GOCE Publication Reprint

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GOCE: ESA'S FIRST EARTH EXPLORER CORE MISSION

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Abstract. This paper introduces the first ESA Core Earth Explorer mission, GOCE, in the context of ESA's Living Planet programme. GOCE will measure highly accurate, high spatial resolution differential accelerations in three dimensions along a well characterised orbit: the mission is planned for launch in early 2006. The mission objectives are to obtain gravity gradient data such that new global and regional models of the static Earth's gravity field and of the geoid can be deduced at length scales down to 100 km. These products will have broad application in the fields of geodesy, oceanography, solid-earth physics and glaciology.

1. Introduction

The European Space Agency's (ESA's) "Living Planet Programme" (ESA, 1998: http://www.esa.int/livingplanet) defines the ESA strategy and plans for satellite Earth Observation (EO) in the 21st century. It marks the beginning of an era in which European EO missions are smaller and more focussed than their predecessors (*e.g.* ERS-1, -2, and Envisat). This programme is user-driven in terms of addressing science and research community measurement requirements with the Earth Explorer series of missions, and applications and operational requirements with the Earth Watch line of missions (Figure 1). Moreover, the main objectives of the programme are to further develop our knowledge of the complex Earth system; to preserve the Earth and its environment and resources; and to provide information with which to more efficiently and effectively manage life on Earth.

ESA Earth Explorer missions are designed to address EO topics using a combination of new technology and new scientific techniques. There are two categories of Earth Explorer missions: 'Core' and 'Opportunity'. Core missions respond directly to specific areas of public concern and are selected through wide consultation with the scientific and research communities. These missions are ESA-led and must be realised with a financial ceiling of $\sim$350 MEuro, with a new mission launched approximately every two years. Opportunity missions are less complex and quicker to implement, and where possible they should use smaller, low-cost satellites and be realised with a financial ceiling of $\sim$100 MEuro. Opportunity missions are designed to respond to new evolving areas of research or areas of immediate en-

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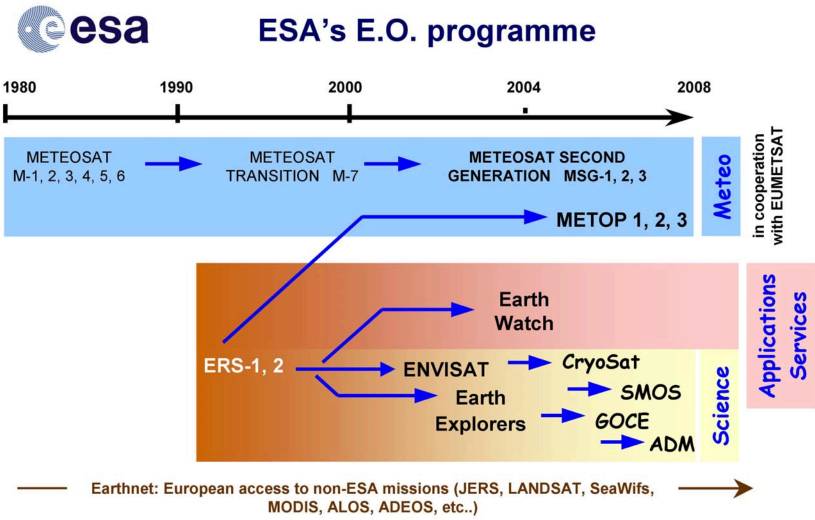

Figure 1. Evolution of the three main elements of ESA's Earth Observation programme. The lower bar indicates the development of two new parallel elements of the Living Planet Programme comprising the Earth Explorer series of missions and the Earth Watch line of future operational missions. Complementing these are the continuing meteorological satellite series and Earthnet.

vironmental concern. These missions can be developed with significant external contributions to ESA.

Out of nine Earth Explorer core missions proposed in the first Call for Core Explorers (*i.e.* Announcement of Opportunity) in 1996, two missions were ultimately selected for implementation in 1999. These were the Gravity field and steady-state Ocean Circulation Explorer (GOCE) and the Atmospheric Dynamics Mission (ADM-Aeolus), respectively. GOCE will be the first of these two missions, with launch scheduled in 2006 with a two-year mission duration (ESA, 2001).

