Mission Objectives and Requirements

Mark Drinkwater,
Roger Haagmans &
Michael Kern

Mission Science Division

www.esa.int/livingplanet/goce
GOCE owes its origin to:
- Solid-Earth Science and Applications Mission for Europe (SESAME) in the Early 1980’s (ESA, SP-1080)
- 1987 ESA-NASA Workshop on Joint Solid Earth Programme (SP-1094)
- Former ESA Aristoteles mission (ESA, 1991)

The first Core missions originated via Consultations with the User community in 1991 and 1994 (ref: SP-1143; SP-1186)
- Gravity mission recommended as a priority for study

Early studies by Consortium Involving Gravity Advanced Research:
- CIGAR I and II
  - Study of precise gravity field determination and mission requirements.
    Phase 1 ended Jan. ’89 and Phase 2 in Mar. ‘90.
- CIGAR III and IV
  - Study on gravity field determination using gradiometry and GPS.
- CIGAR V
Solid Earth Physics
anomalous density structure of lithosphere and upper mantle, and better constraints for modelling of Earth’s interior

Oceanography
determination of dynamic ocean topography, absolute ocean circulation, and mass and heat transfer

Ice Sheets
improved knowledge of ice sheet mass balance

Geodesy
unified height systems, “levelling by GPS” (i.e. orthometric heights)

and from the above, improved rate estimates of Sea Level Rise
Determination of absolute ocean circulation requires knowledge of the static geoid, or mean sea-surface (representing the ocean at rest)

- Ocean ‘dynamic topography’ is the difference between the altimeter-measured ocean surface and the geoid.
- 1 mGal gravity anomaly corresponds to ~1 mrad slope in ocean surface, or a geostrophic surface current velocity of ~0.1 m/s
n To provide high spatial resolution information on gravity anomalies in relation to density structure of the lithosphere and upper mantle

n To deliver information of relevance to the study of Earthquakes, Volcanoes and other natural hazards

n To provide information on high spatial harmonics in post-glacial rebound and improvements in ice sheet mass balance estimates
To provide a unified global height reference surface from which ‘pseudo-levelled’ or ‘orthometric’ heights can be derived.
Unification of tide gauge records achieved with knowledge about post-glacial rebound and by GPS levelling, (to avoid spurious sea-level rise/fall estimates).
Mission Requirements

n To determine the Earth’s gravity field with an accuracy of 1 mGal (1 mGal = 10^{-5} m/s^2 )
  – 1 “milli-Galileo” is ~ 10^{-6} of the acceleration of gravity, g
  – Requires determining the 3d rate of change of gravity between pairs of accelerometers with a desired sensitivity of ~4 mE (milli-Eötvös) in each axis
    Where 1 E = 1 mGal / 10 km ≈ 10^{-9} s^{-2} (i.e. m/s^2 /m)
  – Noise specification for single accelerometer in MBW:
    2 x 10^{-12} m/s^2 /Hz^{0.5} (c.f. CHAMP ~10^{-9}; GRACE ~10^{-10})

n To determine the geoid (= equipotential surface for a hypothetical ocean at rest) with 1-2 cm accuracy

n achieve this at a resolution or half wavelength scale of 100 km (approx. degree and order 200)
... get a feeling for the numbers

Downforce $\approx 2 \times 10^{-3}$ N

Super-tanker acceleration:

$$\frac{2 \times 10^{-3} \text{ N}}{1 \times 10^9 \text{ kg}} \approx 2 \times 10^{-12} \frac{\text{m}}{\text{s}^2}$$

0.2 gram

1 000 000 tonne
Comparison of Gravity Missions

**CHAMP**
- Satellite-satellite tracking in high-low (SST-hl) mode
- cm orbit determination
- no drag-free control
- STAR accelerometer

* mission has developed low resolution geoid

**GRACE**
- Satellite-satellite tracking in high-low and low-low modes
- cm orbit determination
- two platforms with 3d accelerometers
- intersatellite link measures precise platform separation
- no drag-free control
- SuperSTAR accelerometers

* GRACE mission designed to resolve time-varying gravity field at long wavelengths > 300 km

**GOCE**
- Satellite-satellite tracking in high-low mode
- cm orbit determination
- Electrostatic gravity gradiometer comprising 6 accelerometers
- drag-free control to maintain “free-fall” around proof masses.
- new accelerometers

* GOCE mission designed to resolve high spatial resolution gravity field
GOCE combines satellite gradiometry and high-low satellite-to-satellite tracking in a low Earth orbit of ±250km altitude, with unique continuous operation of Drag-Free Attitude Control to combat the effects of air drag.

