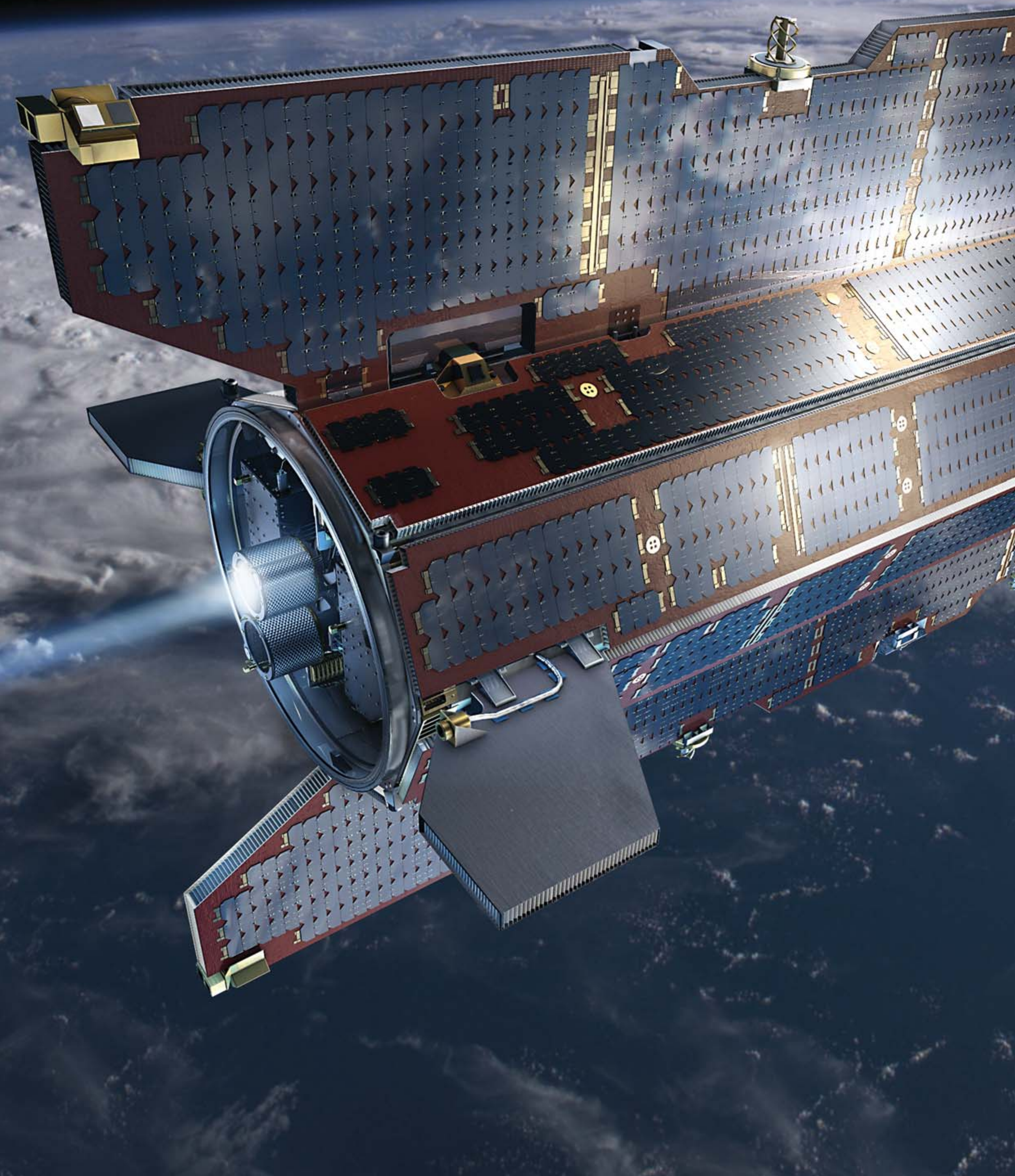
A Jewel in ESA's Crown



GOCE and its Gravity Measurement Systems

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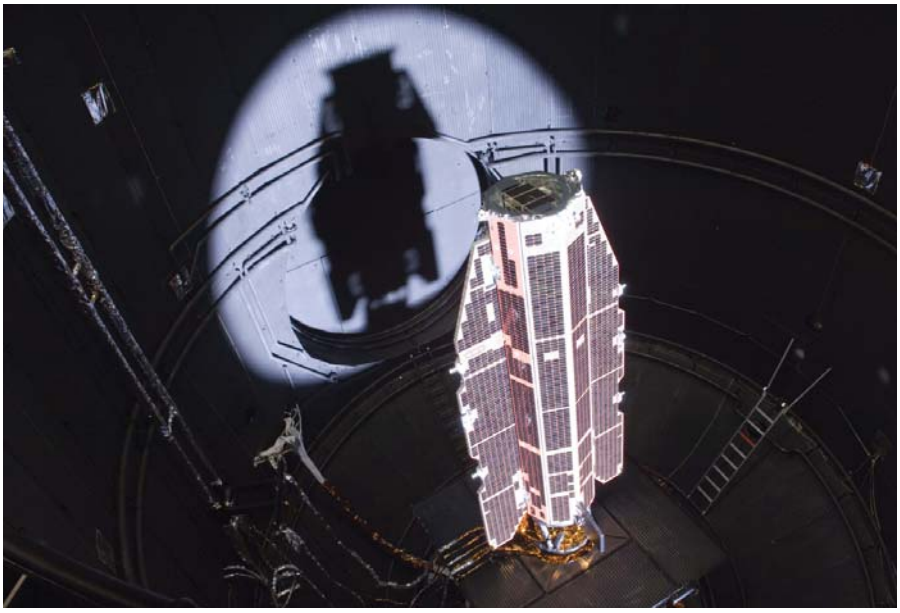
Its elegant and aerodynamic design catches your eye. It is designed to fly as low as 250 km, putting great demands on its thermal and mechanical stability. It uses an ion engine to compensate constantly for atmospheric drag to keep it in orbit. This is GOCE, the 'Ferrari' of gravity field measurement satellites.

