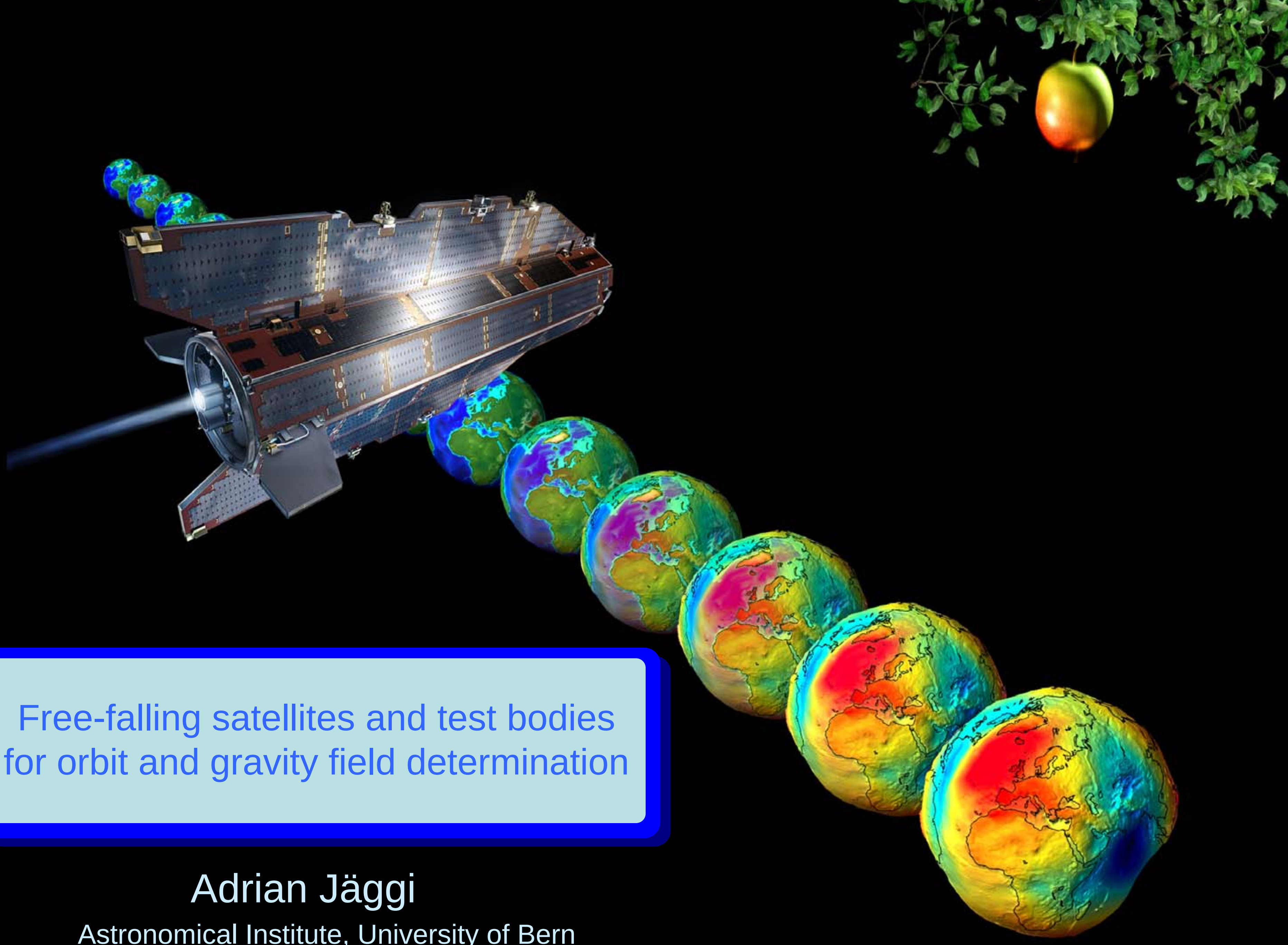

Free-falling satellites and test bodies for orbit and gravity field determination

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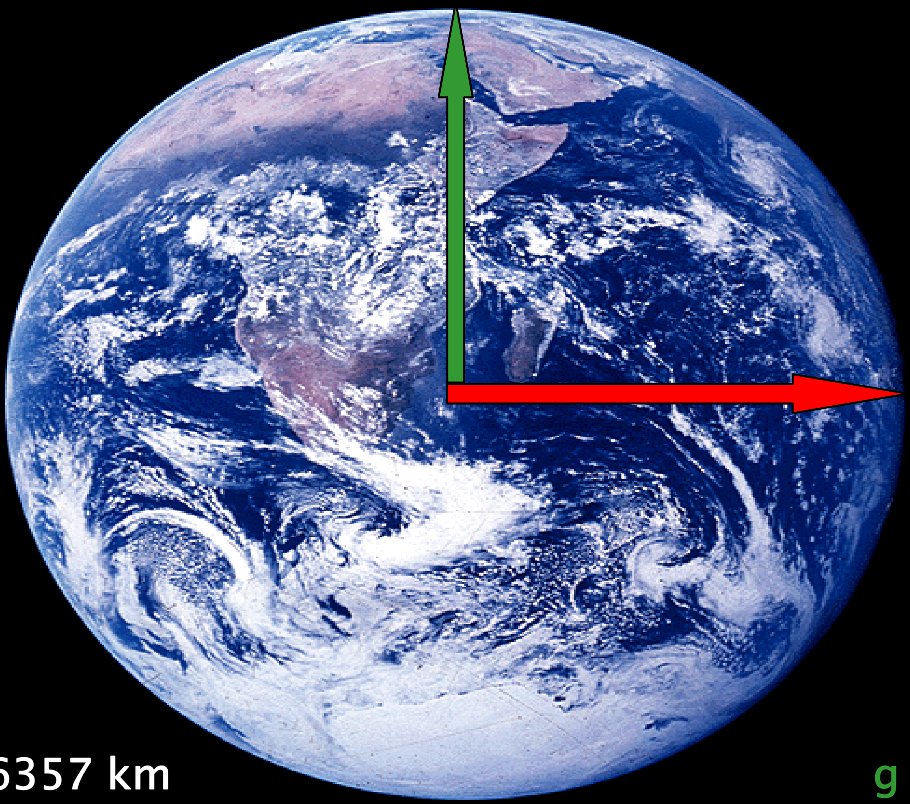
The shape of the Earth is spherical