2. GOCE Mission Objectives

The primary GOCE mission objectives are to:

– determine the Earth's gravity field with an accuracy of 1 mGal (where 1 mGal = 10^{-5} m/s^2) via the measurement of the components of the gravity gradient tensor in combination with satellite to satellite tracking
– determine the geoid (*i.e.* equipotential surface for a hypothetical ocean at rest) with an accuracy of 1 cm
– achieve both of the above at length scales down to 100 km (*i.e.* spherical harmonic degree and order 200).

The GOCE mission serves to support the following multi-disciplinary science objectives:

- to permit precise estimation of the quasi-static marine geoid, needed for the quantitative determination, in combination with satellite altimetry and/or *in situ* data, of absolute ocean circulation and transport of mass.
- to provide a better understanding of the physics of the Earth's interior including geodynamics associated with the lithosphere, mantle composition and rheology, uplifting and subduction processes.
- to provide a high-accuracy global height reference system for datum connection. This may serve as a reference surface for the study of topographic processes, including the evolution of ice sheets and land surface topography; and in GPS Levelling applications.
- to estimate the mass and thickness of the polar ice sheets through a combination of bedrock topography, derived from gravity anomalies and ice-sheet surface elevation (from altimetry).

GOCE addresses two of the themes that underpin the ESA Living Planet Programme. These are Theme 1 — the Earth Interior, and Theme 2 — the Physical Climate System, respectively. GOCE addresses the first by making measurements to address the geoid, the gravity field at various scales, from local and regional to global (see Table I). The second theme is addressed by GOCE in terms of the importance of the derivation of the marine geoid for effective use of other satellite data (such as satellite altimetry) in calculation of the absolute ocean circulation.

3. GOCE Mission History

The *Gravity field and steady-state Ocean Circulation Explorer* (GOCE) mission concept was first proposed and considered at the first User Consultation Workshop held in Granada, Spain in May 1996 (ESA, 1996) along with eight other candidates. The measurement principles exploited by the GOCE mission have a long history (Wolff, 1969; Rummel, 1979) and the concept was conceived in large part in prior preparatory studies for the Solid Earth Science and Application Mission for Europe (*SESAME*) in the 1980's (ESA, 1986) and subsequently the *Aristoteles* mission concept (ESA, 1991). Upon completion of the 1996 Granada Workshop, four mission selection recommendations were made by the ESA Earth Science Advisory Committee (ESAC) from the nine candidates. The Earth Observation Programme Board (PB-EO) subsequently considered the ESAC recommendations and endorsed the selection of GOCE for further detailed study.

Following the 1996 PB-EO approval of GOCE, a Mission Advisory Group (MAG) was established to support the Agency with advice during pre-Phase A studies, and to oversee supporting scientific studies. The MAG was first tasked with establishing scientifically-driven performance requirements in the form of a mission requirements document. In July 1998, a Phase A design feasibility study

TABLE I

Measurement requirements in terms of geoid eight and gravity anomaly accuracies (after Rebhan *et al.*, 2000).

Application	**Accuracy**		**Spatial Resolution**
	Geoid (cm)	Gravity (mGal)	half wavelength (km)
Oceanography:			
- Short scale	1-2		100 km
	0.2		200 km
- Basin scale	~0.1		1000 km
Solid Earth:			
- Lithosphere and upper-mantle density structure		1-2	100 km
- Continental lithosphere			
• Sedimentary basins		1-2	50-100 km
• Rifts		1-2	20-100 km
• Tectonic motions		1-2	100-500 km
• Seismic hazards		1.0	100 km
- Ocean lithosphere & interaction with asthenosphere		0.5-1.0	100-200 km
Geodesy:			
- Levelling by GPS	1.0		100-1000 km
- Unification of worldwide height systems	1.0		100-20000 km
- Inertial navigation system		~1-5	100-1000 km
- Orbits (1 cm radial orbit error for altimetric satellites		~1-3	100-1000 km
Ice sheets:			
- Rock basement		1-5	50-100 km
- Ice vertical movements	2.0		100-1000 km
Sea-level change	Many of the above applications, with their specific requirements, are relevant to sea-level studies		

was initiated with industry on the basis of the resulting system requirements. Upon conclusion of this study in July 1999, a final Report for Mission Selection (ESA, 1999) was drafted by the MAG and presented at the second User Consultation Workshop in Granada, Spain in October, 1999. At this workshop the four competing mission concepts were scientifically reviewed. Following this second Granada meeting GOCE was one of two Core Explorer missions to be recommended by ESAC. The PB-EO subsequently endorsed the ESAC recommendation during its November 1999 meeting and authorised the Executive's proposal to begin GOCE implementation as the first Core Explorer mission.

