EGSIEM

European Gravity Service for Improved Emergency Management

GRACE mission, gravity field determination and EGSIEM scientific combination service

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b UNIVERSITÄT BERN | UNIVERSITÉ DU LUXEMBOURG | GFZ Helmholtz Centre Potsdam | TU Graz Graz University of Technology | Leibniz Universität Hannover | cnes | DLR | géode & cie | Horizon2020

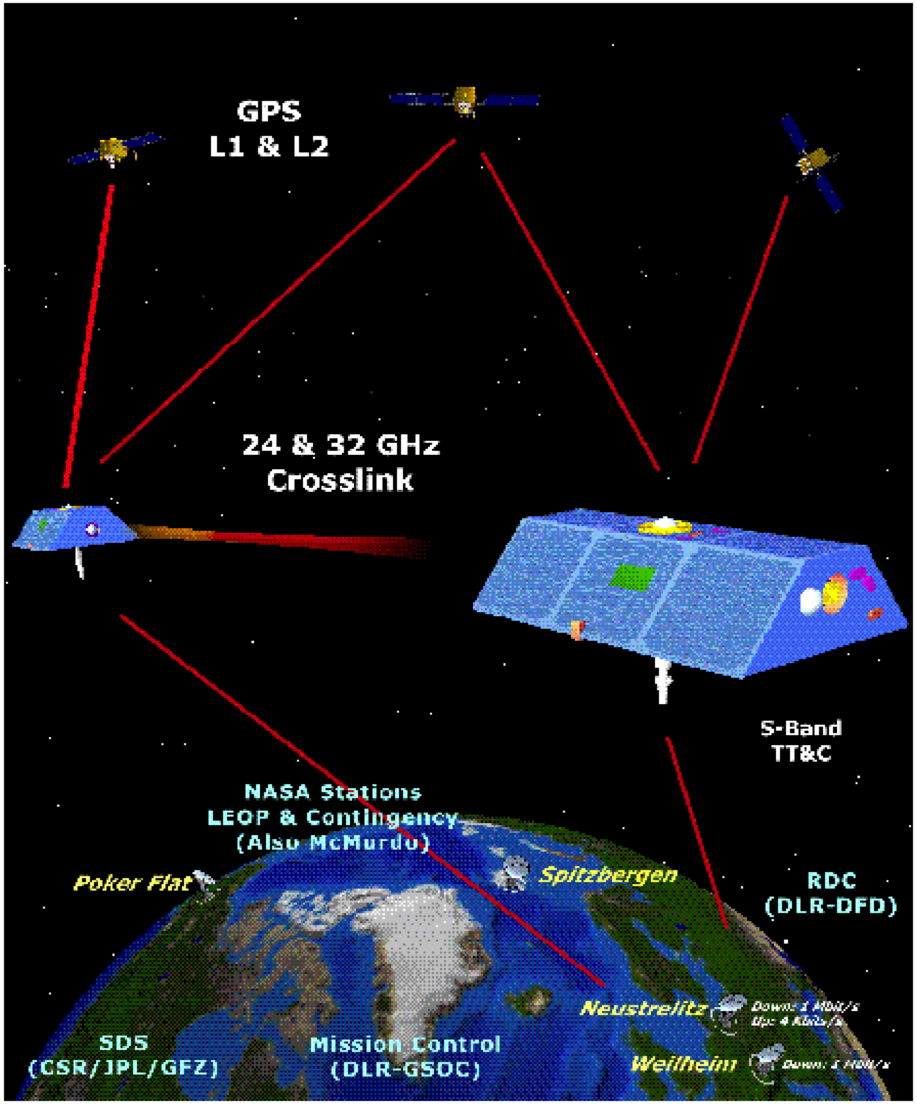
Overview

- GRACE mission overview
  - Orbit design
  - Instrumentation
- Gravity field determination
  - K-band processing
  - Signal separation
- Signal
  - Deterministic model
  - Applications
- Noise
  - Anomalies
  - Differences to mean
- EGSIEM combination service
  - Combination on solution / normal equation level
  - L3-products

GRACE mission overview

GRACE mission concept

- Two satellites (type CHAMP).
- Orbit determination with GPS.
- Non-gravitational accelerations are observed by onboard accelerometers.
- Ultra-precise inter-satellite ranges are observed by dual way K-band link.



The variation in inter-satellite range allows for the determination of the fine structure of the terrestrial gravity field. Monthly gravity field solutions enable the study of mass transport in the system Earth.

Ground Segment

GRACE-Mission:

- **Project: NASA / DLR**
- **Raw data processing / quality control: JPL**
- **Gravity field processing: CSR / GFZ**

Ground segment:

- **Mission operations: DLR Oberpfaffenhofen**
- **Uplink / downlink: Weilheim / Neustrelitz**
- **Data downlink: Ny Alesund**
- **Data archive: POODAC / ISDC**

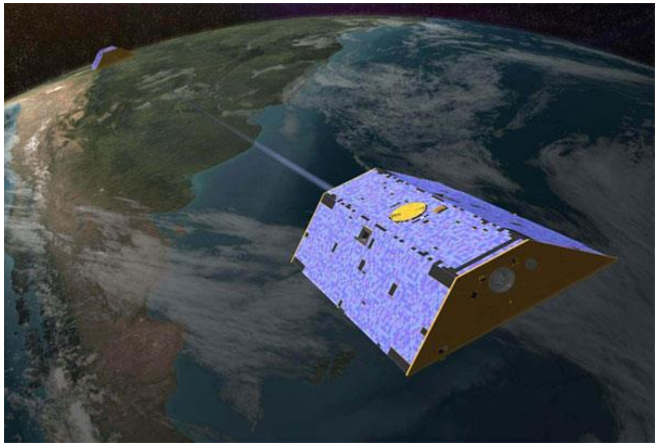
GRACE satellite orbits and mission goals

Satellite orbits

- **Mission start: 17th March 2002**
- **Inclination: 89°**
- **Elevation:**

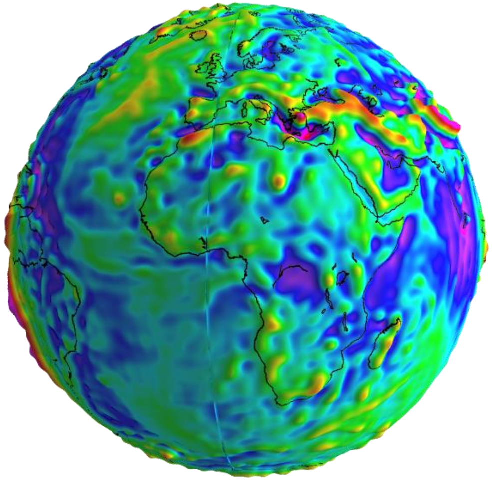
  485 km (start)

  355 km (today)
- **Inter-satellite distance: 220 km**

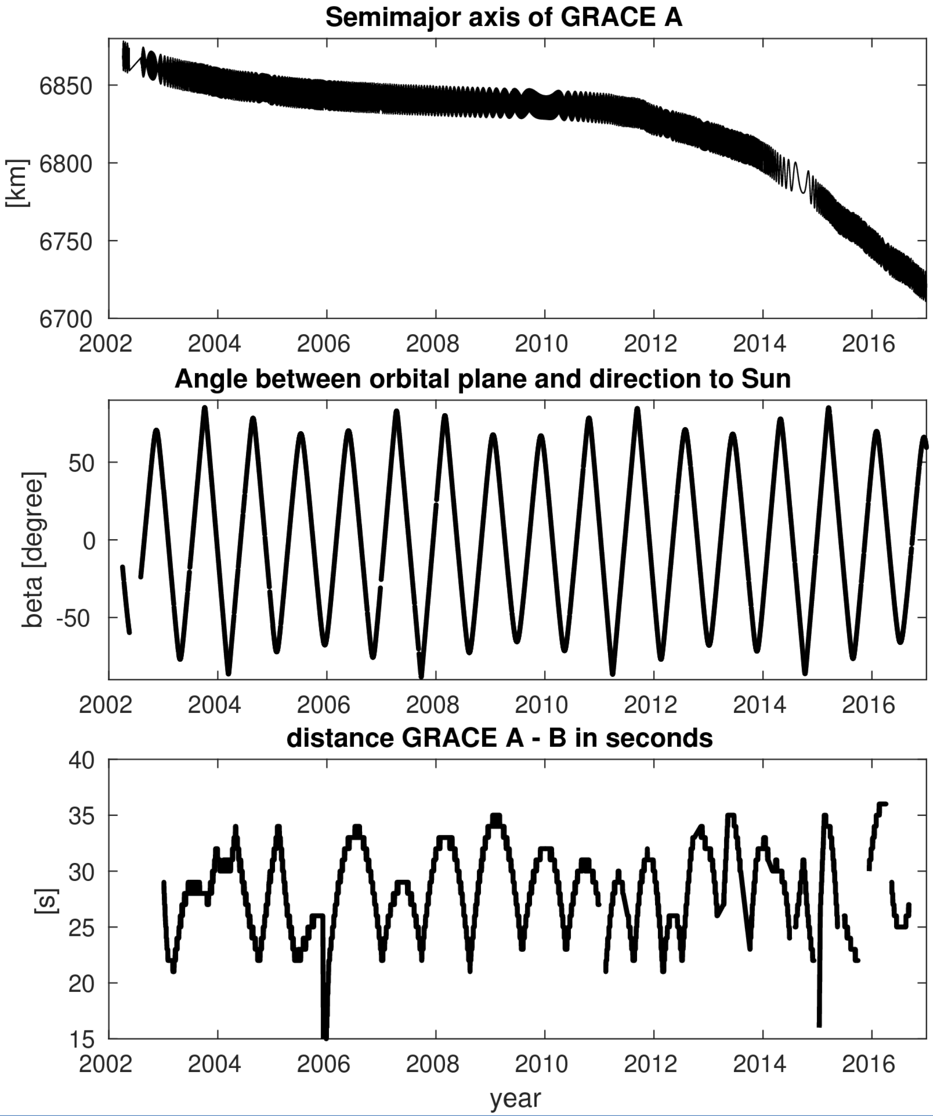


Mission goals

- **Global model of the Earth's static gravity field up to degree and order 160 (now 180).**
- **Temporal variations of monthly gravity fields (due to hydrology, ice mass change, …).**
- **Atmosphere sounding using GPS occultations.**



Orbit

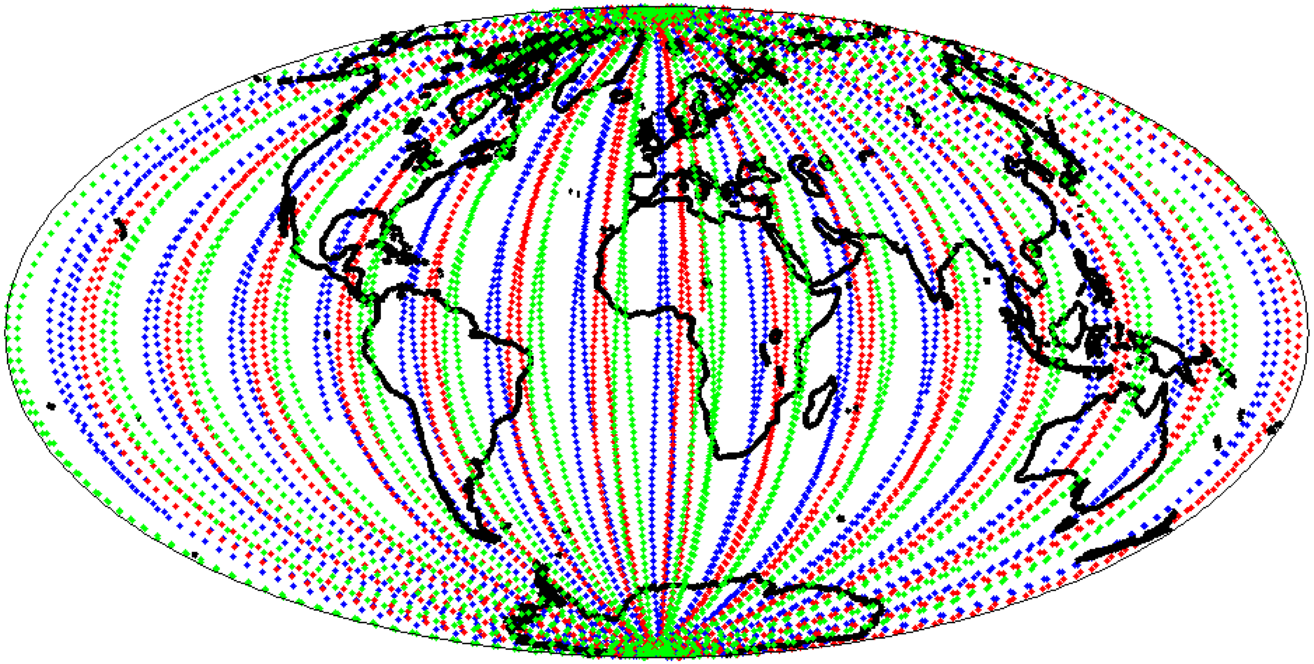


Due to atmospheric drag the altitude of the GRACE satellites is slowly decreasing. The orbit sensitivity for the gravity field increases with lower elevation. On the other hand the satellite environment gets more harsh, making orbit modeling more difficult.

The direction Earth - Sun changes by 360° during a sidereal year (365.25 d). Due to a slow precession the change in angle β‘ between the normal vector of the orbital plane of GRACE and the Sun is slightly faster (180° / 161 d).

The nominal distance between both GRACE satellites is 220 km, corresponding to 28 s. It is kept within certain bounds by regular orbit maneuvers. The K-band ranging noise increases with the distance.

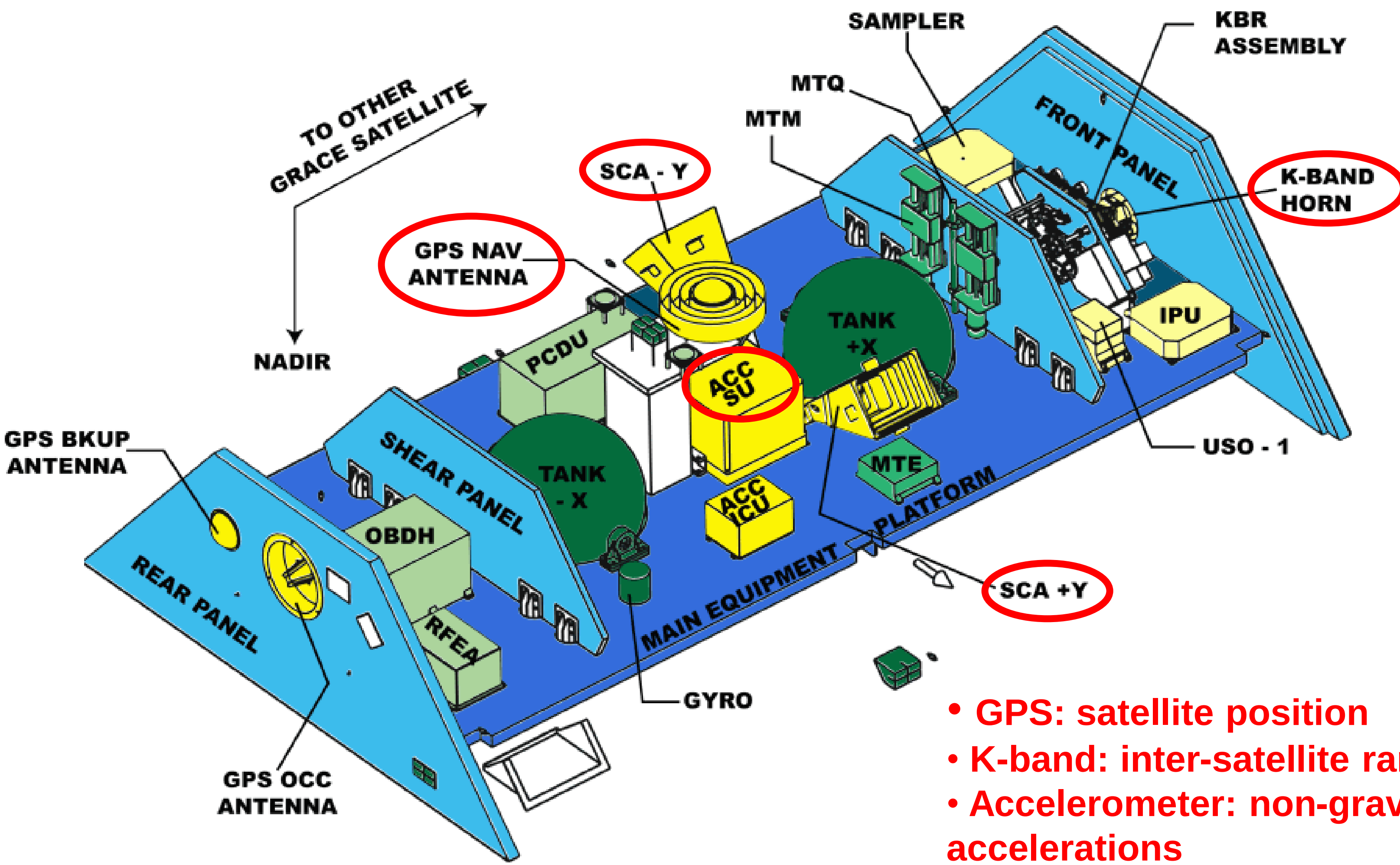
Orbit



To compute a global gravity field model, the whole Earth has to be covered consistently by observations, i.e., by satellite ground tracks.