One of the main problems with observing gravity from space is that the strength of Earth's gravitational attraction diminishes with altitude. The orbit of the satellite must therefore be as low as possible to observe the strongest possible gravity field signal. On the other hand, the measurement environment provided by the satellite needs to be extremely quiet and ideally free of non-gravitational forces.

These two requirements drove the design for the GOCE spacecraft and its mission implementation. As a best compromise, a 270 km altitude Sun-synchronous orbit was chosen for the initial science measurement phase. Two measurement phases with a maximum duration of six months each are planned during the mission.


GOCE inside the Large Space Simulator test chamber at ESTEC

ESA's 'quiet mission'

These specific needs could only be satisfied by assembling a number of novel technologies, including various 'firsts' and making GOCE a technological masterpiece. These technologies include drag-free-control, electric propulsion, electrostatic gravity gradiometry, triple junction GaAs solar cells and the manufacturing of large, 3D carbon-carbon honeycomb structures. A strict screening of all parts that could potentially cause micro-disturbances has been conducted.

The main instrument on GOCE is the Electrostatic Gravity Gradiometer (EGG). The EGG consists of six capacitive accelerometers arranged orthogonally in pairs at a distance of 50 cm, each pair forming a gradiometer arm. The difference in the accelerations measured by the two accelerometers belonging to the same arm is the basic scientific product of the gradiometer.

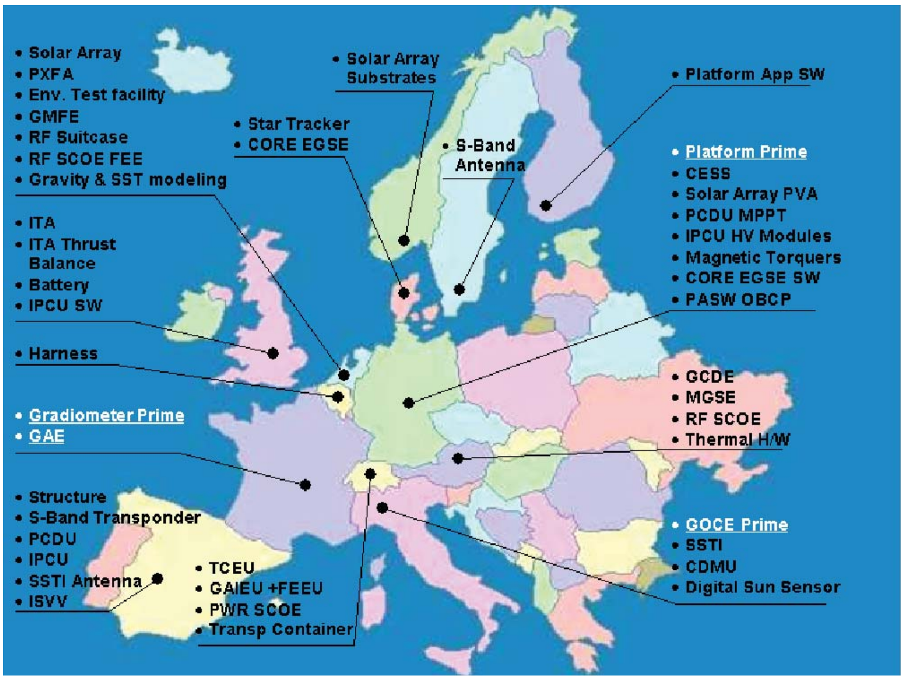
During a period of 200 seconds, the structure of that arm has to be stable to less than the diameter of an atom to achieve the required sensitivity. Half the sum of the accelerations measured by the accelerometers of one arm is representative of external, non-gravitational forces. This information is used to continuously counteract (in closed loop) the atmospheric drag via an electric propulsion system. The GOCE satellite is flown in drag-free-control in the in-flight direction.

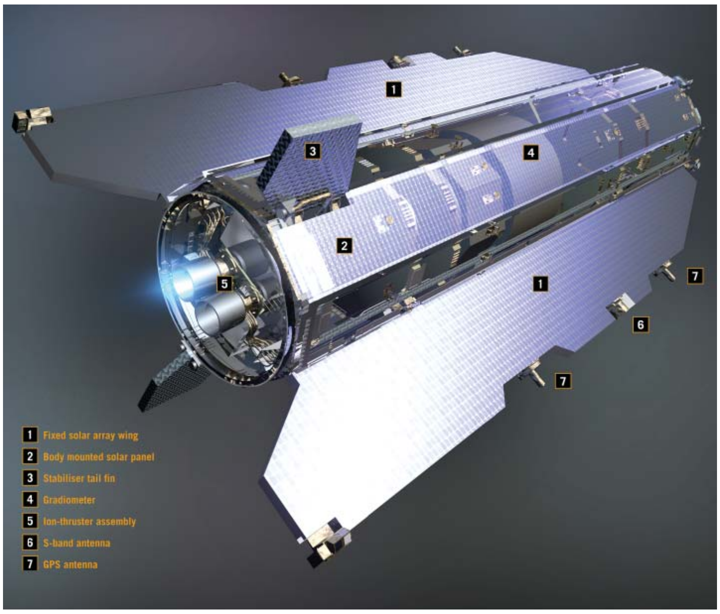
Although the gradiometer is highly accurate, it cannot map the complete gravity field at all spatial scales with the same quality. To overcome this limitation, GOCE is equipped with a second payload, the Satellite-to-Satellite Tracking Instrument SSTI, a state-of-the-art GPS receiver. By exploiting very precise orbit determination based on SSTI data allows obtaining the long wavelength spectrum of the gravity field whereas the EGG provides the short spatial scale components. As with the EGG, the SSTI also acts as a sensor for the orbit control system by providing an on-board real-time navigation solution.