Earth’s radius 6371 km

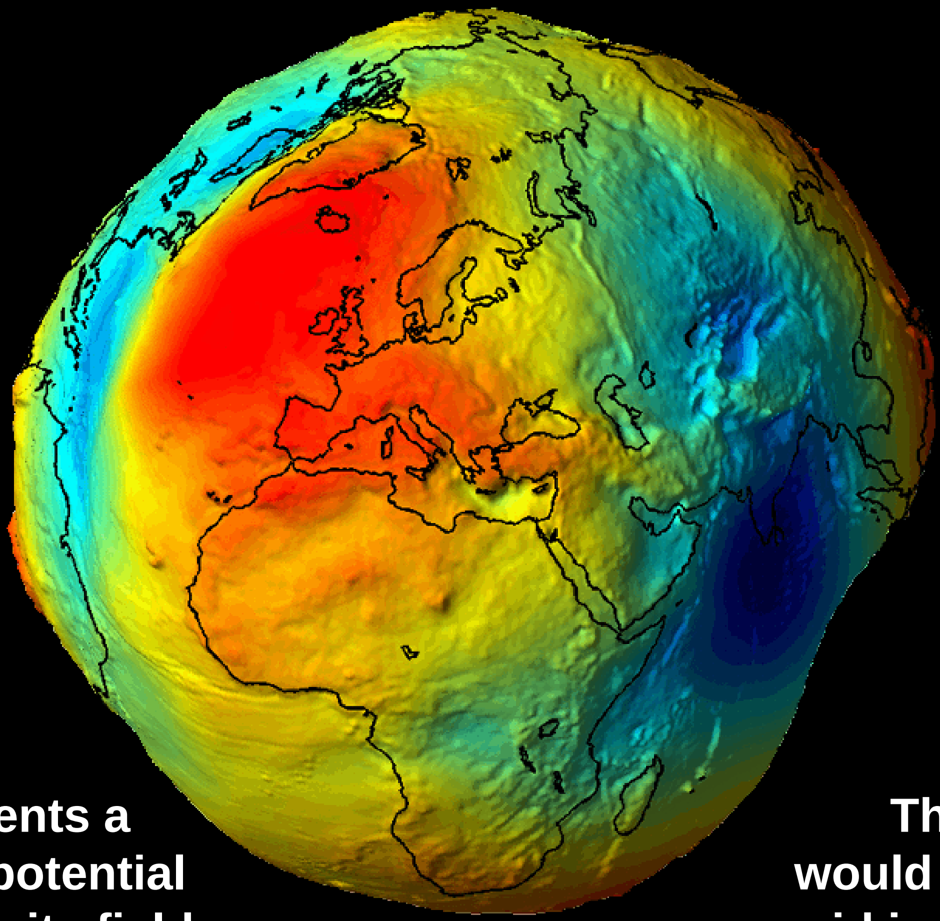
The shape of the Earth is oblate



Polar radius 6357 km
Equatorial radius 6378 km

g = 9.83 m/s^2
g = 9.78 m/s^2

The shape of the Earth is complicated

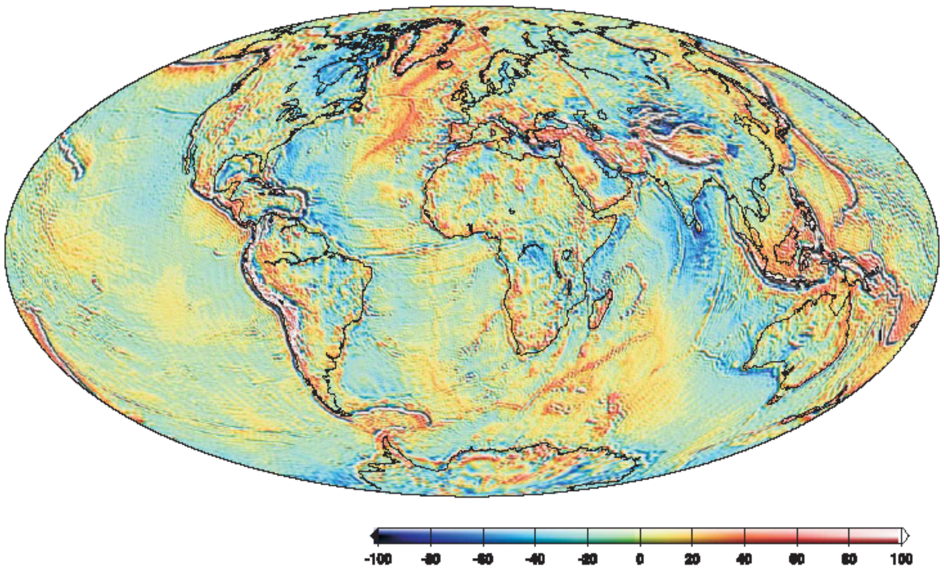


The geoid represents a surface of equal potential of the Earth's gravity field

The Earth's surface would coincide with the geoid in the case of being covered with an ocean at rest

