GOCE Precise Science Orbits for the entire mission and their use for Gravity Field Recovery

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Content

- **The GOCE mission**

- **Precise Science Orbit (PSO) Determination**
  - Bock et al. (2014): GOCE: precise orbit determination for the entire mission, *J Geod*, available online

- **Gravity Field Recovery from PSO positions**
  - Weigelt et al. (2014): A GPS–only time–variable gravity field solution from CHAMP, GRACE and GOCE, Geophys Res Lett, in review

- **Summary**
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
- Altitude: 255 km (lowered later on)
- Mass: 1050 kg at launch
- 5.3 m long, 1.1 m² cross section
- Re-entry: 11 November 2013 near the Falkland Islands

Courtesy: ESA
GOCE satellite mission (2)

- Commissioning
- Routine mission at 255 km mean altitude
- Low orbit operations campaign

Mean altitude [km]

- 30/03/2009
- 01/11/2009
- 01/08/2012


Courtesy: ESA
GOCE satellite mission (3)

- 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

Courtesy: ESA

**Main mission goal:**

Determination of the Earth’s gravity field with an accuracy of 1mGal (= $10^{-5}$ m/s$^2$) at a spatial resolution of 100 km using the concept of space gradiometry

**Released Gravity Field Models:**

- **R1:** 01/11/2009 – 11/01/2010 (TIM, DIR, SPW)
- **R2:** 01/11/2009 – 05/07/2010 (TIM, DIR, SPW)
- **R3:** 01/11/2009 – 17/04/2011 (TIM, DIR)
- **R4:** 01/11/2009 – 19/06/2012 (TIM, DIR)
- **R5:** 01/11/2009 – 20/10/2013 (TIM, DIR)
GOCE satellite mission (5)

• Satellite-to-Satellite Tracking Instrument (SSTI)
• Dual-frequency L1, L2
• 12 channel GPS receiver
• 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)
GOCE High-level Processing Facility (HPF)

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

GOCE GPS data

Pseudorange: first a priori orbit

Receiver clock synchronization

Phase: Iterative data screening

GOCE attitude data

Reduced-dynamic orbit solution (iterative)

Kinematic orbit solution

Piece-wise constant accelerations (6 min)
The results are based on 5h overlaps (21:30–02:30) and reflect the internal consistency of subsequent reduced-dynamic solutions.

The same orbit determination settings were used for the operational PSO computation over the entire mission period.
The results show the consistency between both orbit-types and mainly reflect the quality of the kinematic orbits.

A high correlation with ionosphere activity and L2 data losses is observed.
Differences reduced-dynamic vs. kinematic (2)

Ascending arcs (RMS)

2009

2010

2011

Descending arcs (RMS)

Orbit validation with SLR

SLR Residuals for GOCE (RD PSO orbit)

<table>
<thead>
<tr>
<th>Year</th>
<th>red.-dynamic</th>
<th>kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>0.24 ± 1.73</td>
<td>0.29 ± 1.91</td>
</tr>
<tr>
<td>2010</td>
<td>-0.10 ± 1.56</td>
<td>-0.12 ± 1.84</td>
</tr>
<tr>
<td>2011</td>
<td>0.20 ± 1.53</td>
<td>0.12 ± 2.36</td>
</tr>
<tr>
<td>2012</td>
<td>0.10 ± 1.94</td>
<td>-0.05 ± 2.78</td>
</tr>
<tr>
<td>2013</td>
<td>0.63 ± 2.62</td>
<td>0.45 ± 3.17</td>
</tr>
<tr>
<td>2009–2013</td>
<td>0.18 ± 1.84</td>
<td>0.10 ± 2.42</td>
</tr>
</tbody>
</table>

SLR statistics:
Mean ± RMS (cm)

Reduced–dynamic
Kinematic

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Gravity field recovery from orbital positions

- 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 for the results shown in this presentation.
- Gravity field coefficients are solved without applying any regularization.

\[ \mathbf{r}^j(t - \rho^j/c) \]

\[ \mathbf{r}^k \]

\[ \mathbf{r}^l \]

\[ \mathbf{r}^m \]

\[ \rho^j \]

\[ \rho^k \]

\[ \rho^l \]

\[ \rho^m \]
Impact of polar gap

- $\delta d_i$ 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

The bi-monthly solution for 2009 shows the best quality, slightly worse qualities are obtained for 2010 and 2012, the most degraded solution is obtained for 2011.

