

GOCE Precise Science Orbits and their Contribution to Gravity Field Recovery

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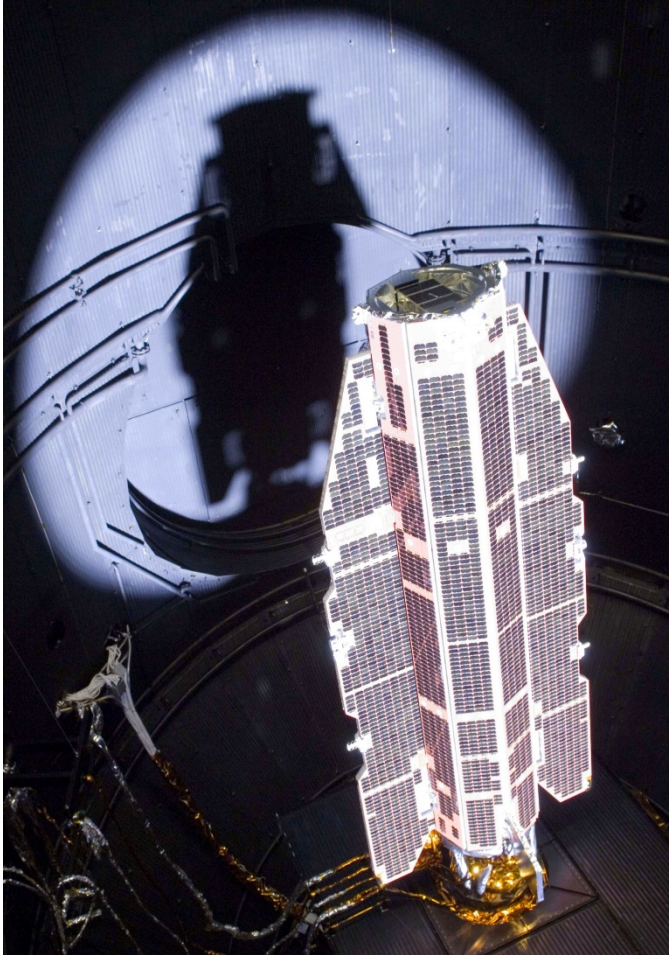
PSD.1

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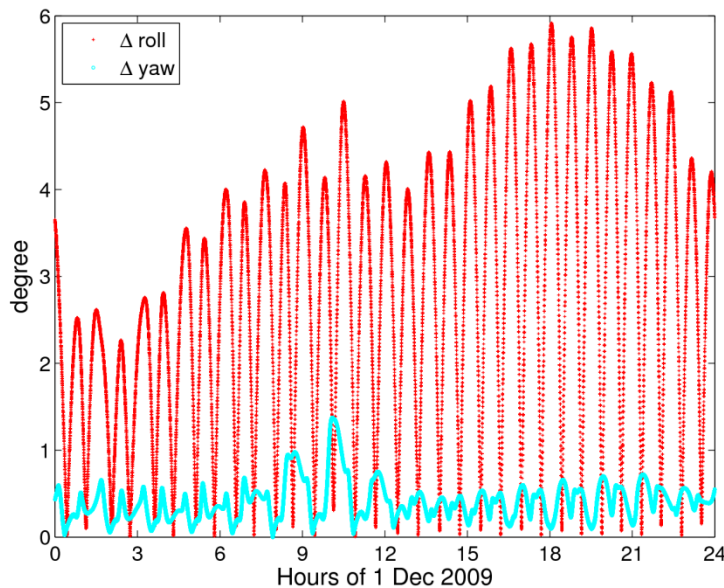
GOCE satellite mission (1)



Courtesy: ESA

- 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 m^2 cross section

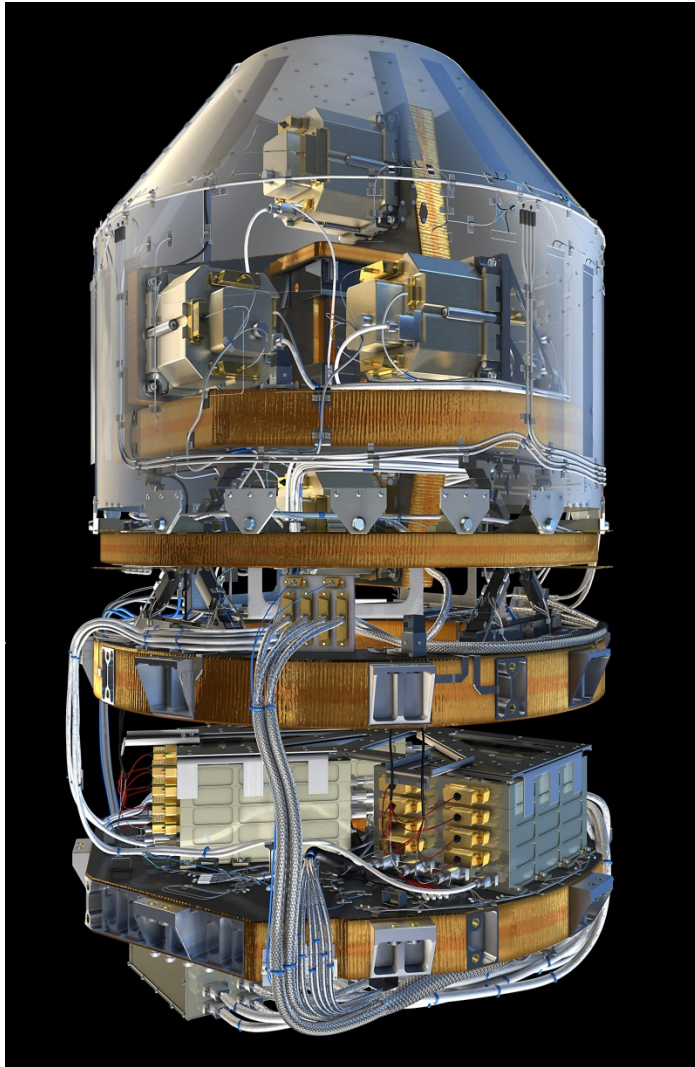
GOCE satellite mission (2)



Courtesy: ESA

- 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

GOCE satellite mission (3)



Courtesy: ESA

Core Payload:

Electrostatic Gravity Gradiometer

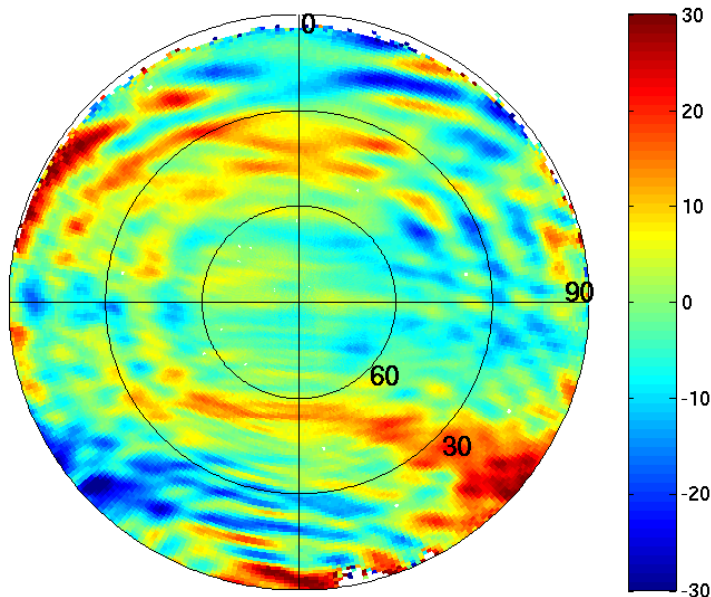
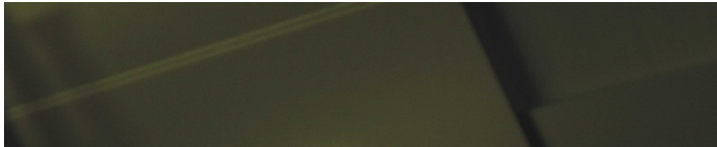
three pairs of accelerometers

0.5 m arm length

Main mission goals:

Determination of the Earth's gravity field with an accuracy of 1 mGal ($= 10^{-5} \text{ m/s}^2$) at a spatial resolution of 100 km

GOCE satellite mission (4)