In April, 2000 the Invitation to Tender (ITT) for "Definition, Design, Development, Manufacture, Integration, Testing, Support to Launch and Commissioning of the Spacecraft, including Payload, for the GOCE mission" was released by ESA to industry. The GOCE Contract Proposal received from Alenia Spazio (of Italy) was accepted for review in July 2000 and a Tender Evaluation Board convened to carefully evaluate the proposal.

Approval of the GOCE Contract Proposal was required from the Industrial Policy Committee (IPC) to continue with Phase B/C/D/E1 activities. After successful negotiations with Alenia Spazio to revise and improve various details, the Executive invited the IPC to approve the placing of a contract with Alenia Spazio. Authorisation was finally given by the IPC in January 2001 for initiation of Phase B industrial design activities. The GOCE prime contractor, Alenia Spazio is supported by an industrial consortium including Astrium GmbH (of Germany), Alcatel Space Industries (of France) and ONERA (of France).

4. GOCE Current Status

4.1. Industrial Activities

Phase B GOCE satellite design activities were concluded in April 2002 with a thorough Space-Segment Preliminary Design Review (PDR), in which a consolidated, baseline spacecraft design was presented (Figure 2).

During the GOCE design phase (Phase B: December 2000–Feb. 2002), the industrial consortium members carried out the necessary analyses in order to refine and consolidate the satellite baseline design and the related spacecraft interfaces. Consolidation activities were a prerequisite to the preparation of equipment specifications included in various ITT packages. These ITT's were issued in 2001 as part of the competitive selection process of sub-contractors for the construction of various elements of the GOCE satellite, in line with the ESA industrial procurement policy.

A key technical investigation conducted during Phase B has been assessment of the robustness of the current accelerometer design along with its capability to withstand vibrations during the spacecraft launch. Each of the six individual accelerometer sensor heads within the Electrostatic Gravity Gradiometer (EGG) instrument has a proof mass approx. 4.6 times heavier than those in previous accelerometers developed and built by ONERA (such as SuperStar accelerometers on the two GRACE satellites). The intention of the heavier proof mass is to improve sensitivity, but in reality this also places much more stringent constraints on the GOCE spacecraft design and mission implementation.

Another area currently under careful investigation is the technical development of the GOCE spacecraft micro thrusters. Due to the need for precise attitude and orbit control, the micro-thrusters are subjected to extremely demanding requirements in terms of thrust performance, thrust quantisation, and noise power spectral