The Earth's Gravity Field

$$V(r,\theta,\lambda) = \frac{GM}{R} \sum_{l=0}^{l_{\max}} \left(\frac{R}{r}\right)^{l+1} \sum_{m=0}^{l} \bar{P}_{lm}(\cos\theta) \cdot \left[\bar{C}_{lm} \cos(m\lambda) + \bar{S}_{lm} \sin(m\lambda) \right]$$



(Gravity Anomalies)

l_{max}	# of Coeff.	λ [km]
20	441	1000
100	10 201	200
200	40 401	100
250	63 001	80

λ … spatial (half) wavelength

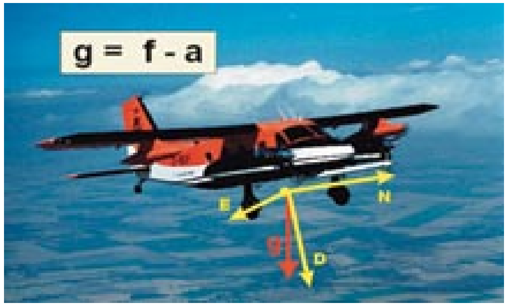
Gravity Anomalies **are differences between gravitational accelerations on the geoid and gravitational accelerations on the ellipsoid**

Measurement Techniques

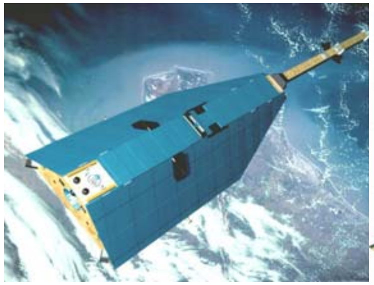
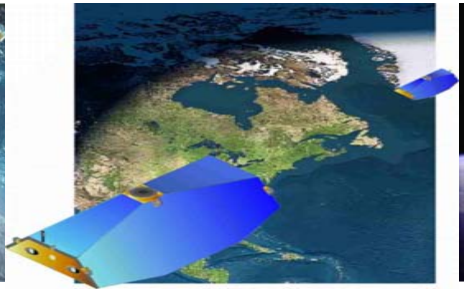
- **Terrestrial Measurements**



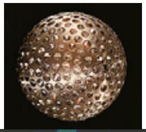
- **Airborne-, Shipborne- Measurements**



