ESA’s gravity field mission
GOCE and beyond

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Mission Science Division
European Space Agency

IV Hotine-Marussi Symposium, Wuhan 29 May - 2 June 2006
- ESA’s Living Planet Programme

- GOCE mission status

- Swarm mission and gravity field potential

- Studies related to future ideas
ESA’s Living Planet Programme

Living Planet Programme

Earth Explorer
- Research driven
  - Core Missions
  - Opportunity Missions

Earth Watch
- Service driven
  - EUMETSAT
    - MSG
    - MTG
    - EPS
    - Post EPS
  - GMES
    - Sentinel 1-5

Call for ideas for next Explorer Core Mission: Evaluation finished

- Earth gravity field
  - GOCE 2007
- Global wind field
  - ADM-Aeolus 2008
- Aerosol cloud radiation interaction
  - EarthCARE 2012
- Variation in ice sheet thickness
  - CryoSAT 2 2009
- Soil moisture & ocean salinity
  - SMOS 2007
- Earth’s magnetic field & its evolution in time
  - Swarm 2010

http://www.esa.int/esaLP
ESA’s Living Planet Programme

Living Planet Programme

Earth Explorer
- Research driven

Earth Watch
- Service driven

Core Missions

Opportunity Missions

Pre-phase A studies

Biomass
- to take global measurements of forest biomass.

Traq
- TRopospheric composition and Air Quality

Premier
- PRocess Exploration through Measurements of Infrared and millimetre-wave Emitted Radiation.

Flex
- FLuorescence EXplorer – to observe global photosynthesis.

A-SCOPE
- Advanced Space Carbon and Climate Observation of Planet Earth

CoreH2O
- Cold Regions Hydrology High-resolution Observatory.

Eumetsat

Gmes
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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
Mission Requirements

- To determine the Earth’s gravity field with an accuracy of 1 mGal (1 mGal = 10^{-5} m/s^2)
- To determine the geoid (= equipotential surface for a hypothetical ocean at rest) with 1-2 cm accuracy
- achieve this at a resolution or half wavelength scale of 100 km (approx. degree and order 200)
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.
AIUB: Astronomical Institute University Bern
CNES: Centre Nationale d'Etudes Spatiale, Toulouse
FAE/A&S: Delft University of Technology, Faculty of Aerospace Engineering
GFZ: GeoForschungsZentrum Potsdam
IAPG: Institute of Astronomical and Physical Geodesy, Techn. University Munich
ITG: Institute for Theoretical Geodesy, Univ. Bonn
POLIMI: Politecnico di Milano
SRON: National Institute for Space Research, The Netherlands
TUG: Institute of Navigation and Satellite Geodesy, Techn. University Graz
UCPH: Department of Geophysics, University Copenhagen
Level 2 Data Products

- Global Earth gravity potential modelled as spherical harmonic series (incl. coefficients and error estimates)

- Variance-covariance matrix of final GOCE Earth gravity field model

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

- Highest sensitivity accelerometers in space
  - CHAMP: $\sim 10^{-9}$ ms$^{-2}$
  - GRACE: $\sim 10^{-10}$ ms$^{-2}$
  - GOCE: $\sim 10^{-12}$ ms$^{-2}$

- Ultra-stable Carbon-Carbon structure with superior thermo-elastic stability properties in the MBW
  - $\sim 1$ pm over 200 s
  - $\sim 10$ mK over 200 s

- Continuous operation and modulation of highly accurate ion thrusters with high thrust and thrust gradient demands
One-Axis Gradiometer

Carbon-Carbon Arm Structure with Accelerometer Pair, including magnetic shielding and connectors

OAGY: Y-direction
Gradiometer Structural Model
As solar activity and consequently atmospheric drag increase, altitude adjustments become necessary.
Consequence of Launch Delay

Performance indicated at degree 200 (100km spatial resolution)

**Launch in May 2007**
- MOP 1 at an altitude of **240 km** and MOP 2 at an altitude of **250 km**

  *Mission performance: Geoid accuracy up to 1 cm*
  *Gravity anomaly well below 1 mgal*

**Launch in September 2007**
- MOP 1 at an altitude of **250 km** and MOP 2 at an altitude **260 km**

  *Mission performance: Geoid accuracy of up to 1.5 cm*
  *Gravity anomaly below 1 mgal*

