GOCE: A SATELLITE FOR MEASURING EARTH GRAVITY FIELD

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Abstract
Scheduled for launch in early 2008, the **G**ravity Field and Steady State **O**cean **C**irculation **E**xplorer (**GOCE**) satellite is the first Earth Explorer Core Missions of ESA's Living Planet Programme. By flying a very low altitude, GOCE will provide global and regional models of the Earth's gravity field and of the geoid, with unprecedented spatial resolution and accuracy, allowing a deeper understanding of the Earth's interior physics, the interaction of the continents, the ocean circulation and the climate change. The challenges of the GOCE mission have requested the adoption of very specific engineering solutions for meeting the scientific requirements, within all boundary constraints and limitations.

GOCE spacecraft is carrying the first three-axis space Gradiometer, together with a precise GPS receiver system. Unique GOCE feature are:
- Flexible and robust attitude control, including a drag-free control mode.
- Optimized S/C aero-dynamic configuration
- High degrees of S/C autonomy
- High thermo-elastic stability and misalignments prediction
- Avoidance of mechanisms and minimization of micro-disturbances.

A high fidelity spacecraft End to End simulator has been developed to assist designers decisions and to predict the in flight performance, not measurable on ground.

The paper will briefly recall the mission, its objectives, challenges and the performances obtained by the satellite, including a description of the various elements, and the envisaged operations strategy.

Introduction
The GOCE Mission is a first in many ways.

It is the first of the Earth Explorer Core Missions of the ESA's Living Planet Programme. Moreover it is the first ESA mission dedicated to the exploration of the Earth Gravity field and the first flying a three axis Gradiometer and a Drag Free Attitude Control (DFAC).

The mission objective of GOCE is to provide unique models of the Earth's gravity field and of the geoid on a global scale with high spatial resolution and accuracy, for a large variety of applications.

Thales Alenia Space Italia is the industrial prime contractor supported by a core team consisting of EADS Astrium (platform), Thales Alenia Space France (Gradiometer instrument) and ONERA (Gradiometer accelerometers and satellite performances support).

The GOCE satellite, now completely integrated and presently subjected to the environmental tests at ESA/ESTEC test facility, will be transferred to the Plesetsk Cosmodrome (Northern Russia) in early 2008 for a launch on Rockot in March 2008.

Scientific Objectives and Applications
The aim of the GOCE Mission is to achieve, after ground processing, very challenging gravity anomalies and geoid heights accuracies as follows:

- 1 mgal (or 10^{-5} m/s^2) accuracy in measuring the Earth's gravity anomaly field,
- 1-2 cm radial accuracy for determining the geoid from the measured gravity anomaly field,
- 100 km or less spatial resolution of the above measurements, equivalent to degree and order equal to or higher than 200 in a spherical harmonics expansion of the field.

The gravity field recovery will be achieved on a global scale, with the exception of a limited area in proximity of Earth's poles.

The main scientific disciplines taking advantage of the GOCE data are:

<u>Geophysics</u>

Accurate gravity field maps enable to provide a new understanding of the physics of the Earth´s interior including geodynamics associated with the lithosphere, mantle composition, uplifting and subduction processes, and to deliver information of relevance to the study of Earthquakes, Volcanoes and other natural hazards.

<u>Oceanography</u>

The precise estimate of the marine geoid, in combination with satellite altimetry, allows the determination of the absolute ocean currents and associated transportation of heat and other properties fundamental for the improvement of the climatic models.

<u>Glaciology</u>

The combination of the geoid and gravity field maps with altimetric data will enable the improvement of the estimate of the thickness and mass of the polar ice sheets.

<u>Geodesy</u>

The high resolution overall geoid map will provide a better global height reference system for datum connection, which can serve as a reference surface for the study of topographic processes, including the evolution of ice-sheets and land-surface topography.

As shown in the table 1, GOCE performance can suite a wide scientific application fields.

Gravity Field Measurement Techniques
GOCE will make use of two techniques for the determination of the Earth gravity field from space:

1) The "gravity gradiometry", consisting in measuring the components of the spatial gravity gradient (i.e. of the difference between the gravity accelerations in different points in space divided by the separation between these points, which is approximately equal to the second spatial derivative of the gravity potential) along the satellite orbit. The gravity accelerations are measured in different points inside the satellite by a set of ultra-sensitive accelerometers.
2) The "satellite-to-satellite tracking" in high-low mode, consisting tracking the GOCE position by means of the GPS satellites to derive a precise orbit determination (at the level of 2 cm accuracy).

The Earth gravity field is then obtained from the gravity gradient maps (providing the information about the medium-high harmonics of the field) and from the satellite orbit perturbations, after having removed the effect of the non-gravitational accelerations measured by the accelerometers (providing the information about the medium-low harmonics of the field). These two gravity field measurement techniques are illustrated in figure 1.