- **Satellite Data**


Classical Gravity Field Determination

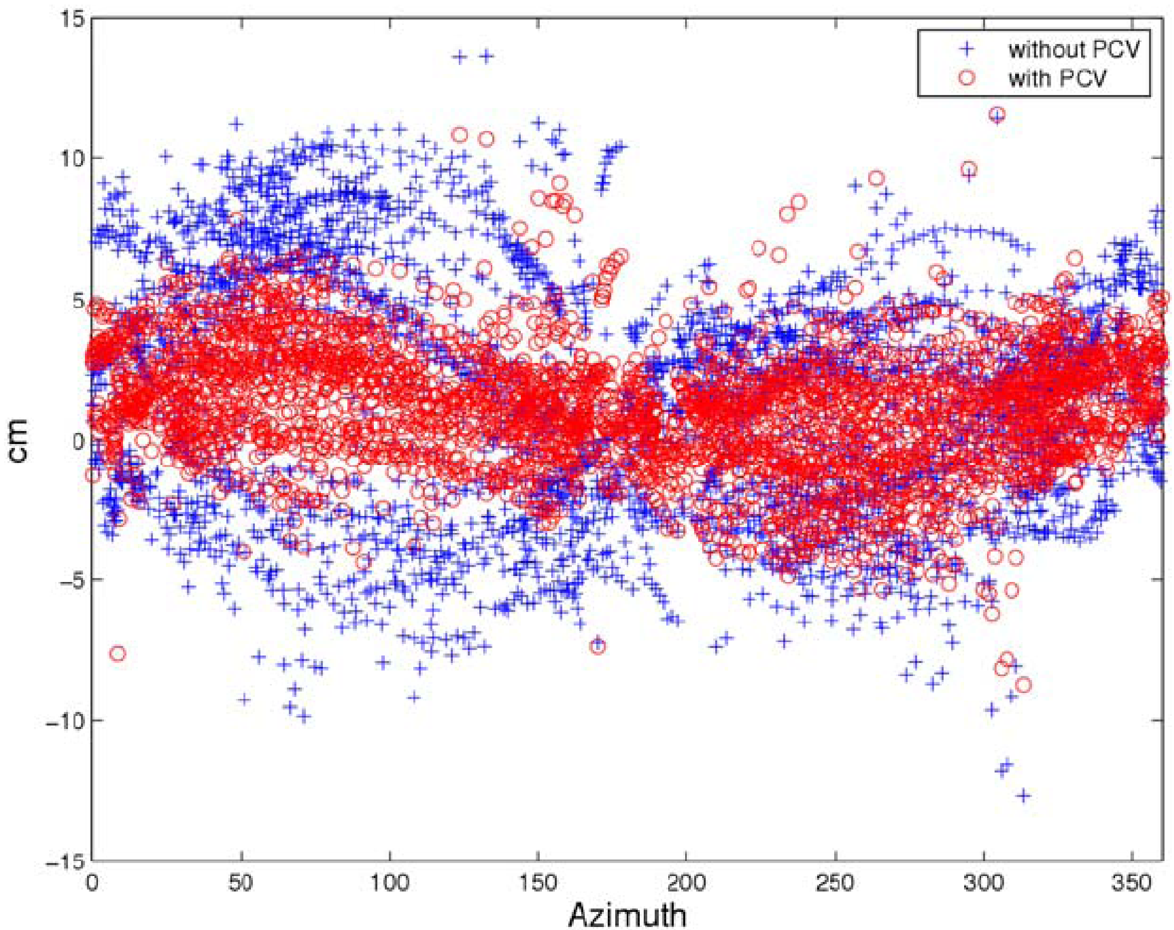


Satellite Laser Ranging (SLR)

- Distances between satellites and dedicated observatories are derived with cm-accuracy by measuring the round-trip time of flight of short laser pulses sent to the satellites and reflected back to the observatories
- SLR measurements collected over decades to satellites with different orbital character-istics allow to derive the low degree gravity field coefficients

This method was successfully used for gravity field determination for decades. The results are, however, limited as the satellites cannot be continuously observed by the satellite laser ranging technique

Orbit Validation with SLR (GOCE)



SLR measurements are perfectly well suited to independently validate and calibrate orbit solutions derived from other measurements, e.g., from GPS data

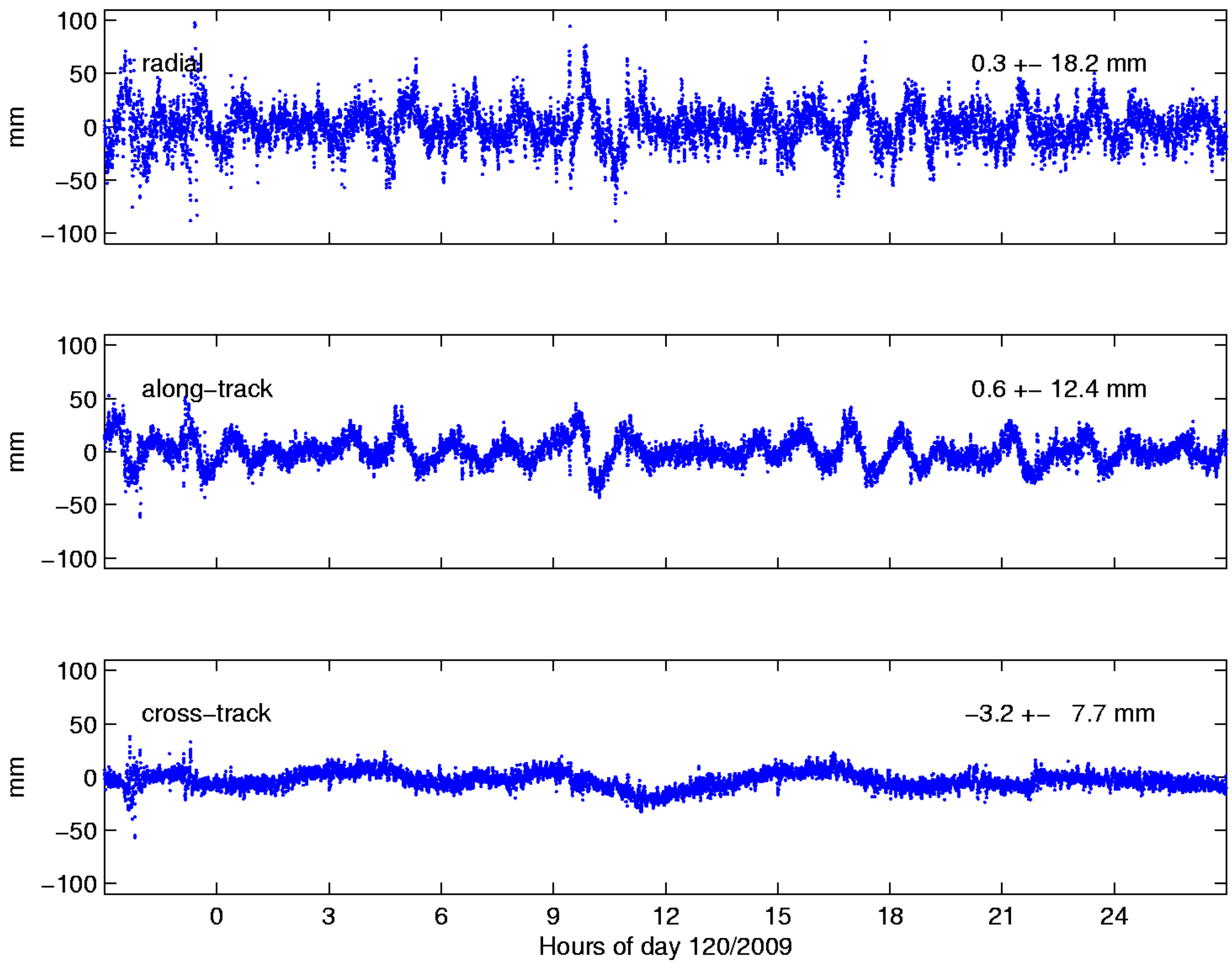
Modern Gravity Field Determination

Global Positioning System (GPS)