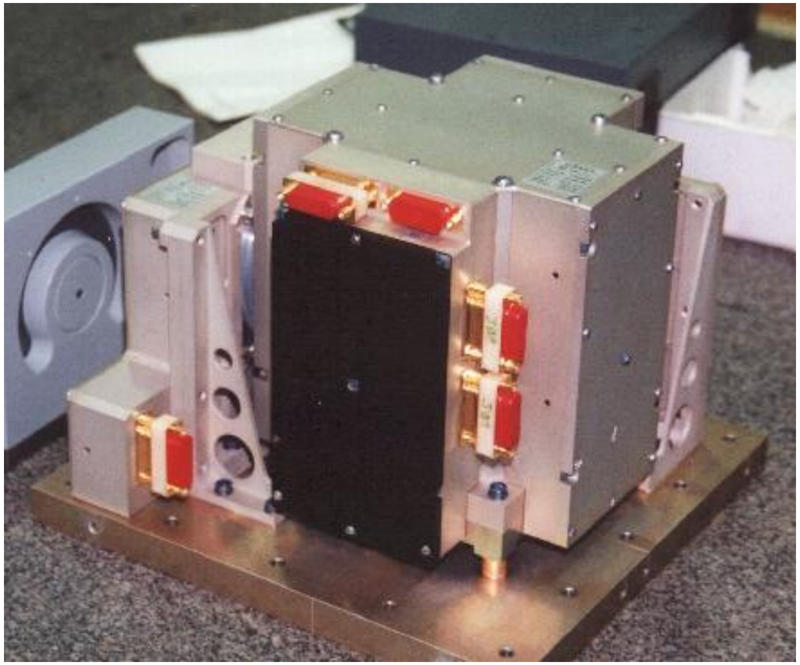
In principle coarse gravity fields can be determined after one day, a sub-cycle of ground tracks is completed after 4-7 days. After one month a resolution of spherical harmonic degree 90 can be achieved with reasonable signal-to-noise ratio.

Instrumentation

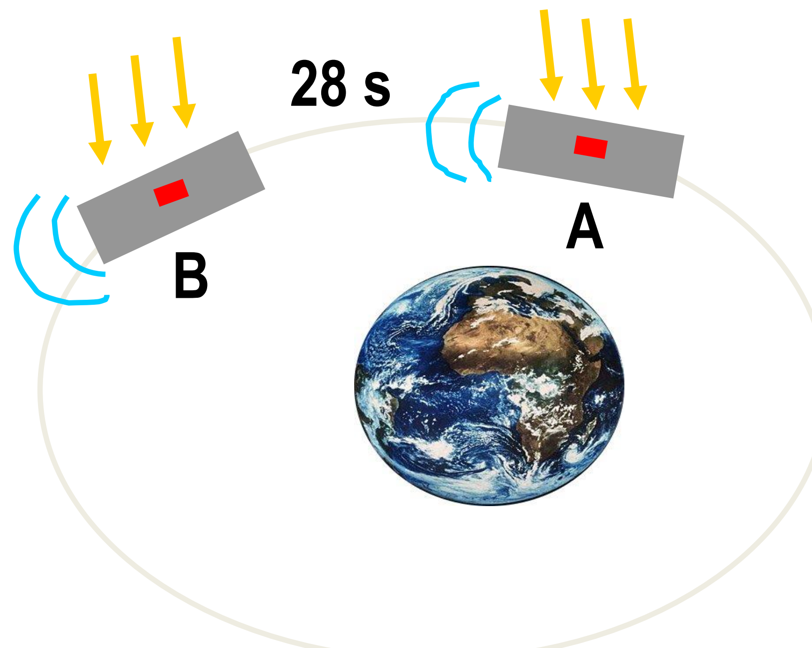


- GPS: satellite position
- K-band: inter-satellite ranging
- Accelerometer: non-gravitational accelerations
- Star cameras: satellite orientation

GRACE instruments: accelerometer



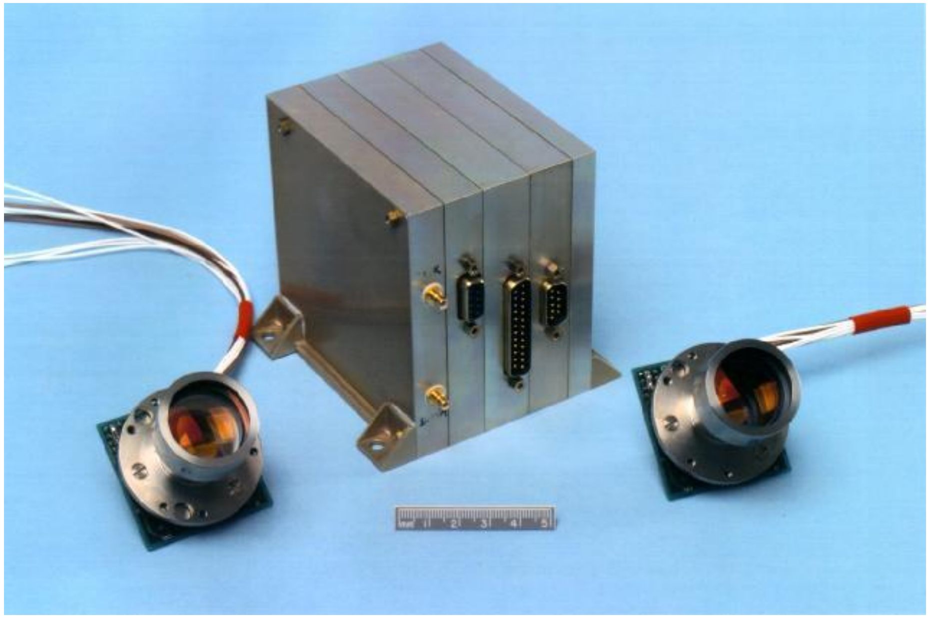
- 3-axes accelerometer,
- cross-track is less sensitive due to construction under 1 G environment,
- located at the center of mass of the satellite (between fuel tanks, in-orbit calibration),
- data artifacts: spikes and twangs (foil covering the satellite?).



Non-gravitational accelerations:

- **atmospheric drag**
- **solar pressure**
- **albedo**
- **thruster-pulses**

GRACE instruments: star cameras



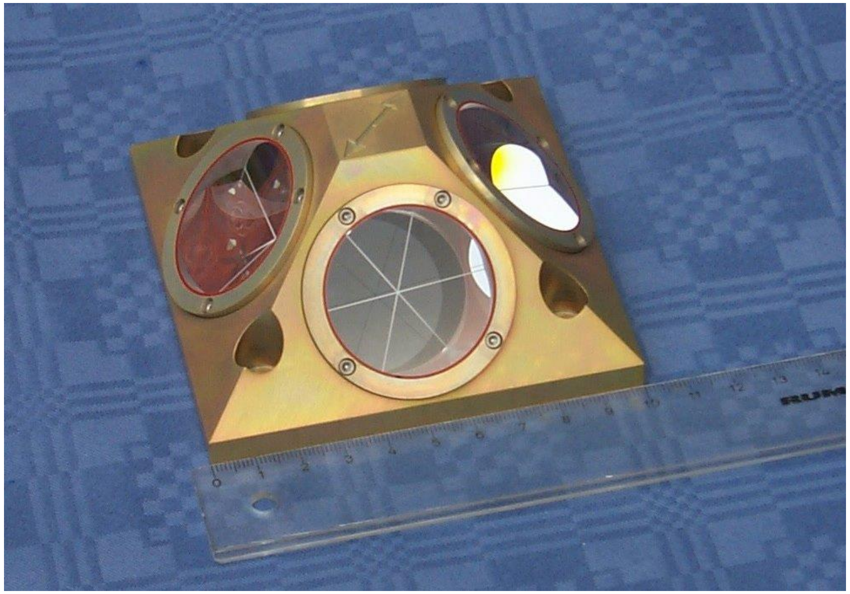
The two star cameras observe the satellite orientation in the inertial frame (realized by star catalogue).

Regularly the star cameras are blinded by sun or moon. Simultaneous blinding leads to loss of orientation and mode drop from science mode to attitude hold mode (GRACE-FO will have 3 star cameras).

The satellite orientation is controlled by 6 pairs of cold gas thrusters and magnetic torquers.

In case of star camera blinding the inertial measurement platform of GRACE B (defect on GRACE A) and the coarse direction to the sun is used to keep the satellite orientation. This leads to increased thruster fire and consequently fuel consumption.

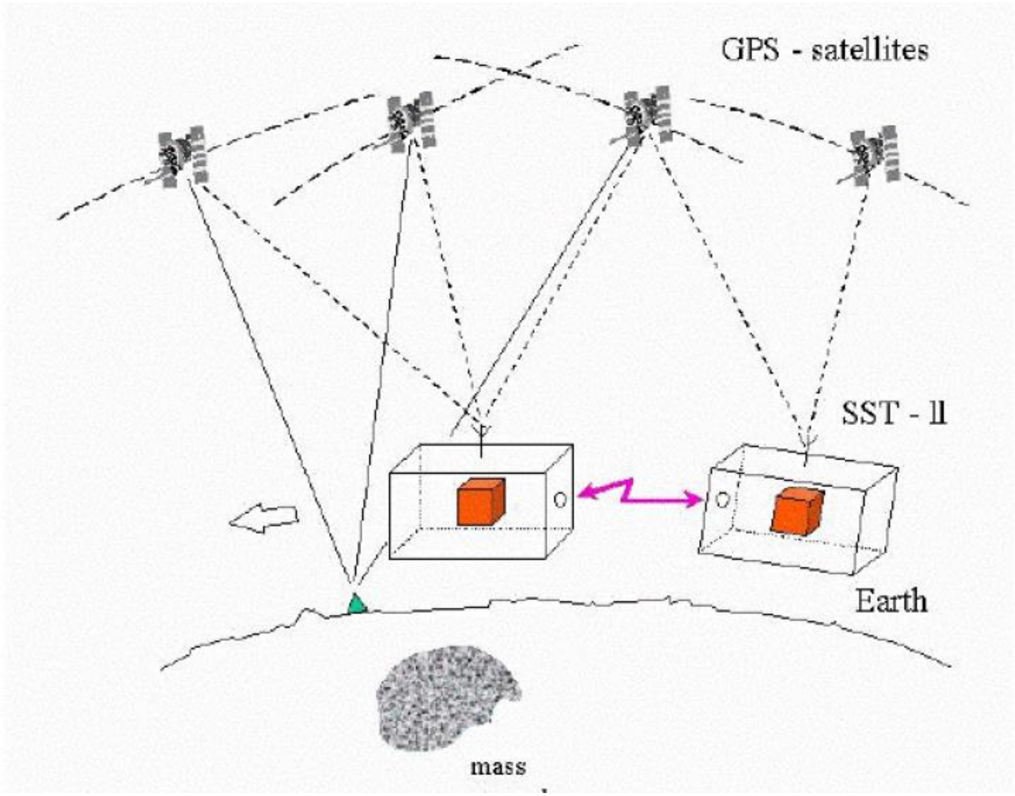
GRACE instruments: laser retro-reflector



• Each day 400-500 satellite laser ranging (SLR) normal points to the GRACE satellites are observed by laser stations all over the world.
• SLR is not routinely used for orbit or gravity field determination, but for quality control.
• The STD of kinematic orbits in 2008 based on a subset of SLR stations and 45.000 (A) resp. 42.500 (B) normal points is 16.4 mm (A) and 19.4 mm (B), the biases are 1.4 mm (A) and 1.5 mm (B).
• The STD of reduced dynamic orbits (making use of stochastic accelerations to absorb model deficiencies) in 2008 is 11.6 mm (A) and 13.0 mm (B).

By analyzing long time-series of SLR observations the radial displacement of the GPS antennas from the satellite’s centers of mass was determined (independently by GFZ and JPL; in consequence different values are since then used by the different SDS processing centers).

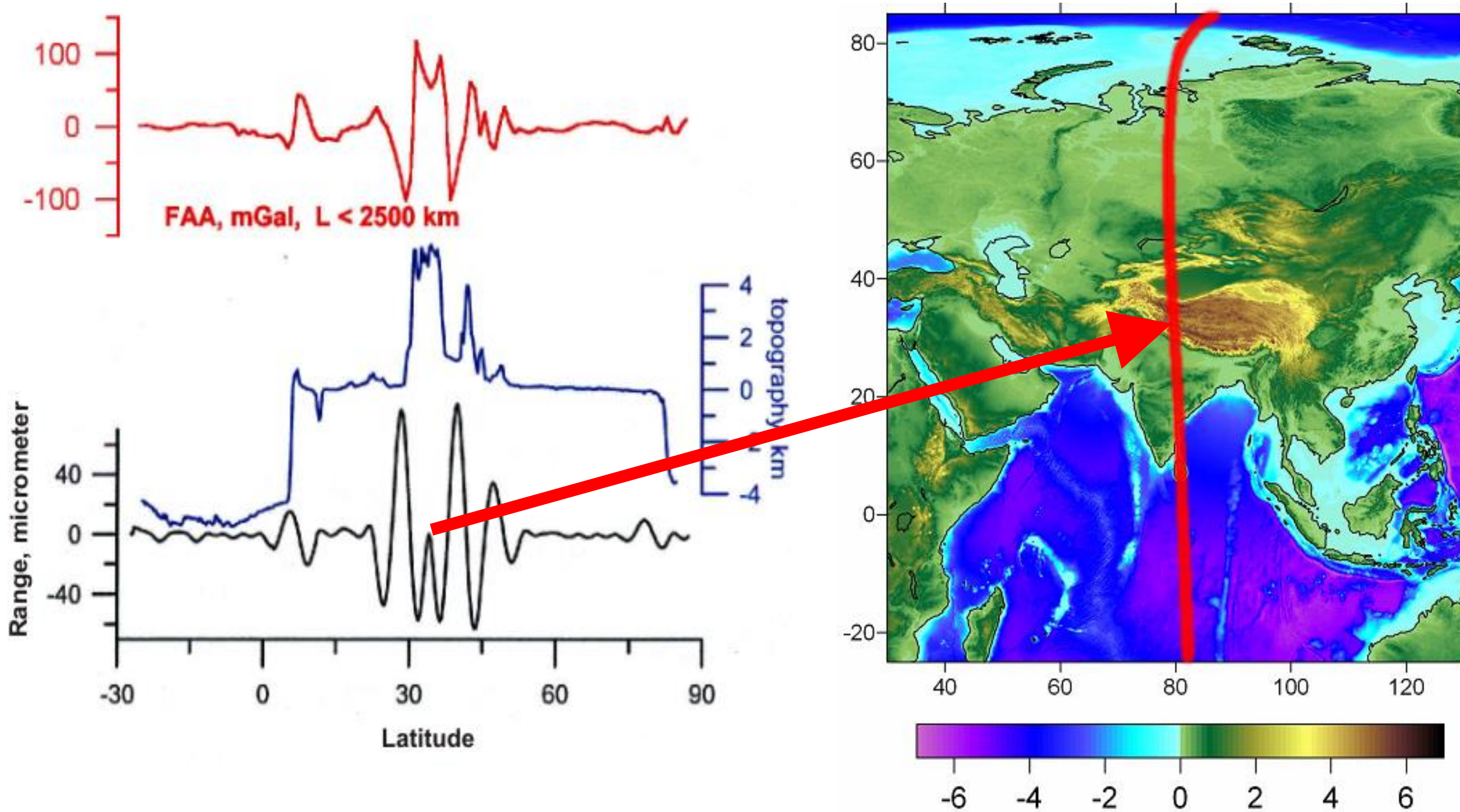
Concept of SST



Low-Low Satellite-to-Satellite Tracking (ll-SST):

The inter-satellite range between two Low Earth Orbiters (LEOs) is observed with micrometer accuracy (apart from an unknown bias) based on the timing of a two-way K-band microwave signal (wavelengths of 1.2 cm and 0.9 cm).

Concept of ll-SST



Free air gravity anomaly (FAA) and topography along a GRACE groundtrack compared to low-pass filtered K-band ranges while passing the Himalayas on 03/05/2003.

Gravity field determination

GPS processing scheme

Kinematic positions
pseudo-observations with
variance-covariance information

Initial orbit determination
- a-priori orbits of GRACE A&B

Orbit improvement by least squares adjustment
- arc-specific (daily) GPS observation equations
  (parameters: gravity field coefficients, arc-specific parameters of both satellites)
- arc-specific (daily) GPS normal equations

GPS observations can either be used directly, or be replaced by kinematic positions that are derived by a precise point positioning (PPP) from the GPS observations. When the latter are introduced as pseudo-observations together with their covariance information, the results are equivalent.

K-band processing scheme

Kinematic positions
pseudo-observations with variance-covariance information

K-band observations

Initial orbit determination
- a-priori orbits of GRACE A&B

Orbit improvement by least squares adjustment
- arc-specific (daily) K-band observation equations
  (parameters: gravity field coefficients, arc-specific parameters of both satellites)
- arc-specific (daily) K-band normal equations

The K-band normal equations alone are singular because this observation type is not sensitive to all arc-specific parameters. Only in combination with the GPS (or kinematic orbit) normal equations a solution can be found.