Application	Accuracy Geoid [cm]	Accuracy, Gravity [mGal]	Spatial Resolution (1/2 λ) [km]
Solid Earth			
Lithosphere and upper-mantle density structure		1-2	100
Continental lithosphere:			
• sedimentary basins		1-2	50-100
• rifts		1-2	20-100
• tectonic motions		1-2	100-500
• Seismic hazards		1	100
Ocean lithosphere and interaction with asthenosphere		0.5-1	100-200
Oceanography			
Short-scale	1-2 0.2		100 200
Basin scale	~0.1		1000
Ice Sheets			
Rock basement		1-5	50-100
Ice vertical movements	2		100-1000
Geodesy			
Levelling by GPS	1		100-1000
Unification of worldwide height systems	1		100-20 000
Inertial Navigation System		~1-5	100-1000
Orbits		~1-3	100-1000

Table 1 – GOCE mission products applications and measurement requirements

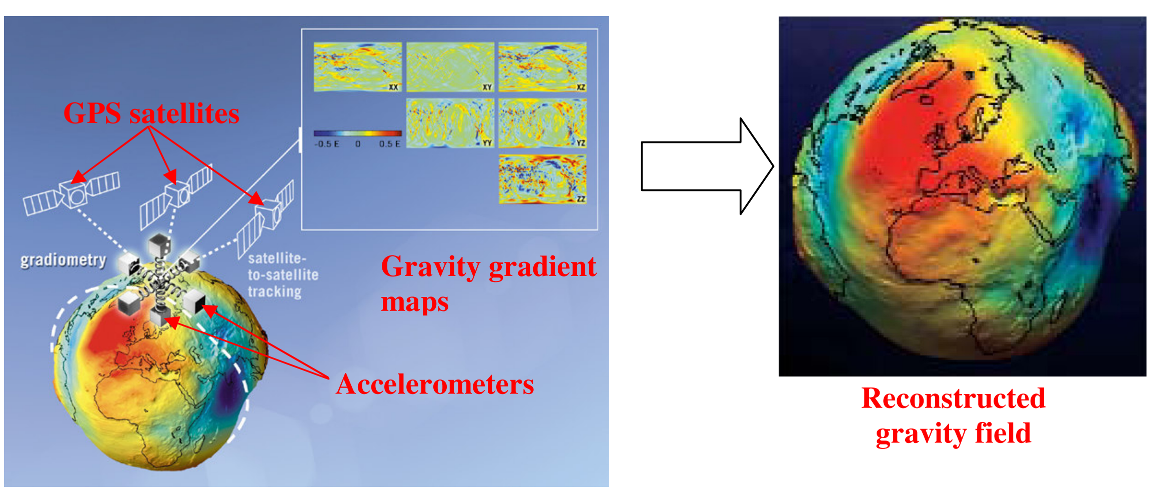

Figure 1 – Gravity field measurement techniques utilized by GOCE

The Mission

The achievement of the mission objectives is obtained if GOCE flies as low as possible taking into account the constraint generated by the evolution of the predicted atmospheric density.

Considering that the solar flux is evolving toward the maximum of the solar cycle the mission profile has been defined assuming, as major requirement, the capability to safely recover the scientific mission in case of contingency. Therefore air density becomes the key parameter which drives the mission profile.

The mission will be carried out on a circular sun-synchronous dawn-dusk orbit (winter launch) with inclination 96.7°, however the satellite is re-configurable also for dusk dawn orbit (summer launch). Such orbit produces a pair of short and a long eclipse every year as shown in figure 3.

The separation altitude will be consistent with an initial density, averaged over one orbit, of $2.81 \cdot 10^{-14}$ g/cm3, equating to 295 Km for the current launch date.
Because of the low control authority of the on-board actuators, highly accurate injection and low attitude rates at separation are required from the launch vehicle.
A natural drag induced decay after separation will be allocated for the early orbit and Commissioning Operation Phase (COP) which will be followed by the gradiometer calibration phase, called POP.
The scientific mission will be carried out when the long eclipses season is over. Two Measurement Operation Phases of about six months (MOP1 and MOP2) are foreseen. During these phases the air density average value will be about $5.6 \cdot 10^{-14}$ g/cm^3, corresponding to a altitude around 260 Km. In these phases the Drag Free and Attitude Control function will compensate the non gravitational forces experienced by the S/C in the flight direction and will align the spacecraft to the Local Orbital Reference Frame (LORF) in which the gravity measurements are referred.

