GOCE Research in Germany: From Sensor Analysis to Earth System Science

Reiner Rummel, Jakob Flury and Thomas Gruber
Institut für Astronomische und Physikalische Geodäsie
Technische Universität München

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6.– 8. November 2006
Contents:

• GOCE Science Objectives and Research Challenges
• GOCE-GRAND-2 second phase
• GOCE related research activities in Germany
• GOCE project office
GOCE Mission Objectives

Acronym: Gravity and Steady-State Ocean Circulation Explorer

Mission Objectives:
Geoid std. dev. 1cm
Gravity (anomalies) std. dev. 1mGal
Spatial resolution: 100 km (Lmax= 200)

Launch:
September 2007
applications of static gravity field

- solid earth
  - gravity anomalies
  - seismic tomography
  - topography
  - deformations
  - laboratory
  - anomalous density structure
- ocean
  - geoid
  - ocean altimetry
- ice
  - gravity anomalies
  - ice topography
- geodesy
  - geoid
  - positioning (GPS)
- sea level
  - tide gauges altimetry

- mean ocean circulation
- bedrock topography
- „levelled“ heights
- unified height system
- INS
- orbits
- post glacial rebound
- mean ocean circulation
  - ice mass balance
  - orbits
  - unified height systems
## Science Requirements

<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></td>
<td>half wavelength - D (km)</td>
<td></td>
</tr>
<tr>
<td>Lithosphere / upper mantle density</td>
<td>1-2</td>
<td>100</td>
</tr>
<tr>
<td>Sedimentary basins</td>
<td>1-2</td>
<td>50-100</td>
</tr>
<tr>
<td>Rifts</td>
<td>1-2</td>
<td>20-100</td>
</tr>
<tr>
<td>Tectonic motions</td>
<td>1-2</td>
<td>100-500</td>
</tr>
<tr>
<td>Seismic hazards</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Ocean lithosphere / asthenosphere</td>
<td>0.5</td>
<td>100-200</td>
</tr>
<tr>
<td>Short scale</td>
<td>1-2</td>
<td>100</td>
</tr>
<tr>
<td>Basin scale</td>
<td>~ 0.2</td>
<td>200</td>
</tr>
<tr>
<td>Rock basement</td>
<td>~ 1-5</td>
<td>50-100</td>
</tr>
<tr>
<td>Ice vertical movements</td>
<td>2</td>
<td>100-1000</td>
</tr>
<tr>
<td>Levelling by GPS</td>
<td>1</td>
<td>100-1000</td>
</tr>
<tr>
<td>Unified height systems</td>
<td>1</td>
<td>100-20000</td>
</tr>
<tr>
<td>INS</td>
<td>~ 1-5</td>
<td>100-1000</td>
</tr>
<tr>
<td>Orbits</td>
<td>~ 1-3</td>
<td>100-1000</td>
</tr>
<tr>
<td>Sea level change</td>
<td>Many of the above applications, with their specific requirements, are relevant to studies of sea level change</td>
<td></td>
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</tbody>
</table>

Gravity Field and Steady-State Ocean Circulation Mission
ESA, SP-1233 (1), 1999, p.80
GOCE and steady-state ocean circulation requires two surfaces and therefore two satellite sensor systems to be globally consistent at the „cm-level“.
**GOCE:** maximum resolution ($s = 80$ km)

**GRACE:** maximum precision (geoid < $\mu$m)
Power Density Spectrum for \{zz\}-component

- noise
- filter
- MBW
GOCE High Level Processing Facility
GOCE Standards

Doc. No.: GO-TN-HPF-GS-00xx
Issue: 1
Revision: 0
Date: October / 2006

Prepared by: The European GOCE Gravity Consortium
EGG-C
GOCE gravity model:
global
spherical harmonic series

terrestrial gravity data:
regional
pointwise, block averages
Calibration and Validation

GOCE

spectral representation
long wavelength short
spatial representation

global regional local

CAL/VAL data sets

spectral representation
long wavelength short
spatial representation

global regional local
 Calibration and Validation

GOCE

CAL/VAL data sets

Spatial representation

Global
Regional
Local

Long wavelength
Short wavelength
Spectral representation
Regional Validation and Combination Experiment

Observations of vertical deflections (courtesy IFE Hannover)
Projektion des Satellitenorbits in die Aquatorebene
A Selection of Research Challenges:

• take into account peculiarities of sensor system
• get lowest harmonics right
• get altimetry and GOCE into one consistent reference system
• ensure definition and implementation of adequate standards
• revisit theory of geodetic boundary value problem
• work on optimal combination of geopotential models
• and on their combination with terrestrial data
• develop appropriate validation methods
• and experiments
GOCE related activities in Germany