Orbit adjustment

$$\boldsymbol{r}_a(t) = \boldsymbol{r}_{a0}(t) + \sum_{i=1}^{n_a} \frac{\partial \boldsymbol{r}_{a0}(t)}{\partial p_{ai}} \cdot \Delta p_{ai} + \sum_{i=1}^{n_c} \frac{\partial \boldsymbol{r}_{a0}(t)}{\partial p_{ci}} \cdot \Delta p_{ci}$$

Taylor-expansion of positions:
based on a-priori orbits,
including all force model and arc-specific parameters:

- arc specific parameters of GRACE A

- common parameters: gravity field coefficients

The above equations are given for the positions of one satellite only. For GRACE B they just have to be copied.

Orbit adjustment

$$\begin{aligned}\boldsymbol{r}_a(t) - \boldsymbol{r}_b(t) = \quad & \boldsymbol{r}_{a0}(t) - \boldsymbol{r}_{b0}(t) \\ & + \sum_{i=1}^{n_a} \frac{\partial \boldsymbol{r}_{a0}(t)}{\partial p_{ai}} \cdot \Delta p_{ai} \\ & - \sum_{i=1}^{n_b} \frac{\partial \boldsymbol{r}_{b0}(t)}{\partial p_{bi}} \cdot \Delta p_{bi} \\ & + \sum_{i=1}^{n_c} \left(\frac{\partial \boldsymbol{r}_{a0}(t)}{\partial p_{ci}} - \frac{\partial \boldsymbol{r}_{b0}(t)}{\partial p_{ci}} \right) \cdot \Delta p_{ci}\end{aligned}$$

Taylor-expansion of position differences:
based on a-priori orbits,
including all force model and arc-specific parameters:

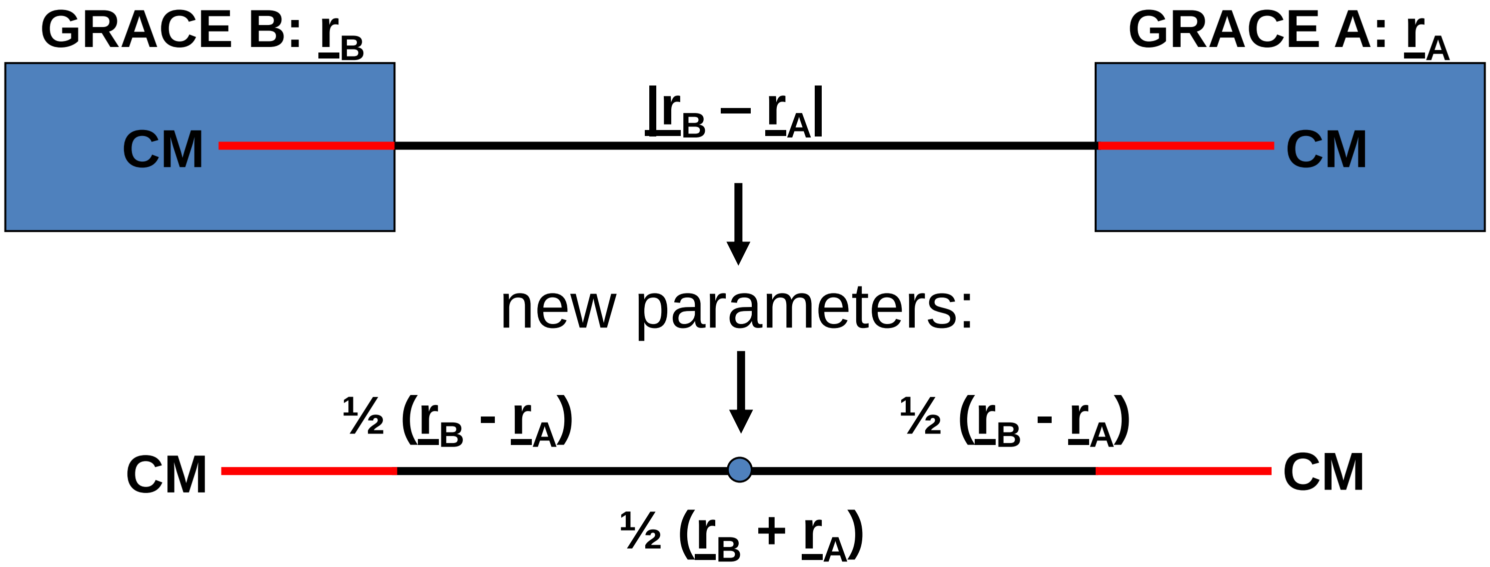
- arc specific parameters of GRACE A
- arc specific parameters of GRACE B
- common parameters: gravity field coefficients

The above equations are given for position differences. Actually only ranges are observed and therefore the position differences have to be projected onto the line of sight between both satellites.

Special notes on K-band ranging

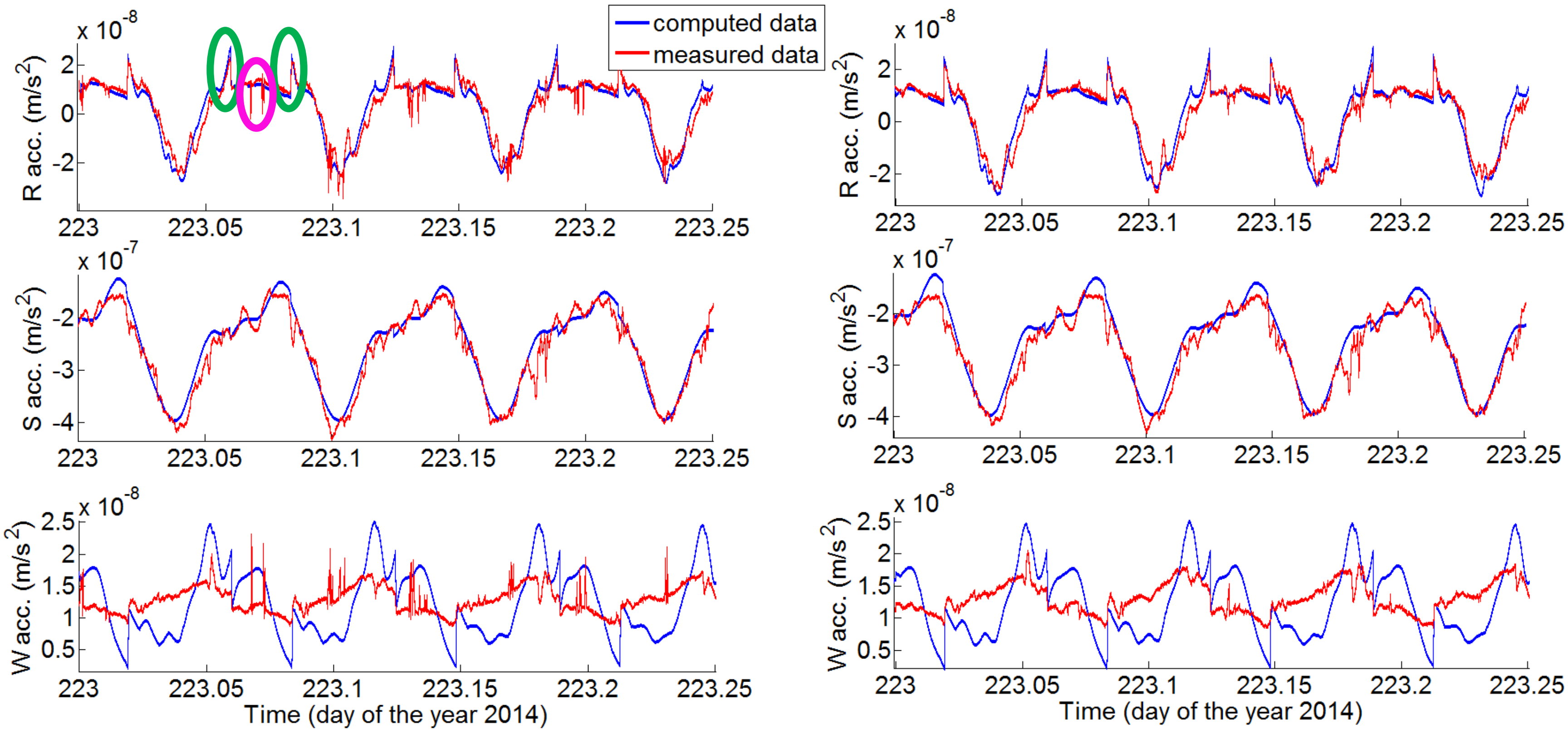
The K-band ranges are not used directly, but numerically differenced to range-rates. By the differentiation the high-frequency noise is increased, but low-frequency differences of unknown origin cancel out.

Despite the stupendous accuracy of the K-band observations of about 1 μm no orbit or gravity field determination is possible from K-band alone. For the determination of the orbital plane and the satellites' motion on the orbital plane GPS is needed.



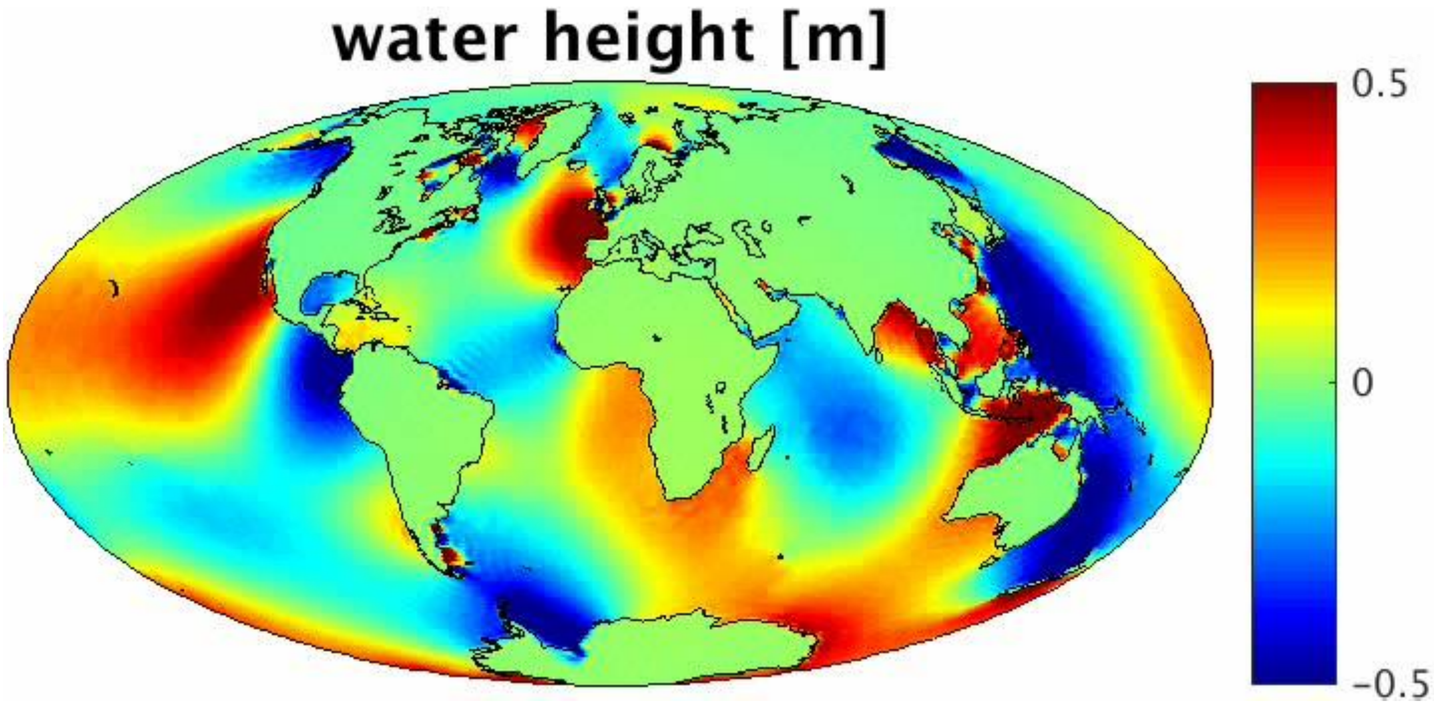
Signal

Non-Gravitational Accelerations



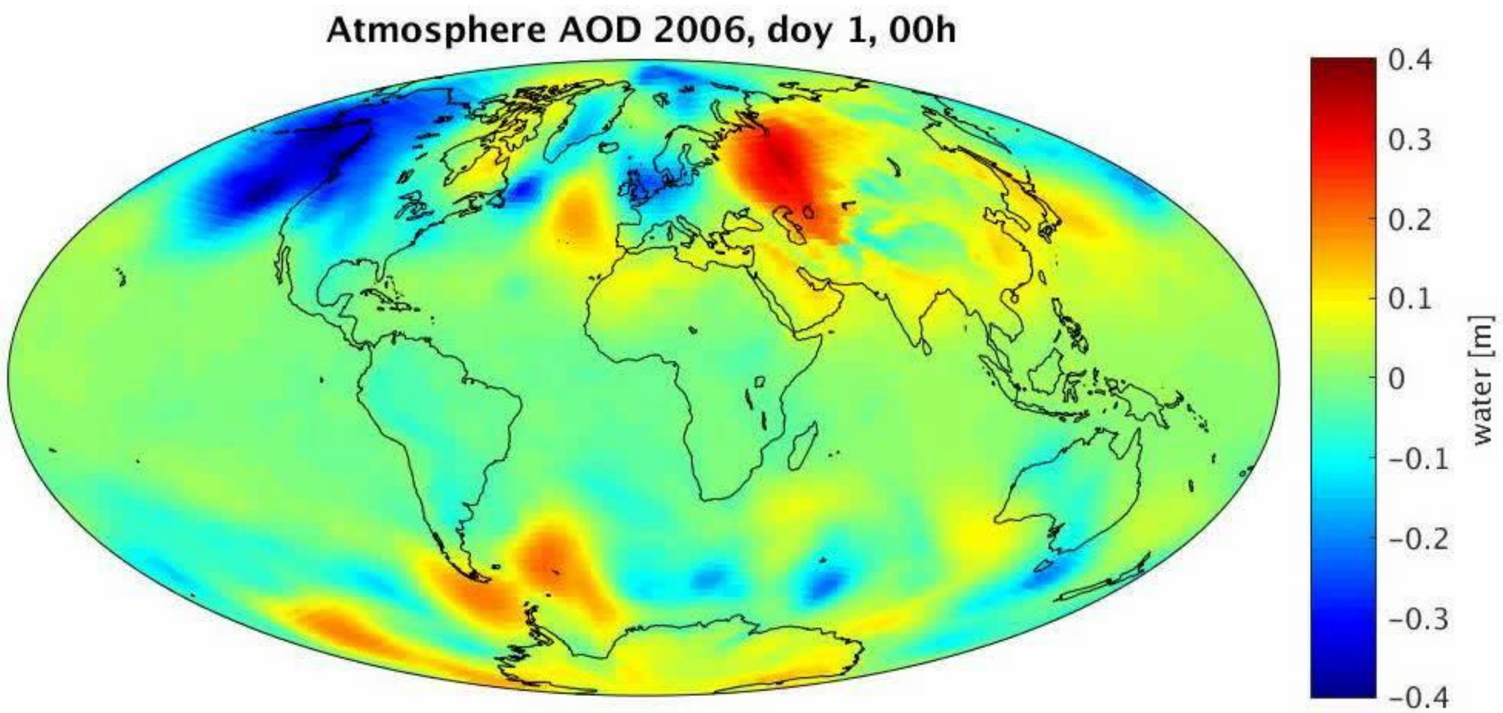
The surface forces acting on the satellite (atmospheric drag, solar radiation pressure, Earth albedo) are measured by the onboard accelerometers. They are applied directly (without any error estimates) in the equations of motion of the satellites. The accelerometers also sense linear accelerations by the thruster pulses (artifacts due to non-symmetric thruster firing).

Other Gravitational Accelerations: Ocean Tides



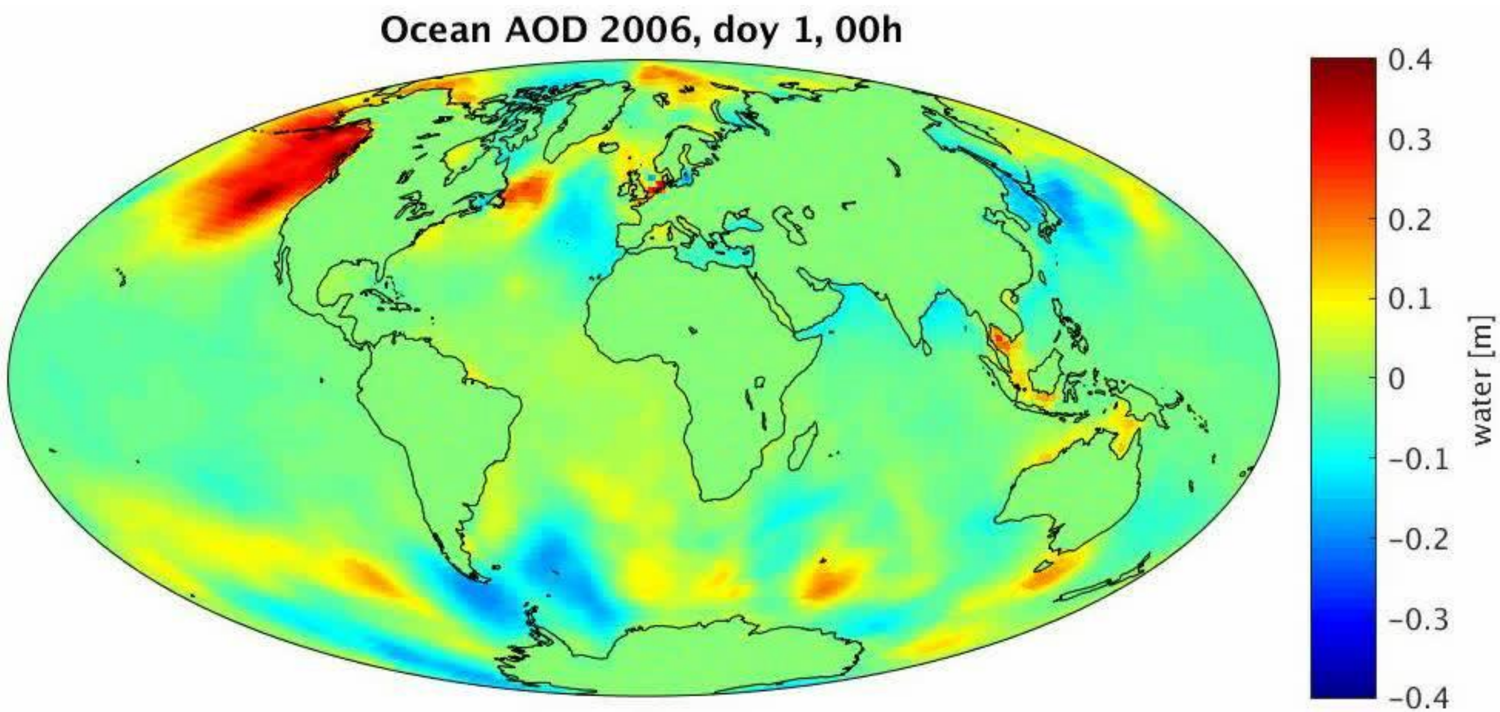
Not all gravitational signals that are sensed by the GRACE satellites can be resolved by the monthly gravity fields, and not all are of interest. For signal separation, background models are introduced for Earth and ocean tides and third bodies (sun, moon, planets).