- Electrostatic Gravity Gradiometer (EGG):
  Measures the components of the gravity gradient tensor in the gradiometer reference frame within a bandwidth of 5-100 mHz.

- Satellite-to-Satellite Tracking Instrument (SSTI):
  Geodetic-quality GPS receiver allows orbit reconstitution with an accuracy of ~1 cm in all directions and recovery of lower order harmonics.
Gradiometer Principle
Gravity gradients: 2\textsuperscript{nd} spatial derivatives of gravitational potential $V$

- Gravity gradient tensor (GGT) consists of 9 elements, of which 5 (shown below) are independent due to symmetry and traceless condition

$$MBW = 5 \times 10^{-3} - 10^{-1} \text{Hz}$$
$$40 - 1600 \text{km}$$
$$5 - 200 \text{s}$$
Gravity Field Requirements for Science (see SP-1233(1), July 1999)

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>ACCURACY</th>
<th>SPATIAL RESOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Geoid (cm)</td>
<td>Gravity (mgal)</td>
</tr>
<tr>
<td>SOLID EARTH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithosphere and upper-mantle density structure</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>Continental lithosphere:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* sedimentary basins</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>* rifts</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>* tectonic motions</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>Seismic hazards</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ocean lithosphere and interaction with asthenosphere</td>
<td>0.5-1</td>
<td></td>
</tr>
<tr>
<td>OCEANOGRAPHY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Short-scale</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>* Basin scale</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>ICE SHEETS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Rock basement</td>
<td></td>
<td>1-5</td>
</tr>
<tr>
<td>* Ice vertical movements</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>GEOODESY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Levelling by GPS</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>* Unification of worldwide height systems</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>* Inertial Navigation System</td>
<td>–1-5</td>
<td></td>
</tr>
<tr>
<td>* Orbits</td>
<td>–1-3</td>
<td></td>
</tr>
<tr>
<td>SEA-LEVEL CHANGE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Many of the above applications, with their specific requirements, are relevant to studies of sea-level change.
Requirements: Solid-Earth Physics

GRACE gravity field

GOCE

Solid-Earth Physics

Continental Lithosphere

Mantle

Oceanic Lithosphere

Ice

required gravity accuracy [mGal]

horizontal resolution [km]

Present state

Trenches

Mountains

Fracture Zones

Under-Plating

Rifting

Sedimentation

Bedrock

Ridges

Roots

Basins

Plateaus

Rheology

Convection

Viscosity

Mass Balance

Rheology

Convection

Viscosity

Mass Balance
Requirements: Oceanography

- Oceanography
- GRACE geoid
- GOCE
- Gyres
- ACC-DP
- ACC-AA
- Tropics (zonal)
- Coastal Currents
- Stronger WBC
- Weaker WBC
- Shorter Straits

Legend:
- ACC - Antarctic Circumpolar Current
- AA - African & Australian Chokepoints
- DP - Drake Passage
- WBC - Western Boundary Current
Requirements: Geodesy

![Diagram of Geodesy Requirements](image)

- **Geodesy**
- **GRACE geoid**
- **Present state**
- **GOCE**
- **Inertial Navigation**
- **Available Regional Geoids**
- **Orbits**
- **Leveling by GPS**
- **Unification of Height Systems**
- **Sea-level Monitoring**

Horizontal resolution [km] vs. required geoid accuracy [cm].
Science and Applications

- **Solid Earth**: gravity anomalies, seismic tomography, topography, deformations, laboratory.
  - anomalous density structure
- **Ocean**: geoid, ocean altimetry.
  - mean ocean circulation
- **Ice**: gravity anomalies, ice topography.
  - bedrock topography
  - mass balance of ice sheets
  - INS + orbits
- **Geodesy**: geoid, positioning (GPS).
  - levelled heights
  - unified height system
  - gravity anomalies
- **Sea Level**: tide gauges altimetry.
  - post glacial Rebound
  - mean ocean circulation
  - ice mass balance
  - orbits
  - unified height systems