Before the long eclipses period is starting the measurements are suspended and GOCE will enter the Hibernation Operating Phase (HOP) reaching, by an orbit-raise manoeuvre, an orbit altitude in which the average density is about $3 \cdot 10^{-14}$ g/cm3.
GOCE nominal mission is lasting 20 months as depicted in Figure 2 and in addition, an extended mission consisting of HOP2, POP3, MOP3 will be performed if allowed by the on board consumables.

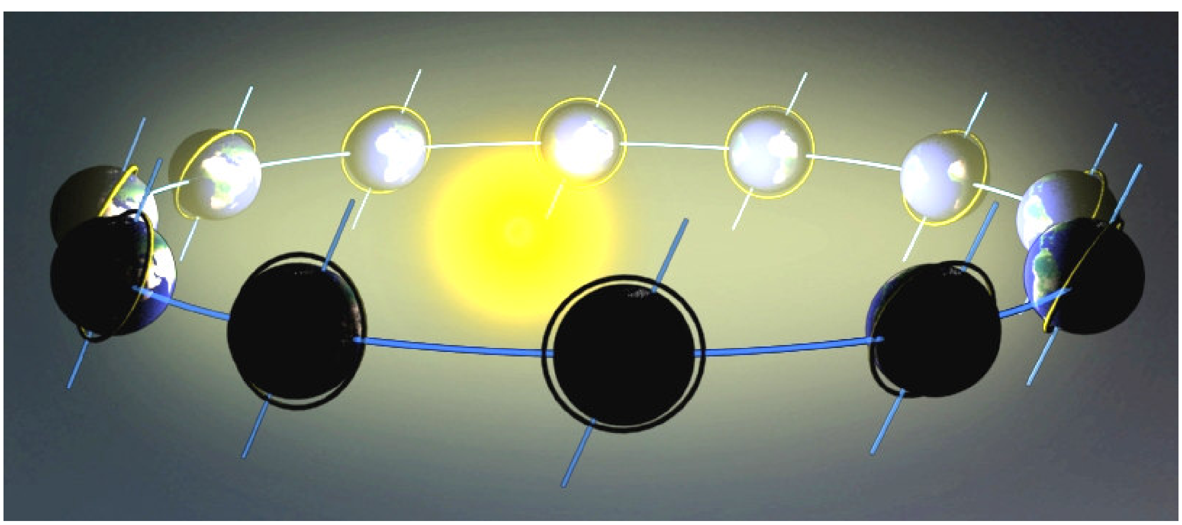

Figure 2 – The GOCE sun-synchronous orbit

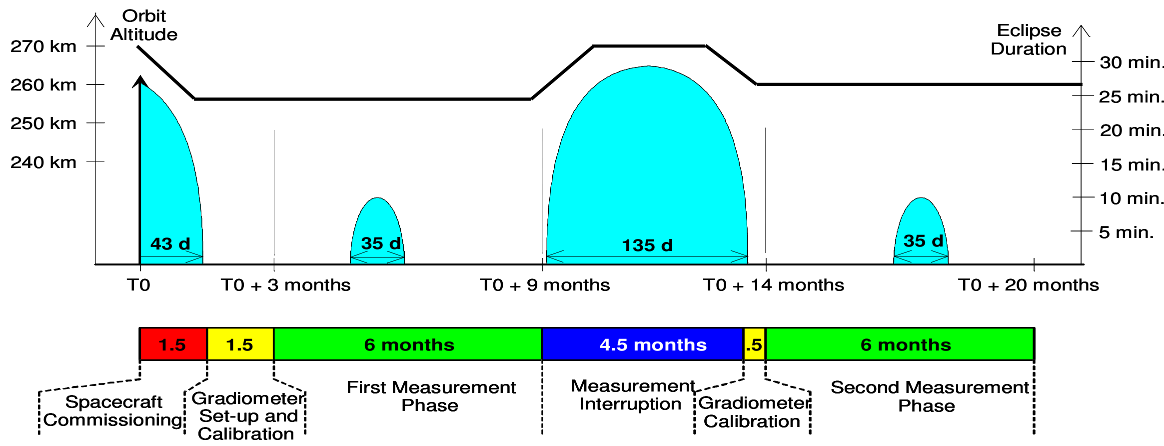

Figure 3 – The GOCE mission profile

Satellite Design Description

The satellite configuration has been designed accounting for the mission requirements from which it is highly dependent. The main driving factors have been:

- The minimization of the air drag forces and torques
- The minimization of the measurement errors induce by the structure distortions
- The stability and knowledge of the alignments.
- The orbiting constraints, S-band communication antennas looking downward, SSTI antennas looking upward and the sun impingement always on the same face.
- The avoidance of intentional and minimization of unintentional micro-vibration sources.
- The engineering constraints imposed by the Launch Vehicle (volume, mass, interfaces)

As a consequence the satellite body has an octagonal prism shape, 5.3 m long and with a transversal cross section of 1.1 m^2, equipped with two long solar array wings fitting the launcher fairing dynamic envelope, while triple-junction solar cell technology has been used to get the maximum possible power.