Atmosphere Dealiasing



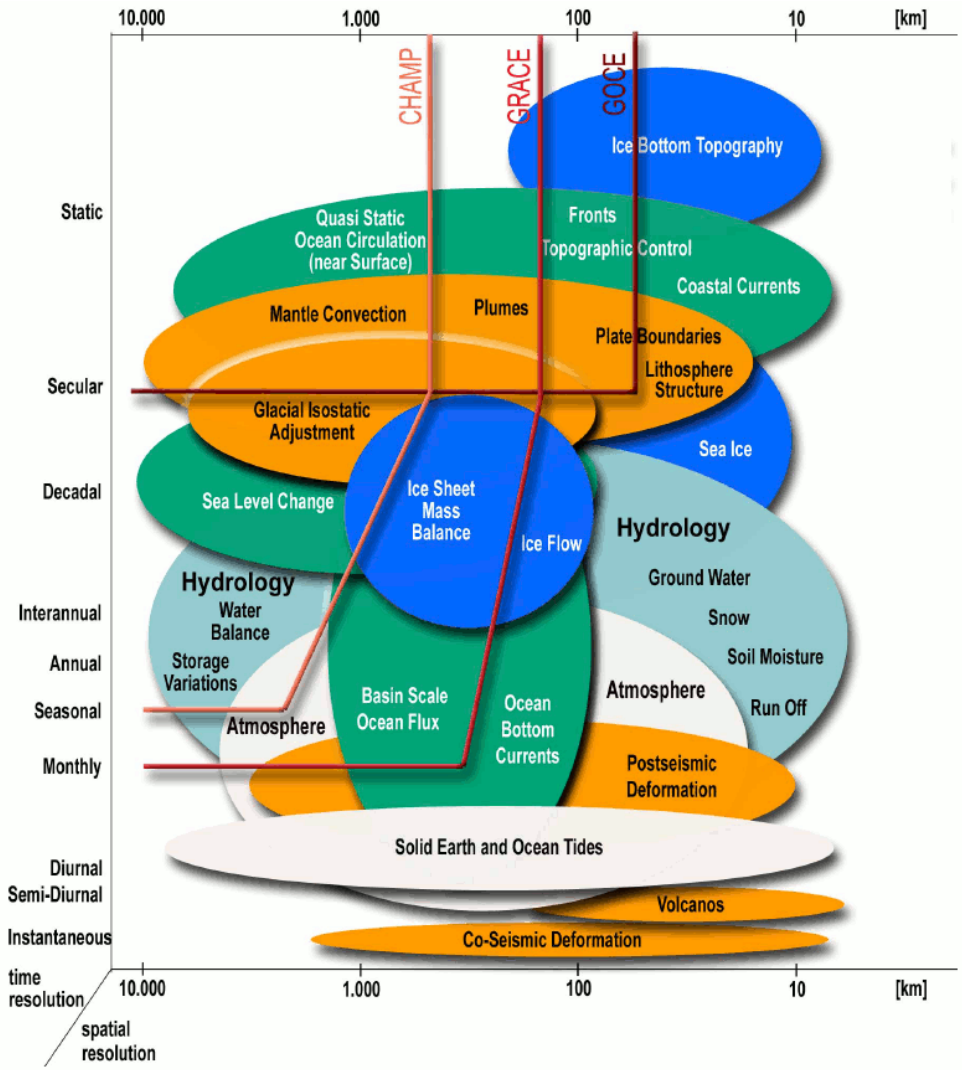
Weather induced (non-tidal) mass variations of the atmosphere change rapidly and cannot be represented by the monthly gravity fields. They are modelled by 6 hourly de-aliasing products. Depending on the application the monthly mean of these variations later has to be restored.

Ocean Dealiasing



The rapidly varying mass of the atmosphere causes a reaction by the oceans with comparable amplitude but inverse sign. These variations are also modelled by the de-aliasing products and depending on the application their monthly mean later has to be restored.

Applications

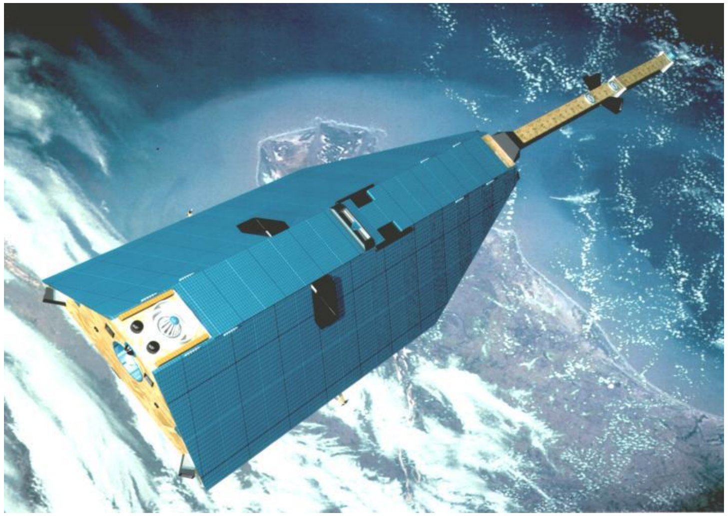


With CHAMP data for the first time a static gravity field could be determined up to a medium resolution from one satellite alone.

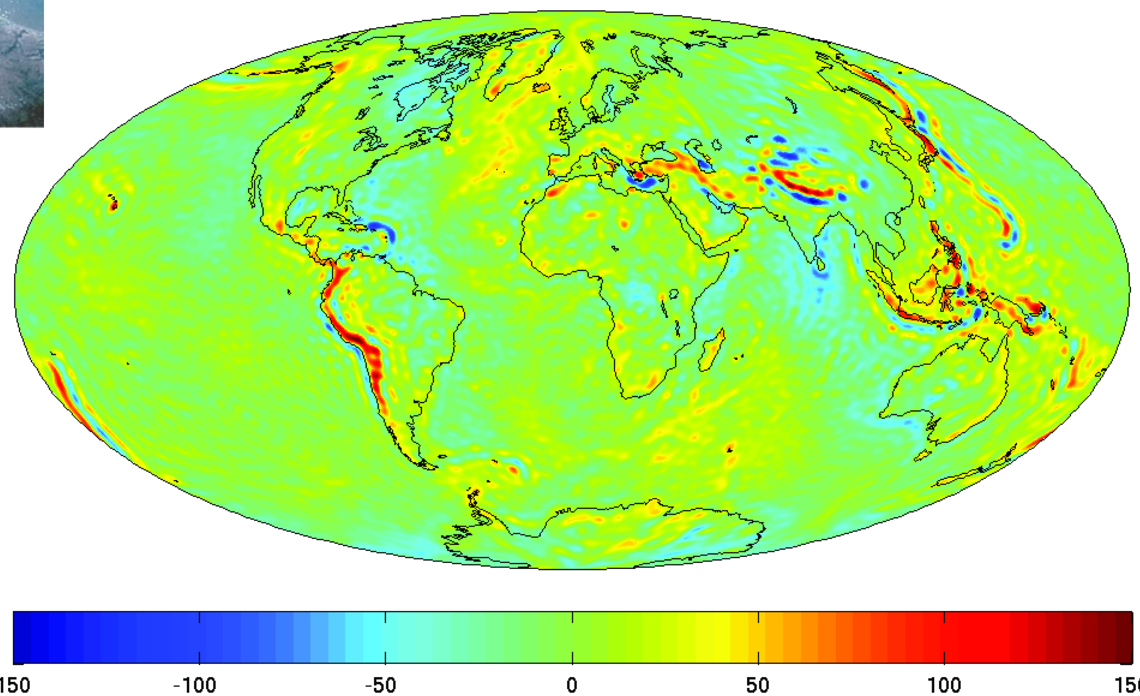
GRACE significantly improved our knowledge of the static gravity field, but its main goal are monthly gravity fields of reduced resolution to monitor temporal gravity variations.

GOCE enabled another major step forward in terms of resolution of the static gravity field, but due to orbit design was not well suited for the derivation of its temporal variations.

Static field: Gravity Anomalies CHAMP (8 years)

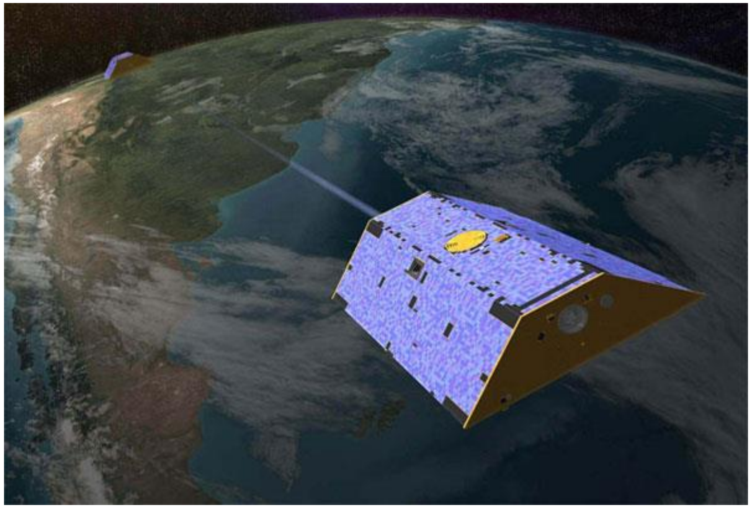


The CHAMP satellite orbited the Earth from 2000 to 2010, starting at an elevation of 450 km. The analysis of the orbit enabled the first static gravity field determination up to medium degree and order of about 120 using only one satellite.

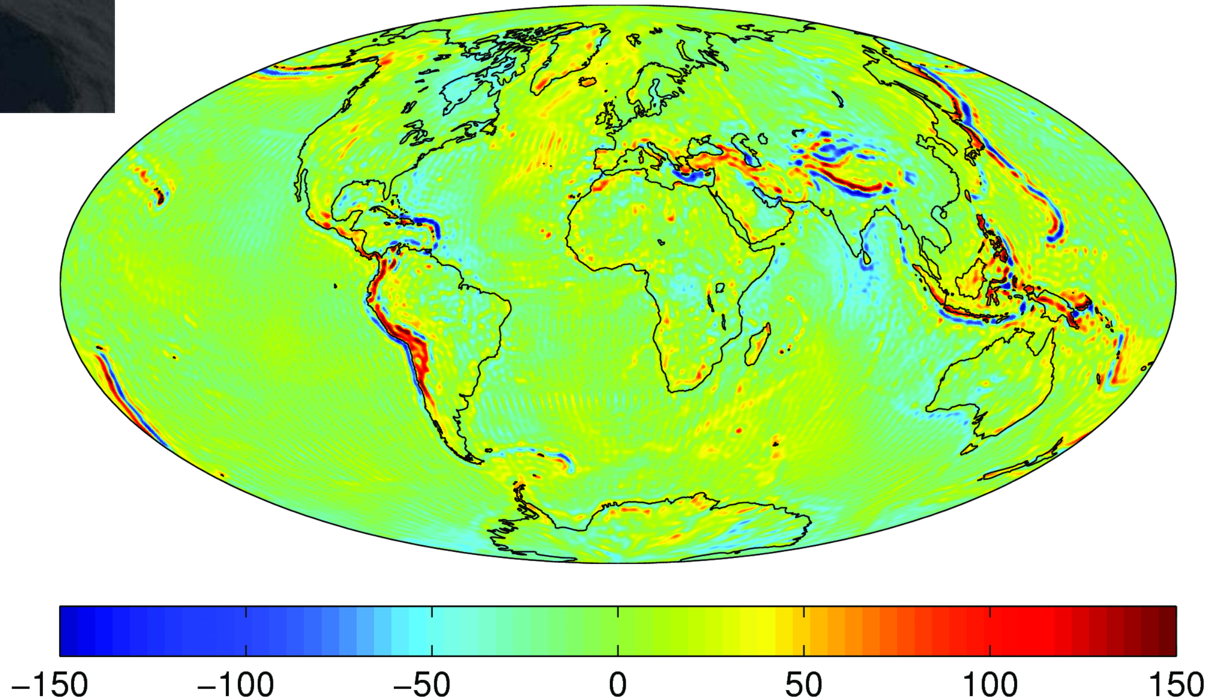


Shown are gravity anomalies, the unit is mGal = 10 μm / s^2

Static field: Gravity Anomalies GRACE (7 years)



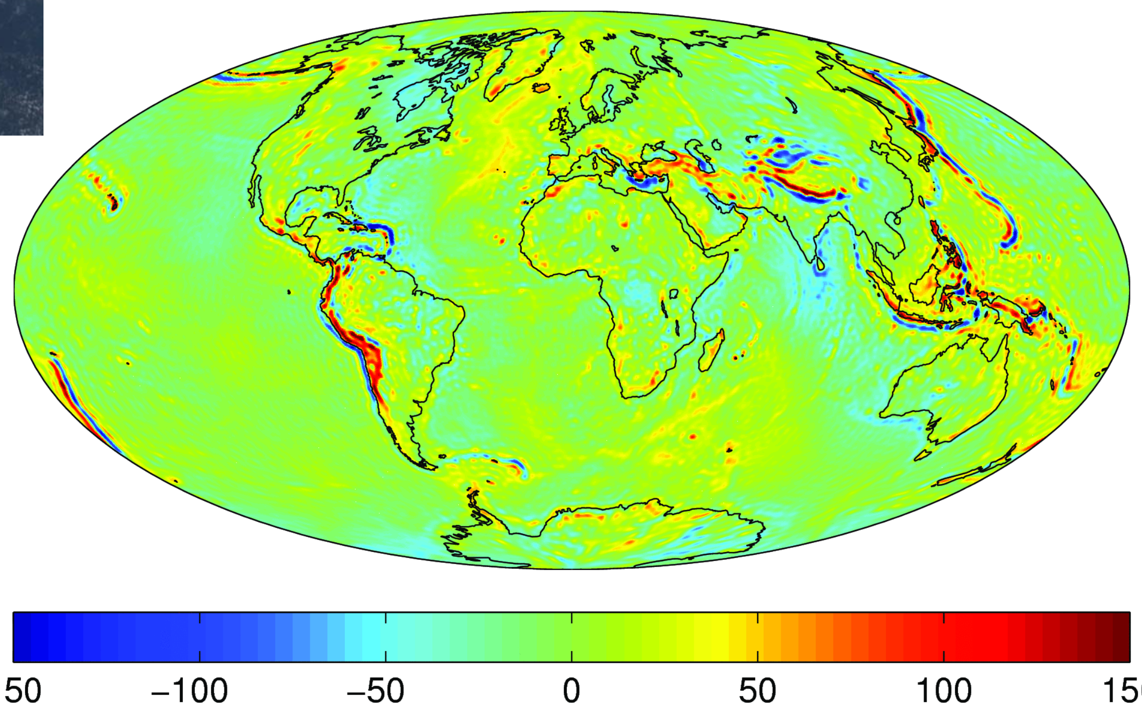
With GRACE the static gravity field can be determined up to a much higher degree and order of about 180. But at high resolution vertical striping becomes visible. These stripes are artifacts caused by the along-track K-band observation geometry.



Shown are gravity anomalies, the unit is mGal = 10 μm / s²

Static field: Gravity Anomalies GRACE + GOCE (8 months)

The most accurate static gravity fields to date are based on the combination of GRACE with GOCE data. GOCE alone is sensitive to about order and degree 250, but suffers from polar gaps due to the inclined sun-synchronous orbits.