- GPS significantly contributes to the realization of the terrestrial reference frame, to modern surveying, and to a variety of geophysical research
- Positions of permanent GPS stations are nowadays determined with a few millimeter accuracies
- It was only a question of time until low Earth orbiting satellites were also equipped with GPS antennas to continuously determine their orbits with unprecedented accuracy

GPS antennas on-board low Earth orbiting satellites nowadays belong to the standard equipment since the three-dimensional satellite positions may be determined with cm-accuracy at high temporal resolutions

Typical Orbit Results (GOCE)

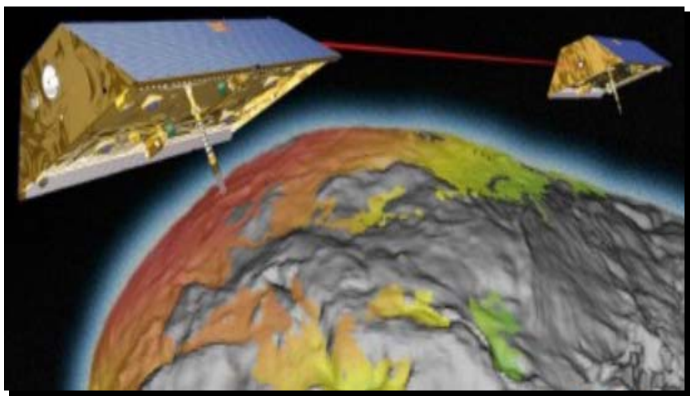


Shown are the differences between so-called „kinematic“ and „reduced-dynamic“ orbits

Current Gravity Field Missions

CHAMP (2000)

CHAllenging
Minisatellit
Payload



GRACE (2002)

Gravity
Recovery
And
Climate
Experiment

GOCE (2009)