Courtesy: ESA

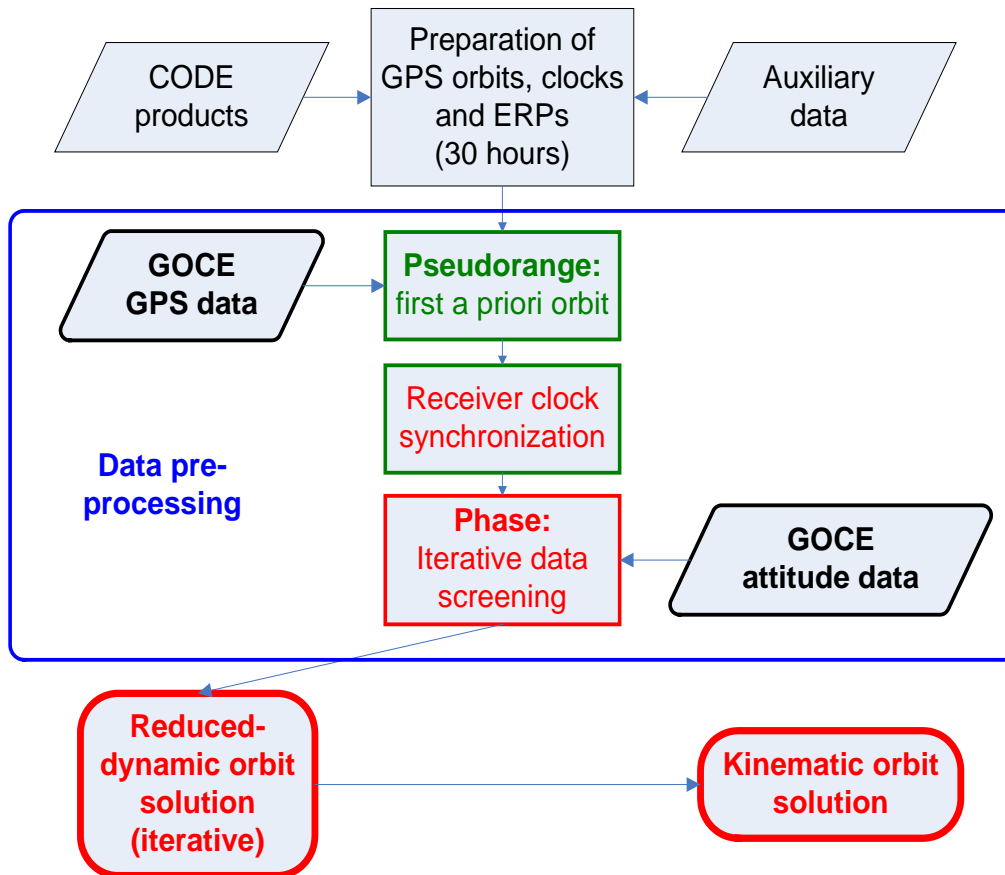
- **Satellite-to-Satellite Tracking Instrument (SSTI)**
- **Dual-frequency L1, L2**
- **12 channel GPS receiver**
- **Real time position and velocity (3D, 3 sigma < 100 m, < 0.3 m/s)**
- **1 Hz data rate**
- **=> Primary instrument for orbit determination**
- **Antenna phase center variations amount up to ± 3 cm 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

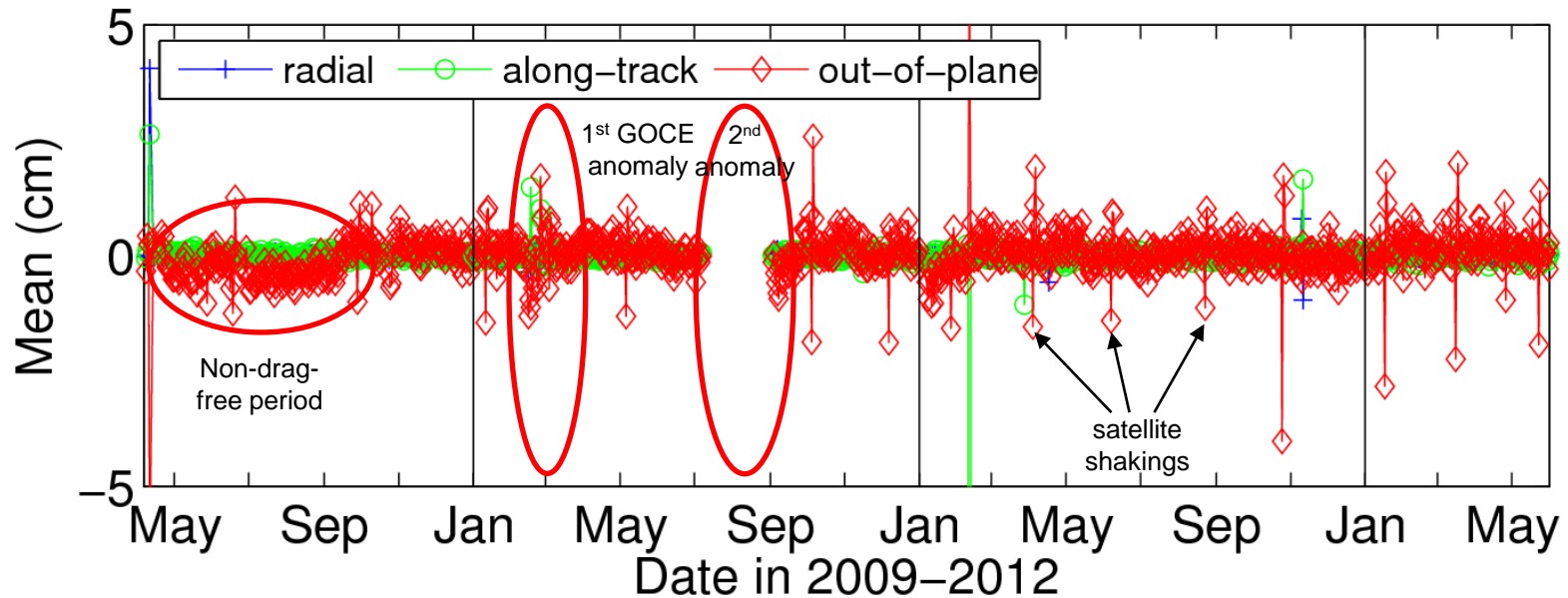
GOCE PSO procedure



Piece-wise constant accelerations (6 min)