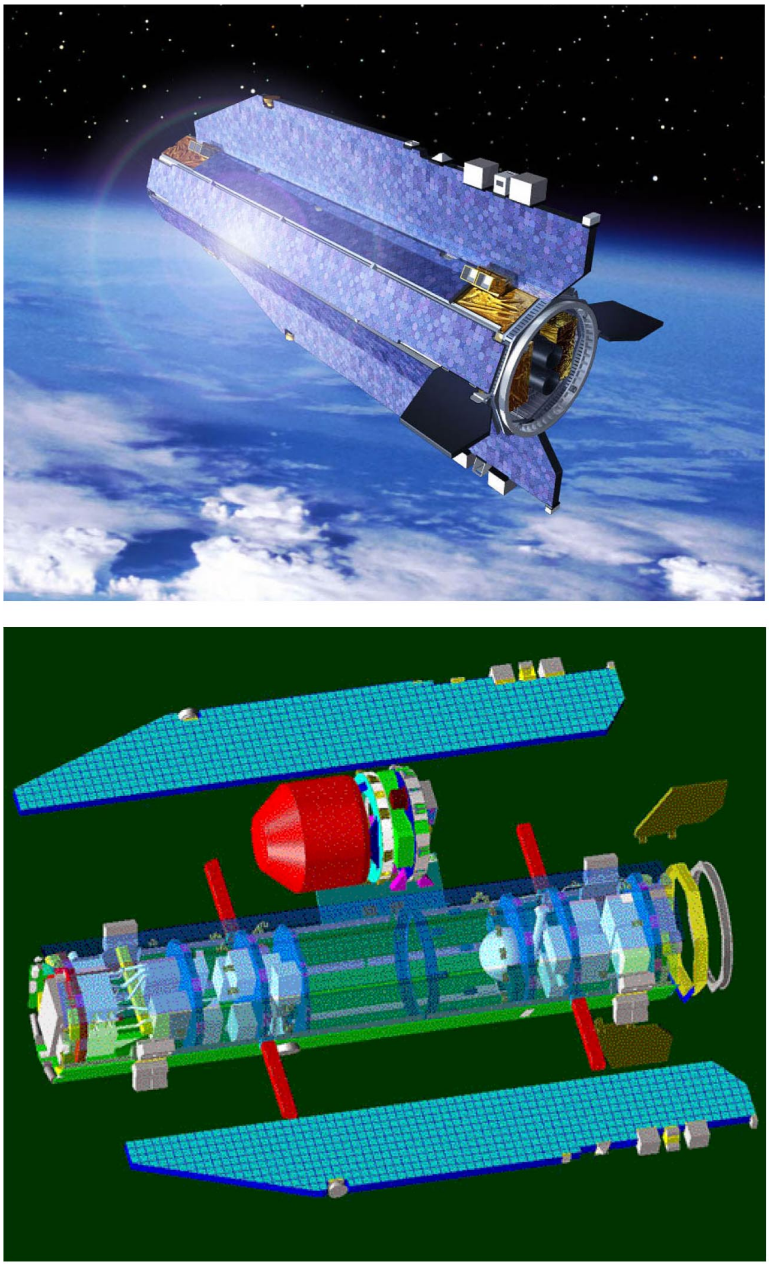

Figure 2. Upper panel: View of the sun-illuminated side of the GOCE spacecraft. *Lower panel:* view of the interior of the GOCE spacecraft with detached solar panels, winglets and the gradiometer assembly (courtesy Astrium GmbH and Alenia Spazio).

density (see Canuto *et al.*, 2003). After evaluation of the trade-offs for mass and micro-disturbances, field emission electric propulsion (FEEP) was selected for the micro-propulsion system rather than the cold gas option. This choice was made because of the FEEP technology's superior performance in relation to the minimisation of spacecraft-induced perturbations on the accelerometer sensor-heads. A final selection of the supplier will be made in the near future on the basis of the criteria related to performance, lifetime, cost and impact on the system.

An April 2002 PDR Board meeting considered the findings and conclusions of the design review, concentrating on what were considered to be residual problem areas. The Board reported positively that no technical "show-stopper" has been identified, confirming that the overall approach for the design of the GOCE Space Segment is robust. Nonetheless, some refinements to the present design are inevitable, and anticipated in order to comply with the challenging GOCE gradiometric performance requirements and spacecraft and instrument construction schedule.

4.2. Future Mission Schedule

The positive outcome of the PDR signals the successful completion of Phase B, and the transition of GOCE project activities into the Construction Phase (Phase C). An approximate 3.5 year Phase C/D is envisaged, incorporating a Critical Design Review (CDR) in May 2004. A Flight Acceptance Review is planned for around November 2005, to be compatible with a launch date in 2006.

5. The GOCE Spacecraft

The GOCE mission employs the principle of gravity gradiometry. Satellite gradiometry requires measurement of acceleration differences between the test masses of an ensemble of accelerometers inside an orbiting vehicle. The measured signal is the difference in gravitational acceleration inside the spacecraft, where the gravitational signal reflects the pull of the Earth's varying gravity field caused by varying masses of mountains and valleys, ocean ridges and trenches, subduction zones and mantle inhomogeneities, etc. The measured signals correspond to the second derivatives of the gravitational potential. The gradiometer measurements are supplemented by high-accuracy Satellite-to Satellite Tracking (SST) measurements and star-tracker information.