Two fins enhance the passive aerodynamic stability, while the antenna and sensor appendages mounted on a wing rim are replicated on the other wing for maintaining a symmetrical cross section. A highly stable structure has been implemented in the Platform and into the EGG; thermo-elastic distortion analysis and test have been conducted to validate design and to verify the stringent alignment requirements. No deployable and other sort of mechanisms are used, while extensive micro-vibration campaign including, unit internal design guidelines, development testing and verification analyses has been carried out for minimizing micro-disturbances and thermal clanks. Due to the orbit configuration, the satellite has a sun-facing hot side and a shadowed cold side. High-dissipation units are mounted on the cold side.

The satellite mass at launch is about 1100 kg, including 40 kg of propellant for the ion thrusters.

Payload Instruments

Two instruments constitute the primary GOCE payload: the Electrostatic Gravity Gradiometer (EGG) and the Satellite to Satellite Tracking Instrument (SSTI), based on precise GPS receiver.

The two instruments are complementary. The EGG is particularly sensitive to the short-wave length part of the geopotential whereas the SSTI works best at providing the long-and medium-wavelength part. The EGG is accommodated such as to get its COG near to the COG of the satellite and correlation to the SSTI antenna center of phase has been evaluated in the cm range.

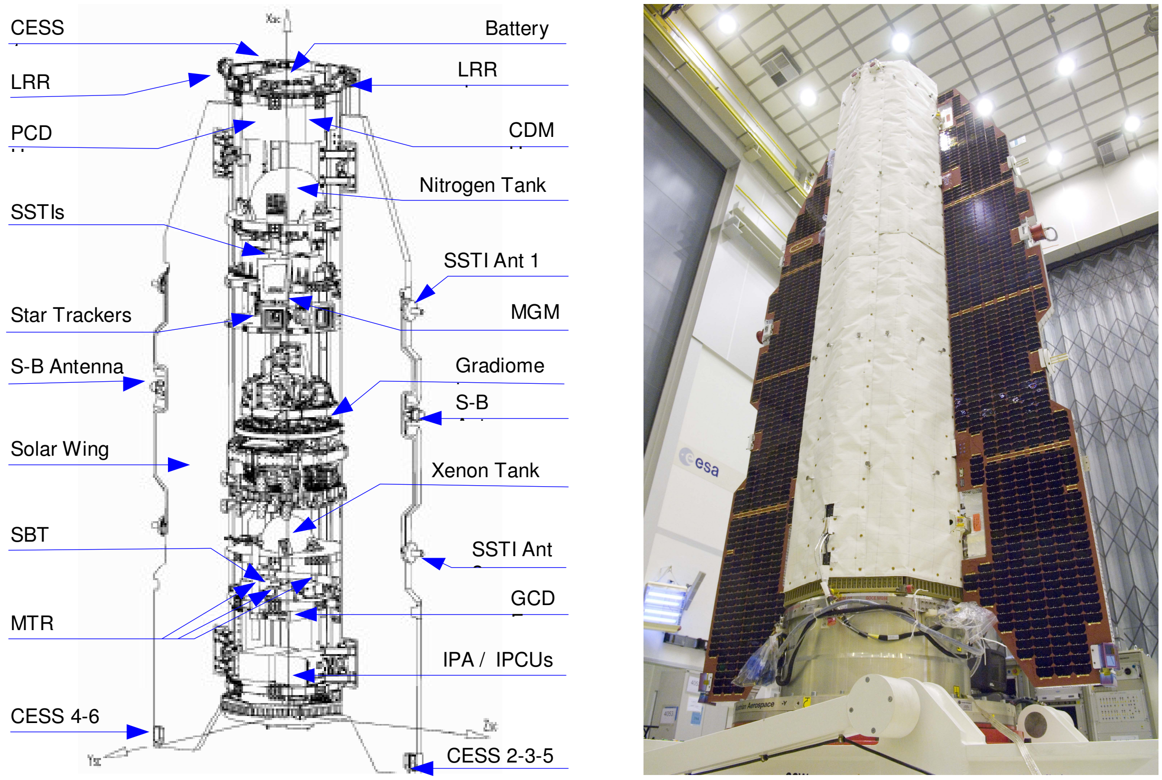

Figure 4 – Satellite configuration and components (left); GOCE in the integration room (right)

The EGG consists of a set of six 3-axis capacitive accelerometers developed by ONERA, mounted in a diamond configuration on an ultra-stable Carbon/Carbon structure developed on purpose by Thales Alenia Space France (figure 4). A pair of identical accelerometers, separated by 50 cm, forms a ‘gradiometer arm’. The difference of acceleration measured by each accelerometer is the basic gradiometric datum.