- 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

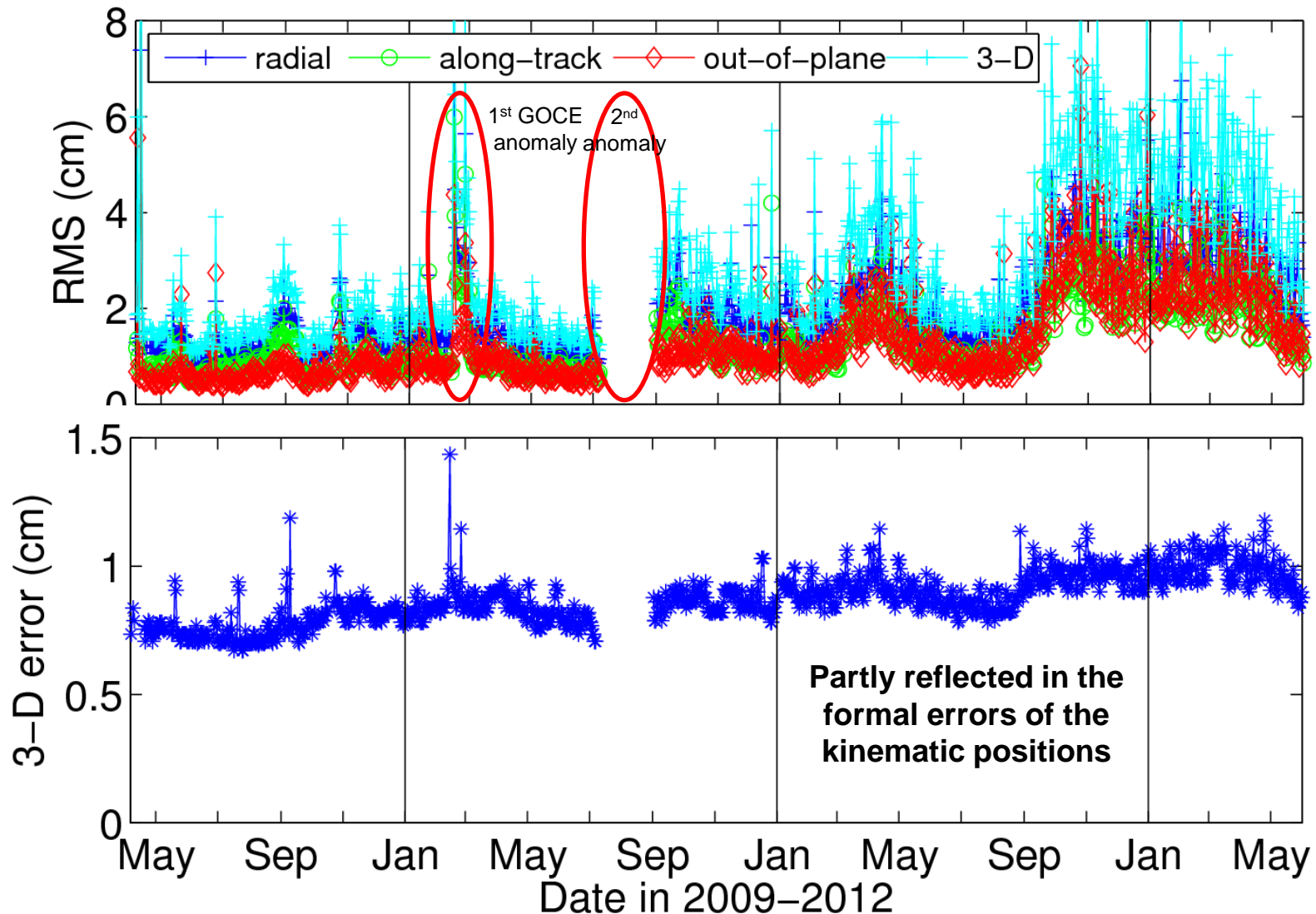
Overlaps of reduced-dynamic solutions



	2009:	2010:	2011:	2012:
RMS:	6.7 mm	6.8 mm	6.8 mm	7.1 mm
Mean:	-1.5 mm	0.7 mm	0.2 mm	1.5 mm
Out-of-plane				

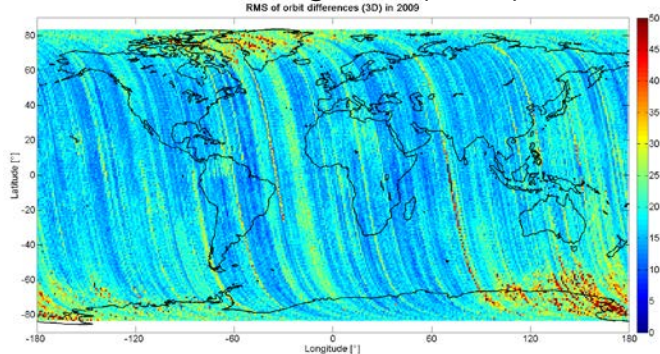
The results are based on 5h overlaps (21:30–02:30) and reflect the **internal consistency** of subsequent reduced-dynamic solutions.

Differences reduced-dynamic vs. kinematic

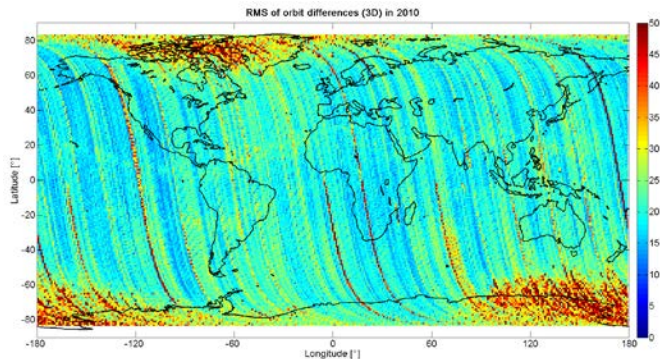


Differences reduced-dynamic vs. kinematic

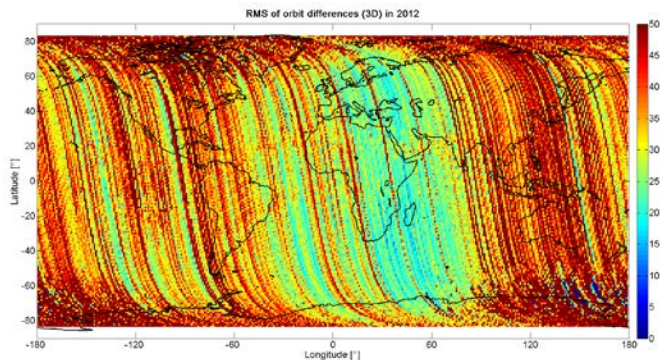
Ascending arcs (RMS)



2009

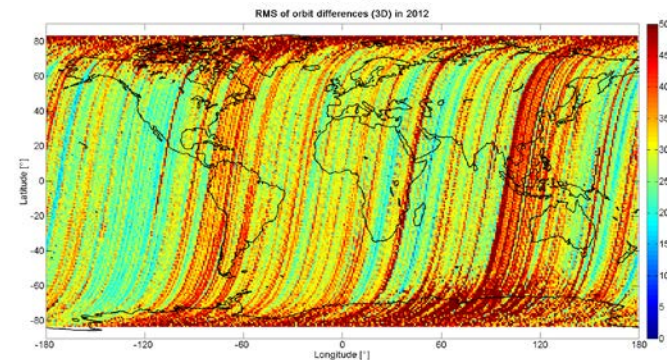
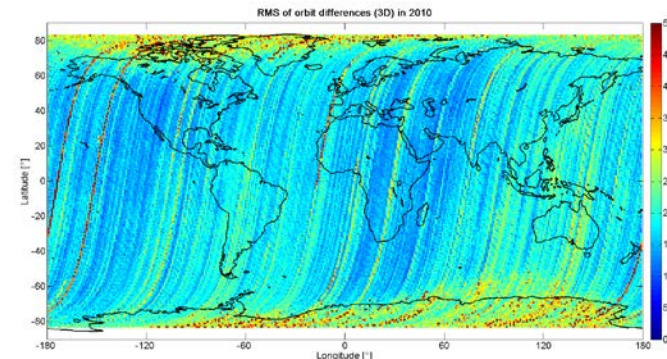
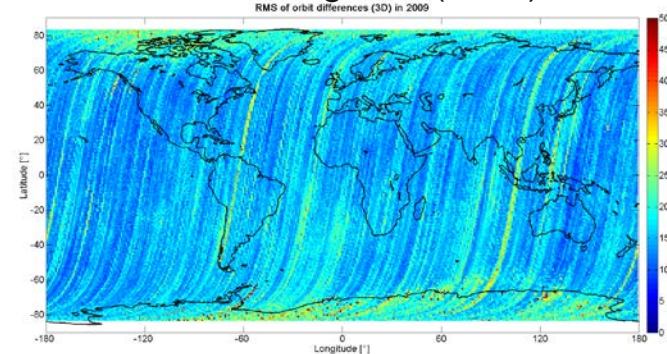


2010



2012

Descending arcs (RMS)

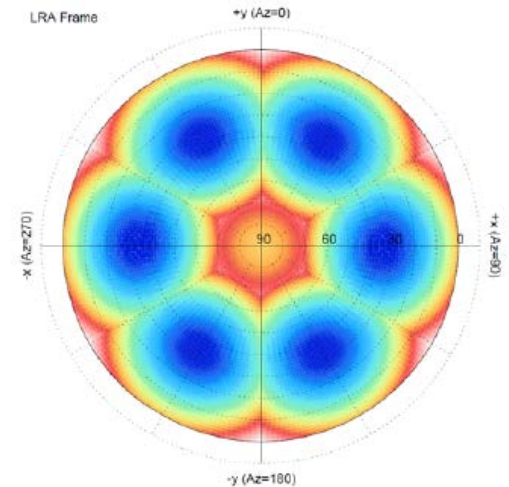


Orbit validation with SLR

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-reflector Arrays“ (Montenbruck & Neubert, 2011, DLR/ GSOC TN 11-01).



Range Correction for the CryoSat and GOCE Laser Retroreflector Arrays
© Montenbruck (DLR/GSOC), Neubert (GFZ)

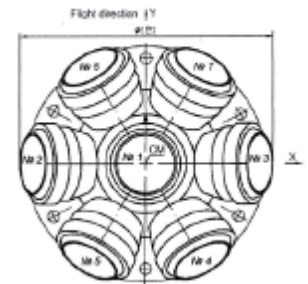


Fig. 1. PFE laser retroreflector array for GOCE (left) and CryoSat (right) type arrays. Images courtesy DLR and GFZ.