Two core instruments are employed on GOCE: an Electrostatic Gravity Gradiometer (EGG) and an SST Instrument (SSTI). SSTI incorporates a Geodetic GPS receiver for high-low (hl) tracking between the satellites of the GPS constellation, and the low flying GOCE spacecraft (referred to as SST-hl). The EGG is a three-axis satellite gravity gradiometer, each arm of which comprises a pair of accelerometers. The gradiometer thus exploits the principle of differential accelerometry.

Drag-free attitude and orbital control, together with the common mode accelerations recorded by the pairs of accelerometers in the EGG, allow the separation of the gravitational signal from non-gravitational satellite skin forces and angular motion. Time variable effects of eigen-gravitation will be kept (by design) below the instrument noise level. The SSTI allows the retrieval of the long wavelength terms of the gravity field while the EGG is devoted to the medium and shorter wavelength terms. The gravity field information derived from both instruments overlap at low frequencies, around 0.005 Hz.

From the measurement principle point of view, the GOCE mission concept is unique in meeting four fundamental criteria for gravity field missions, namely:

– Uninterrupted tracking in three spatial dimensions
– Continuous compensation of the effect of non-gravitational forces
– Selection of a low orbital altitude for a strong gravity signal
– Counteracting of the gravity field attenuation at altitude by employing satellite gravity gradiometry.

5.1. Spacecraft Elements

Within the industrial consortium led by prime contractor Alenia Spazio, Astrium GmbH is responsible for the platform, Alcatel Space Industries (of France) are responsible for the EGG, and ONERA is responsible for the accelerometers and support to the performance assessment.

5.1.1. *Electrostatic Gravity Gradiometer (EGG)*

The objective of EGG is to measure the three components of the gravity-gradient tensor (*i.e.* gradiometer data). The EGG instrument which will be built at Alcatel incorporates accelerometers designed and developed at ONERA, and is based on an ambient temperature, closed loop, capacitive accelerometer concept. EGG is a three-axis gradiometer consisting of 3 pairs of three-axis servo-controlled capacitive accelerometers on an ultra-stable carbon-carbon structure. The thermal control (passive with heaters) provides 10 mK stability during 200 s. The performance is better than 3 mE $\mathrm{Hz}^{-1/2}$ (see Table II). The EGG assembly has a mass of 150 kg and requires up to 75 W of electric power.

The principle of operation of the EGG is based on the measurement of the forces needed to maintain a proof mass at the centre of a cage. A six degree of freedom servo-controlled electrostatic suspension provides control of the proof mass in terms of translation and rotation. A pair of identical accelerometers, mounted on the ultra-stable structure 50 cm apart, form a “gradiometer arm”. The difference between accelerations measured by each of the two accelerometers, in the direction joining them, is the basic gradiometric datum (differential measurement), while half the sum is mainly proportional to the externally induced perturbing drag acceleration (common mode measurement). Three identical arms are mounted orthogonal to one another. The gradiometer axes so defined are nominally aligned in

TABLE II
Electrostatic Gravity Gradiometer (EGG) performance details

Measurement Band Width (MBW)	5×10^{-3} to 10^{-1} Hz
Baseline length	0.5 m
Accelerometer noise level in MBW	10^{-12} m s^{-2} Hz$^{-1/2}$
Proof-mass positioning error	6×10^{-8} m Hz$^{-1/2}$
Absolute/relative scale factors	$10^{-3}/10^{-5}$
Absolute/relative misalignment	10^{-3} rad/10^{-5} rad

the along-track, cross-track and a third direction pointing approximately towards the Earth's centre (forming a right-handed triad). The three resulting differential accelerations provide direct, independent measurements: not only of the diagonal gravity components, but also of the perturbing angular accelerations (Rummel *et al.*, 2000).

In-orbit calibration of EGG involves carefully-planned, coordinated series of S/C manoeuvres and digital force-feedback information from the gradiometer to the Attitude and Orbit Control System (AOCS). Such calibrations will be repeated to check parameter stability with respect to thermal drifts and fluctuations. The objective of in-orbit calibration is to enhance the level of balancing to 10^{-5} in both scale-factor matching and alignment.