**Launch in January 2008**
- MOP 1 at an altitude of **255 km** and MOP 2 at an altitude **265 km**

  *Mission performance: Geoid accuracy of up to 2 cm*
  *Gravity anomaly 1 mgal*
Level 2: Simulated Product Accuracy

Geoid Error [m]

Gravity Anomaly Error [mGal]

GMs

2 cm

1 cm

100%

90%

original baseline

spherical harmonic degree

spherical harmonic degree

1 mGal

100%

90%

original baseline
Meetings and Studies

- **3rd International GOCE User Workshop**, planned for Nov. 2006 - ESRIN (ESA, SP-627)
  [http://earth.esa.int/goce06/](http://earth.esa.int/goce06/)

- **IUGG XXIV**, Perugia, Italy, planned for July 2007

- **Ongoing Scientific Studies**
  - GSP - Gravity improvement of ocean shelf circulation (underway)
  - GSP – Combination of Space, airborne, and in-situ gravity measurements in support of Arctic sea-ice thickness mapping (underway)
  - GOCE Toolbox study (underway)
Announcements of Opportunities

- **GOCE Cal/Val AO: May-July 2003**
  - L1-L2 Processing Facility capability
    - Data screening (incl. QL analysis for quality control)
    - Outlier detection
    - Temporal gravity effect removal (e.g. tides)
    - Assessment of residual uncertainties in instrument data
  - External calibration of GGT observations
  - Validation of L1b data products

- **Planned GOCE Data AO: Sept. 2006**
  - Data quality assessment/performance verification
  - Proposals for scientific data use
  - Synergies with other platform data

- **Launch and Phase E1 starting Spring 2007 (TBC)**
ESAs Living Planet Programme

GOCE mission status

Swarm mission and gravity field potential
(Christian Gerlach TUM and Pieter Visser DUT)

Studies related to future ideas
The Swarm Mission

Primary Objectives
- core dynamics, geodynamo processes, and core-mantle interaction
- lithospheric magnetisation
- 3-D electrical conductivity of the mantle
- electric currents in magnetosphere and ionosphere

Secondary Objectives
- magnetic forcing of the upper atmosphere
- magnetic signature related to ocean circulation

Theme: Earth’s Interior
Unique view “inside” the Earth from space for core, mantle & crust

Theme: Physical Climate
Sun’s influence within Earth system

Sun’s influence within Earth system
Swarm Satellite & Constellation

GPS Patch

Antennas

Accelerometer

<table>
<thead>
<tr>
<th>launch</th>
<th>after 1.5 yr</th>
<th>after 3 yrs</th>
<th>after 4.5 yrs</th>
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<tbody>
<tr>
<td>red (C)</td>
<td>530 km</td>
<td>500 km</td>
<td></td>
</tr>
<tr>
<td>yellow (A,B)</td>
<td>450 km</td>
<td>300 km</td>
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Observation: GPS-baseline between satellites

Geometry:
- GRACE A-B: along-track (KBR, scalar)
- Swarm A-B: cross-track (GPS, vector)
- Swarm A-C: ~ radial (GPS, vector)
Swarm and Gravity
Use of GPS-Baseline Observations

(1) **Error propagation**: incination functions using transfer coefficients for potential gradients $V_x, V_y, V_z$

For short baselines: $\frac{\Delta V}{||\Delta x||} \approx V_x$

(2) **Full simulation**: energy integral for potential differences

<table>
<thead>
<tr>
<th>Swarm and Gravity Differences</th>
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<tr>
<td>GRACE 1-2</td>
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<tr>
<td>Swarm A-B</td>
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<tr>
<td>Swarm A-C</td>
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$\Delta V_{\text{along-track}}$

$\Delta V_{\text{cross-track}}$

$\Delta V_{\text{radial}}$
High-pass filtered GRACE inter-satellite ranging

From KBR

Empirical range errors (GPS vs. KBR)

\[
\begin{align*}
\sigma_{\text{along}} & = 2.1 \text{ mm} \\
\sigma_{\text{cross}} & = 2.0 \text{ mm} \\
\sigma_{\text{radial}} & = 2.7 \text{ mm}
\end{align*}
\]

Expected range-rate accuracy:

\[\sigma \approx 10^{-2} \text{ mm/s}\]
SH-Error Characteristics
Along-track simulations vs. real data (GRACE)