Introduction
The Institute of Precision Instruments Engineering (PIE), Moscow, provides various types of laser retroreflector arrays (LRAs) for Earth-orbiting satellites. Among others, PIE has manufactured LRAs for the CryoSat-2 [1], GOCE [2] and Proba-2 [3] missions of the European Space Agency (ESA), as well as the GOCE-2 and Proba-2 missions. For use in low Earth orbit (LEO), a common design with one nadir-looking prism and six side-looking prisms is employed (Fig. 1). However, a slightly larger tilt angle of the side-looking prisms is used for GOCE in comparison to CryoSat and Proba-2 to account for the much lower orbital altitude.

For the precision analysis of satellite laser ranging (SLR) measurements, a line-of-sight-dependent range correction must be considered. This correction describes the difference between the distance of the SLR station from a presumed LRA reference point and the actual range measurement. The range correction accounts for the path length within the prisms as well as the position of the primary input face centers with respect to the adopted reference point.

Elevation-dependent range corrections for the two LRA types have been provided by PIE in [2] and [3], and are, for example, adopted as processing standard for the validation of GOCE precise science orbit products [4,5]. However, a pronounced azimuth dependence must be considered from the LRA design and a one-dimensional correction function is obviously unsuitable for a proper modeling of SLR measurements. An effort is therefore made to derive a simulation-elevation-dependent range correction for the GOCE and CryoSat-Proba-2 reflectors that will support an improved analysis of satellite laser ranging data for these missions. The analytical formulation of the range correction is based on previous work of Neubert [6] for the LRA of Geoforschungsstation (GFS, Potsdam), but takes into account the specific geometry and parameters of the PIE design.



$$\Delta \rho_i = \left[L \sqrt{n_g^2 + (\mathbf{e}^T \mathbf{n}_i)^2} - 1 \right] - \left[\mathbf{e}^T \mathbf{r}_i \right]$$

DLR/GSOC/TN 11-01

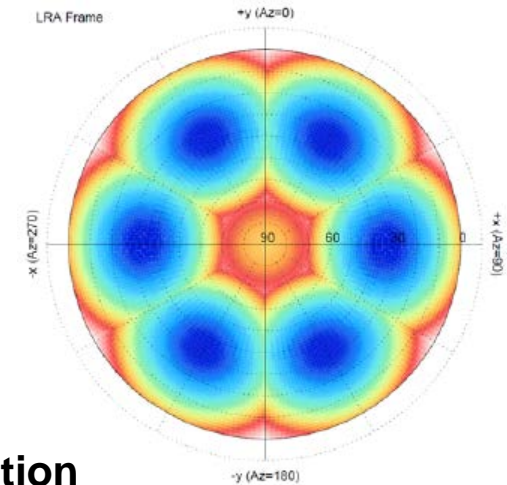
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Rev. 1.2 2011/08/02

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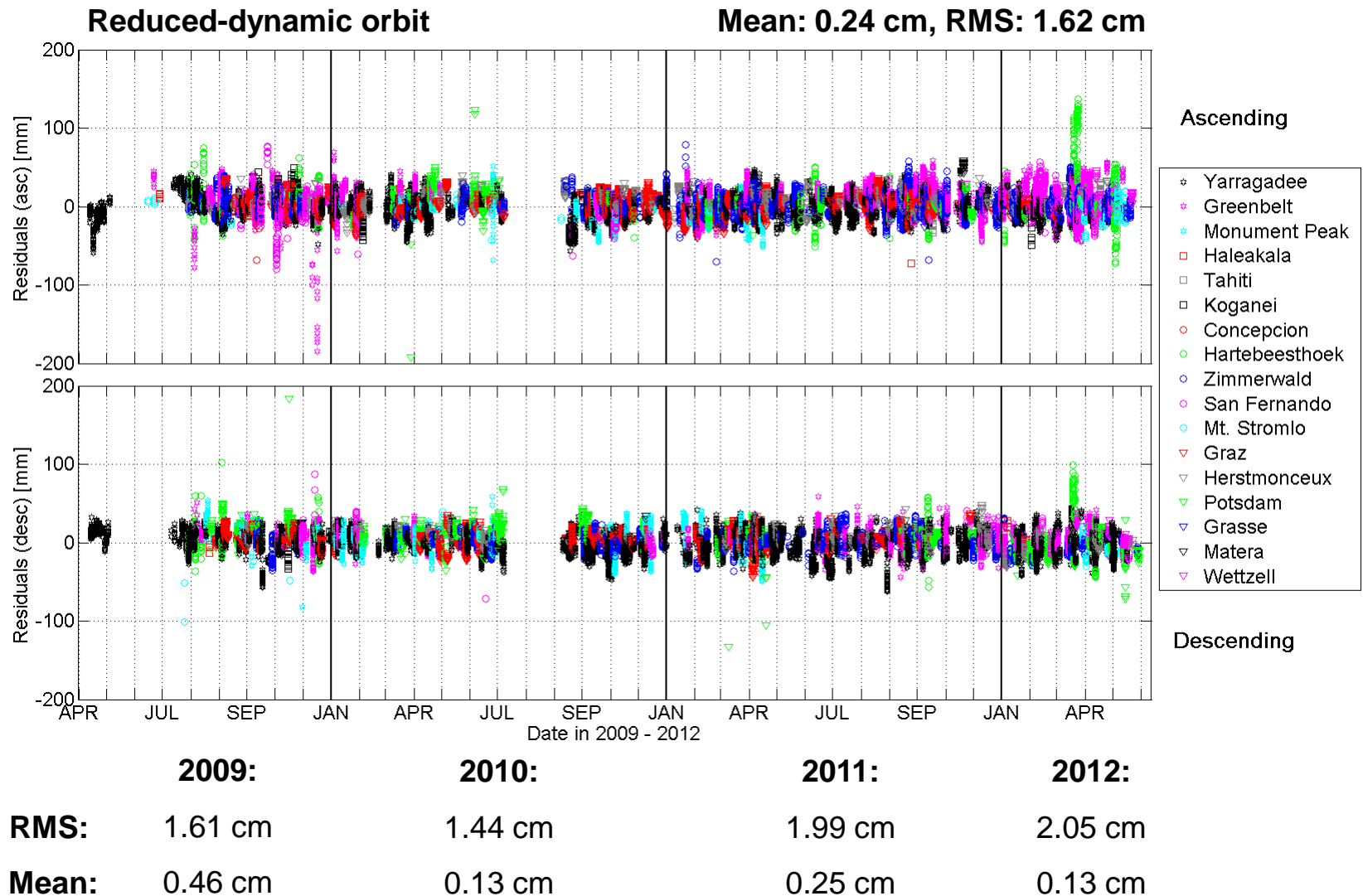


(A): - SLRF2005 (B): - SLRF2008 (C): - SLRF2008
- no correction - no correction - with correction