The GOCE Satellite

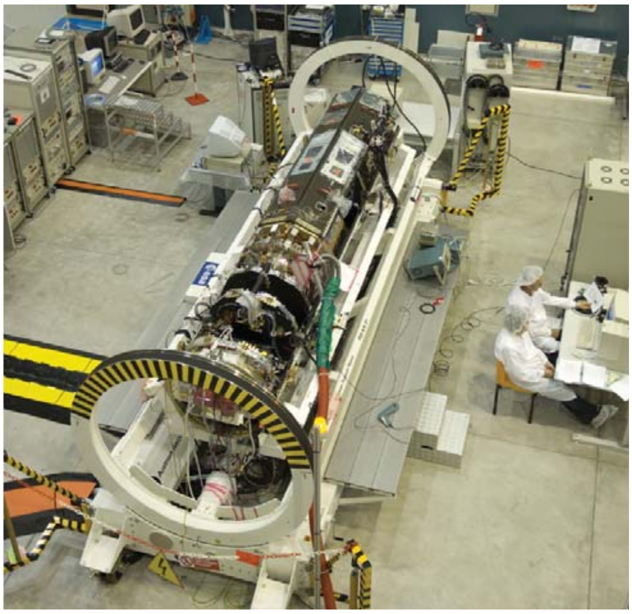
The need for low, quiet flight means the design must minimise air drag forces and torques, and eliminates mechanical disturbances. The result is a very slim satellite with a cross-sectional area of 1.1 m^2, 5.3 m in length and weighing about 1000 kg. The satellite is symmetrical about its flight direction and two winglets provide additional aerodynamic stability. Once in orbit, the same side of the satellite will always face the Sun. The satellite is equipped with four body-mounted and two wing-mounted solar panels that use triple junction GaAs solar

GOCE industrial consortium





Artist's view highlighting the electric propulsion and other subsystems



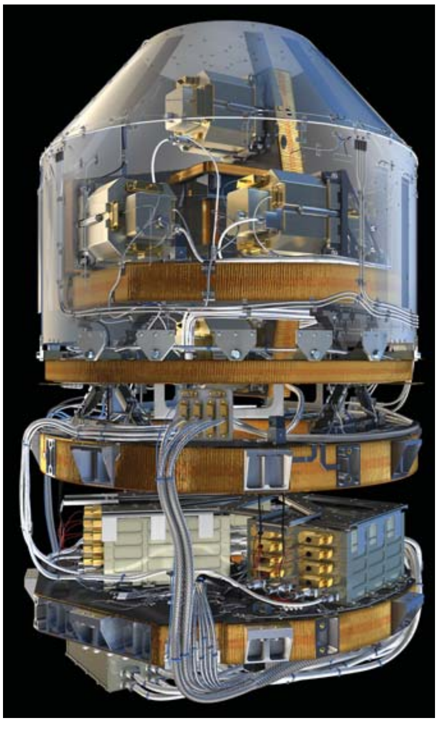
View of instruments without covering panels

cells. One S-band communication antenna is mounted on each wing: one points upwards and one downwards so that full spherical coverage is granted. The wing pointing towards space carries two GPS antennas.

The satellite consists of a central tube with seven internal floors that support the equipment and electronic units. Two of the floors support the gradiometer, mounted close to the satellite's centre of mass. The spacecraft structure is largely built of carbon-fibre reinforced plastic sandwich panels to guarantee stable conditions under varying thermal loads and at the same time to minimise its mass.

Thermal control is achieved by passive means and it is designed to be able to cope with eclipses lasting up to 15 minutes during measurement phases and up to 30 minutes in survival mode. Due to its unprecedented temperature stability requirements in the few milli-degrees Kelvin range, the gradiometer is thermally decoupled from the satellite and has a very special thermal control concept. An outer, actively controlled thermal domain is kept at a very stable temperature by heaters and is separated by blankets from an inner passive domain that provides an extremely homogeneous environment for the accelerometers. The temperature must be stable to within 10 milli-degrees for a period of 200 seconds. The side facing away from the Sun is mainly used as a radiator. All external surfaces are protected against atomic oxygen.

The Electrostatic Gravity Gradiometer (AOES Medialab)

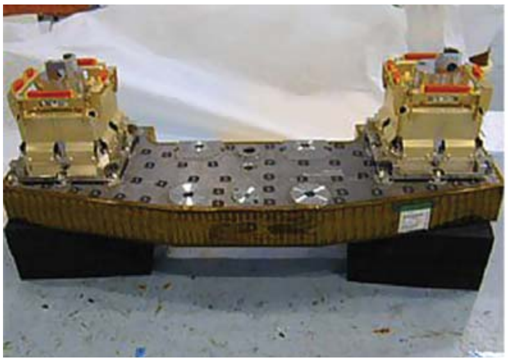


GOCE was built by an all-European industrial consortium. The prime contractor is Thales Alenia Space Italy, with Astrium Friedrichshafen responsible for the platform and Thales Alenia Space France and ONERA for the gradiometer. About 40 other contractors are involved, see the figure opposite.