5.1.2. *Satellite to Satellite Tracking Instrument (SSTI)*

The objective of the SSTI is to provide support to the gravity field recovery, by using the positioning provided by the simultaneous tracking of up to 12 GPS satellite signals (in the SST-hl configuration). As such this payload element is an integral part of the system and not an independent instrument. In addition, the SSTI provides data for precise orbit determination and is used for real-time on-board navigation and attitude-reference-frame determination.

The selected Lagrange SST instrument has a redundant 12-channel dual-frequency receiver with a codeless tracking capability. It processes, demodulates and decodes the signals from GPS, received through a hemispherical antenna pointing in the zenith direction. The frequency bands L1 and L2 signals are used to allow the compensation of ionospheric delays by ground post-processing. Each channel of SSTI receives GPS signals and provides the following measurements: coarse acquisition pseudo range (L1; with provision for L2), L1 and L2 carrier phase (with phase noise <1 mm), P1 and P2 code pseudo range (L1 and L2), L1-L2 differential carrier phase and P1-P2 differential pseudo range. In addition, the Lagrange SSTI provides the following capabilities:

- position and velocity measurements

- one pulse per second output synchronized with GPS time
- measurement time-tagging with respect to on-board spacecraft time
- fully redundant receiver and receiver processing unit
- optimisation of the number of measurement channels for power saving.

The total mass of the fully-redundant SSTI sub-system is approx. 15 kg, with a peak power demand of <40 W.

5.1.3. *Laser Retro Reflector (LRR)*

The LRR allows acquisition of a supplementary data set of satellite laser ranging (SLR) observations (by the existing SLR ground network) as backup for precise orbit determination post-processing. The LRR is a corner-cube array capable of reflecting laser pulses back along the incident light path.

5.1.4. *Ion Thruster Assembly (ITA)*

The ITA is Qinetiq's T5 Mk-5 dished-grid, magnetic field system. It consists of a quartz discharge chamber around which an RF field coil is wrapped, which induces the internal ionising electric field. Separate Xenon propellant flows feed the discharge chamber and a hollow-cathode neutralizer. A positive voltage on the screen grid attracts electrons into the discharge chamber from the neutralizer plasma, to initiate the discharge. A flat triple-grid system is used to extract the ion beam, with the thruster grid at +1200 V, the acceleration grid at –500 V, and a grounded deceleration grid. To minimize erosion, the acceleration grid is made from graphite. The ITA system on GOCE is operated in the drag control range; it goes from 100 W for 1 mN to 500 W for 12 mN. The 20 mN required for orbit reboost require 625 W of power input. The total mass of the ITA is approx. 60 kg.

The ITA system was already test-flown on the EURECA-1 mission (launch July 31, 1992–retrieval July 1, 1993). The ARTEMIS data relay satellite of ESA (launched in 2001) also employs an ITA propulsion system.

5.1.5. *Standard Radiation Environment Monitor (SREM)*

The objective is to provide radiation environment measurements. Since the EGG instrument of the primary payload is sensitive to electrical charging, SREM data can be used to correlate its measurements with encountered electron and proton fluxes. The ESA SREM instrument has already flown on the DERA mission STRV-1c (Space Technology Research Vehicle-1c). The SREM detector unit features two heads, each with a 20° half-cone field of view. The electronics unit comprises three particle detectors for electron and proton spectroscopy (measurement error <1%), cosmic-ray events counting and radiation-dose measurements. SREM has a mass of 2.6 kg and a power demand of 2.6 W.

5.2. Spacecraft Design

The spacecraft consists of a long slender octagon structure, with a cross sectional area of approx. 0.9 m^2 and a length of approx. 5.0 m (Figure 2). It features total symmetry (about two planes) to minimize disturbances and there are no deployable appendages or moving parts. Within the structure there are several platforms upon which the payload modules are mounted, and which subdivide the platform into 3 modules for ease of integration. The lower module contains the AOCS/DFACS (Attitude and Orbit Control System/Drag-Free Attitude Control System) and Ion Thruster Assembly (ITA). The central module houses the EGG assembly and its electronics. In fact, the EGG assembly is located at the centre of mass of the spacecraft (and is required to stay within close proximity of the centre of mass throughout the spacecraft lifetime). The upper module largely contains the electrical equipment, data-handling and radio-frequency equipment, and houses the 40 kg Xenon propellant gas storage tank for the ion thruster.