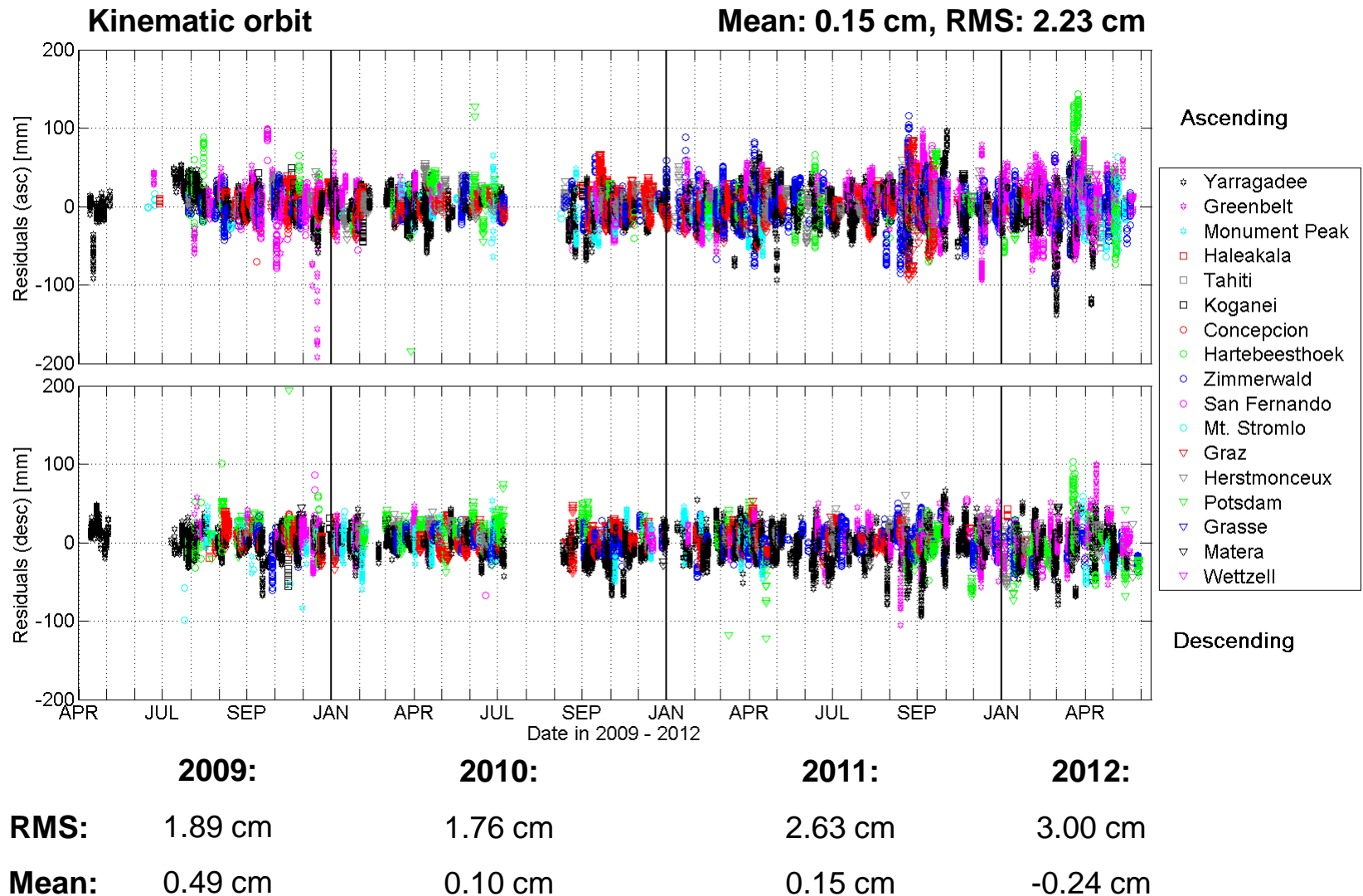
SLR validation (cm) of red.-dyn. solutions (DOYs 251,2010 – 226,2011):