- Participation in ESA GOCE processing (ESA contracts): PDS, HPF, CMF, CAL/VAL, GUTs, studies
- Connection to GT Theme 2 „Observation of Earth System from Space“
- Participation in DFG Priority Programme 1257 „Mass Transport and Mass Distribution in System Earth“
- Involvement in IAG Pilot Project: GGOS (will belong to IGOS and GEO)
GOCE-Grand 2

Financed by German Research Ministry through GeoTechnology Programme its Theme 2 „Observation of Earth System from Space“
<table>
<thead>
<tr>
<th>GOCE Standards</th>
<th>System Transformations; Geometrical Models; Dynamical Models.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOCE and Surface Data</td>
<td>Combination &amp; Validation; Corrections to be applied; Data Weighting; Aliasing &amp; Filtering Techniques.</td>
</tr>
<tr>
<td>GOCE and Applications</td>
<td>Identification of Needs; Reference Potential $W_0$; Derived Gravity Field Quantities on Ellipsoid or Earth Surface.</td>
</tr>
</tbody>
</table>
Mass Transport and Mass Distribution in the Earth System

Proposal for a German Priority Research Program

Proposal to German Research Foundation (DFG)

coordinator: K-H Ilk

granted: 2005
Mass Transport in the Earth System

Gravity field missions
- CHAMP
- GRACE
- GOCE

Altimetry missions
- Envisat
- Jason-1
- CryoSat
- ICESat

From satellite sensor data to mass signals
- Combination of geometry and gravity in space and time in one reference system, data preparation for model assimilation, terrestrial/airborne data, separation of signal effects, complementary data

Ocean transport (mass/heat)
- Ocean surface circulation (altimetry - geoid)
- Deep ocean circulation (bottom pressure)
- Sea level mass vs. volume change (altimetry/gravimetry)

Atmosphere

Hydrological cycle
- Continental water budget, closure of global and regional water balance, water storage variation, trends and climate change

Ice mass balance and sea level
- Ice surface: height change, velocities, mass budget of ice sheets, bottom topography, sea level rise from melting, dynamic ice models, sea ice: coverage, thickness

Dynamics of mantle and crust
- Mantle dynamics and geoid signal, geoid time variation from glacial isostatic adjustment, plumes, slabs, gravity signal of crustal and lithosphere structure

Complementary remote sensing
- TerraSAR, topography, sea surface temperature, winds, salinity, soil moisture (SMOS) etc.
IAG Pilot Project: Global Geodetic Observing System

http://www.ggos.org
Coordination of GOCE activities
by GOCE project office

financed by DLR (German Aerospace Center)

responsible for:

• activation of user community
• coordination of GOCE activities
• public relations
• contact with industry and funding agencies
Enabling Observation Technologies for Future Solid Earth Missions
Future Satellite Gravimetry and Earth Dynamics

Jakob Flury and Reiner Rummel (Eds.)
GGOS: Geodesy and System Earth

Earth Rotation
- Precession/ nutation
- Polar motion
- Variations in l.o.d.

Geometry
- 3D+T: shape of land surfaces
- Ice shields
- Oceans

Gravity/ Geoid
- 3D+T: detailed geoid
- Gravity anomaly field

From space and terrestrial geodetic data to Earth System Parameters
- Consistent models
- Separation of effects
- Data processing
- Data combination
- Filtering

Oceanic transport
- Ocean circulation (quasi-static and time variation)
- Mass and heat transport
- Eddies
- Sea level: mass and volume change

Atmosphere and Ionosphere
- Composition of ionosphere
- Atmospheric sounding (T, H, P)
- Tropospheric models
- Mass balance

Continental hydrology
- Continental water budget
- Closure of water balance (global, regional)
- Water storage variation
- Trends and climate change

Ice mass balance and sea level
- Ice surface: height change, velocities
- Mass budget of ice sheets
- Sea level rise from melting, dynamic ice models
- Sea ice: coverage, thickness

Dynamics of mantle and crust
- Mantle dynamics and geoid signal
- Time variation from global isostatic adjustment
- Plumes, slabs, gravity signal of crustal and lithospheric structures

Earth Deep Interior
- Core-Mantle Coupling
- Mantle anelasticity
- ICB flattening

From Earth to Planets
- Moments of Inertia
- Fluid core?
- Isostatic (un)equilibrium
- Shape and gravity field

(after Ilk KH et al., 2005)
GOCE

ground segment

GOCE Cal/Val Team

GOCE Application Studies

GOCE User Toolbox

GOCE Users

level 0

level 1a/1b

level 2

level 3
Users (Science and Application)

