GOCE Precise Science Orbits and their Contribution to Gravity Field Recovery

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GOCE satellite mission (1)

- Gravity and steady-state Ocean Circulation Explorer
- First Earth Explorer of the Living Planet Program of the European Space Agency
- Launch: 17 March 2009 from Plesetsk, Russia
- Sun-synchronous orbit with inclination of 96.5°
- Altitude: 254.9 km
- Mass: 1050 kg at launch
- 5.3 m long, 1.1 m² cross section

Courtesy: ESA
GOCE satellite mission (2)

- Three axes stabilized, nadir pointing, aerodynamically shaped satellite
- Drag-free attitude control (DFAC) in flight direction employing a proportional Xe electric propulsion system
- Very rigid structure, no moving parts
- Attitude control by magnetorquers
- Attitude measured by star cameras
- => used for orbit determination

Courtesy: ESA
GOCE satellite mission (3)

Core Payload:
Electrostatic Gravity Gradiometer
three pairs of accelerometers
0.5 m arm length

Main mission goals:
Determination of the Earth’s gravity field with an accuracy of 1mGal (= $10^{-5}$ m/s$^2$) at a spatial resolution of 100 km
GOCE satellite mission (4)

- Satellite-to-Satellite Tracking Instrument (SSTI)
- Dual-frequency L1, L2
- 12 channel GPS receiver
- Real time position and velocity (3D, 3 sigma < 100 m, < 0.3 m/s)
- 1 Hz data rate
- => Primary instrument for orbit determination
- Antenna phase center variations amount up to ±3cm on ionosphere-free linear combination
- => Mission requirement for precise science orbits: 2 cm (1D RMS)

Courtesy: ESA
GOCE High-level Processing Facility (HPF)

- Responsibilities for orbit generation:
  - **DEOS:**
    => RSO (Rapid Science Orbit)
  - **AIUB:**
    => PSO (Precise Science Orbit)
  - **IAPG:**
    => Validation
GOCE PSO procedure

- Tailored version of Bernese GPS Software used
- Undifferenced processing
- Automated procedure
- 30 h batches => overlaps
- CODE final products
- Reduced-dynamic and kinematic orbit solutions are computed

Data pre-processing

- CODE products
- Preparation of GPS orbits, clocks and ERPs (30 hours)
- Auxiliary data

GOCE GPS data

- Pseudorange: first a priori orbit
- Receiver clock synchronization
- Phase: Iterative data screening
- GOCE attitude data

Auxiliary data

- CODE products
- GOCE GPS data
- Prepation of GPS orbits, clocks and ERPs (30 hours)
- Auxiliary data

Reduced-dynamic orbit solution (iterative)

Kinematic orbit solution

Piece-wise constant accelerations (6 min)
Overlaps of reduced-dynamic solutions

The results are based on 5h overlaps (21:30–02:30) and reflect the internal consistency of subsequent reduced-dynamic solutions.

<table>
<thead>
<tr>
<th>Year</th>
<th>RMS</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>6.7 mm</td>
<td>-1.5 mm</td>
</tr>
<tr>
<td>2010</td>
<td>6.8 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>2011</td>
<td>6.8 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>2012</td>
<td>7.1 mm</td>
<td>1.5 mm</td>
</tr>
</tbody>
</table>
Differences reduced-dynamic vs. kinematic

The results show the consistency between both orbit-types and mainly reflect the quality of the kinematic orbits. It is, however, not a direct measure of orbit quality.

<table>
<thead>
<tr>
<th>Year</th>
<th>RMS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1.7</td>
</tr>
<tr>
<td>2010</td>
<td>2.2</td>
</tr>
<tr>
<td>2011</td>
<td>3.4</td>
</tr>
<tr>
<td>2012</td>
<td>4.3</td>
</tr>
</tbody>
</table>

RMS shows high correlation with ionosphere activity and L2 data losses. Partly reflected in the formal errors of the kinematic positions.
Differences reduced-dynamic vs. kinematic

Ascending arcs (RMS)

Descending arcs (RMS)

2009

2010

2012
Orbit validation with SLR

Improved modeling of SLR observations:

- use of SLRF2008 coordinate set
- application of azimuth- & nadir-dependent range corrections

Range corrections exhibit total variations of 5-7mm about the mean value. Details may be found in a Technical Note about the „Range Correction for the CryoSat and GOCE Laser Retro-reflectors Arrays“ (Montenbruck & Neubert, 2011, DLR/GSOC TN 11-01).
Improved modeling of SLR observations:

- use of SLRF2008 coordinate set
- application of azimuth- & nadir-dependent range corrections

SLR validation (cm) of red.-dyn. solutions (DOYs 251,2010 – 226,2011):

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>0.37</td>
<td>1.62</td>
</tr>
<tr>
<td>(B)</td>
<td>0.52</td>
<td>1.45</td>
</tr>
<tr>
<td>(C)</td>
<td>0.01</td>
<td>1.44</td>
</tr>
</tbody>
</table>
Orbit validation with SLR

Reduced-dynamic orbit

Mean: 0.24 cm, RMS: 1.62 cm

2009:
RMS: 1.61 cm
Mean: 0.46 cm

2010:
RMS: 1.44 cm
Mean: 0.13 cm

2011:
RMS: 1.99 cm
Mean: 0.25 cm

2012:
RMS: 2.05 cm
Mean: 0.13 cm
Orbit validation with SLR

Kinematic orbit

Mean: 0.15 cm, RMS: 2.23 cm

2009:
- RMS: 1.89 cm
- Mean: 0.49 cm

2010:
- RMS: 1.76 cm
- Mean: 0.10 cm

2011:
- RMS: 2.63 cm
- Mean: 0.15 cm

2012:
- RMS: 3.00 cm
- Mean: -0.24 cm
Gravity field recovery

- Kinematic GOCE positions contain independent information about the long-wavelength part of the Earth’s gravity field
- 1-sec kinematic positions serve as pseudo-observations together with covariance information to set-up an orbit determination problem, which also includes gravity field parameters
- Non-gravitational forces are absorbed by empirical parameters in the course of the generalized orbit determination problem, accelerometer data are not used
- Gravity field coefficients are either solved for up to d/o 120 or d/o 160 without applying any regularization
Impact of polar gap

\[ \delta d_i = \sqrt{\sum_{m=0}^{i} (\Delta \tilde{C}_{i,m}^2 + \Delta \tilde{S}_{i,m}^2)} \]

- \( \delta d_i \) is dominated by zonal and near-zonal terms, degradation depends on max. d/o
- \( \Rightarrow \) exclusion according to the rule of thumb by van Gelderen & Koop (1997)
Impact of maximum resolution

- Omission errors are avoided, ...
- ..., but artifacts appear at low degrees
- Artifacts are restricted to near-zonal coefficients. Rule of thumb needs to be enlarged

Stronger artifacts in 2010, ...

..., but again mostly related to near-zonal coefficients, which are very sensitive to the increasing data problems such as the L2 losses
Solution characteristics

Differences to ITG-GRACE2010
unfiltered, d/o 100

increased noise over polar regions

300 km Gauss-filtered

magnetic equator visible

- 2009:
  RMS (unfiltered): 113.3 cm
  RMS (filtered): 4.9 cm

- 2009-10:
  RMS (unfiltered): 76.1 cm
  RMS (filtered): 3.1 cm

- 2009-11:
  RMS (unfiltered): 38.9 cm
  RMS (filtered): 2.0 cm
Differences reduced-dynamic vs. kinematic

Ascending arcs (mean)  
Descending arcs (mean)

2009

2011
Missing L2 data

Zero L2 observations during middle of a pass mostly occur at geomagnetic poles as well as on both sides of the geomagnetic equator.
Comparison with CHAMP gravity field recovery

- Better recovery of high degrees from GOCE due to lower orbital altitude
- Better recovery of low degrees from CHAMP due to longer data period
Combination with CHAMP multi-year solution

- Down-weighting of the GOCE normal equations is required due to an only marginal contribution of the 1-sec data wrt 5-sec sampled data.
- No degradation due to the polar gap in the combined solution.
- Small degradation when including the most recent GOCE data.

Zonals and near-zonals not excluded.
Impact on gradiometer solution

- 8 months of GPS and gradiometer data used
- GPS dominates the combination up to about degree 20 and contributes up to about degree 70
- No omission artifacts in the combined solution when using GPS beyond degree 120. No need to artificially down-weight the GPS contribution
Conclusions

- Precise Science Orbits are of excellent quality
  - 1.62 cm SLR RMS for reduced-dynamic orbits
  - 2.23 cm SLR RMS for kinematic orbits

- Orbit quality is correlated with ionosphere activity
  - L2 losses over geomagnetic poles
  - Systematic effects around geomagnetic equator

- GPS-only gravity field solutions
  - Sensitivity at least up to d/o 120
  - Contribution to gradiometer solution up to d/o 70