1. Inclination functions
   - error propagation

2. Energy integral
   - full simulation

Covariance Matrix
EIGEN-GRACE02s (GFZ)
Gravity Field Gradients

along-track

cross-track

radial
SH-Error Characteristics from Gradients in $x$, $y$ and $z$
SH-Error Characteristics from Different Observation Directions

(2)

- **along-track**
- **cross-track**
- **along + cross**
- **radial**
Simulation results: 1 Month

Degree RMS

Radial: GRACE & GOCE

Cross & Along: Swarm A-B & GRACE

KBR

Kaala

CHAMP

\[ \text{De gre e RMS} \]

\[ \text{KBR} \]

\[ \text{Kaala} \]

\[ \text{CHAMP} \]

\[ \text{Radial: GRACE & GOCE} \]

\[ \text{Cross & Along: Swarm A-B & GRACE} \]
Simulation results: 1 Month

Degree RMS

Kaula

CHAMP

Swarms

GRACE

KBR

A-B and A-C

s h-de gre e

[10^{-6}, 10^{0}]

[10^{0}, 10^{7}]

[10^{-1}, 10^{2}]

[10^{-2}, 10^{3}]

[10^{-3}, 10^{4}]

[10^{-4}, 10^{5}]

[10^{-5}, 10^{6}]

s h-de gre e

10

20

30

40

50

60

70

Simulation results: 1 Month

Degree RMS

Kaula

CHAMP

Swarms

GRACE

KBR

A-B and A-C

s h-de gre e

[10^{-6}, 10^{0}]

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[10^{-3}, 10^{4}]

[10^{-4}, 10^{5}]

[10^{-5}, 10^{6}]

s h-de gre e

10

20

30

40

50

60

70
Remarks

- Gravity field recovery with Swarm is possible
- Continuation of decade of gravity field mapping possible (but, with reduced accuracy)
- Radial component most sensitive at end of mission (but, bad visibility)
- Simulation must include full GPS-simulation (visibility)
- Realistic error estimates for GPS?
- Different analysis methods possible (not necessarily energy integral)
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Studies Recently Performed

- **Gravity Gradient sensor technology for future planetary missions** [ESA ITT AO/1-3829/01/NL/ND](#) (MEMS, Atom interferometry)

  **University of Nantes:** Christophe Sotin and his team
  **University of Twente:** Jaap Flokstra, Remco Wiegerink, Herman Hemmes, Javier Sese, Reinder Cuperus

- **Laser Doppler Interferometry Mission for determination of the Earth’s Gravity Field**

  Marco PISANI (IMGC), Andrea Milani (UniPi), Roberto Sabadini (UniMi), Federica Migliaccio, F. Sansò (PoliMi)
  Alcatel Alenia Space Italia S.p.A. Stefano Cesare and team
- Orbit altitude: $h = 325 \text{ km}$, circular

- Orbit inclination: $i = 96.78^\circ$ (sunsynchronous)

- Longitude of ascending node: $\Omega = \text{RA} \pm 90^\circ$ (dusk-dawn/dawn-dusk orbit)

- Measurement phase duration: 6 years

- Satellite number, arrangement: 2 satellites moving along the same orbital path

- Inter-satellite distance: $d = 10 \text{ km}$
Measurement and control elements of the SSI mission

- Navigation satellites (GPS/Galileo)
- Interferometer
- BSM
- GPS/G receiver
- Star tracker
- Drag and attitude control actuators
- Non-gravitational forces
- Angle and lateral displacement metrology
- Accelerometer
Non-gravitational acceleration measurement requirements

Accelerometer noise spectral density (in-line axis): level comparable to GOCE but to be optimized in a lower spectral band.

Accelerometer absolute scale factor knowledge accuracy $\leq 2 \times 10^{-4}$ (ten times better than in GOCE)

Absolute scale factor stability also more demanding than in GOCE.
Satellite-satellite distance measurement requirements

Laser interferometer measurement error: \( \leq 1.2 \, \text{nm} \, 1\sigma \) in MBW

Satellite orientation relative to laser beam measurement error

Laser beam pointing towards retroreflector on satellite 2
The Linear Motion Control in charge of:
- satellite formation keeping (relative position control)
- drag-free control for each spacecraft

The Angular Motion Control in charge of:
- spacecraft angular acceleration, angular rate and attitude control

Beam Steering Control in charge of:
- pointing of the laser beam emitted by satellite 1 to the satellite 2
Future Concepts?

GSP - Mass distribution and mass transports in the Earth system (ITT in prep.)

Courtesy: C. Barton