Shown are gravity anomalies, the unit is mGal = 10 μm / s^2

Temporal Gravity Variations

The main temporal variations in gravity are either seasonal (induced by the hydrological cycle), or secular (ice mass loss near the poles, global isostatic adjustment). They can be modeled by a simple deterministic model:

$$m(t) = m_0 + m'*t + a*\sin(p_1+w_1*t) + b*\sin(p_2+w_2*t)$$

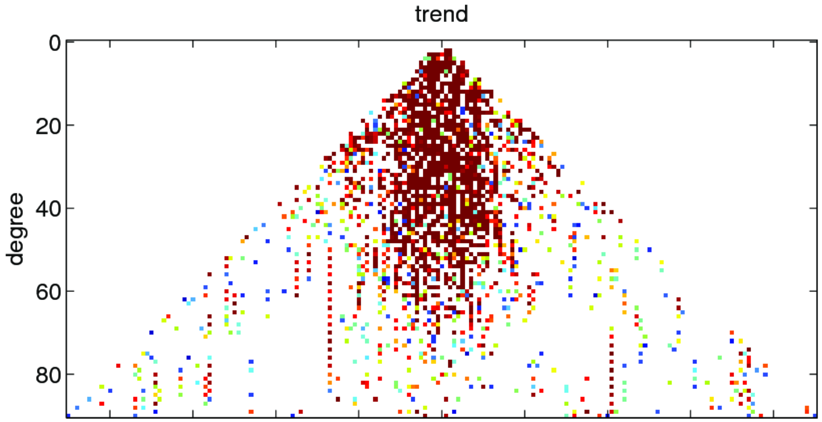
$$\text{annual frequency: } w_1=2*pi/365d$$

$$\text{semi-annual frequency: } w_2=2*w_1$$

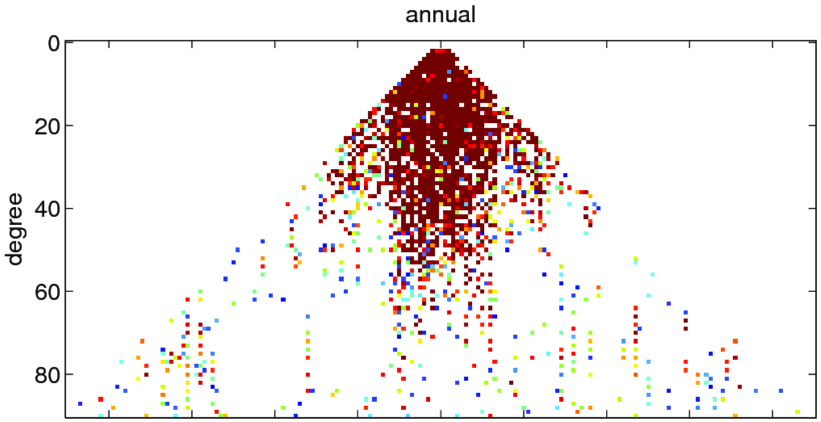
To avoid the non-linear determination of the phases *p_1* and *p_2*, the model is rewritten in a linear representation, where only bias *m_0*, trend *m'*, and the amplitudes *a* and *b* of annual or semi-annual variations have to be determined:

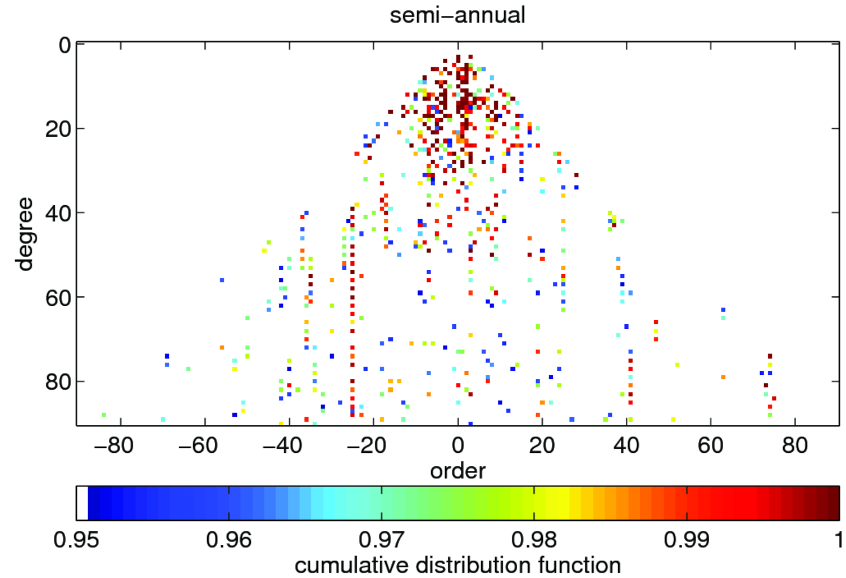
$$m(t) = m0 + m'*t + a_1*\sin(w_1*t) + b_1*\cos(w_1*t)$$
$$+ a_2*\sin(w_2*t) + b_2*\cos(w_2*t)$$

Sensitivity to Temporal Variations



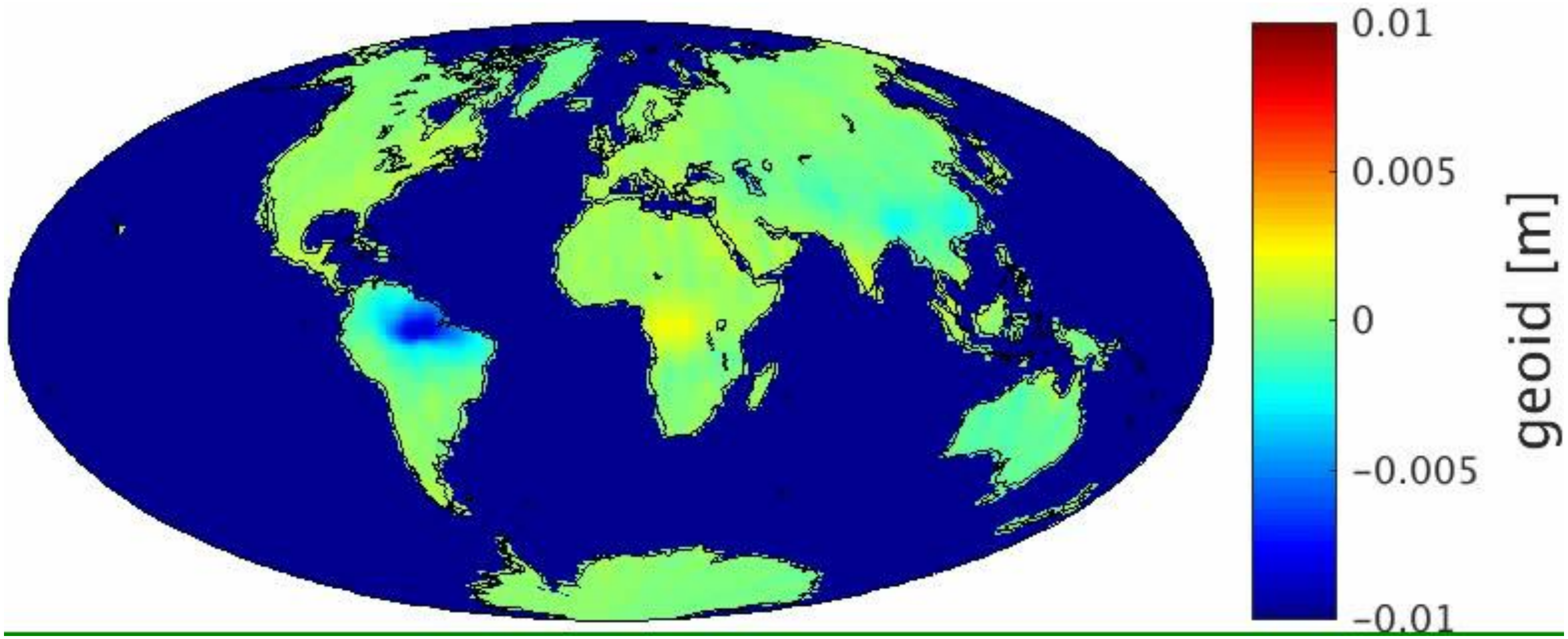
The sensitivity of the individual spherical harmonic coefficients to secular or seasonal temporal variations can be tested applying a statistical test of significance (F-test) to all parameters of the determin-istic model.





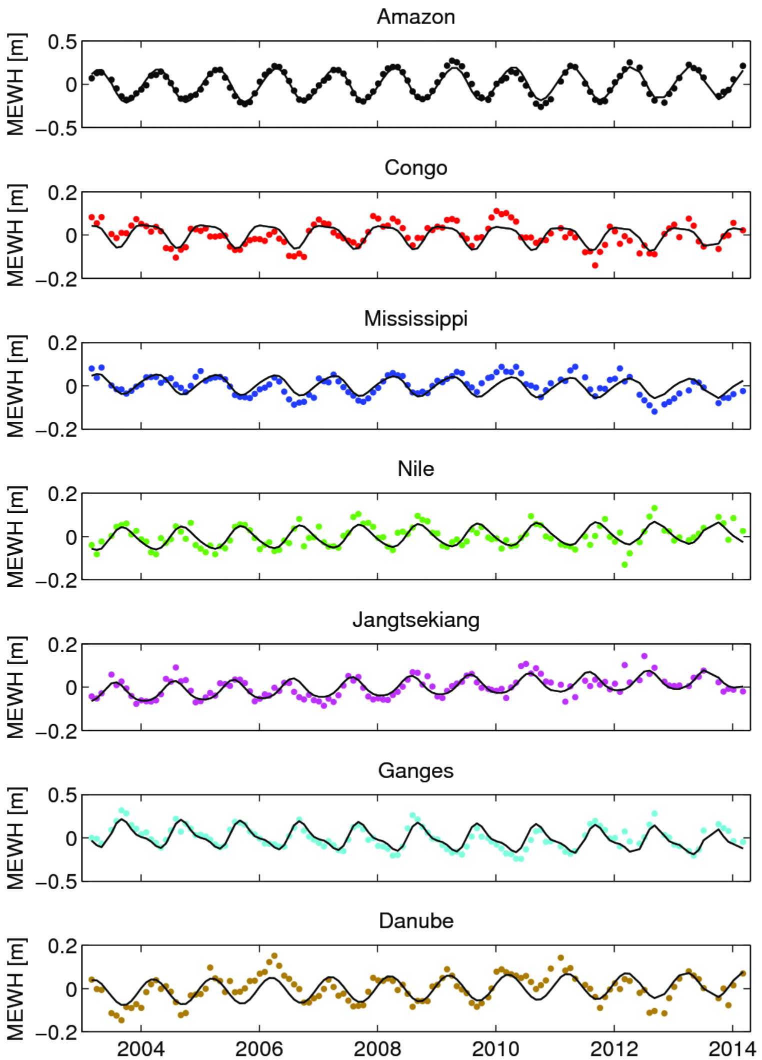
The significance tests confirm the applications summarized earlier.

Applications: Hydrology



The strongest time-variable signal sensed by GRACE is caused by the hydrological cycle over the continents. Variations in equivalent water height reach more then ± 30 cm in the major tropical and sub-tropical river basins. But also much shorter flood events can be reconstructed with daily time-resolution.

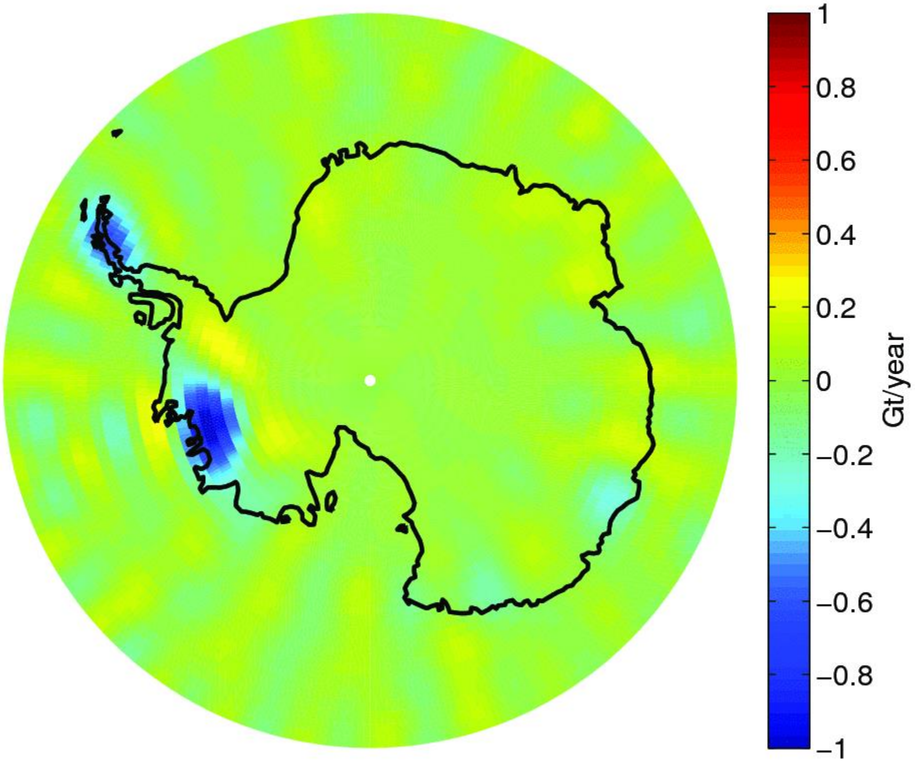
Applications: Hydrology



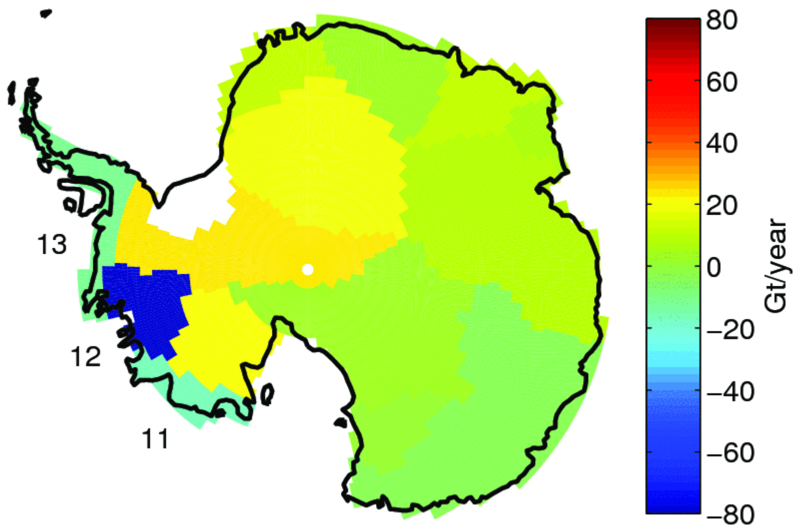
Continental mass variations are mainly of hydrological origin and show a strong seasonal and, to a much smaller extent, also semi-annual signal that is visible evaluating the mass variations within large river basins.

The largest seasonal variations can be observed in tropical and sub-tropical river basins with pronounced rainy seasons. But also in the large river basins of the temperate zone (Danube, Mississippi, …) a distinct seasonal signal can be observed.

Applications: Ice Mass Change

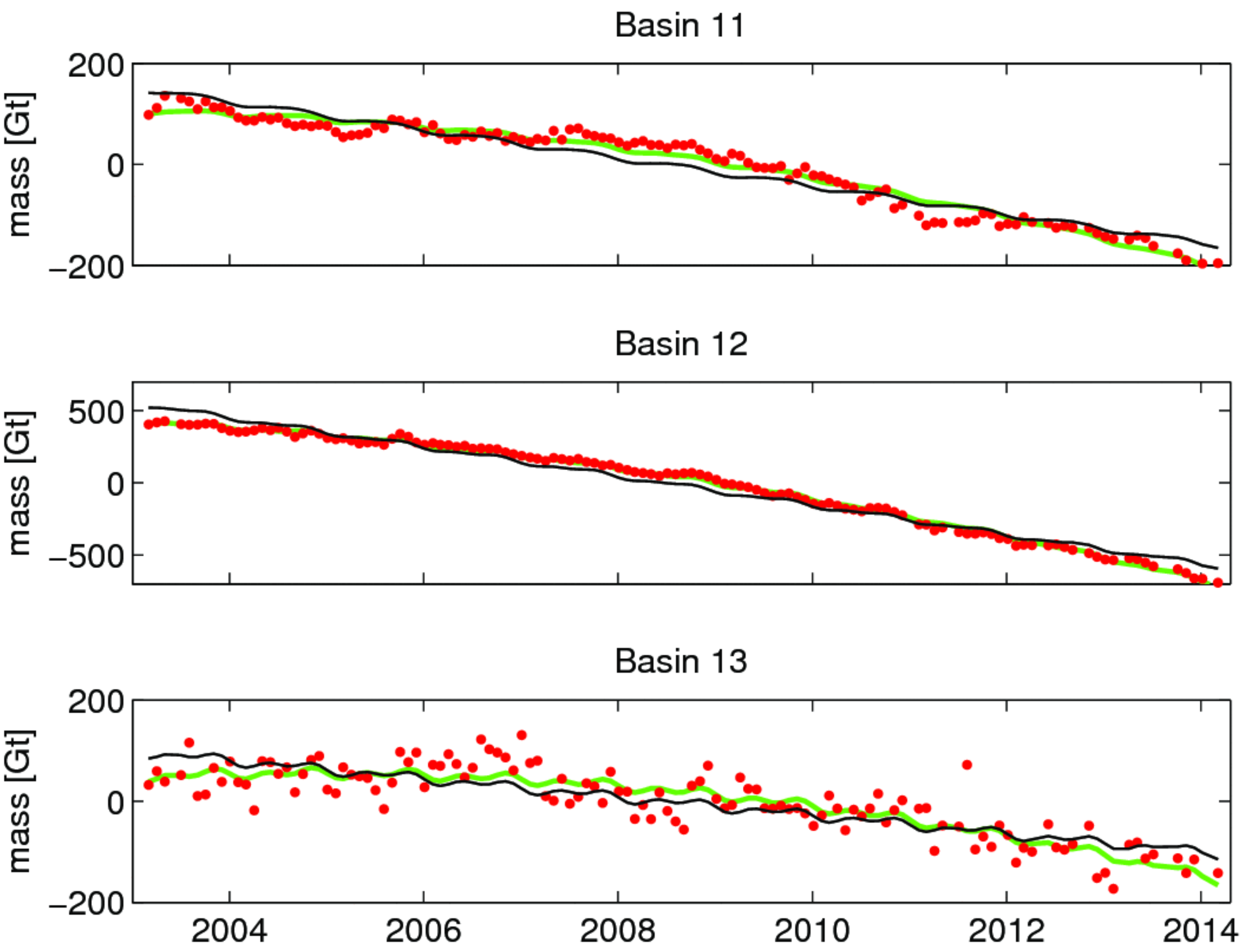


Mass loss in Western Antarctica and Greenland is caused by ice melt. Superimposed (counteracting) is the mass change signal induced by global isostatic adjustment (GIA). To separate both effects sophisticated GIA models are needed.