The long-term solution R4 shows no significantly improved quality with respect to the bi-monthly solutions below degree 30.
Systematic effects in the orbits (1)

Ascending arcs (mean)  Descending arcs (mean)

2009

2010

Geomagnetic equator

2011

Systematic effects in the orbits (2)

- Systematic effects around the geomagnetic equator are present in the ionosphere–free GPS phase residuals \( \Rightarrow \) affects kinematic positions
- Degradation of kinematic positions around the geomagnetic equator propagates into gravity field solutions.

Phase observation residuals \((-2 \text{ mm} \ldots +2 \text{ mm})\) mapped to the ionosphere piercing point

Geoid height differences \((-5 \text{ cm} \ldots 5 \text{ cm})\): TIM–R4 model
Removal of systematic effects (1)

- One possible cause is the neglection of the higher order ionosphere (HOI) correction terms.
- First tests using HOI correction terms did, however, not show any improvement in the results.
- But an empirical approach can be adopted:
  - Removal of observations, which have large ionosphere changes from one epoch to the next (e.g. >5cm/s).
Removal of systematic effects (2)

Loss of kinematic positions:
- 2009: 0.1%
- 2010: 0.2%
- 2011: 6.2%
- 2012: 3.7%
Attempts to model the systematic effects (1)

- Conventional modeling of HOI correction terms does not show any improvements. Also the application of further HOI correction terms than recommended by the IERS Conventions 2010 does not bring any further improvements.

- Ionosphere delays (= slant TEC) need to be directly derived from the geometry–free linear combination to compute more realistic HOI correction terms.

Ionosphere–free linear combination

STEC from GPS data

Ionosphere

First order effect

Higher order effects

Ionosphere-free linear combination

STEC

Ionosphere

First order effect

Higher order effects

Conventional modeling of HOI correction terms does not show any improvements. Also the application of further HOI correction terms than recommended by the IERS Conventions 2010 does not bring any further improvements.

Ionosphere delays (= slant TEC) need to be directly derived from the geometry–free linear combination to compute more realistic HOI correction terms.
Attempts to model the systematic effects (2)

- STEC estimations are fed into the kinematic orbit determination instead of the global ionosphere map
- HOI correction terms are computed based on the STEC estimations
- Only partial reduction achieved so far in gravity field solutions

Phase observation residuals
(-2 mm ... +2 mm)
mapped to the ionosphere piercing point

Geoid height differences
(-5 cm ... 5 cm);
Nov–Dec 2011
Solutions from different antennas

SSTI-A

SSTI-B

Aug2013

Sep2013

Oct2013

Time variability from GOCE, CHAMP, GRACE (1)

GOCE
GRACE A,B
CHAMP

Trend

Amplitude

GRACE
GFZ
Rel05a

Time variability from GOCE, CHAMP, GRACE (2)

GOCE kinematic solutions have only a limited sensitivity to time variable gravity signals. The presence of the polar gap further limits GOCE-only time variable gravity field solutions even when adopting Kalman filter approaches. Together with other satellites tracked by GPS, SST GOCE helps to improve time variable solutions derived from orbital positions.
Summary

- Precise Science Orbits are of excellent quality
  - 1.84 cm SLR RMS for reduced-dynamic orbits
  - 2.42 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 (static part)
  - Limited sensitivity to annual time variable signals
Impact of accelerometer data and optimal constraining of empirical parameters.

=> Only very low degrees are affected.