Three identical arms are mounted orthogonal to one another, and, in orbit, the three arms are aligned to the in-track, cross-track and vertical directions.
The three differential accelerations so obtained provide independent measurements of the ‘diagonal’ gravity gradient components. The gradiometer also provides the basic data for the satellite DFAC. In-axis common accelerations measure the non-gravitational accelerations, and cross-axis accelerations are combined to produce measurements of the angular accelerations.

The gradiometer accelerometers are based on electrostatic suspension of a proof-mass kept at the center of the electrodes by a digital controller working at 1 kHz sampling frequency. The position and the attitude of the mass are measured with capacitive sensors. The variations of the capacitances between the mass and the instrument cage depend on the variations of the gaps between the mass and the electrodes. The accelerometer outputs are derived from the voltages applied on the electrodes to control the mass motionless at the centre of the cage. Each accelerometer consists of an Accelerometer Sensor Head (ASH), containing the proof mass and the electrodes, readout electronics and digital control electronics. Each ASH measures the acceleration along two ultra-sensitive axes and one less sensitive axis. The measurement noise spectral density along the ultra-sensitive axes is $\leq 2 \cdot 10^{-12}$ $m/s^2/\sqrt{Hz}$ between 5 and 100 mHz, the measurement bandwidth of the mission.

The EGG is configured as a self-standing payload, with its own structure, thermal control and electronics, designed to provide to the accelerometer the level of dimensional stability and signal processing accuracy required to fulfill the outstanding measurement goals of the mission. DFAC data are provided at 10 Hz while the more accurate scientific data are generated at 1 Hz.

The EGG is functionally organized in three areas as shown in figure 4:

- the Gradiometer Core, where the ASHs are located, thermally controlled to a very high degree of stability, typically better than 100 μK/√Hz
- the Proximity Electronics Area, containing the 3 Front End Electronic Units (FEEUs), one for each accelerometer pair, is an area of a high thermal stability as close as possible to the sensors for avoiding signal losses.
- the General Electronics Area, where the overall control of the instrument is performed, including the precise control of the proof masses position and the thermal control.

The heat generated by the Gradiometer Electronics is dumped externally by means of a dedicated radiator, installed in the shadowed side of the satellite.

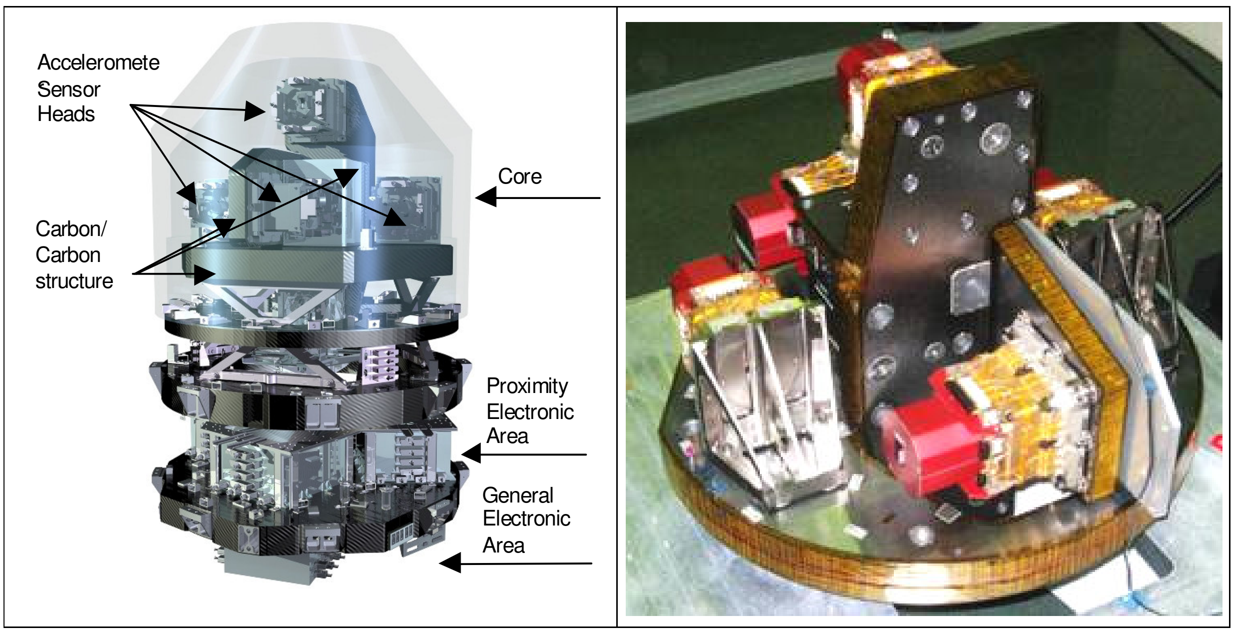

Figure 5 – EGG configuration and components (left); the EGG core with the accelerometers (right)

The SSTI is composed of a receiver pair and the associated antennas. The integrated Global Navigation Satellite System (GNSS) receiver is processing up to 12 GPS satellite signals, in dual frequency mode, providing measurements of code and carrier phase signals.
It is also able to provide real-time navigation data (position, velocity and time) using GPS C/A signals.