GRACE is one of the main tools to observe and quantify the effects of climate change in polar regions.

Applications: Ice Mass Change

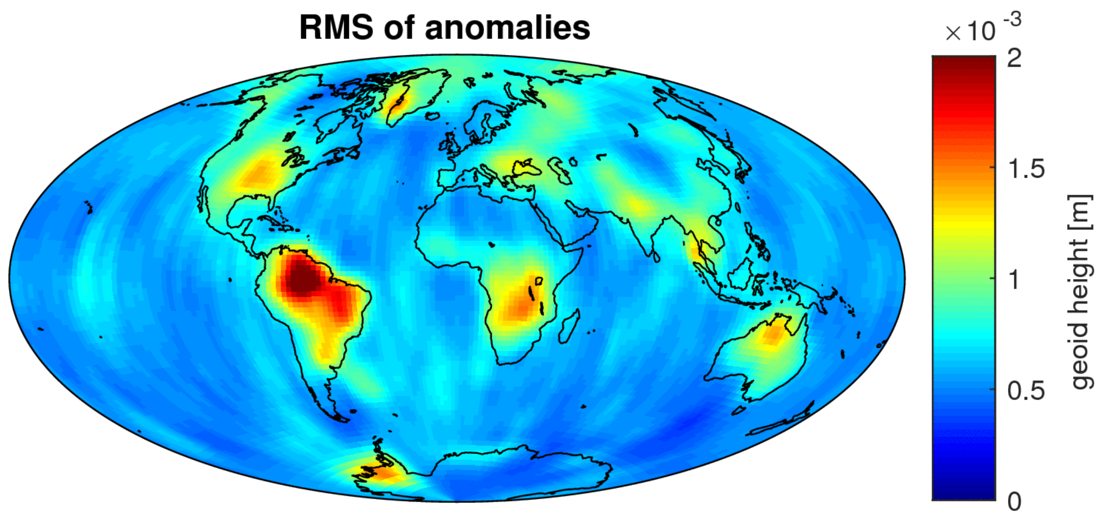


monthly estimates
linear model
quadratic model

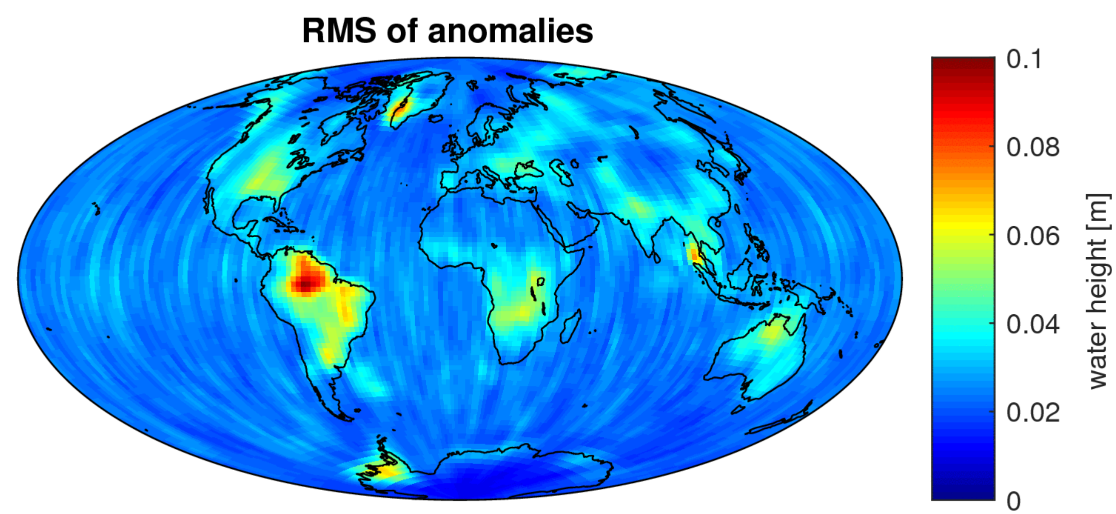
An optimal fit is achieved modelling mass loss by a quadratic model, the mass loss thus is accelerating.

Noise

Non-Seasonal Variability: Anomalies

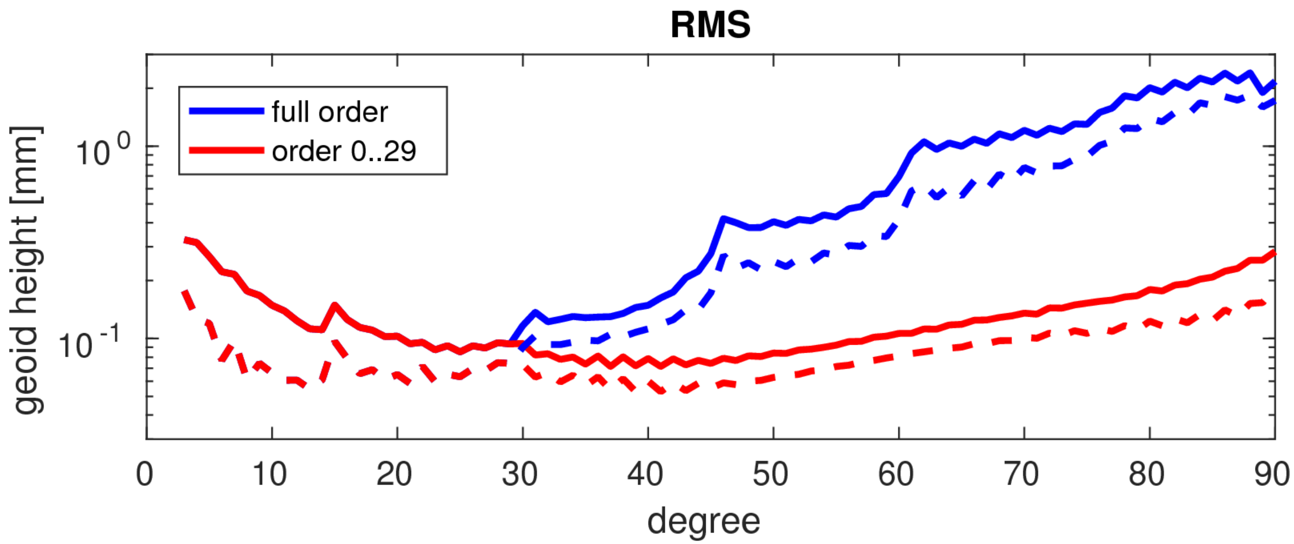


Not all mass variations in the system Earth are either secular or periodic with the seasons. To visualize them we remove the secular and annual variations by subtraction of a best fitting model.



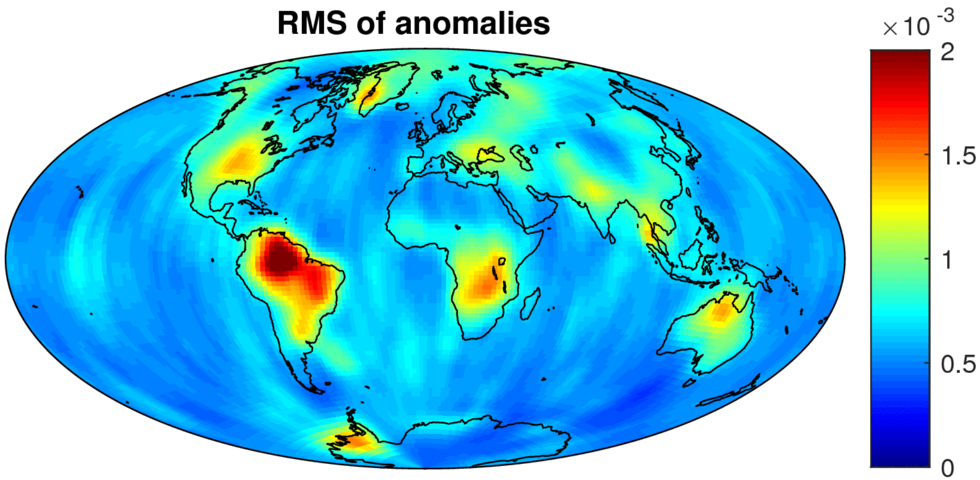
The remaining signal we call anomalies. Over the continents the anomalies are caused mainly by weather extremes (draught, flooding) and are of interest for scientific applica-tions or disaster management. Over the oceans the anomalies mainly represent noise.

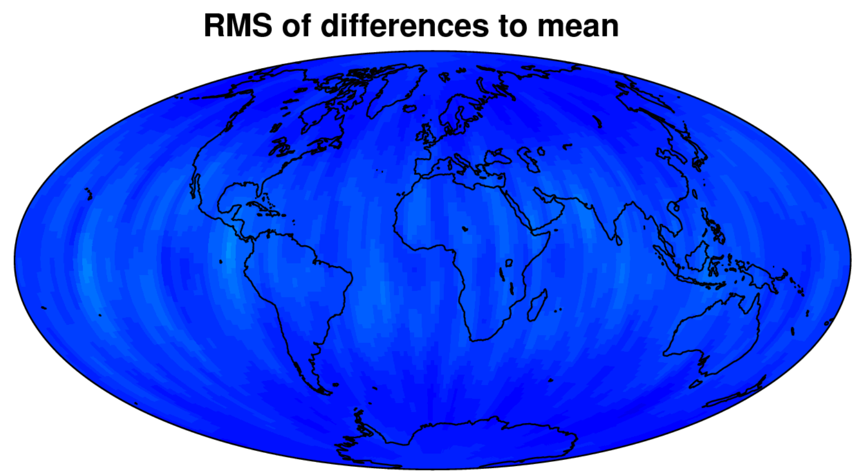
Noise Assessment



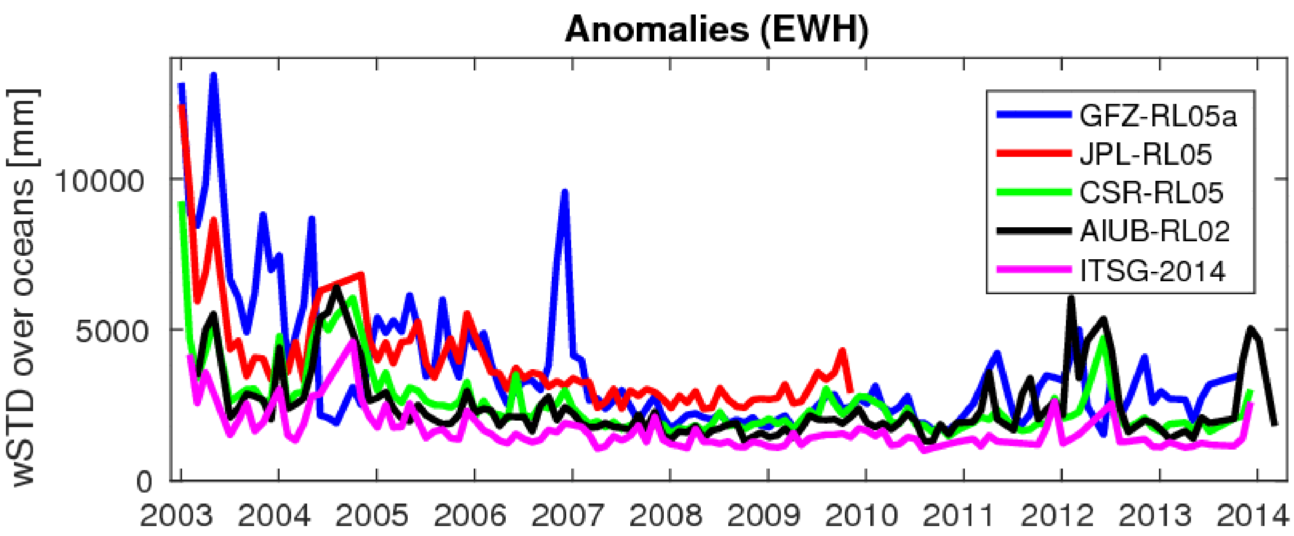
Differences to mean (to derive relative weights).

Anomalies over quiet regions (to independently assess quality).

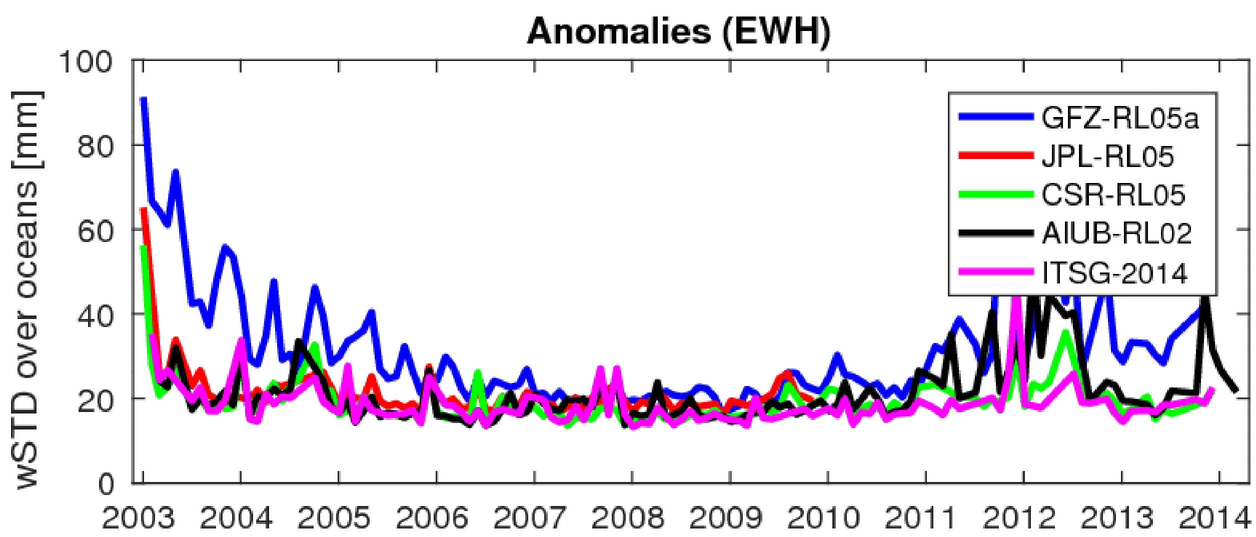




Anomalies over Oceans

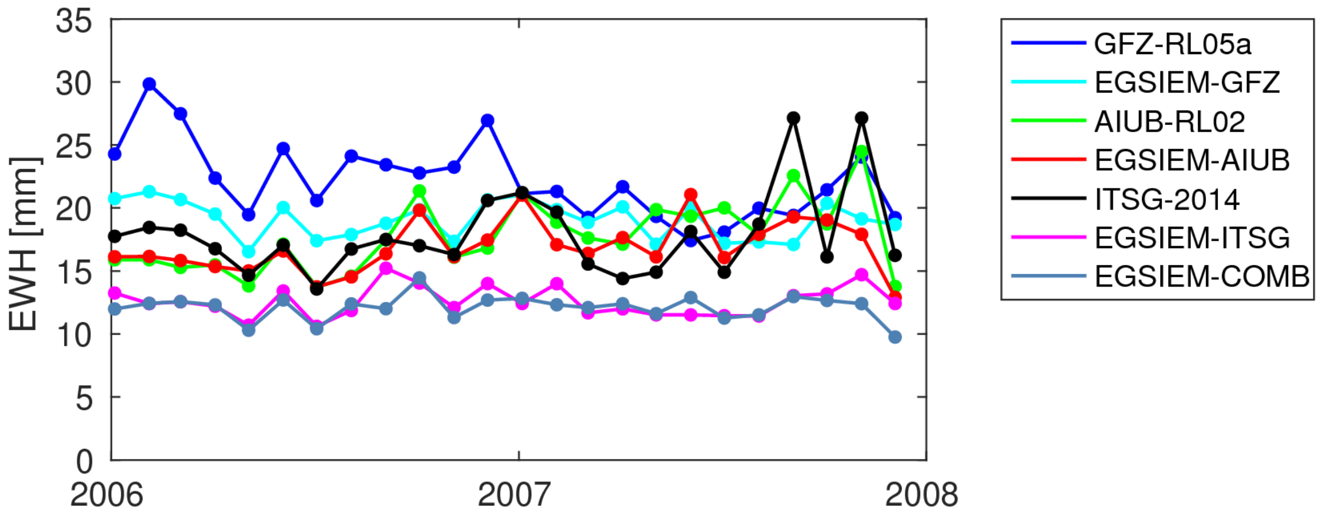


STD of anomalies over ocean areas, weighted by the cosine of the latitude, can be used to assess noise levels.