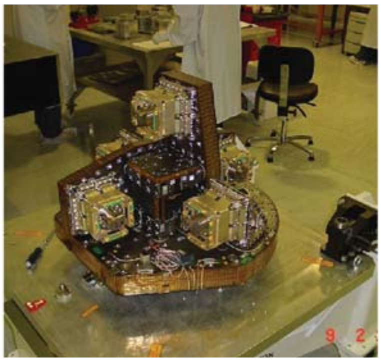
The Electrostatic Gravity Gradiometer (EGG)

EGG consists of three pairs of capacitive accelerometers mounted on an ultra stable carbon-carbon honeycomb support structure. The principle of operation of one of these accelerometers is that a proof mass is floated in a small cage and is kept in the centre of the cage by electrostatic forces, i.e. by applying voltages between the cage and the different sides of the parallelipedic shaped mass. These voltages are representative to the accelerations seen by the proof mass and are the initial input to a long chain of investigatory steps that, for example, will ultimately determine where the water in the oceans flows.

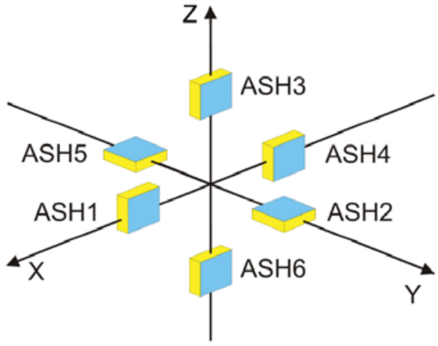
The requirements on the gradiometer are unique. The accelerations measured by each accelerometer can be as small as one part in 10 000 000 000 000 of the gravity experienced on



Gradiometric arm with two accelerometers mounted on an ultrastable carbon-carbon structure



Gradiometer core consisting of three orthogonally mounted pairs of accelerometers



Flight configuration of the six individual accelerometers. X indicates flight direction, Z is pointing radially away from Earth

Earth. The GOCE accelerometers are about 100 times more sensitive than any accelerometers previously flown. The distance between each sensor pair must not vary by more than 1% of an Ångstrom (the diameter of an atom!) over a mean time interval of about three minutes. This can only be achieved by using the 3D carbon-carbon structure.

Two accelerometers of the same pair are mounted at 50 cm distance to each other and form a 'gradiometric arm'. The two proof masses of the same pair have the tendency to move towards or away from each other under the influence of Earth's gravity field. The gradiometer measures this movement.

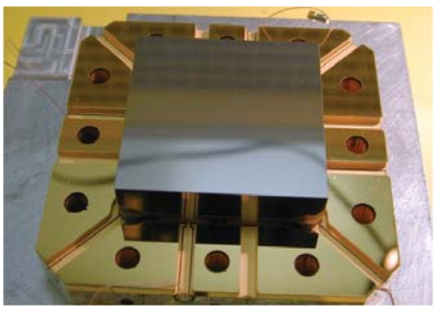
Because the pull of Earth, or in other words the acceleration of the masses, is very weak and subject to noise or forces other than gravity, the method of differential measurement is used. The results from two accelerometers in one arm are subtracted from each other, removing noise and disturbing forces that affect both accelerometers. This is called 'common mode rejection'. What remains is the difference in acceleration due to Earth, measured at two locations separated by 50 cm. This difference is also called the 'gravity gradient' and is the main scientific product of GOCE.

In addition to the differential measurement, the average acceleration of two measurements in one arm is also exploited. This average is representative of external forces on the spacecraft like atmospheric drag and solar radiation pressure. This information is used to command the electric propulsion (ion) engine to continuously counteract the atmospheric drag and keep the satellite flying undisturbed and drag-free.

The three gradiometric arms are arranged at 90° to each other so that the gradients are obtained in all three dimensions. The result of a science measurement phase is a gravity gradient map evenly covering our planet except for small areas around the poles.

The proof masses are made of bulk platinum-rhodium alloy with a dimension of 4 cm by 4 cm by 1 cm. This shape allows the accelerometer to be tested on ground by applying high voltage on the electrodes on the larger sides of the proof mass in order to electrostatically levitate the mass and so compensate for its weight. In spite of this sophisticated instrumentation, it is not possible to achieve on ground the complete verification of the sensitivity of the accelerometers. To advance confidence the GOCE accelerometers were also all tested in freefall at the ZARM drop tower in Bremen.

Accelerometer proof mass



The disadvantage of the adopted proof mass geometry is the lower accelerometer sensitivity in one direction. This means that the GOCE accelerometer has two ultra-sensitive axes and a less sensitive axis. The in-line direction of each accelerometer is the most important one, and is covered by ultra-sensitive axes. The directions of the remaining ultra-sensitive axes have not been randomly selected. They have been chosen to lie in the XZ plane to maximise the sensitivity of the determination of the angular accelerations about the Y-axis, see the figure above. This angular rotation is indeed the most important in the gravity gradient determination, because it has a large constant component due to the rotation of the spacecraft itself.

EGG in Attitude and Orbit Control

The EGG has a double role. It is providing the gravity gradient measurements and it is also used as a main sensor in the attitude and orbit control system (AOCS). If this common mode acceleration in flight direction is not zero, the AOCS will respond by either increasing or decreasing the ion engine thrust to maintain the spacecraft in near-freefall conditions.