Electric power is generated by four fixed body-mounted solar array panels and two wing-mounted solar panels (approx. 5.0 m^2) with GaAs triple-junction cells. A Lithium Ion battery with 2.246 kWh total energy and 78 Ah capacity provide energy storage. The spacecraft thermal design and control is based on passive insulation and radiation techniques. The spacecraft has a launch mass of approx. 1000 kg, including propellant.

The key element of the AOCS/DFACS system on the GOCE spacecraft is the drag-free attitude control requirement. The DFACS is designed to compensate for the effects which atmospheric drag forces and torques have upon the gradiometer measurements using ion thrusters and micro-thrusters within the measurement bandwidth of 5 mHz to 100 mHz (see Canuto *et al.*, 2003). The total error budget for the gradiometer is of the order of 3 mE $Hz^{-1/2}$ (Note: 1 E = 1 Eötvös = 10^{-9} s^{-2}, a unit of gravity gradient). In drag-free science operations mode, spacecraft attitude control (with an absolute pointing accuracy of 0.38 mrad) requires star tracker and EGG input data. However, attitude information is provided by an earth-sensor, sun-sensor and a three-axis magnetometer in other mission modes. Two 20 mN RF ion thrusters and eight pods of two micro-Newton proportional thrusters, based on field emission electric propulsion (FEEP), are used as actuators.

A conventional data handling system is used on-board, based on the MIL-1553 bus, an ERC 32 processor, and 2.5 Gbit data storage. Spacecraft communications are in S-band (two coherent S-band transponders, two antennas and a radio frequency distribution unit, 1 W RF power) with data rates of 2 kbit/s in the uplink and up to 850 kbit/s in the downlink. The ground receiving station is Kiruna and mission operations and control of GOCE will be conducted at ESOC.

The GOCE reference orbit is a sun-synchronous low-Earth orbit (altitude = 250 km; inclination = 96.5°), with a 06:00 hrs equatorial crossing, *i.e.* dawn-dusk orbit, or an equatorial crossing at 18:00 hrs, *i.e.* dusk-dawn orbit, at the ascending node (with the selection depending upon season of launch). Global coverage outside the polar caps is reached after about 30–40 days. On this basis, a nominal mission duration of 20 months is planned for GOCE. A Rockot-class launch vehicle is used as the reference launcher.

6. GOCE Data Processing

The GOCE mission also requires a ground segment comprising reception and processing of the satellite telemetry data up to Level 1a/1b, managed by the Agency, and a higher-level data processing segment planned to be developed outside the Agency. Upon Delegations' request in the PB-EO, the Agency currently plans to include the Level 1 to Level 2 data processing within the scope of the GOCE Project activities, provided that the related additional funding is made available. A preparatory study has been conducted with the main objective of defining the architecture and the interfaces of the GOCE Level 1 to Level 2 processor. Based upon the outputs of this activity, and the available funding, the Agency will establish the framework within which it will manage the development of the Level 1 to Level 2 processor. This processor development is anticipated to take place in close cooperation with European centres of excellence with gravity field modelling and data processing expertise. Current plans exist to review aspects of ground segment design and the development of scientific data processing elements (level 1b to level 2) in Phase C/D.

The definitions for the different levels of data products are (ESA, 1996):

Level 0: time-ordered raw data as measured by GOCE. The satellite will downlink the data during contact with a dedicated ground receiving station.

Level 1a: instrument time series with the calibration data attached.

Level 1b: time series of calibrated and corrected instrument data along the orbit. These data include the primary instrument data: gravity gradients, SST-hl observations and GOCE satellite position; and other ancillary data such as the satellite linear and angular accelerations, satellite attitude, AOCS/DFAC thrust history, etc.

The two primary elements of the ground data processing chain are:
ESA Payload Data Segment (Level 0–Level 1a/b):
- mission performance assessment
- calibration and verification activities
- monitoring of the performance of the space segment and level 1b ground segment, feeding back to ESA Level 1a/b data products.