	Mean	STD
(A)	0.37	1.62
(B)	0.52	1.45
(C)	0.01	1.44

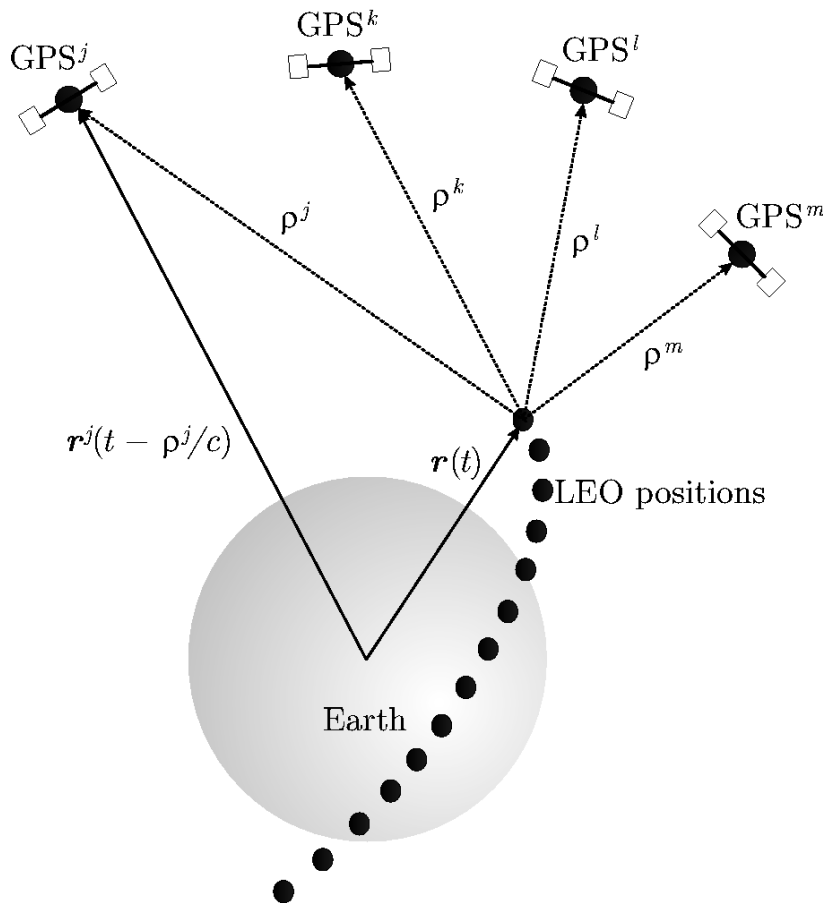
Orbit validation with SLR



Orbit validation with SLR

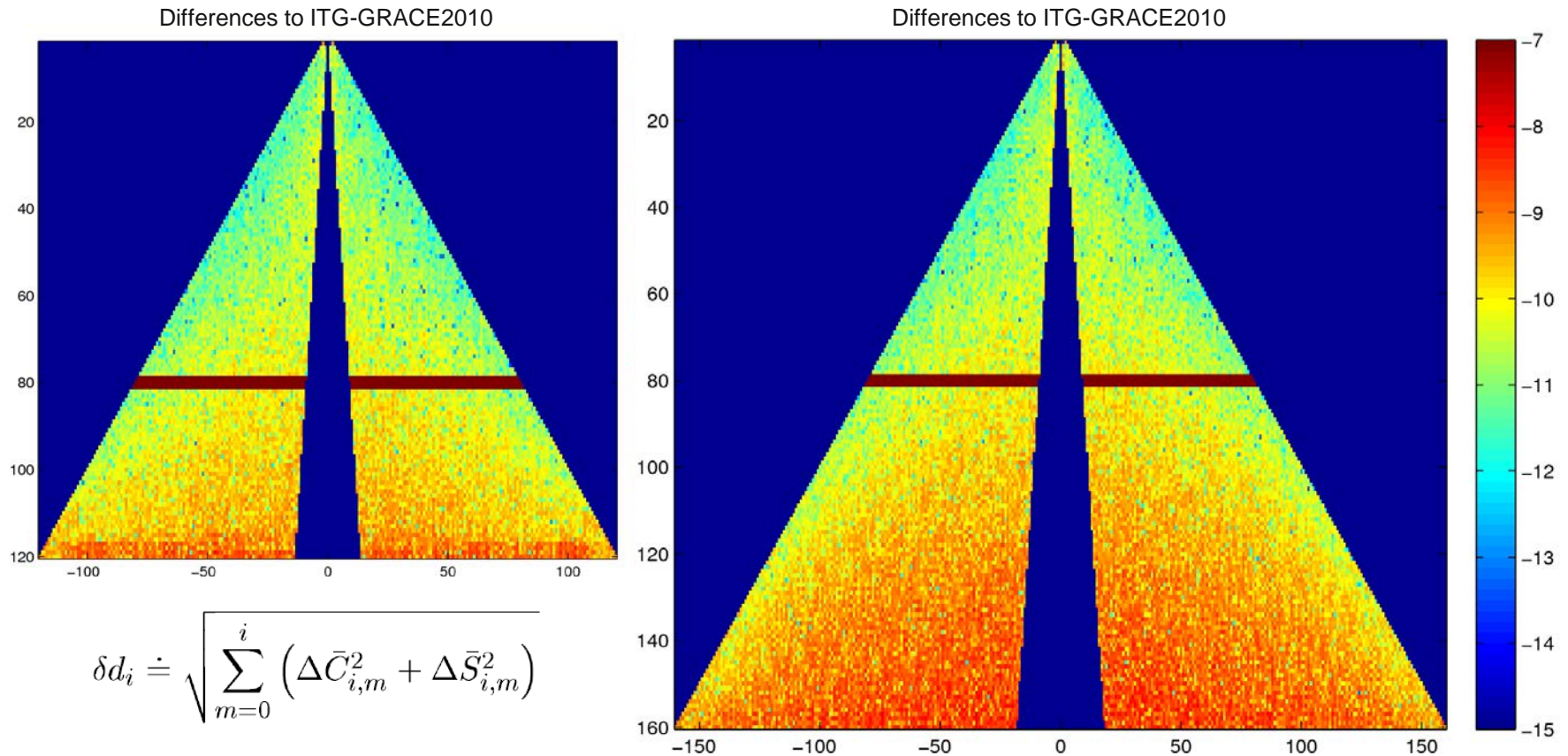


Gravity field recovery



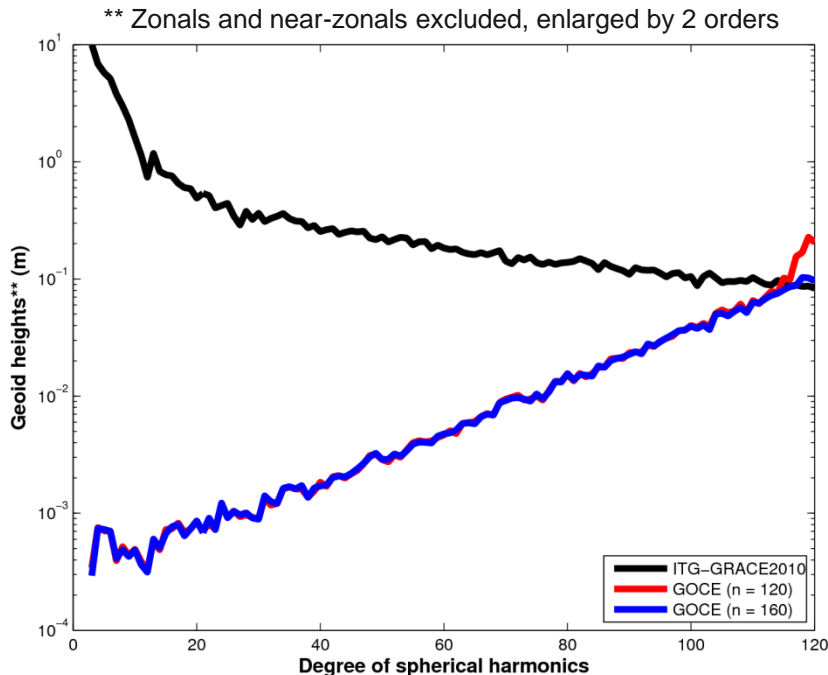
- Kinematic GOCE positions contain independent information about the long-wavelength part of the Earth's gravity field
- **1-sec kinematic positions** serve as pseudo-observations together with **covariance information** to set-up an orbit determination problem, which also includes gravity field parameters
- 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

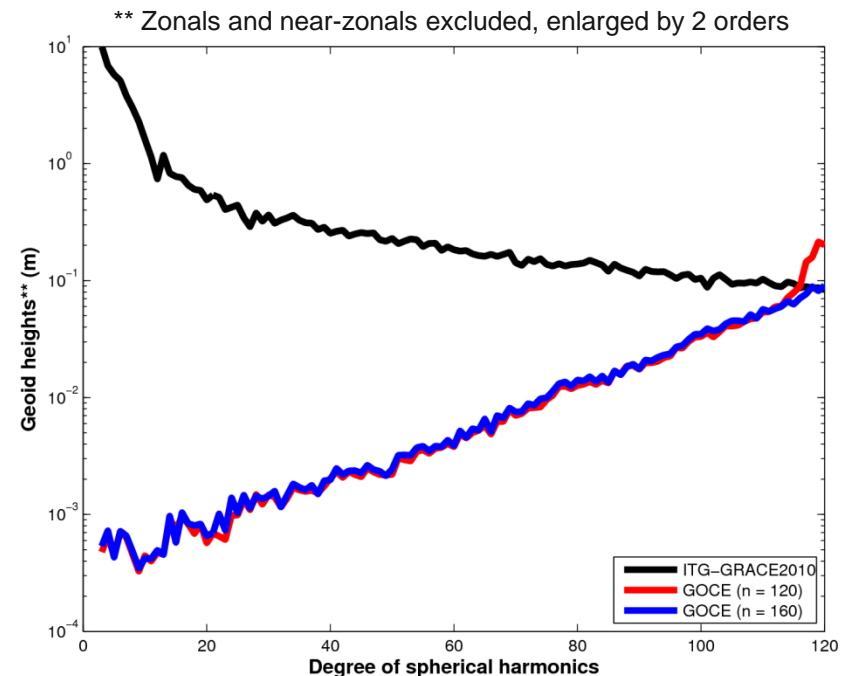


- δd_i is dominated by zonal and near-zonal terms, degradation depends on max. d/o
- \Rightarrow exclusion according to the rule of thumb by van Gelderen & Koop (1997)

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

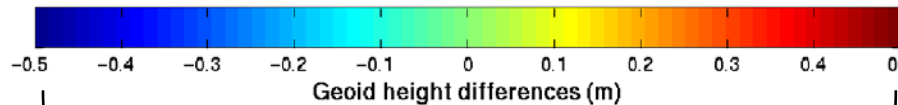
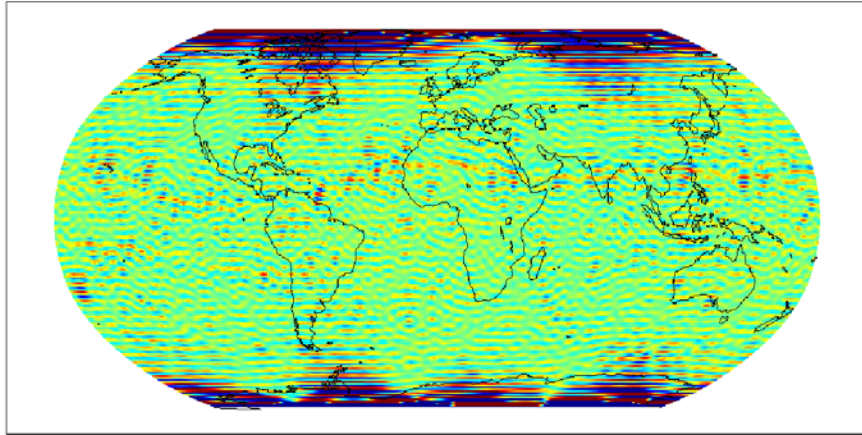


- Stronger artifacts in 2010 , ...
- ..., but again mostly related to near-zonal coefficients, which are very sensitive to the increasing data problems such as the L2 losses

Solution characteristics

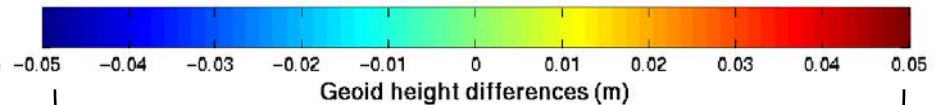
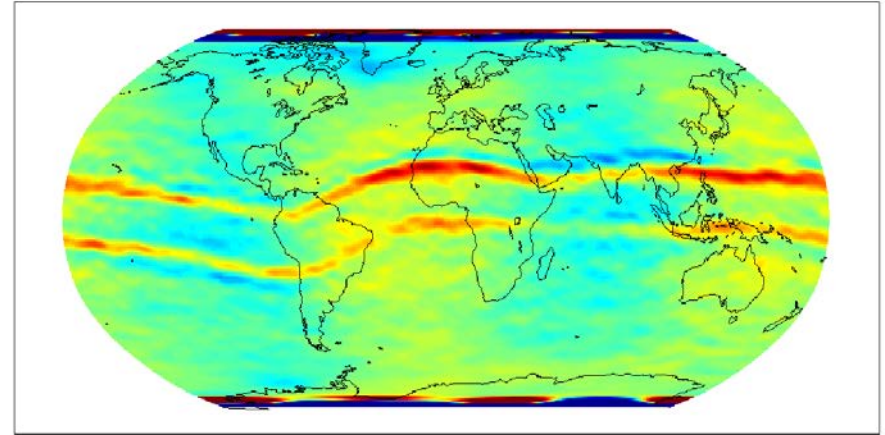
Differences to ITG-GRACE2010