Mark Drinkwater, R. Haagmans & M. Kern – November 2006
## GOCE Scientific Issues

<table>
<thead>
<tr>
<th>Issue</th>
<th>Activities</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission analysis</td>
<td>GOCE End to End Performance Analysis and Observation Requirements Studies</td>
<td>Baseline gradiometer and DFAC</td>
</tr>
<tr>
<td>Mission impact</td>
<td>Ocean circulation retrieval</td>
<td>Baseline concept confirmed</td>
</tr>
<tr>
<td></td>
<td>Tectonics, GIA and Sea level</td>
<td></td>
</tr>
<tr>
<td>Level 1 and 2</td>
<td>3 studies on algorithms, products, calibration/validation, quick look tools</td>
<td>Baseline for methods &amp; products</td>
</tr>
<tr>
<td>Polar Gap, Calibration and Validation</td>
<td>ESAG airborne campaign and ArcGP project</td>
<td>Arctic gap filled</td>
</tr>
<tr>
<td></td>
<td>Level 1b Cal/Val plan available</td>
<td>AO closed</td>
</tr>
<tr>
<td>Data combination and altimetry data exploitation/assimilation</td>
<td>Ocean shelf study, sea-ice (ArcGICE) See R. Forsberg presentation this morning &amp; Poster by E. Jeansou</td>
<td>ongoing</td>
</tr>
<tr>
<td>Data A.O.</td>
<td>Released Oct. 06 – closing date Dec. 06</td>
<td>ongoing</td>
</tr>
</tbody>
</table>
Level 2 Data Products

- Externally calibrated and corrected gravity gradients

- Global Earth gravity potential modelled as spherical harmonic series up to deg/order 200 – corresponding to 100km spatial res. (incl. coefficients and error estimates)

- Global ground-referenced gridded values of:
  - geoid heights (Earth geoid map)
  - gravity anomalies (Earth gravity map)
  - geoid slopes

- Variance-covariance matrix of final GOCE Earth gravity field model
GOCE Level 2 Products

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Description</th>
</tr>
</thead>
</table>
| EGG_NOM_2    | - Externally calibrated and corrected gravity gradients in GRF (2 weeks latency)  
- Corrections to gravity gradients for temporal gravity variations  
- Flags for outliers, fill-in gravity gradients for data gaps with flags  
- Statistical information                                                                 |
| EGG_TRF_2    | - Externally calibrated gravity gradients in Earth fixed reference frame including error estimates for transformed gradients  
- Transformation parameters to Earth fixed reference frame                                      |
| SST_PSO_2    | - GOCE precise science orbits final product  
- Quality report for precise orbits                                                             |
| EGM_GOC_2    | - Final GOCE Earth gravity field model as spherical harmonic series including error estimates.  
Target: 1-2 cm / 1 mGal up to degree and order 200 corresponding to 100 km spatial resolution.  
- Grids of geoid heights, gravity anomalies and geoid slopes computed from final GOCE Earth gravity field model including propagated error estimates  
- Quality report for final GOCE gravity field model                                              |
| EGM_GVC_2    | - Variance-covariance matrix of final GOCE Earth gravity field model                                                                          |
Uniqueness and Relevance

- Only mission with satellite gradiometry (3D) and drag-free control in low orbit (250km)

- GOCE will provide global static gravity field with homogeneous quality of unprecedented accuracy and resolution

- Key step in improving ocean, solid Earth and sea-level modelling

- Large impact on national height systems and surveying applications on land and sea

- Essential benchmark technique for understanding mass distribution and change
Future Outlook

- GOCE Scientific Preparations almost complete
- GOCE Ground Segment development on track (including L2 scientific data processing)
- Planned GOCE Data AO Release – Oct 2006
- Data AO Deadline – 8 December 2006
- GOCE Science Data Users have “cut their teeth” on CHAMP and GRACE data
- Main technical challenge is completion of flight model programme
- GOCE primary Mission Objectives can still be met with a launch in late 2007

- GOCE launch scheduled for Sept. 2007