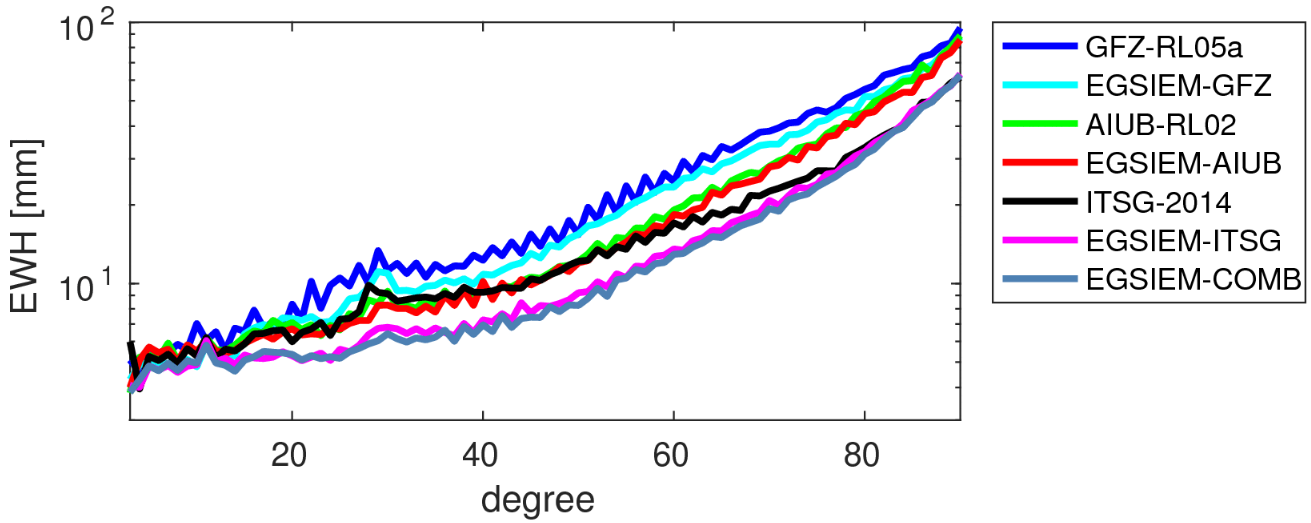


Smoothing by a 400 km Gauss-filter drastically reduces noise.

Noise Assessment



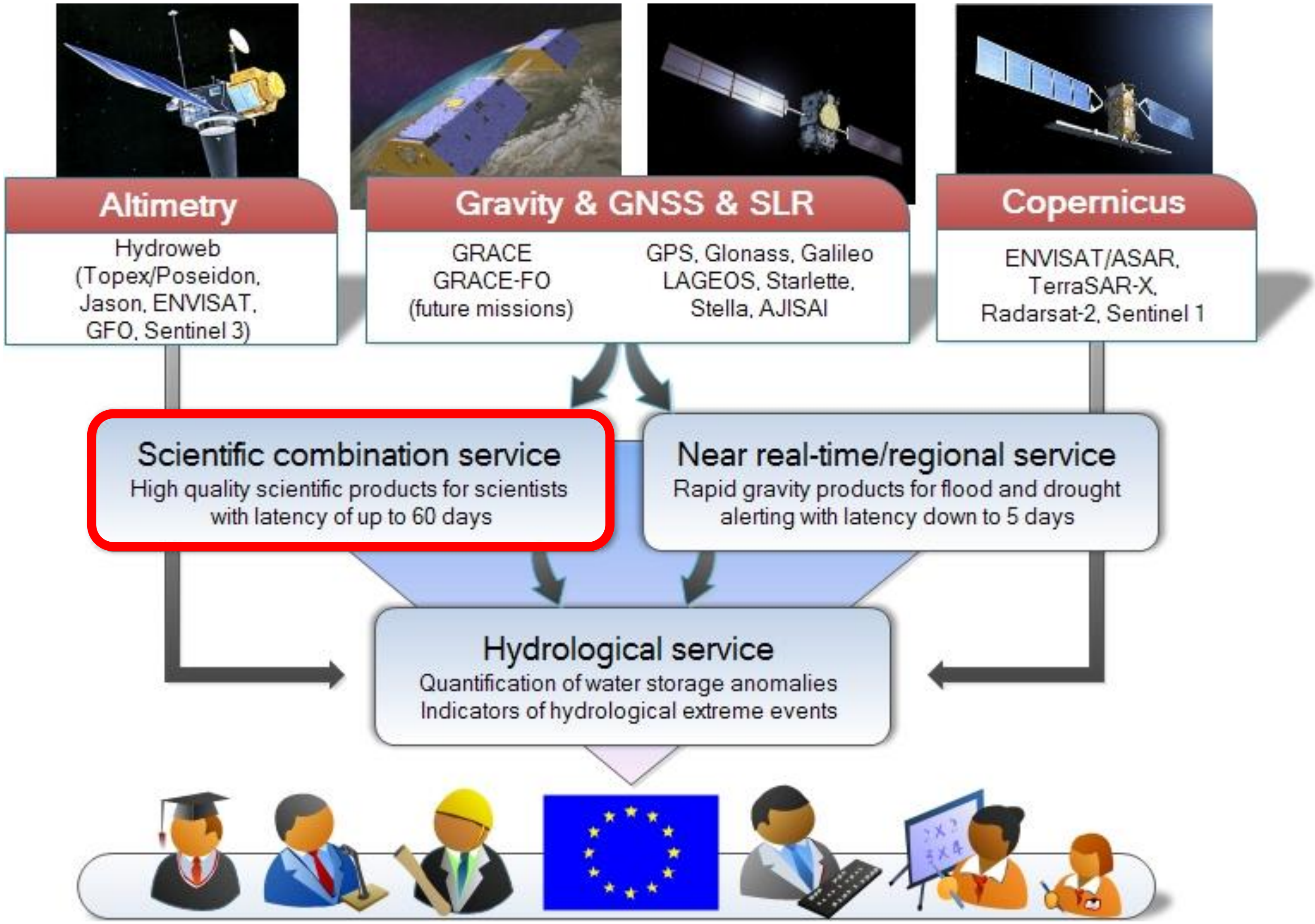
Anomalies over the oceans of EGSIEM monthly gravity models and combinations.



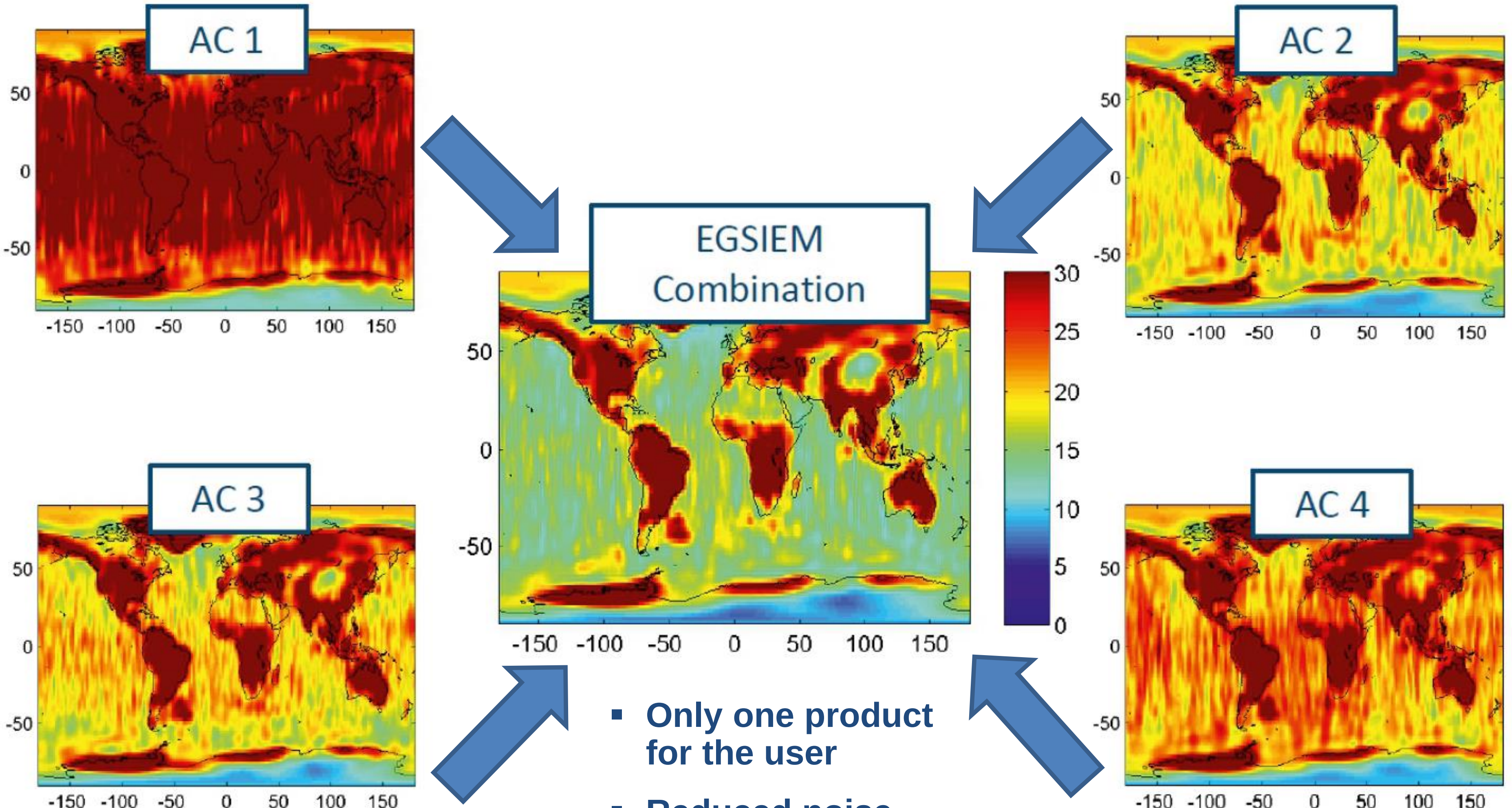
Degree amplitudes (up to order 29) of anomalies allow for a similar noise assessment in the spherical harmonic domain.

EGSIEM Scientific Combination Service

EGSIEM: Three Services



Scientific Combination Service



- **Only one product for the user**
- **Reduced noise**

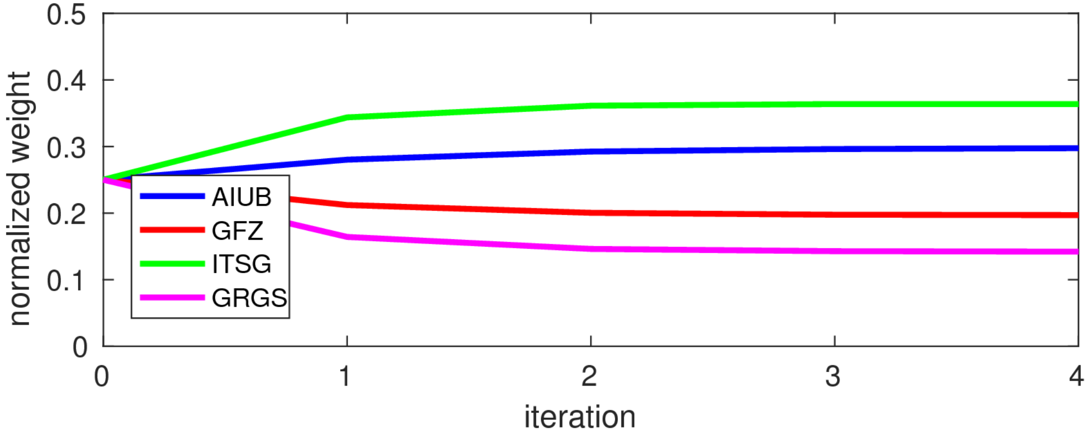
Combination Strategy

- First a careful screening of the individual contributions on solution level is performed, with the goal to guarantee comparable signal content and to identify cross outliers.

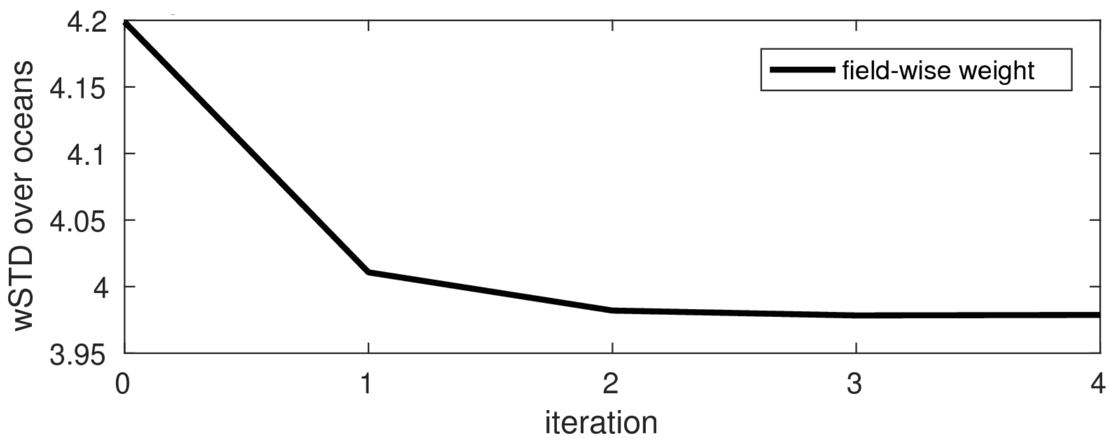
- Then a combination on solution level is computed, where relative weights are defined based on pair-wise comparison to the mean of all contributions and thus representing the different noise-levels.

- Finally the different ACs' contributions are combined on normal equation level applying the weights defined on solution level. The combination on normal equation level is conceptually superior to the combination on solution level because all correlations between the gravity field parameters and the pre-eliminated orbit parameters of the satellites are correctly taken into account.

Combination on Solution Level

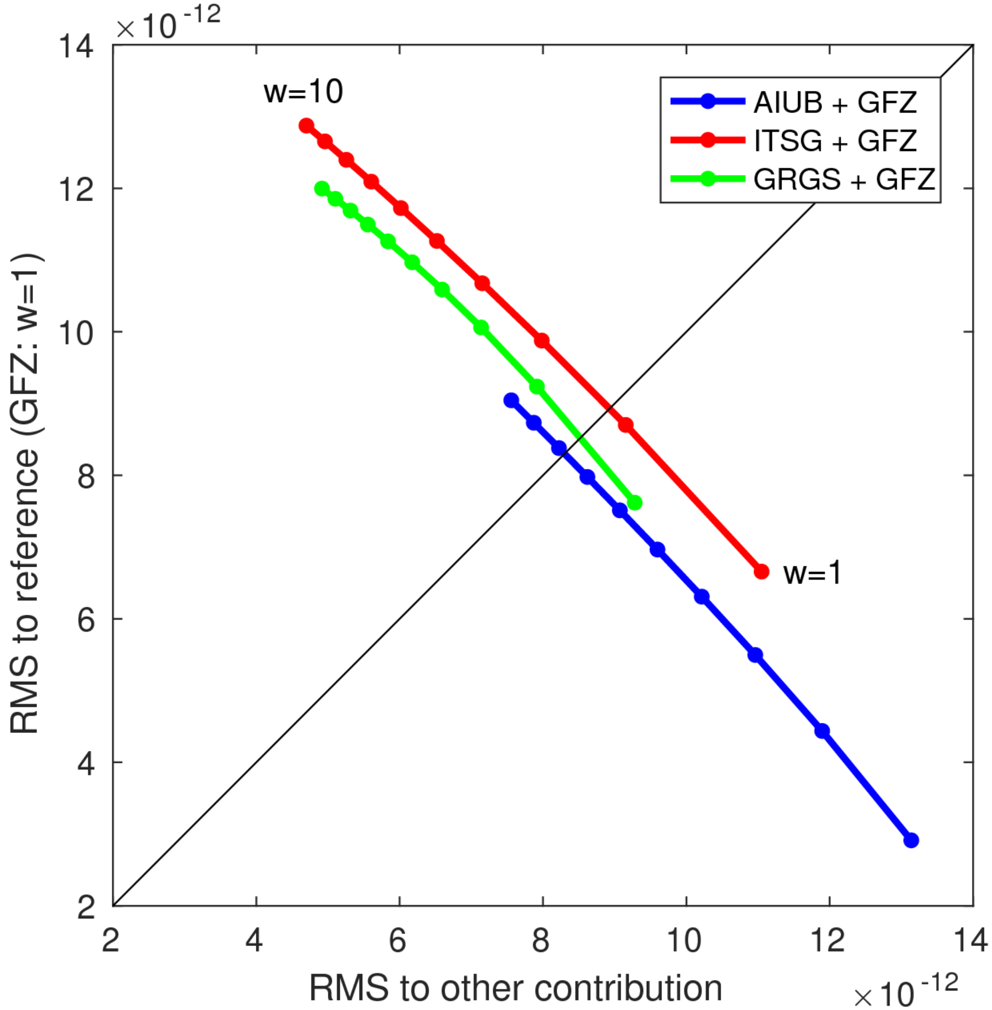


Relative weights are computed iteratively by variance component estimation. These weights represent the different noise levels of the individual contributions.