unfiltered, d/o 100



increased noise over polar regions

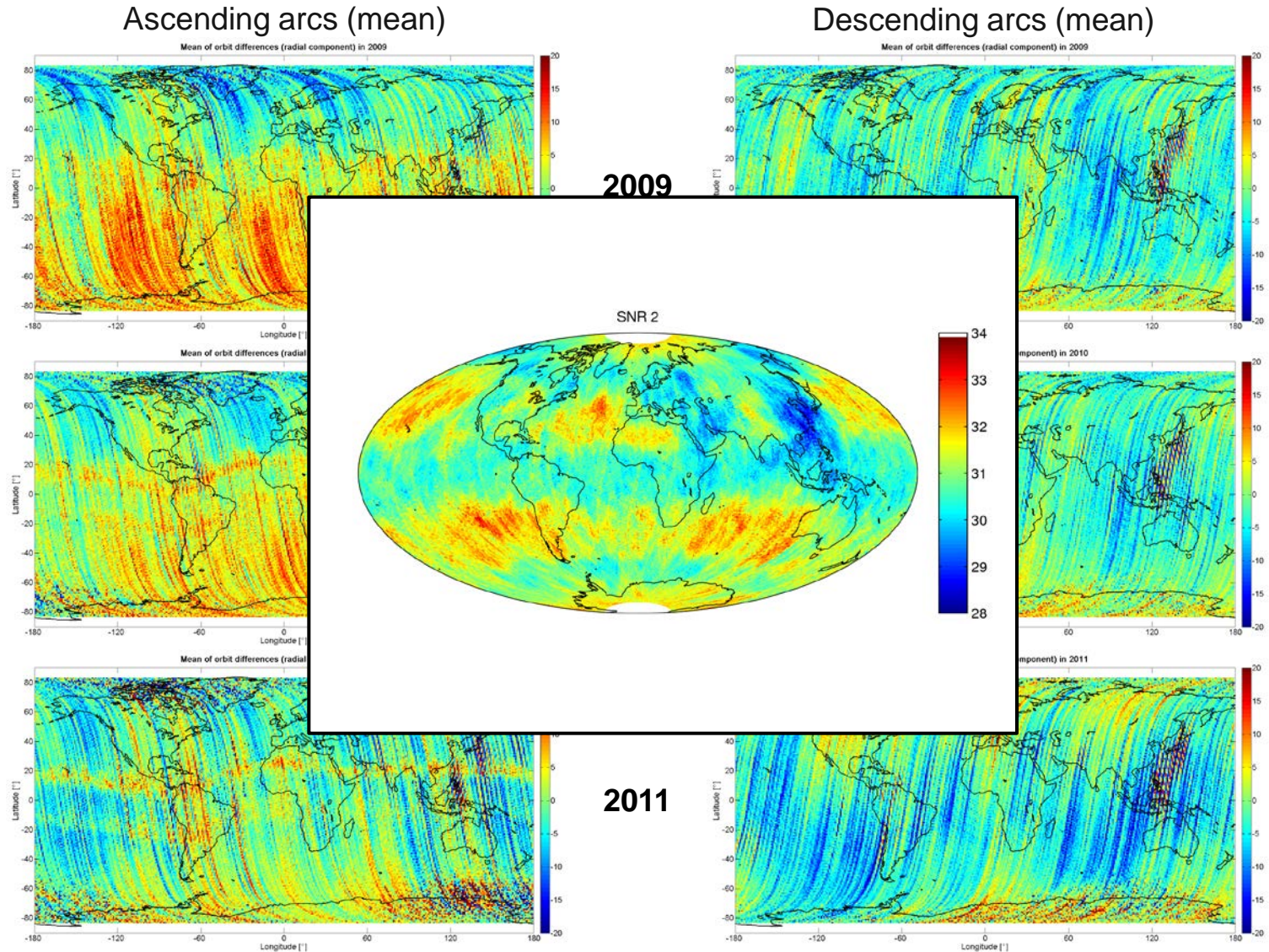
300 km Gauss-filtered



magnetic equator visible

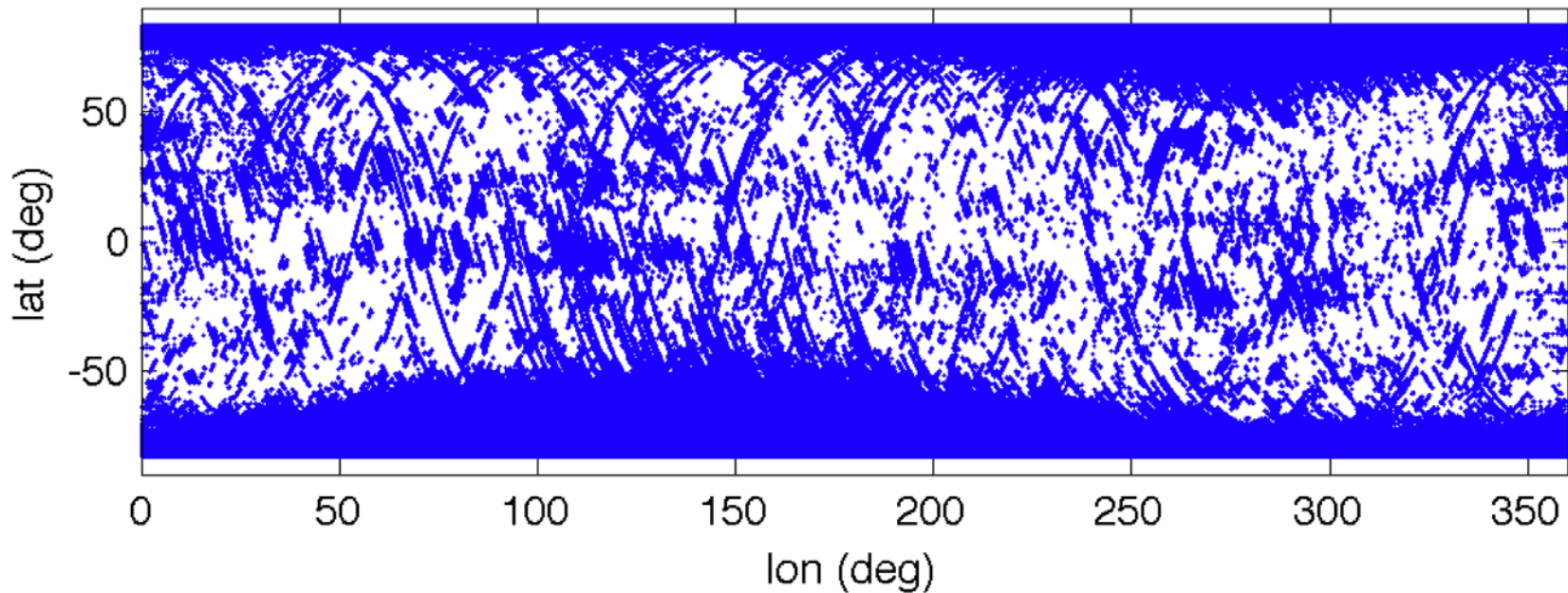
	2009:	2009-10:	2009-11:
RMS (unfiltered):	113.3 cm	76.1 cm	38.9 cm
RMS (filtered):	4.9 cm	3.1 cm	2.0 cm