High Level Data Segment (Level 1–Level 2):
- processing to level 2 data products from level 1a /1b data
- precise orbit determination

– external calibration and validation.

Within the scope of the Level 2 data processor, the following three global products will be produced:

– gravity potential modelled as harmonic coefficients
– ground-referenced gridded values of geoid heights (Earth geoid map)
– global ground-referenced gridded values of gravity anomalies (Earth gravity map).

These Level 2 products will be accompanied by appropriate quality assessment products.

Level 2 data products are regarded as the starting point for further scientific analysis, and will be GOCE-only gravity-field solutions. Level 3 products are thus value-added, derivative or custom products developed for application in further studies of solid-earth physics, absolute ocean circulation, geodesy, sea- level rise etc. Additionally, products requiring combinations of surface or airborne gravimetric data, or other satellite or in-situ data with the GOCE data are regarded as Level 3 data products.

7. Conclusions

The GOCE mission will provide the first global, high spatial resolution and high accuracy observations of the Earth's gravity gradient tensor. These data will allow global and regional models of the (static) Earth's gravity field with unprecedented precision and spatial detail.

GOCE will obtain measurements with high spatial resolution and high (homogeneous) accuracy. Such a spatially detailed knowledge of Earth's gravity field will facilitate computation of an accurate equipotential reference surface, the "geoid" and quasi-exact orbit determination, particularly for low-earth orbiting satellites. The geoid as a reference surface is also directly applicable in applications such as levelling height determination using satellite techniques (known as 'GPS Levelling') and mapping of ocean and land surfaces.

New details of the Earth's gravity field provided by GOCE will also benefit a variety of Earth science disciplines. They will help to better understand processes that take place within the Earth's interior, and on and above its surface. Knowledge of the geoid, for instance, allows for studies of the solid Earth's mass distribution, interpretation of sea-level changes, ocean water flows/ocean heat transport and related with these, climate studies and model predictions.

In summary, GOCE data will undoubtedly find broad application in the fields of geodesy, oceanography and solid-earth physics.

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References

Canuto, E., Martella, P., and Sechi, G.: 2003, ‘Attitude and drag control: an application for the GOCE satellite’, *Space Sci. Rev.*, this volume.

European Space Agency (ESA): 1986, ‘SESAME: Solid Earth Science & Application Mission for Europe’, ESA Special Workshop Proceedings, ESA SP-1080, 128pp.

European Space Agency (ESA): 1991, ‘The Solid-Earth Mission ARISTOTELES’, International Workshop Proceedings, ESA SP-329, 137pp.

European Space Agency (ESA): 1996, ‘Gravity Field and Steady-State Ocean Circulation Mission’, ESA SP-1196(1), Report for Assessment of the Nine Candidate Earth Explorer Missions, 77pp.

European Space Agency (ESA): 1998, ’The Science and Research Elements of ESA’s Living Planet Programme’, ESA SP-1227, 105pp.

European Space Agency (ESA): 1999, ’Gravity Field and Steady-State Ocean Circulation Mission’, Report for Mission Selection, ESA SP-1233(1), 217pp.

European Space Agency (ESA): 2001, `http://www.esa.int/livingplanet/goce`.

Rebhan H., Aguirre, M., Johannessen, J. A.: 2000, ’The Gravity Field and Steady-State Ocean Circulation Explorer Mission — GOCE’, *Earth Observation Quarterly* **66**, July 2000, 6–11.

Rummel, R.: 1979, ’Determination of short-wavelength components of the gravity field from satellite-to-satellite tracking or satellite gradiometry; an attempt to an identification of problem areas’, *Manuscripta Geodetica* **4**, 107–148.

Rummel, R., Müller, J., Oberndorfer, J. H., and Sneeuw, N.: 2000, *in* R. Rummel, H. Drewes, W. Bosch, and H. Hornik (eds.), *Satellite Gravity Gradiometry with GOCE, Towards an Integrated Global Geodetic Observing System (IGGOS)*, IAG Section II Symposium, 1998, Springer Verlag, pp. 66–72.

Wolff, M.: 1969, ’Direct Measurement of the Earth’s Gravitational Potential Using a Satellite Pair’, *J. Geophys. Res.* **74**, 5295–5300.