The gradiometer provides very sensitive measurements of the three linear and the three angular accelerations of the spacecraft, the three in-line gravity gradient components which are the objective of the scientific measurement, and of one off-diagonal

Mass:	180 kg
Power:	100 W
Distance between accelerometers:	0.5 m
Bandwidth as AOCS sensor:	DC to 5 Hz
Gravity measurement bandwidth:	5 mHz to 100 mHz
Accelerometer Sensitivity:	2x10^{-12} m/s^2 √Hz
Structure stability:	0.2 ppm/K
Temperature stability:	0.01°C over 200 s

Characteristic gradiometer parameters

gravity gradient term (the one in the XZ plane). The two remaining off-diagonal gravity gradient terms are estimated with much lower sensitivity.

Gradiometer In-Flight Calibration

To reach a performance that is limited by the intrinsic fundamental noise of the instrumentation, the six accelerometers of the gradiometer must be well-aligned with each other and have the same gain and phase (electrical delay) in converting an acceleration into an output voltage. In total, 72 parameters define, in the gradiometer frame, the positions of the accelerometers, the orientations and the gains of all sensitive directions. These 72 parameters have to be calibrated in flight. In addition, the response of the accelerometer is not perfectly linear. The output voltage is not simply equal to the input acceleration multiplied by a scale factor. This non-linearity is best characterised and nulled in flight rather than characterised and processed afterwards on the ground.

The measurement of the accelerometer non-linearity is performed at accelerometer level, by injecting into the control loop of the relevant axis a modulated high-frequency signal, in effect 'shaking the test mass'. The output signal is then proportional to the modulation signal and to the quadratic factor. Nulling of the non-linearity is then achieved by offsetting the proof mass along the relevant axis. This process of characterising and nulling the quadratic factor is repeated a few times until the desired accuracy has been achieved.

The characterisation of the misalignments and scale factors cannot be done at gradiometer level. Here the complete spacecraft is being 'shaken'. Excitation along the X-axis is achieved by the modulation of the ion thruster. Excitation of the other five degrees of freedom is achieved by activation of eight cold gas thrusters specially implemented for this calibration function. The in-flight calibration takes about 24 hours and is expected to be repeated every month.

Satellite-to-Satellite Tracking Instrument (SSTI)

The SSTI is a state-of-the-art GPS receiver that has been designed to operate in a low-Earth orbit environment. It can simultaneously track 12 GPS satellites and works on L1/L2 frequencies. This eliminates errors caused by the ionosphere, which extends between the GOCE and the GPS orbits. In the case of GOCE, the GPS receiver is located on the satellite instead of on ground: the receiver is moving at a considerable speed with respect to the GPS satellites. The received signals are thus affected by a Doppler shift, the same way as the pitch of the noise of a passing train.

The SSTI provides both science data and real-time information on spacecraft position and velocity. The latter is used on board for orbit and attitude control.

The SSTI receiver uses a hemispherical-coverage quadrifilar helix antenna. Due to the targeted POD performance, the SSTI antenna design and performance verification have been very challenging. The SSTI antenna was first tested in an anechoic chamber and the outcome used to compute the antenna phase centre, the precise point where the GPS measurements applies. Because the satellite body influences the antenna performance due to GPS signal reflections and multiple paths, numerous simulation runs were necessary. To crosscheck the simulations made at satellite level, a test with a partial assembly consisting of the SSTI antenna and a section of the GOCE solar wing mounted on an automatic robot was performed with live GPS signals outdoors. To further reduce path errors, (programmable) elevation cut-offs of 5° and 15° in the hemispherical coverage of the SSTI antenna are used for the best

Characteristic SSTI parameters

Mass:	6.1 kg (incl. antenna)
Power:	< 35 W
Performance (at 1 Hz):	
– Real time position (3D, 3σ)	< 100 m
– Real time velocity (3D, 3σ)	< 0.3 m/s
– time (1σ):	< 300 ns
– L1/L2 carrier phase (anti-spoofing on):	< 3.55 mm / < 17.22 mm
– L1/L2 P-code (anti-spoofing on):	< 1.9 m / < 1.9 m
– L1 C/A-code:	< 0.92 m
– Inter-channel bias (carrier phase/code range):	0 mm / 0.4 m
– Inter-frequency bias:	< 10 mm
– Phase centre knowledge accuracy (L1/L2):	1.84 mm/2.35 mm

GOCE Subsystems

1. Drag-Free and Attitude Control Subsystem (DFACS)

GOCE is the first ESA satellite employing 'drag-free control' and the first ever satellite to use electric propulsion to continually compensate for atmospheric drag.

Drag-free control means that the 'freefall' environment that space already provides is further enhanced by a factor of about 100 to exclude disturbances that otherwise would mask the gravitational forces on the test masses.

DFACS provides all on-board hardware and software functions to perform autonomous determination and control of the spacecraft attitude pointing, angular rates and linear and angular accelerations.

There are four DFAC modes for different stages of the mission or emergency and maintenance situations.

Coarse Pointing Mode (CPM)
Nominally entered after separation from the launcher. The satellite motions need to be damped and a safe attitude is acquired.

Extended Coarse Pointing Mode (ECPM)
The satellite attitude control is improved to minimise the cross-section exposed to the atmosphere and so limit altitude decay. This is necessary because in that stage the ion engine is not operating.

Fine Pointing Mode (FPM)
The satellite maintains its nominal attitude, waiting for the science measurement periods.

Drag Free Mode (DFM)
The satellite dynamics are controlled to a level that allows the science objectives to be fulfilled.

Attitude control is provided by the electric propulsion (ion) engine and 'magnetotorquers'. Magnetotorquers are tuneable electromagnets that use Earth's magnetic field as a stable frame against which to move the satellite. They exploit the same effect that aligns the needle of a compass to the north-south direction. The magnetotorquer would be the 'needle' and the strength of this 'needle' can be modulated to apply controlled torques to the spacecraft. Magnetotorquers can only provide instantaneous control in a plane orthogonal to the Earth magnetic field lines, thus only two axes can be controlled simultaneously. Advantages of a fully magnetic control are a low actuation noise due to fine command quantisation, high reliability and low mass.