Differences reduced-dynamic vs. kinematic



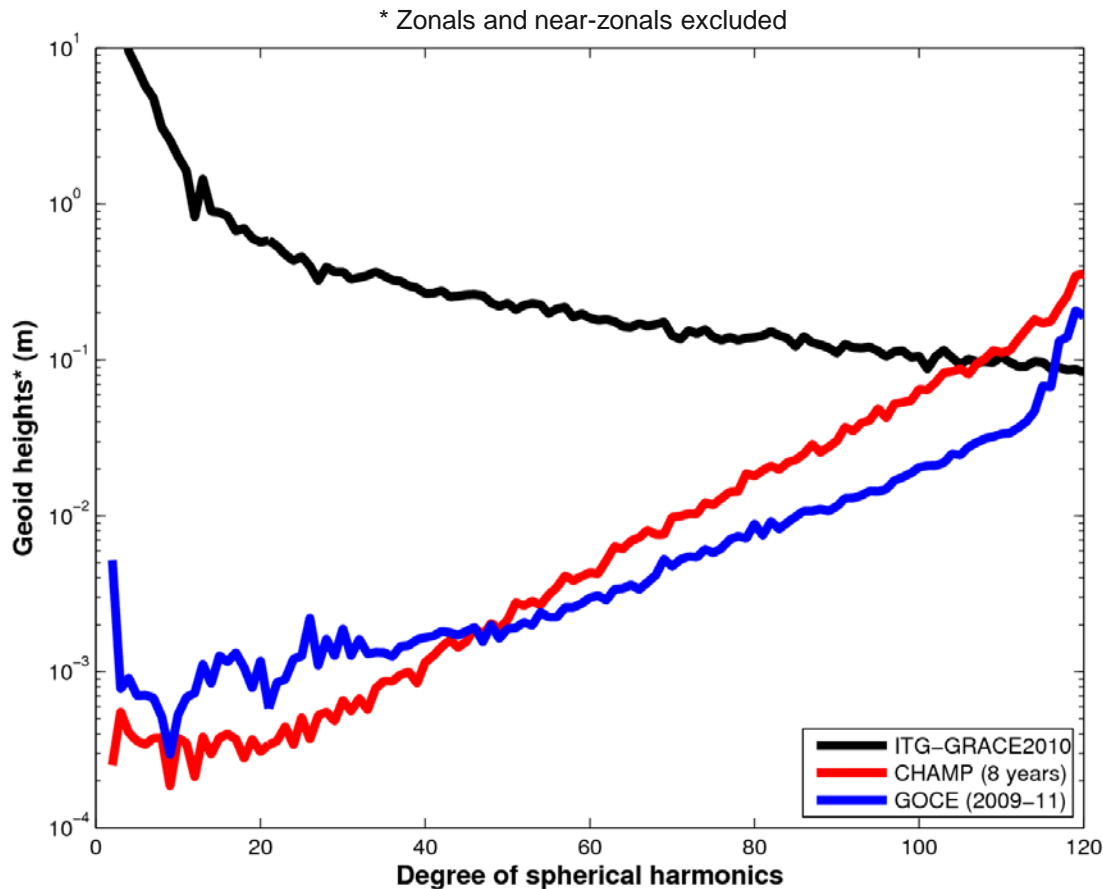
Missing L2 data

L2 zero observations in the middle of pass



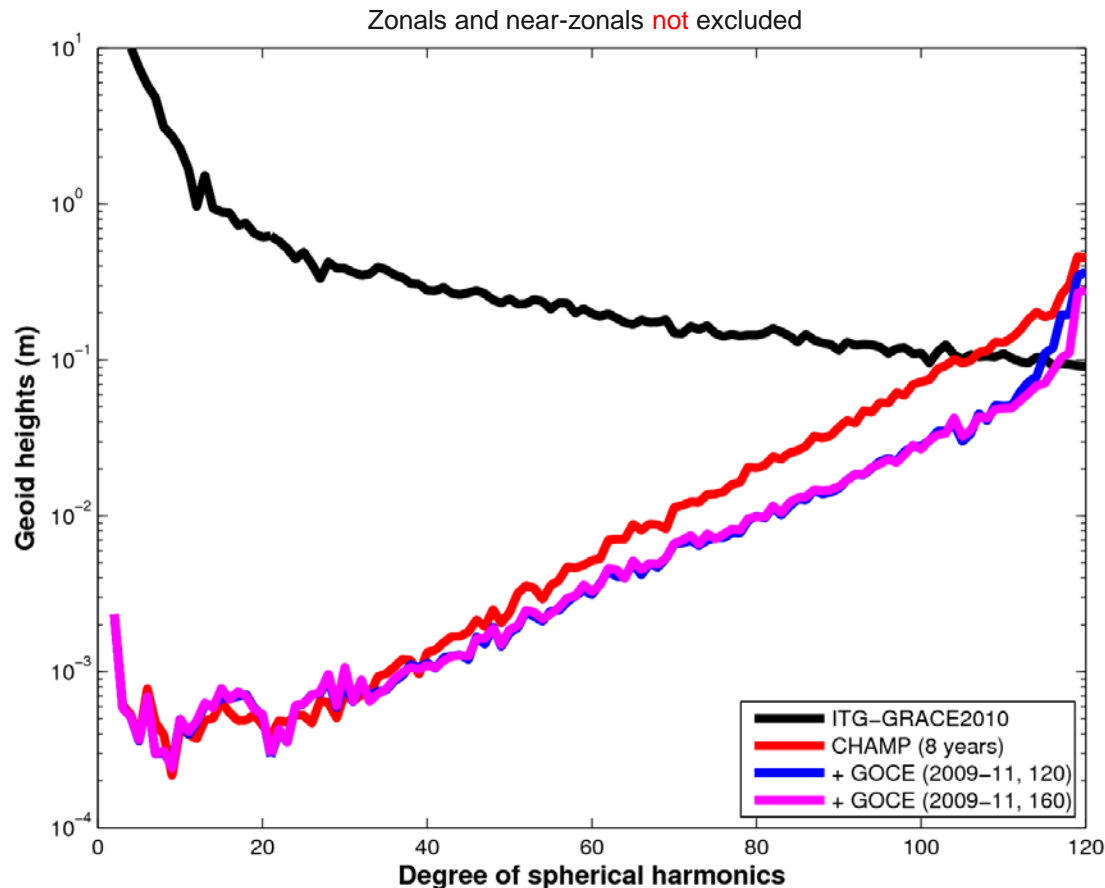
Zero L2 observations during middle of a pass mostly occur at geomagnetic poles as well as on both sides of the geomagnetic equator

Comparison with CHAMP gravity field recovery



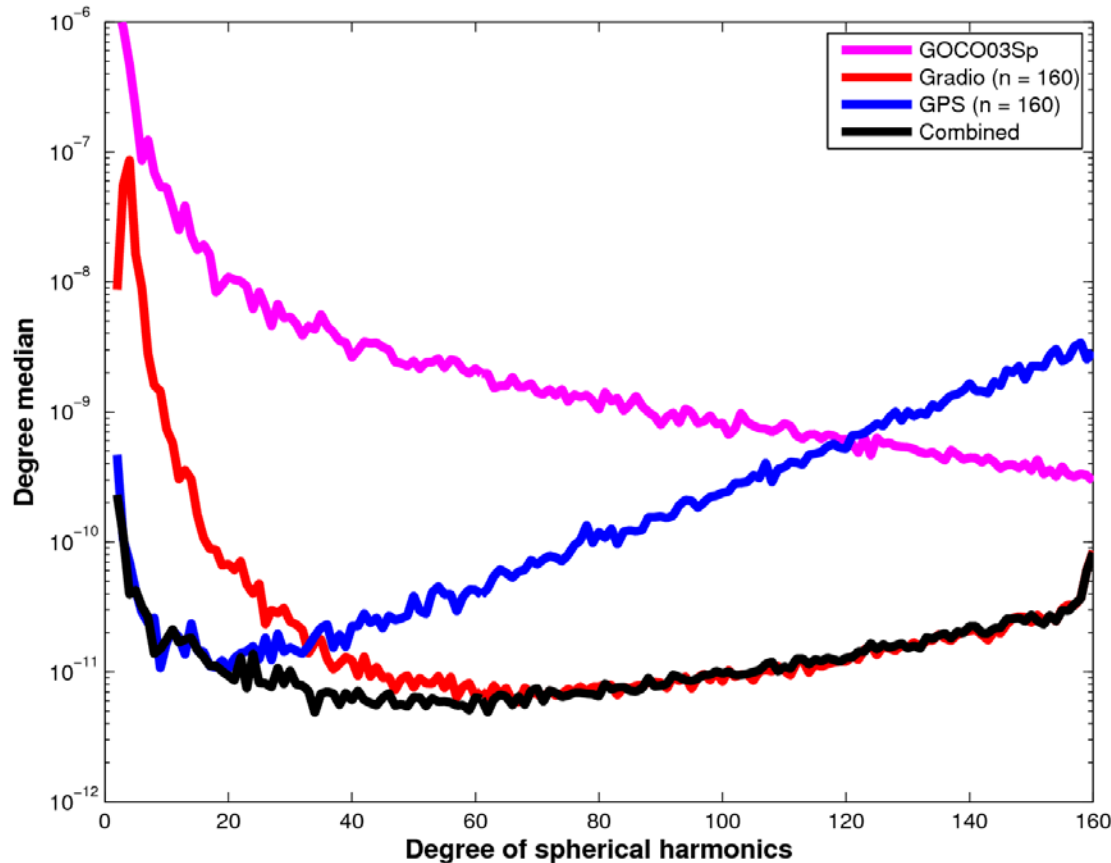
- Better recovery of high degrees from **GOCE** due to **lower orbital altitude**
- Better recovery of low degrees from **CHAMP** due to **longer data period**

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

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**