Gravity Field & Steady-state
Ocean
Circulation
Explorer

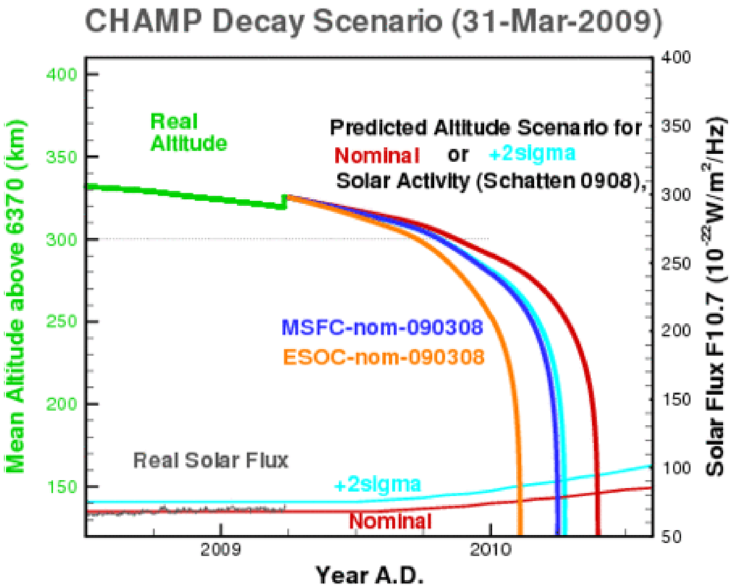
The CHAMP Satellite

Satellite Orbit

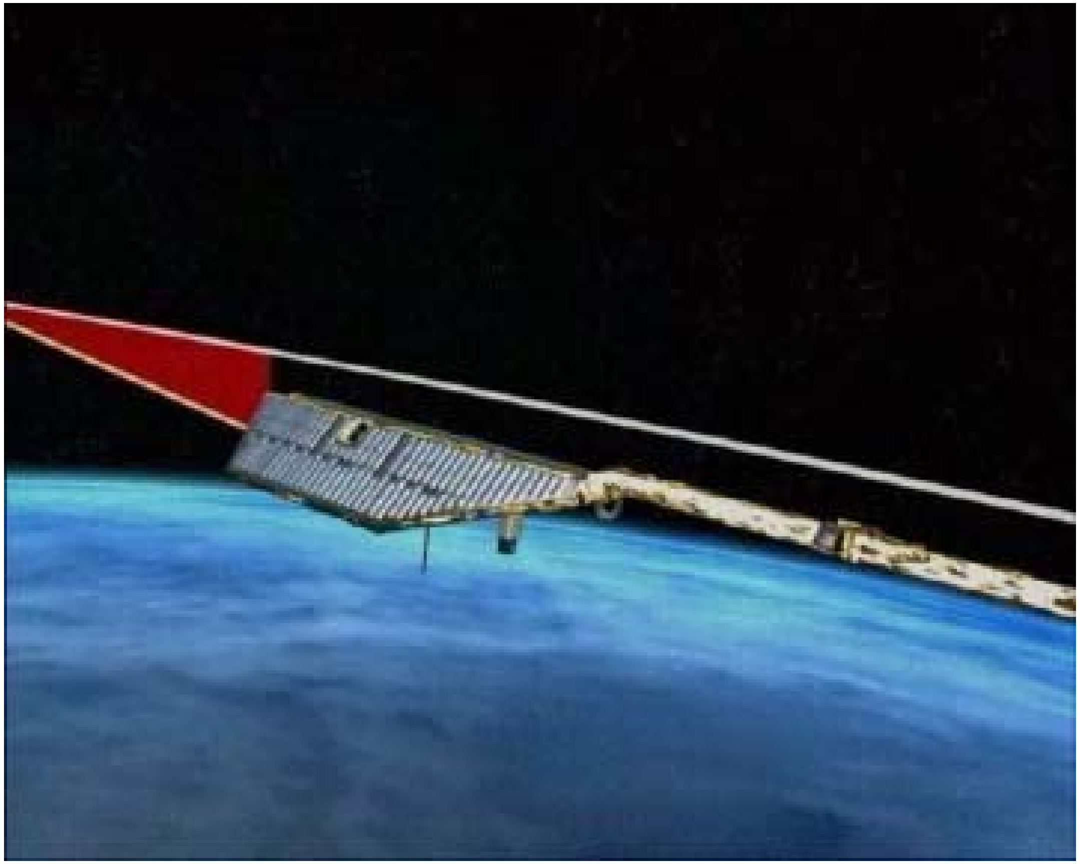
- Launch: 15. July 2000
- Inclination: 87°
- Initial altitude: 454 km; today: < 300 km

Mission Goals

- Global models of the gravity field up to about degree 70
- Global models of the magnetic field
- Atmosphere sounding

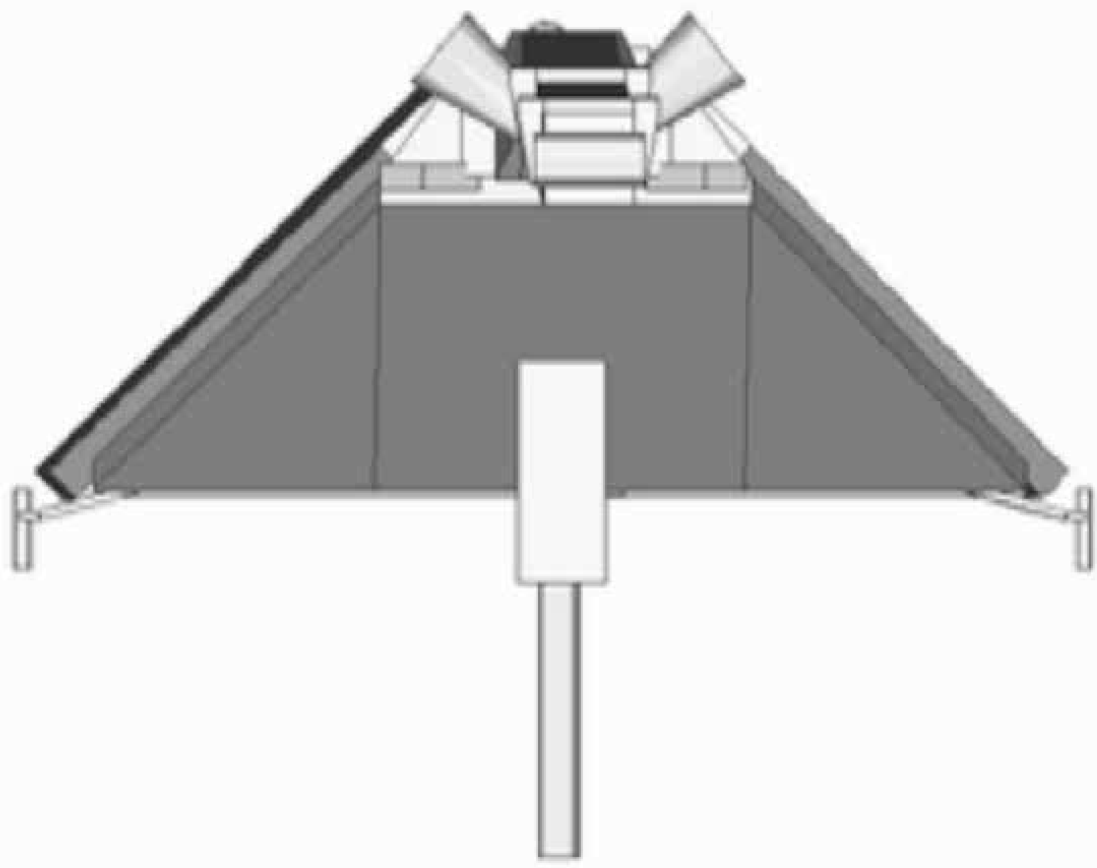


The CHAMP Satellite



The differences between the true orbit (determined by GPS) and the reference orbit (based on known models) contain (among others) information to improve the models of the Earth‘s gravity field