2. Avionics and Radio Frequency Subsystem (RFS)

The Command & Data Management Unit (CDMU) consists of two sections: the on-board computer and the remote unit. The CDMU is fully internally redundant and makes use of fault tolerance features. The ERC32 32-bit RISC single chip processor (17 Mips/3.6 Mflops at 24 MHz) runs the Platform Application Software (PASW). This software is in charge of the data management, the thermal control, the drag-free attitude control and the overall fault detection, isolation and recovery.

Surveillance of the processor is performed by two Reconfiguration Modules (RMs). Main RM functions are the autonomous recovery function, the protected memory resources and the on-board time reference. Using an ultra-stable oscillator, the CDMU keeps the on-board elapsed time reference and maintains the on-board synchronisation across the GOCE platform with an accuracy of 200 nsec.

The CDMU communicates with other GOCE equipment either via a redundant Mil-Std-1553B bus and/or indirectly via the Remote Unit and its >500 discrete interfaces. Telemetry acquisition is supported by a 4 Gbit mass memory

Two S-band receivers are permanently active and are fed by the combined signal coming from both nadir- and zenith-pointing antennas located on the edge of each solar array wing. The resulting full spherical antenna ensures reception of telecommands even in case of attitude loss.

Operated in cold redundancy, the S-band transmitter is active during passes over ground stations only and transmits via the same nadir antenna as the one used for reception. Two TM modes are supported. TM-1, a low data rate mode of 63.7 kbps that allows tone ranging and the nominal mode TM-2 providing a 1.21 Mbps telemetry stream. Telecommands can be received at a bitstream of 4 kbps. Due to the low orbit ground station, contacts are very short. They typically last five minutes with a mean value of around 26 minutes per day. The satellite is able to autonomously operate for 72 hours without loss of science data.

3. The Ion Propulsion Assembly (IPA)

The electric propulsion system is the vital subsystem on GOCE. If it does not work for longer than eight days in a row, the mission runs the serious risk of being lost due to unrecoverable orbital decay. Apart from controlling and safeguarding the orbit, the other task of the engine is to ensure the drag-free attitude control in the flight direction.

At the engine's heart is an ion thruster, mounted on an adjustable alignment bracket to direct the thrust vector through the spacecraft centre of mass. For redundancy, two complete ion thruster assemblies are mounted externally on the last panel of the satellite. The spacecraft has a fuel tank with 40 kg xenon, sufficient for a 30-month mission.

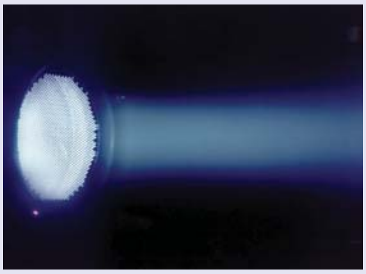
The ion thruster is a 'Kaufman'-type electron bombardment ion motor and runs on xenon gas which is fed into a 10 cm diameter cylindrical discharge chamber both via a hollow cathode and a normal feed pipe.

The hollow cathode serves as an electron source to ignite and sustain the Xe plasma discharge inside the thruster chamber. An external magnetic field is applied to enhance the ionisation efficiency of the electrons and to guide the Xe ions towards the extraction grid system at the thruster exit.

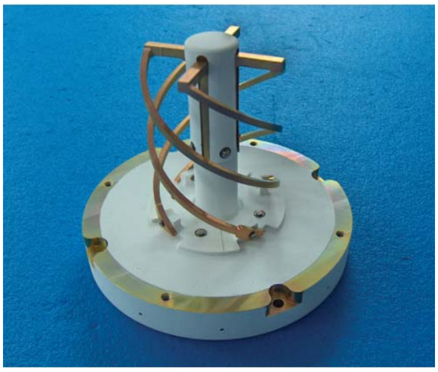
Two carbon grids, well aligned and separated by about 1 mm, accomplish the acceleration of the Xe ions to 1170 eV and at the same time prevent unwanted backstreaming of ambient plasma electrons into the thruster. To prevent spacecraft charging, a second hollow cathode is used to emit an electron beam of equal magnitude but opposite sign to the ion beam.

The thruster can be throttled between 1 and 20 mN at rates compatible with the targeted mission profile and expected drag changes over individual orbits. Individual thrust steps as low as 12 μN can be commanded and slew rates between 1.7 mN/s to 2.5 mN/s depending on the thrust range are achievable. The measured thrust noise ranges between 1 and 10 $\mu N/Hz^{1/2}$.

Special care has been taken during the development and acceptance test campaign to assess thrust vector motion due to launch impact or ageing of the thruster. The thrust vector will be aligned to point exactly at GOCE's centre of mass prior to launch. Any deviation would otherwise introduce unwanted torques on the satellite.



Left, ion thruster. Right, GOCE ion thruster operating at full thrust.



