Mode

The limits for attitude control in (B)AHM, the second fine pointing mode are the same as in (B)SM, namely ~0.2°. The desired attitude in this mode can have any orientation with respect to the orbit frame and can be set by command from ground.

The main difference with the science mode is that TLE's are no longer used, but a fixed default attitude and GPS data for the s/c position instead. In case of GPS outages a low-precision keplerian orbit propagator (KOP) is invoked to bridge the gap. As was the case in (B)SM, the outtimes for the required products in (B)AHM are also limited. After violation of such a persistence an automatic transition into safe mode will follow.

In order to allow for smooth transitions between the two fine pointing modes, the default attitude for the leader is set to a yaw bias of 180°, and for the follower to 0°. In addition both spacecraft have a pitch bias of -1°, roughly the average value for a separation of 220 km in science mode.

Attitude hold mode is used for a number of AOCS specific tasks:

- 2 – 3 orbit maintenance manoeuvres per year; the OC thrusters are located at the backside of the spacecraft only, so in some cases it has to be turned by 180° in order to get the thrust in the right direction.

- centre of mass calibrations; the slow depletion of the fuel tanks cause slight changes in the centre of mass, which can be balanced by adjusting a proof mass (one for each axis). A correct centring of the accelerometer proof-mass is important to eliminate non-gravitational forces. CoM calibrations in all three axes are carried out about three times per year simultaneously on both spacecraft.

- any special operations such as AOCS parameter changes or software upload.

Both satellites have spent about 13% of the mission time in attitude hold mode until now. Science data can also be collected – albeit with somewhat lower precision – in (B)AHM, provided the default attitude of both spacecraft is such that they can "see" each other. This means that the actual percentage of days with science return is well over 85% (Bettadpur/University Texas; private communication).

2.3.3 CPM – Coarse Pointing Mode

The CPM's are the safe modes of the satellite, designed to guarantee thermal and power survival in the first place.

In each instance where CPM is entered, e.g. in case of problems and a subsequent mode drop, or after an on-board computer reboot, the first action will always be rate damping. In this sub-mode the orientation of the spacecraft is arbitrary, but the angular rates are damped below a threshold value of 2 mrad/s.

In general rates will be small or become so quite soon and the spacecraft will be orientated with the z-axis towards the Earth. The tolerance for an Earth-pointing alarm is 35° and the standard deviation of the pointing accuracy based upon the CESS is ~8°.

No further control takes place, if the Sun is near the spacecraft's zenith; any motion around the z-axis will be uncontrolled. When the Sun is orientated further towards the side panels, yaw-steering may – and normally is – activated. Then the Sun is kept in the y-z plane of the satellite in order to guarantee illumination of the side solar panels.

CPM is safe in terms of temperature control and power, but from the point of view of fuel consumption it is very expensive. Depending upon the s/c zenith-Sun angle – whereby intermediate angles are most expensive – expenditure lies in the range 300 – 1000 grams/day (c.f. <3 g/d in FPM!).

Every effort is made therefore to minimise the dwelling time in safe mode. At the moment of writing GRACE 1 has spent ~0.9% of the mission in CPM and GRACE 2 0.5% (~7.5 and 5.5 days respectively). This directly translates into the currently observed difference of 3 kg in tank mass between the two satellites. Most of the safe modes occurred during the early test-out phases of the mission. In the next section it is shown that by now the dwelling time in CPM has been reduced on both spacecraft to "minutes" per year.

3. DIFFERENCES BETWEEN THE TWO SPACECRAFT, SOLUTIONS AND FURTHER IMPROVEMENTS

In the previous sections it was shown, that the AOCS is working very well and that the mission requirements are not only met but even surpassed. Yet, a couple of interesting challenges arose because of non-critical hardware failures, or increased demands on the performance.

A few hours after launch it was discovered that some hardware, which is working perfectly on GRACE 2 since 2½ years now, had failed on GRACE 1. The main ICU (instrument control unit) for the accelerometer and main USO were defunct, as well as the IMU. The former two units still have a functioning back-up on-board, but the last one has not.

This means that for GRACE 1 the back-up FPM's are no longer existent and CMCPM, which is more expensive than CICPM in terms of thruster activity, has to be used as safe mode. A lot of effort was put into the fine tuning of the several CMCPM parameters in order to minimise fuel expenditure there. Although the gains were relatively small, on the order of 10% at most, the absolute savings still made this worthwhile. Most important, though, is to minimise the chances of GRACE 1 dropping to CMCPM in the first place and to limit the dwelling time in safe mode to the absolute minimum. To this purpose several new FDIR's (Failure Detection Isolation and Recovery) were developed and installed on-board. For example, the IPU can have a hang-up under specific circumstances; no products are then delivered to the AOCS, which leads to a drop to CPM. If such a hang-up is detected, a power cycle is automatically executed which normally solves the problem. Also the star cameras, and to a lesser extent GPS or reference attitude, experience some kind of longer outage now and then. Especially the star camera hang-up surveillance developed into quite a complex chain and combination of numerous FDIR's and on-board macro's. These additional safety measures are very successful, as can be seen from the fact that the dwelling time in safe mode decreased from days to minutes in the third year of the mission.

Each star camera turned out to have a different performance, whereby the assemblies mounted on the -y-side are the better ones on both spacecraft (notice however, that the AOCS performance with the "worst" camera on control is still much better than the mission requirements).