Some small complications …



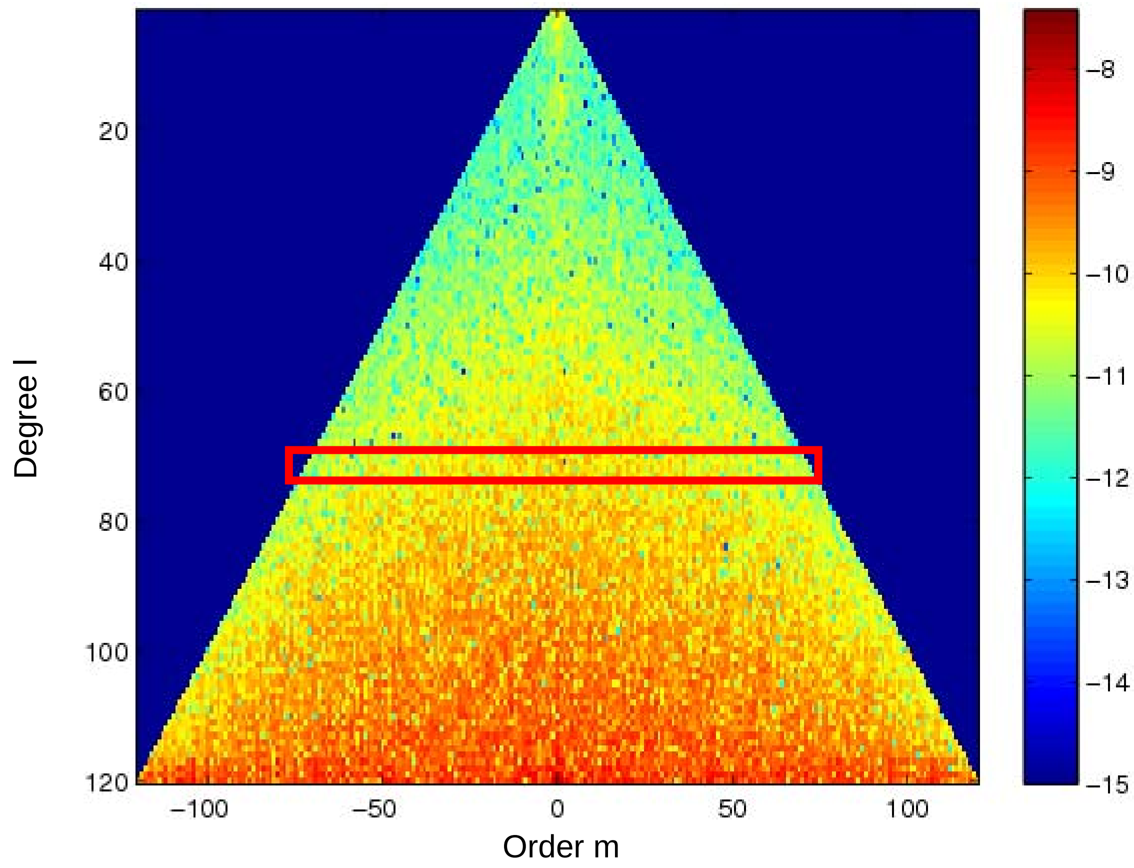
Accelerations acting on CHAMP

Source	**Acceleration** (m/s^2)
Central term of Earth's gravity	8.42
Oblateness of the Earth	0.015
Air-drag in the upper atmosphere	0.00000079
Further terms of Earth's gravity	0.00025
Gravitational attraction by the Moon	0.0000054
Gravitational attraction by the Sun	0.0000005
Direct radiation pressure of the Sun	0.000000097
.	.

Based on the GPS-derived orbits, the Earth's gravitational accelerations have to be separated in order to derive the coefficients of the Earth's gravity field

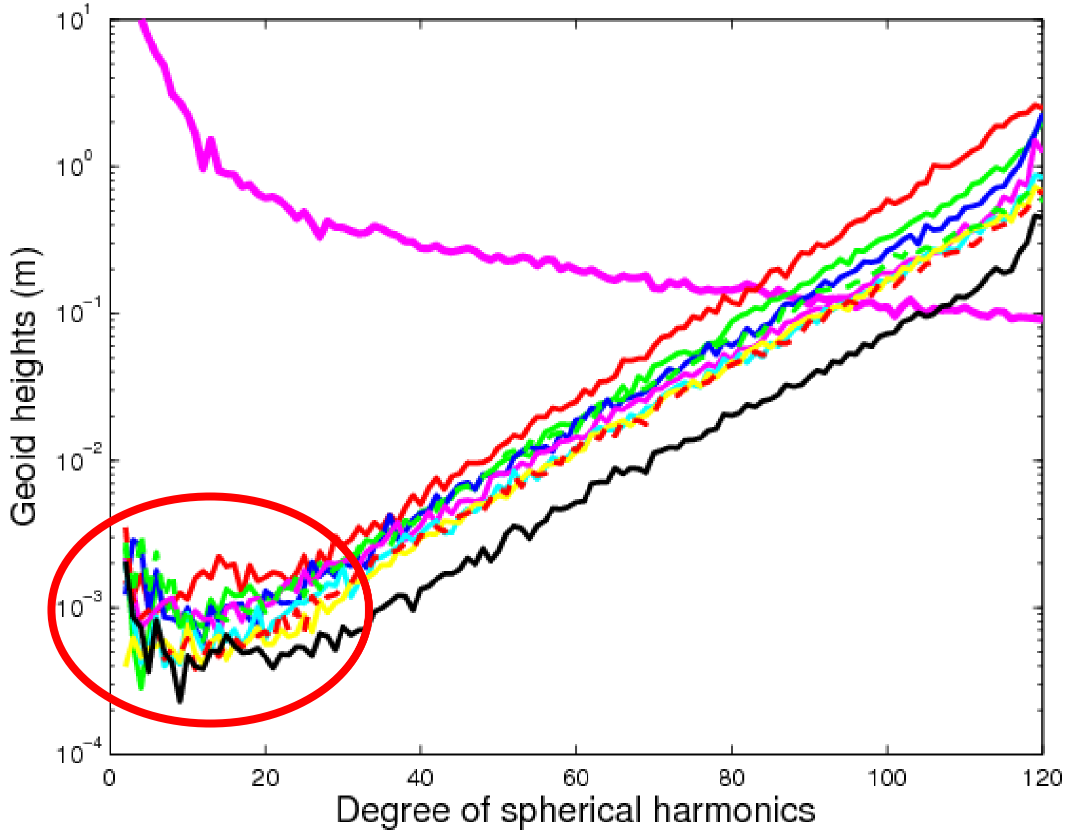
The other accelerations have either to be measured onboard the satellite, or they have to be described by external models