GOCE GPS antenna

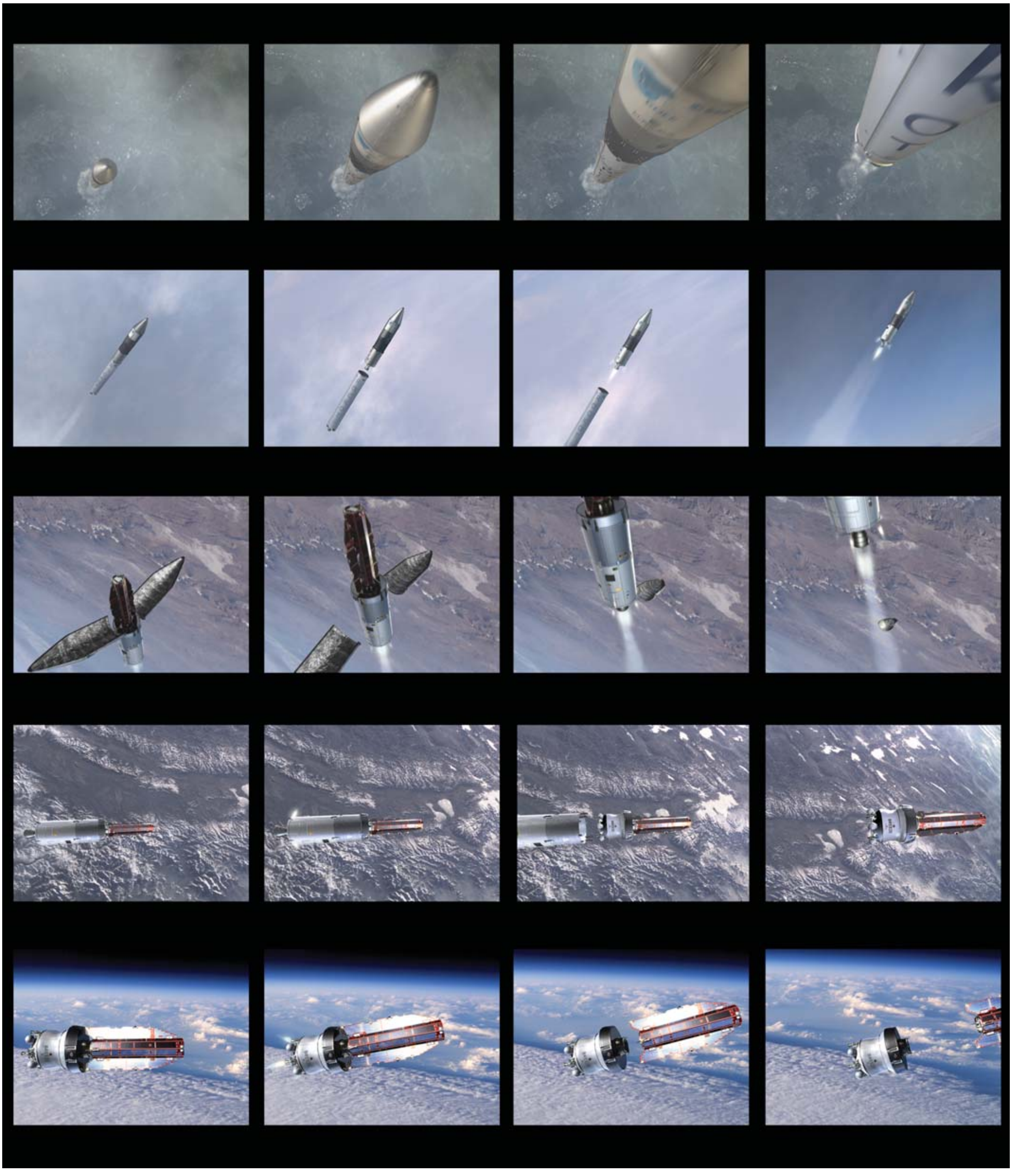
quality GPS signal. On average, eight GPS satellites are visible.

Launch and Mission Analysis

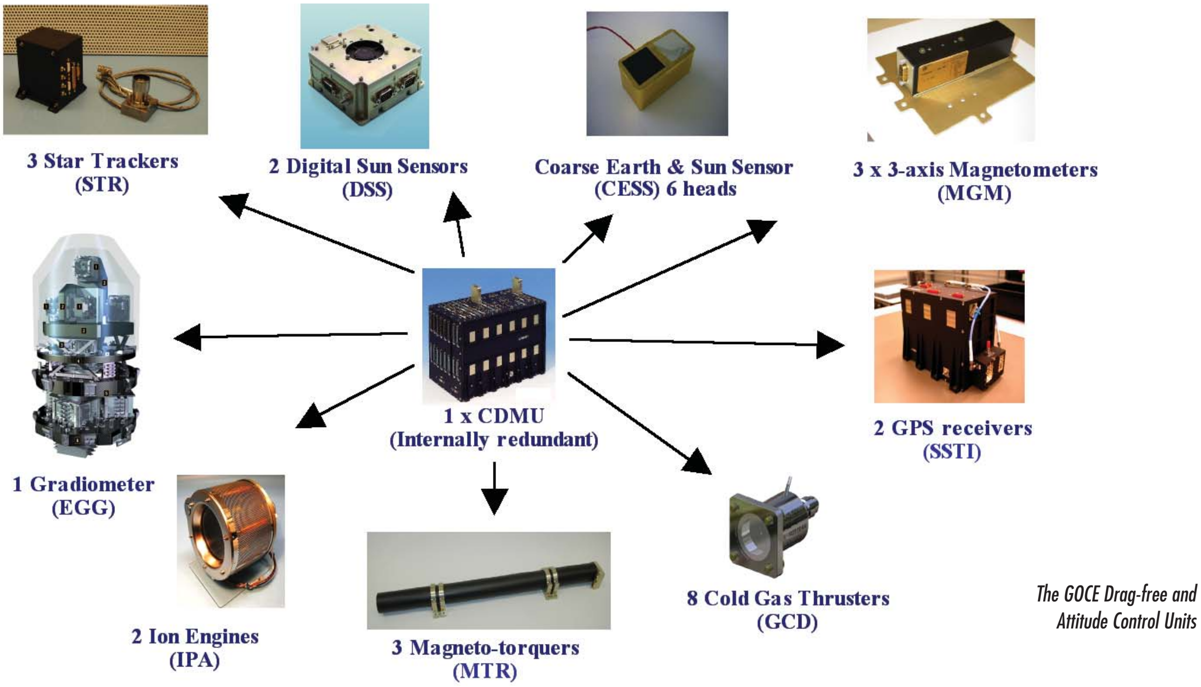
GOCE will be the first ESA spacecraft having to face the danger of literally falling from the sky within weeks after a successful launch. GOCE mission analysis experts were given the challenge of a low flight, maintainable even without an ion engine for up to eight days. The task was delicate because of the lack of reliable atmospheric density data for altitudes between 250 km and 300 km. Furthermore, density variations by a factor of two are not unrealistic at short timescales, due to extreme solar conditions and on longer scales because of the 11-year solar cycle.