- solid Earth physics
- physical oceanography and climate research
- geodesy
- sea level research
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-axis gravity gradiometer</td>
<td>Gravity gradients $\Gamma_{xx}$, $\Gamma_{yy}$, $\Gamma_{zz}$ in instrument system and inside MBW (measurement bandwidth)</td>
</tr>
<tr>
<td>Star sensors</td>
<td>High rate and high precision inertial orientation</td>
</tr>
<tr>
<td>GPS receiver</td>
<td>Orbit trajectory with cm-precision</td>
</tr>
<tr>
<td>Drag control with 2 ion thrusters</td>
<td>Based on common mode accelerations from gradiometer data</td>
</tr>
<tr>
<td>Angular control with magnetic torquers</td>
<td>Based on angular rates from star sensors and gradiometer</td>
</tr>
<tr>
<td>Orbit altitude maintenance</td>
<td>Based on GPS orbit</td>
</tr>
<tr>
<td>Internal calibration of gradiometer (and quadratic factors)</td>
<td>Random shaking with cold gas thrusters (and random pulses)</td>
</tr>
</tbody>
</table>
Status of GOCE development

newly developed GPS receiver

laser tracking
Status of GOCE development

Attitude and Drag-free control
Status of GOCE development

- accelerometers
- 1-axis gradiometer
- 3-axis gradiometer
GOCE: maximum resolution (s = 80 km)

GRACE: maximum precision (geoid < μm)
B.G.I. GRAVITY DATA BASE (density per 30°*30°)

gravity measurements: 12 649 246
10 535 654 marine data & 2 113 592 land data
**Klassische Bilanzgleichungen**

**Impulsbilanz**

\[ M \dot{R} - \int K \, dt = P_0 \]

- Impuls = Anfangsimpuls + integrierte Kraft

**Drehimpulsbilanz**

\[ M \ddot{R} - K = 0 \]

- Drehimpuls = Anfangsdrehimpuls + integriertes Drehmoment

**Energiebilanz**

\[ \frac{1}{2} M \dot{\mathbf{R}}^2 - \int \mathbf{R} \cdot \mathbf{K} \, dt = E \]

- Energie = kinetische Energie - integrierte Arbeit
Mass Transport and Mass Distribution in the Earth System

Contribution of the New Generation of Satellite Gravity and Altimetry Missions to Geosciences

Proposal for a German Priority Research Program
Mass Transport in the Earth System

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- GRACE
- GOCE

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From satellite sensor data to mass signals
- Combination of geometry and gravity in space and time in one reference system,
- Data preparation for model assimilation,
- Terrestrial/airborne data,
- Separation of signal effects,
- Complementary data

Ocean transport (mass/heat)
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- Geoid time variation from glacial isostatic adjustment, plumes, slabs,
- Gravity signal of crustal and lithosphere structure

Complementary remote sensing
- TerraSAR,
- Topography, sea surface temperature,
- Winds, salinity, soil moisture (SMOS) etc.
GOCE design elements:
- 3-axis gravity gradiometer
- GPS (orbit + low harmonics)
- star sensor (orientation in space)
- active attitude control (magnetic torquers)
- active drag compensation (along-track)
- stable and rigid material

now: magnetic torquers
**Instrument Concept**

- **translational forces**
- **angular forces**

- **GPS/GLONASS SST -hl**
- **star sensors**

**GRAVITY GRADIOMETER**

Measures:
- Gravity gradients
- Angular accelerations
- Common mode acc.

- **drag control**
- **angular control**
unified height systems

sea surface topography

ocean mass transport

sea level changes

GEOID: REFERENCE SURFACE FOR LAND - ICE - OCEAN CHANGES AND INTERACTION

GRAVITY: MIRROR OF EARTH'S INTERIOR PROCESSES

Glacial isostatic adjustment

Earthquakes - slow component

Bathymetry

continental lithosphere
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>orbit altitude</td>
<td>250 km</td>
</tr>
<tr>
<td>inclination</td>
<td>96.5°</td>
</tr>
<tr>
<td>one orbit cycle</td>
<td>~ 30 to 40 days</td>
</tr>
<tr>
<td>mission duration</td>
<td>20 months</td>
</tr>
<tr>
<td>gradiometer</td>
<td>3 mE/√Hz</td>
</tr>
<tr>
<td>orbit</td>
<td>1-3 cm</td>
</tr>
<tr>
<td>launcher</td>
<td>Rockot class</td>
</tr>
</tbody>
</table>
Electrostatic Gravity Gradiometer
GOCE ground segment
Auslenkung der tatsächlichen Meeresoberfläche (gemessen mit Satellitenaltimetrie) bezüglich der Niveaufläche auf Meeresniveau, dem Geoid (berechnet aus Schwerefeldmodell) = dynamische Meerestopographie