The GOCE payload comprises as well a secondary instrument, a Laser Retro-Reflector (LRR), for corroborating the measurements of the satellite position in the centimeter range. The LRR consists of an array of 7 corner Cubes symmetrically mounted on a hemispherical frame with one corner cube in the centre of the top face, surrounded by an angled ring of 6 corner cubes. This arrangement endows the LRR with field of view angles of 360º in azimuth and 60º elevation.

The Drag Free and Attitude Control

The Drag Free and Attitude Control (DFAC) is a key subsystem of GOCE in charge of controlling the satellite to the target reference attitude and to compensate the non-gravitational accelerations experienced by the satellite due to the air density variations in the flight direction. This task is accomplished by an HW architecture which uses as sensors:

- two Digital Sun Sensors (DSS) in hot redundancy
- three Star Trackers (STR) in hot redundancy
- six heads of the Coarse Earth and Sun Sensors (CESS) internally redundant
- three 3-axis magnetometer (MGM) in hot redundancy

The innovation of GOCE is also constituted by the fact that the Payloads are also sensors for the DFAC. The EGG provides very accurate acceleration measurements used to perform the linear acceleration along the direction of motion control and the SSTI provides orbital position and velocity information.

The DFAC actuators are:

- The Ion Propulsion Assembly, two branches in cold redundancy, for drag free and orbit maintenance. Each ion thruster has a selectable thrust level between 1 and 20 mN and can be commanded in steps between 170 and 250 µN, with a slew rate between 1.7 to 2.5 mN/s @10Hz. A tank with 40 Kg of Xenon, sufficient for the entire mission, is then supplying both branches.
- Three internally redundant magnetic torquers (MTR) for attitude control.
- One internally redundant cold-gas thruster assembly (the Gradiometer Calibration Device) utilized to apply to the satellite linear and angular shakings for the purpose of calibrating the EGG in flight (not used nominally for orbit, drag and attitude control).