GOCE will be launched from the Plesetsk Cosmodrome in northern Russia with a Rockot vehicle. The Rockot is a modified SS-19 inter-continental ballistic missile that was decommissioned after the Strategic Arms Reduction Treaty. The launcher uses the two lower liquid fuel stages of the original SS-19 and is equipped with a third stage developed for precise orbit injection. Rockot is marketed by the German-Russian company Eurockot.

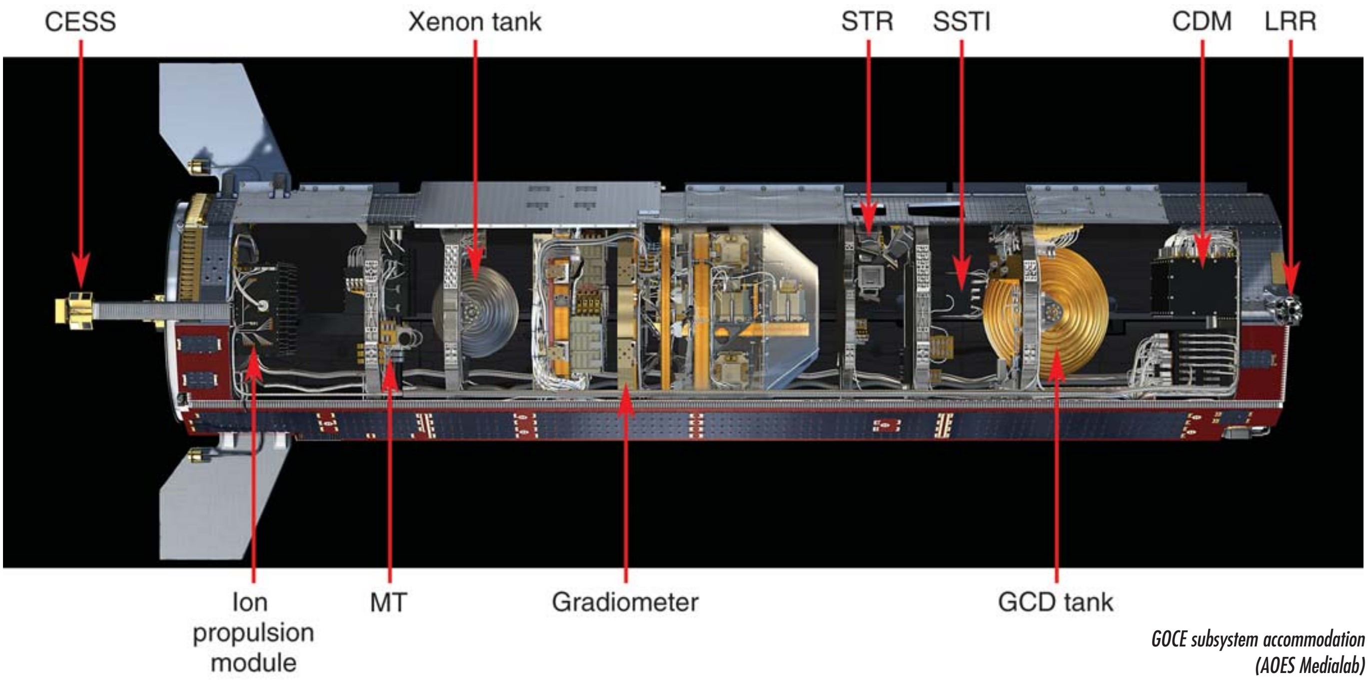
GOCE will be launched into a Sun-synchronous dawn-dusk orbit with an inclination of 96.70° and an ascending node at 6:00. Separation from the launcher will be at 295 km. The satellite's orbit will then decay over a period of 45 days to an operational altitude of 270 km. During this time, the spacecraft will be commissioned and the electrical



The GOCE launch sequence: the Rockot launcher, separation of the second stage, the fairing, and the separation of the GOCE spacecraft and the Rockot third stage (AOES Medialab)



The GOCE Drag-free and Attitude Control Units



GOCE subsystem accommodation (AOES Medialab)

propulsion system will be checked for reliability in attitude control.

GOCE During Eclipse Season

The low orbit inevitably leads to two eclipse seasons per year. Short eclipses around 11 minutes per orbit occur during June and July; they do not affect the scientific measurements. The eclipse seasons during October and February, however, lead to eclipse durations of typically 28 minutes and, due to power constraints, necessitate raising the orbit during that time. The actual power situation in orbit will determine whether the satellite needs to go into hibernation or if scientific measurements can be continued. The nominal GOCE mission scenario includes two measurement phases interrupted by a hibernation phase. Due to the evolving solar cycle that leads to higher atmospheric densities, the second measurement phase needs to be carried out at a higher altitude. The exact value will be decided once in orbit when the actual spacecraft performance is known.