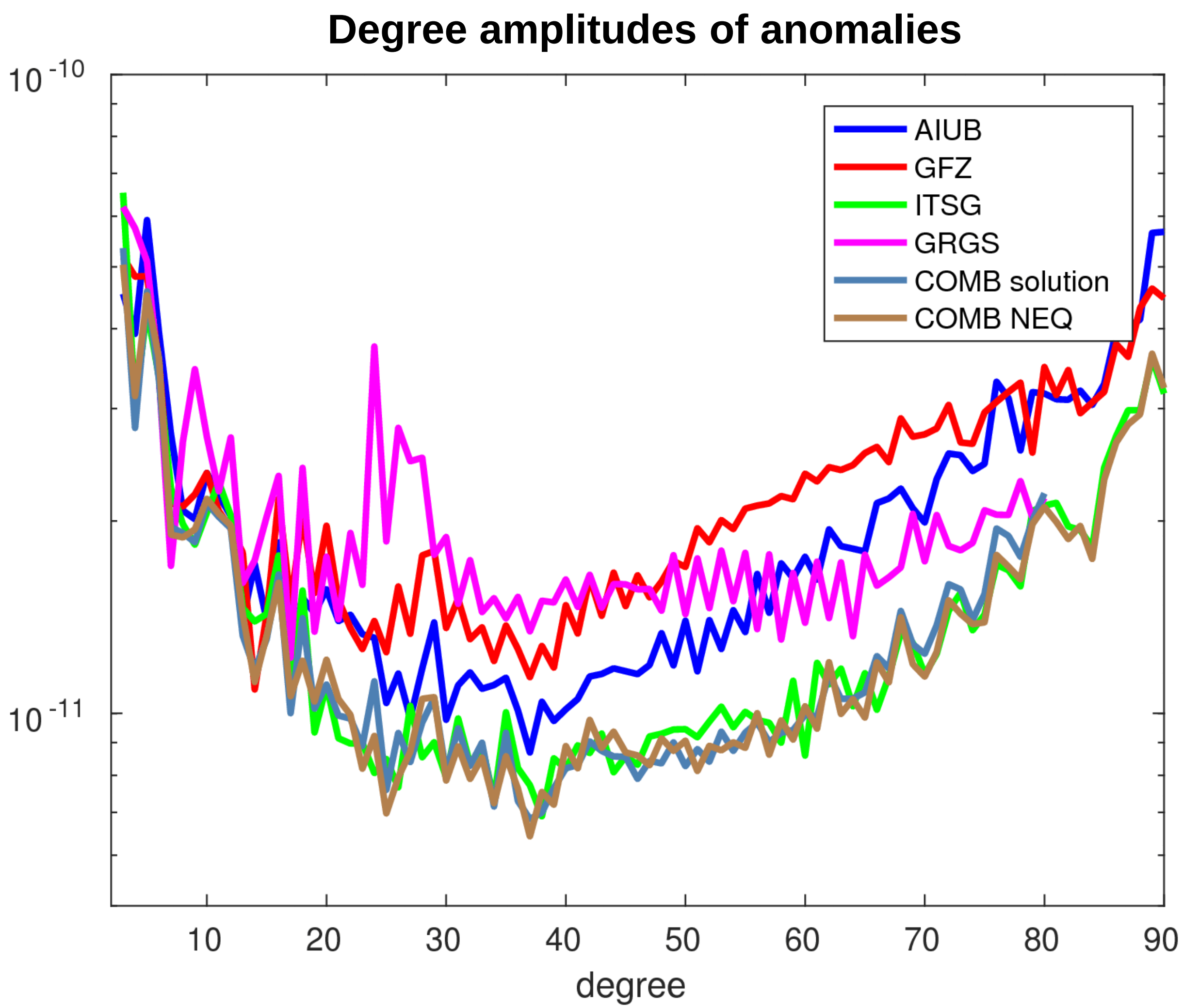
The STD of the anomalies over the ocean areas is used as independent quality criterion. Convergence usually is reached after 3-4 iterations.

Combination on Normal Equation Level



The weights defined on solution level are also applied to the normal equations. But first the intrinsic weights of the individual normal equations (due to different observation types, number of observations and noise models) have to be removed applying an empirical weighting scheme based on pair-wise combinations.

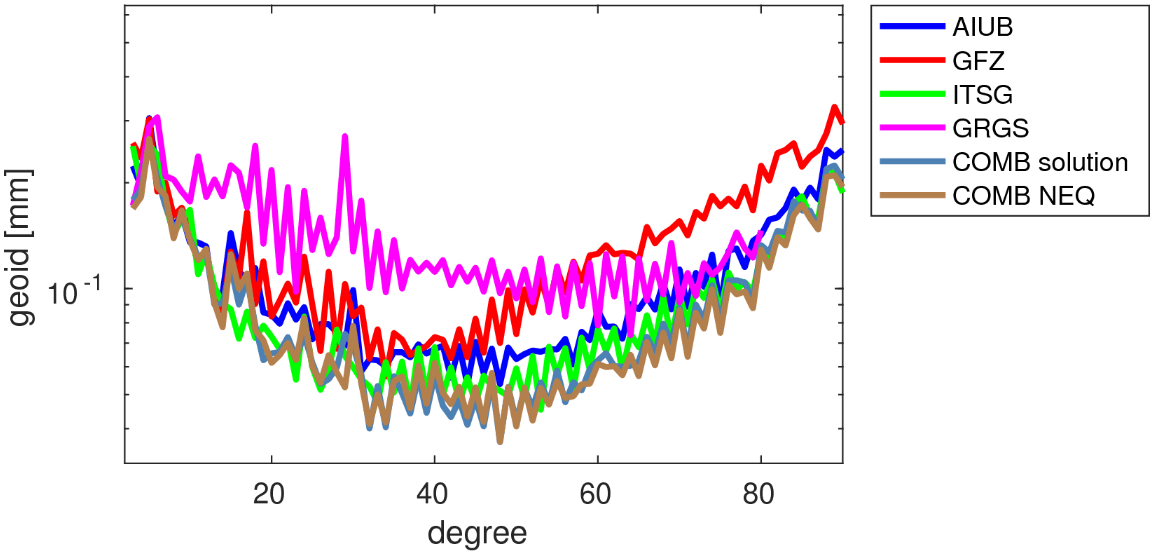
Combination: 2006/01



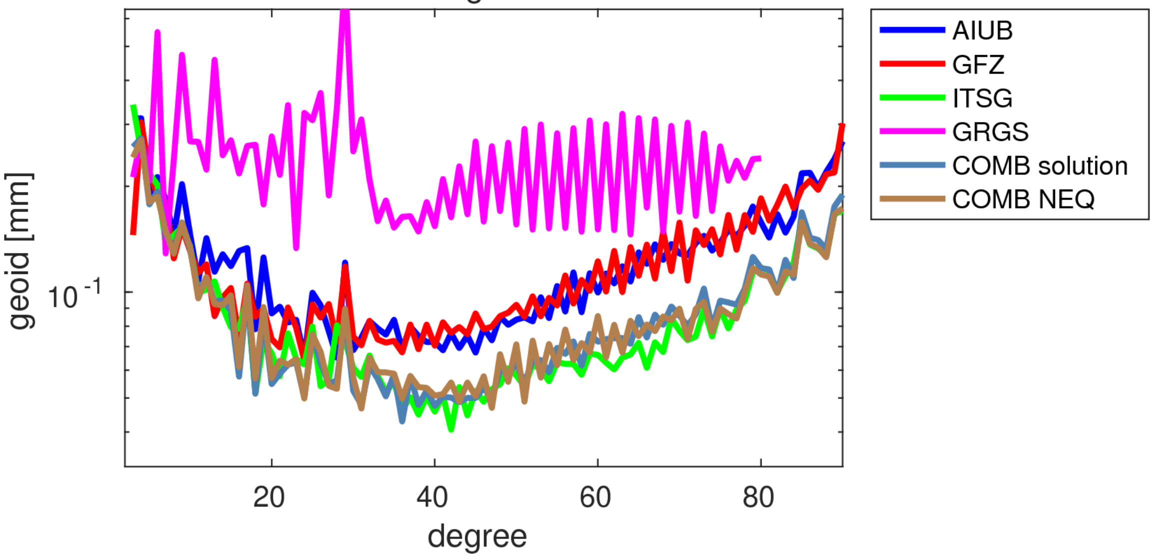
equalizing weight	
GRGS	1.60
GFZ	1.00
AIUB	7.81
ITSG	2.21

Solution:	weight
GRGS	0.14
GFZ	0.19
AIUB	0.29
ITSG	0.38

Combination results



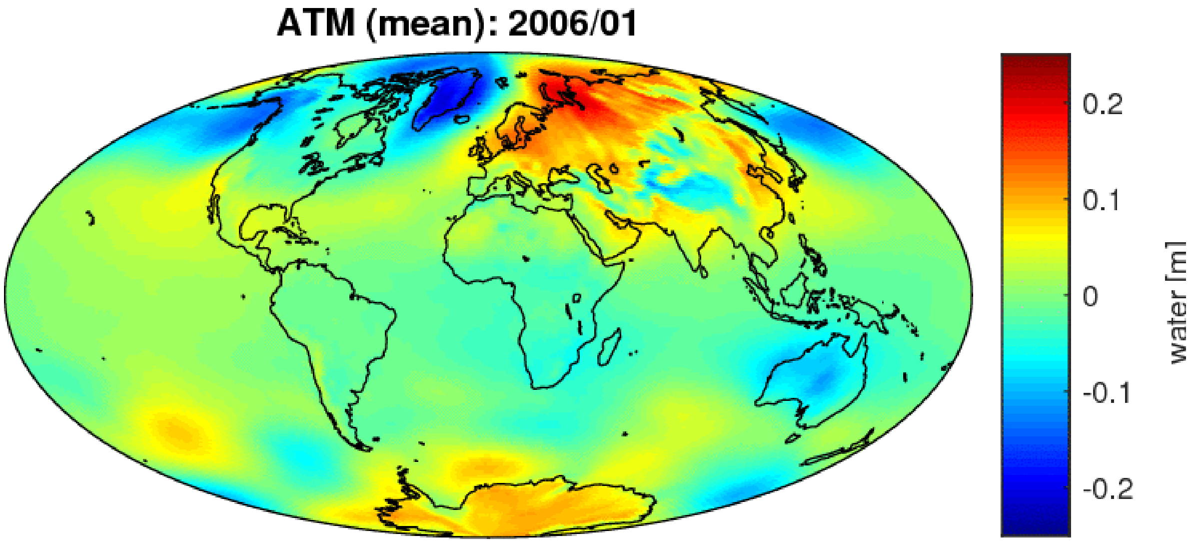
June 2006: in case of homogeneous quality among ACs both combinations outperform the best individual contribution.



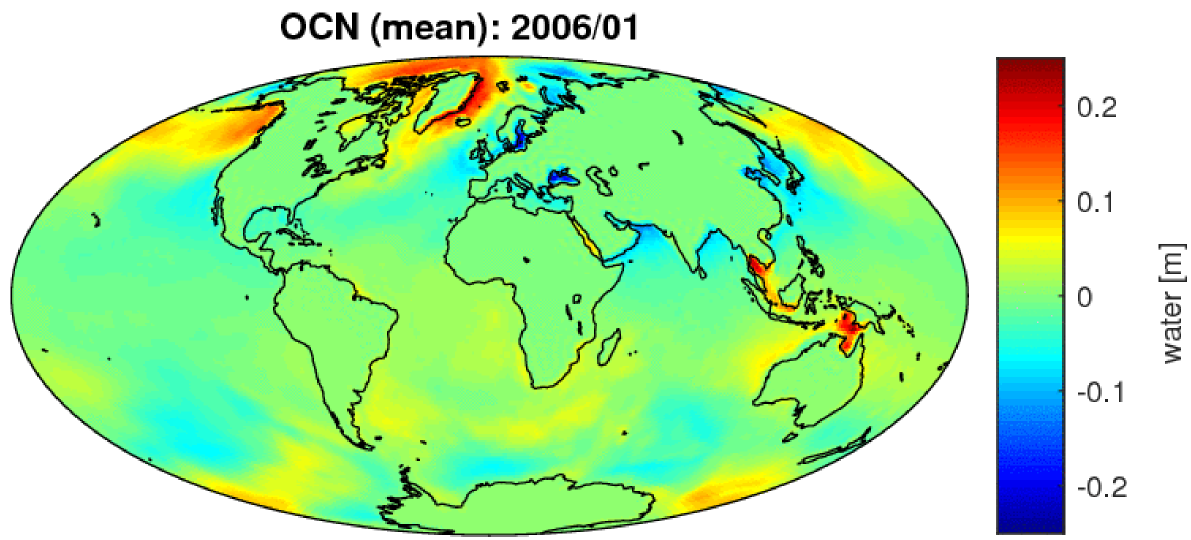
Oct. 2006: in case of cross outliers, screening of the individual contributions is necessary, otherwise the combinations are degraded.

Monthly mean of Dealiasing Products

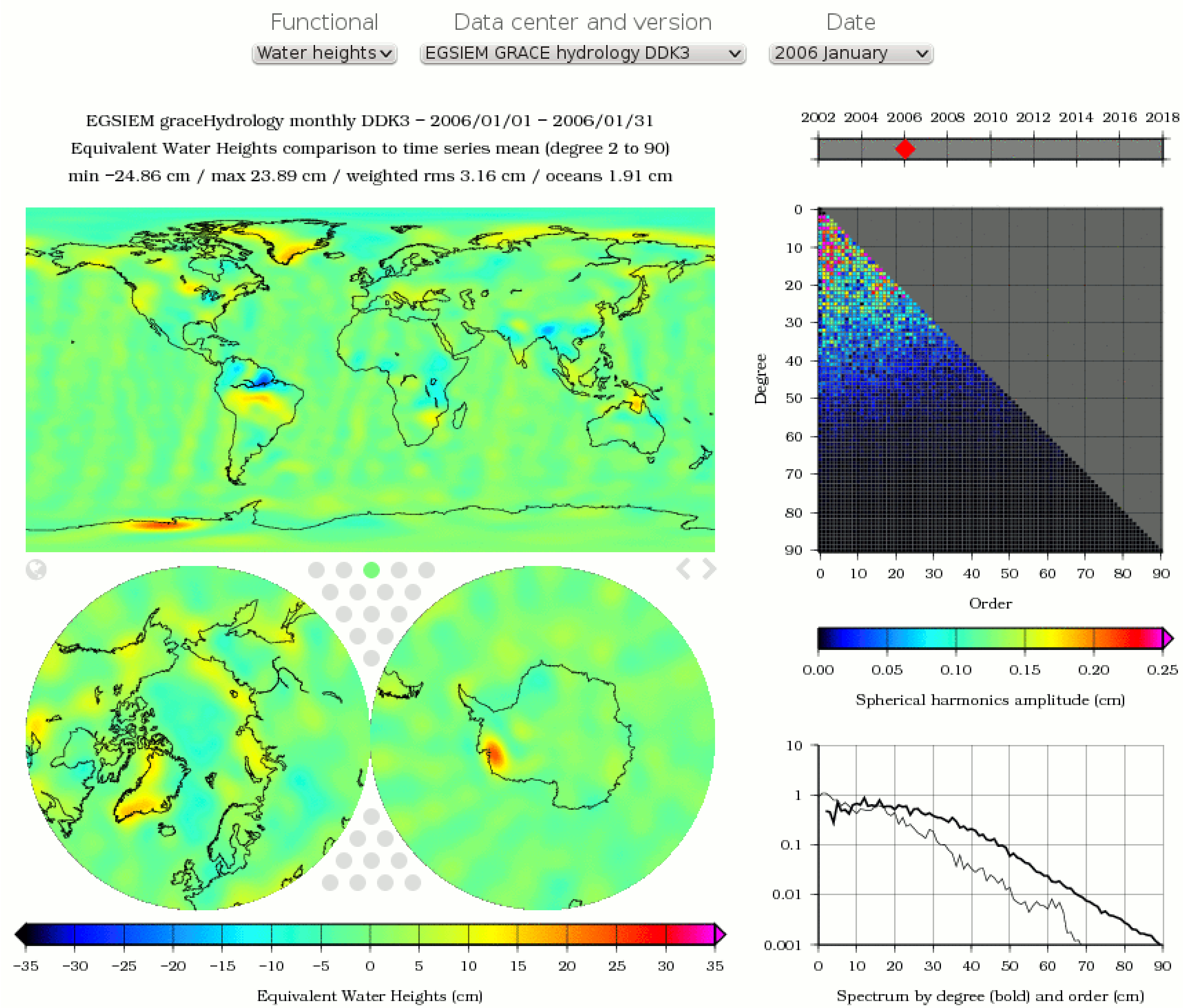
To restore full signal content the monthly means of the atmosphere and ocean de-aliasing products have to be restored.



Therefore the correspond-ing monthly means of the de-aliasing products applied by the different processing centers have to be combined using the same weights as for the gravity field combination.



L3-Products: www.egsiem.eu -> Data -> EGSIEM-Plotter



The combined monthly gravity models are transformed from spherical harmonics to user-friendly L3-products (post-processed grids) that can be visualized by the EGSIEM plotter and downloaded from www.egsiem.eu

In the frame of the EGSIEM project the two test years 2006 and 2007 were processed. More years (2004 until 2010) are under preparation.