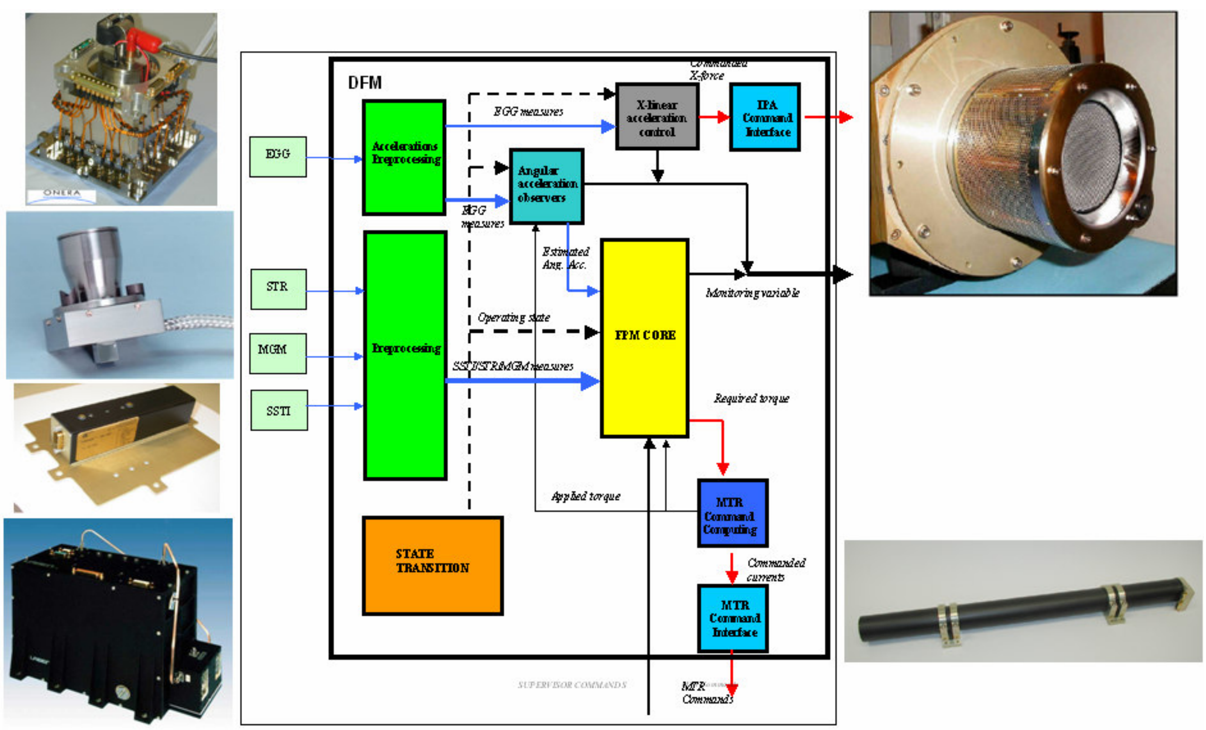

Figure 6 – DFAC architecture and involved sensors (left side: accelerometer, star sensor, magnetometer, GPS receiver) and actuators (ion thruster, magnetometer)

Performance Prediction

The performance verification cannot be done on ground because the gravity is saturating the accelerometer sensors. In addition the scientific performances can be evaluated only if EGG, SSTI and STR data are evaluated over a long period of time. Therefore since the beginning of the GOCE project effort have been spent to set up a high fidelity simulator, faster than the real time, needed to support design, trade-off analyses, development and verification, prediction and assessment of performance. The concept of this simulator, called End to End Simulator, is shown in Figure 7.

The simulator solves for the GOCE dynamics along an orbit resulting from the application of Earth's gravity field (EGM96 up to degree & order 360x360), non-conservative environmental disturbances (atmospheric drag, coupling with Earth's magnetic field, etc.) and control forces/torques. The drag free control forces, as well as the attitude control torques, are generated by the DFAC algorithms which are fully integrated in the simulator. Sensors (DSS, CESS, MGM, Star Tracker, SSTI receiver and EGG) feeding the control algorithms and actuators (ion thruster, magnetic torquers, CGD) generating the commanded forces and torques, are represented by high-fidelity SW models either obtained by the subcontractors or developed by TAS-I.

The capability of the simulator to provide long telemetry data stream (so far exercised up to 2 months of mission) in the same satellite telemetry format, has been very useful for the validation of the GOCE ground segment data processing, including the Gradiometer Calibration Facility.