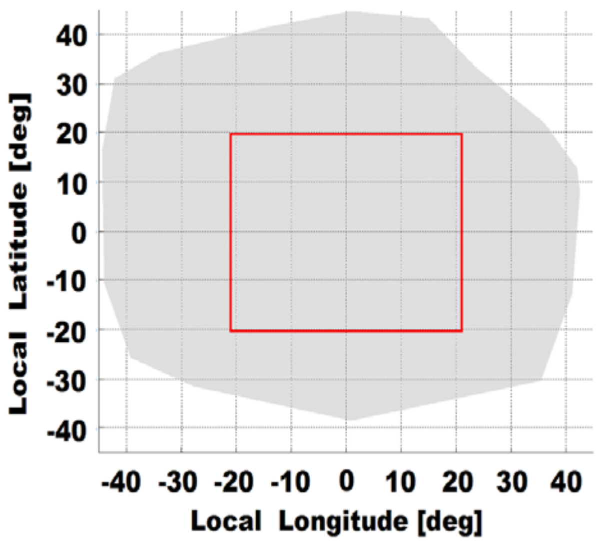

Fig.3. The field-of-view of the star cameras on Grace is ±7° by ±9.5° for stars. The *a priori* expected sensitive area for straylight is shown as a box centred on the SCA boresight. The grey shaded region shows the measured FOV where straylight from the Sun is seen (preliminary result). Note that this affects the secondary camera which is only used by the AOCS when the prime camera is blinded by the Moon.

Therefore, the IMU is used all the time on GRACE 2 in conjunction with the SCA in order to reduce the noise in the attitude information delivered by the star camera. Furthermore, the IPU software was changed to allow the individual adjustment of each star camera and its automatic gain control. Other parameters, such as focal length, threshold for the minimum number of stars, and the camera boresight were optimised for each camera. Through this fine-tuning it is expected to bring the performance of all four cameras to the level of the best one, implying a fuel consumption of ≤2 g/day (Cf. for a five year mission the "allowed" expenditure is ~15 g/day!).

Also the field-of-view for straylight from the Sun or the Moon turned out to be larger than expected (see Fig. 3 for an example). This is taken into account in the planning of camera switching times and also by allowing longer outages before a transition into safe mode is induced.

Two of the six CESS heads on GRACE 1 gradually got one malfunctioning thermistor (out of three). Later in the mission a second -z thermistor also deteriorated. The consequence was an occasionally poorly determined, or wrong Sun-vector. On GRACE 2 only one thermistor is not working properly. The cause is now completely understood and can be avoided in future models.

The satellites are normally in FPM, where the CESS is only used as an additional check on the star camera performance (if the deviation from nadir pointing is continuously >35°, it is assumed there is a problem with the camera). However, in safe mode the CESS is the main instrument for attitude determination.

Although safe mode occurs <<1% of the time, the 100 – 500 times higher fuel consumption still prompted the team to put a lot of effort in devising a work-around for those periods where two out of three thermistors of one head showed spurious data. Loss of the Sun-vector could namely cause a hang-up in the CPM rate damping sub-mode (the "turn-on" of the other sub-modes requires a reliable Sun-vector) and might even lead to an insufficient power situation.

A new version of the OBDH s/w was installed which allows the automatic disabling of one, or two (out of 3) thermistors, when malfunctioning is detected. In addition, some macro's were installed, that give the possibility to switch off Sun-vector-based yaw-steering completely, but minimising at the same time the risk of a low-power situation. Finally, a new algorithm for yaw-steering is being developed which will use the magnetic field to align the spacecraft in N-S direction. Such magnetic yaw-steering would then serve as a back-up in case the CESS fails to deliver a reliable Sun-vector altogether. As the alignment in N-S direction more or less coincides with the orientation in science mode, there will be no power problems. This algorithm is expected to be installed on-board in 2005.

In some positions of the orbit, especially around the so-called southern anomaly, the measured magnetic field components showed too much noise for a smooth operation of the torquers and occasionally the field strength dropped below the minimum acceptable level. Therefore, a mix of the measured magnetic field and the on-board model (in the ratio 70 : 30 %) is used.

After some 600 days of mission the main GPS antenna on Grace 1 seemed to degrade in sensitivity and at the same time the top solar panels delivered occasionally up to 20% less power. For specific Sun-angles there appeared to be a shadowing of the top panel, of the –z Sun-sensors and of the GPS antenna. Around the 8th of July 2004 these effects spontaneously disappeared again! Analysis with ray-tracing programs at Astrium and JPL had already revealed a loosened piece of isolation material to be the most likely cause for the shadowing. The strongest confirmation for this came from NORAD, who observed a small object of the expected size (~10 cm) and mass (~30 gr) in the vicinity of GRACE 1 for a short time after the disappearance of the problem. The orbit of this object then decayed quickly due to its high area-to-mass ratio.

CONCLUSION

The AOCS for GRACE meets all requirements for this low-flying formation with narrow limits on attitude and orbit tolerance. Already now, less than halfway through the mission , the scientific return surpasses expectations. Also, the life expectancy based upon the expenditure of not-renewable resources is at least 3 years longer than the minimum requirement of 5 years.

The high redundancy of on-board hardware and the flexibility of the software enabled the operations team to cope successfully with a number of unexpected occurrences, several unforeseen differences between the two spacecraft and additional wishes from the science team.

It may be expected that the coming >2/3 of the mission will still improve the scientific return considerably and also keep the operations team busy!

References

1. SpaceSystems/LORAL, *GRACE Attitude and Orbit Control System (AOCS); Specification and Description*, 327-440, USA, 1999.

2. DaimlerChrysler Aerospace, *GRACE Design & Interface Document AOCS*, GR-DSS-DID-0004, Germany, 1999

3. Astrium GmbH, *CESS Performance Verification Report*, CESS-AED-RP0002, Germany, 2003