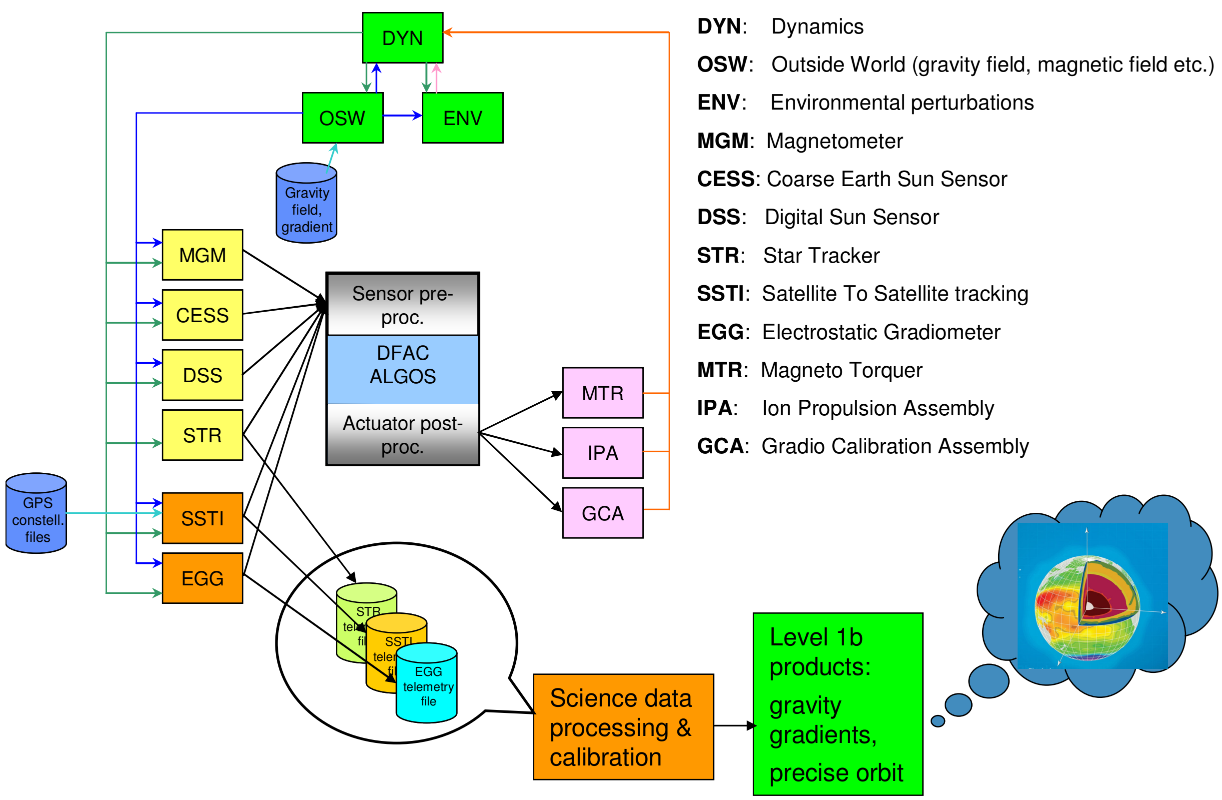

Figure 7 – Concept and scheme of the GOCE End to End Simulator

Operations and Ground Data Processing

Once in orbit, GOCE satellite will be controlled by the ESA/ESOC control center at Darmstad, Germany via a single ground station, located in Kiruna, Sweden.

Due to the low orbit altitude, the ground passes are very short (1 to 8 minutes) and the nominal operations schedule uses up to eight ground passes per day, with an average daily coverage of about 30 minutes. The telemetry downlink occurs in S-Band at 1.2 Mbps for dumping the data stored into the mass memory.

The GOCE gravimetry mission goal is to provide, after Level 0 and Level 1a/1b ground processing the diagonal components of the Earth gravity gradient tensor (GGT) according to a trace determination error as in Figure 8, in the measurement band 5 mHz to 100 mHz.

Figure 8 reports as well the current prediction of the GGT diagonal components worst case measurement performance.

Ground processing of the Level 0 to Level 1a/1b products (accelerometer raw measurements) will occur into the Payload Data Segment (PDS) where the transformation of the raw accelerations into “calibrated” accelerations and the estimation and removal of the centrifugal accelerations about the gradiometer axes from the calibrated accelerations gradients, will take place.

Level 0 and Level 1a/1b data will be then provided to the High-Level Processing Facility (HPF), where the generation Level 2 geophysical products which will be produced.

Such data will include:

- Global gravity potential modeled as harmonic coefficients
- Global ground-referenced gridded values of geoid heights (Earth geoid map)
- Global ground-referenced gridded value of gravity anomalies (Earth gravity map)

Supplementary outputs will be:

- Quality assessment of gravity field products
- Regional gravity field models

Level 2 data will then return to the PDS for distribution to the GOCE data user community.

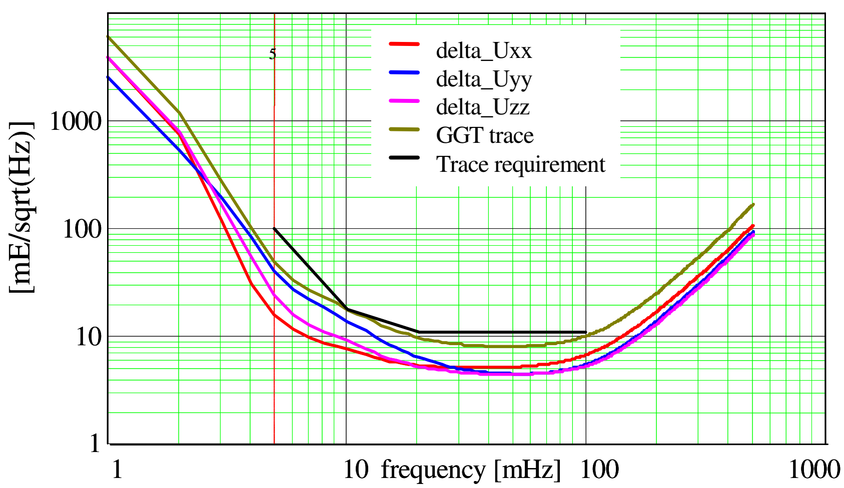

Figure 8 – GGT diagonal components and trace errors prediction

Conclusions

GOCE is the first gravity mission to employ the technique of satellite gradiometry complemented by geodetic satellite to satellite tracking. Moreover, the GOCE spacecraft will be the first one to measure gravity gradients from a very low-orbit (~260 Km) using drag-free control**.** The spacecraft development has required the adoption of highly innovative cutting-edge solutions and state of the art technologies. The GOCE data will allow recovery of a high resolution static gravity field and associated geoid with homogeneous quality and unprecedented accuracy**.** These mission products will lead to a major step forward in improving ocean, solid Earth and sea-level modelling. Consequently, GOCE data will have a positive impact on a variety of domains such as the resolution of differences between national height systems or the understanding of climate change via a better knowledge of ocean currents and polar ice evolution. The launch of GOCE is currently foreseen for the end of March 2008. For more details about the GOCE mission please see: www.esa.int/livingplanet/goce.