Most recent CHAMP results



Coefficient differences to another (superior) solution

Most recent CHAMP results



Reference field:

ITG-GRACE03S

Differences:

Year 2002

Year 2003

Year 2004

Year 2005

Year 2006

Year 2007

Year 2008

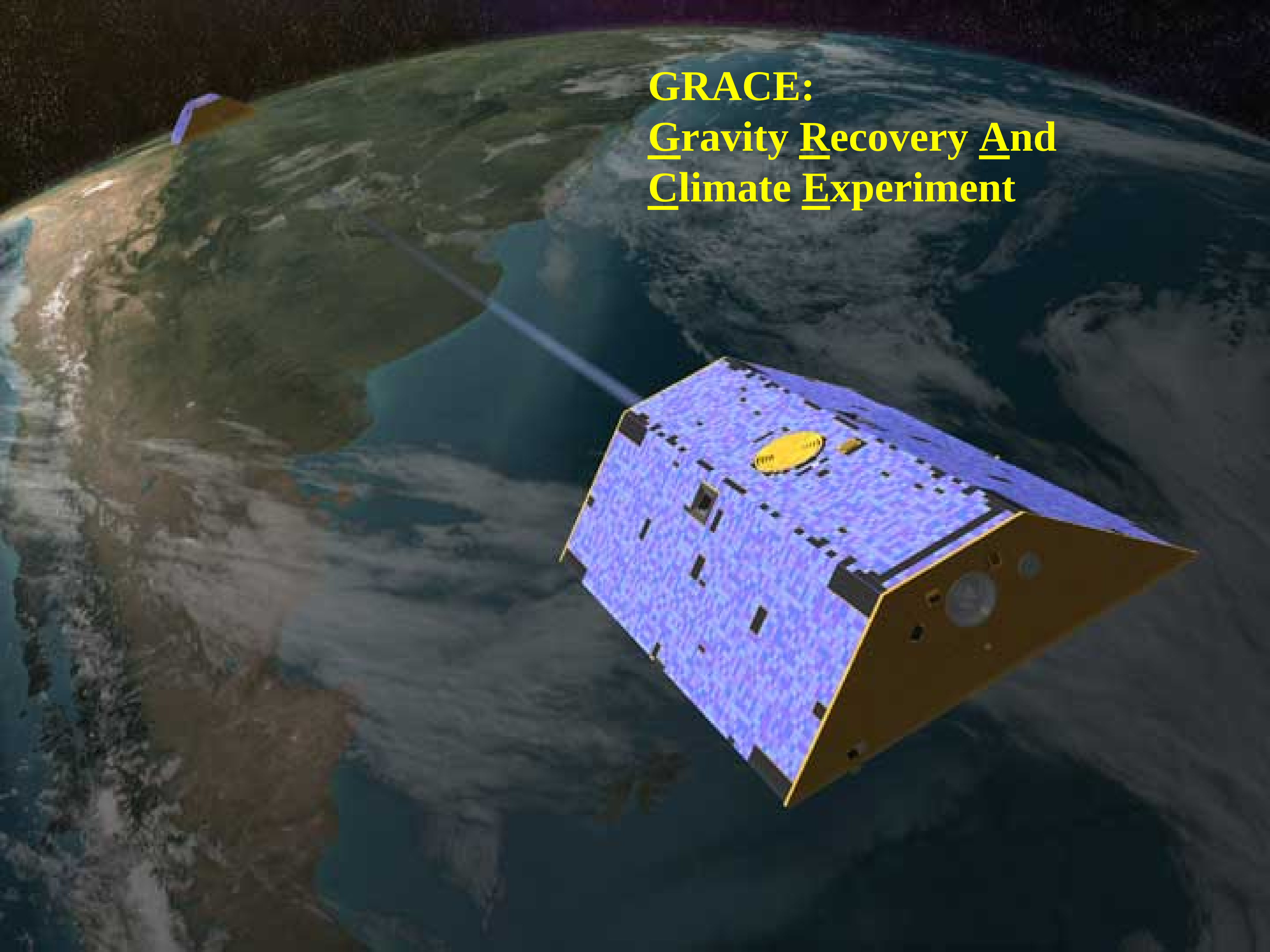
Year 2009

Combination:

8-year solution

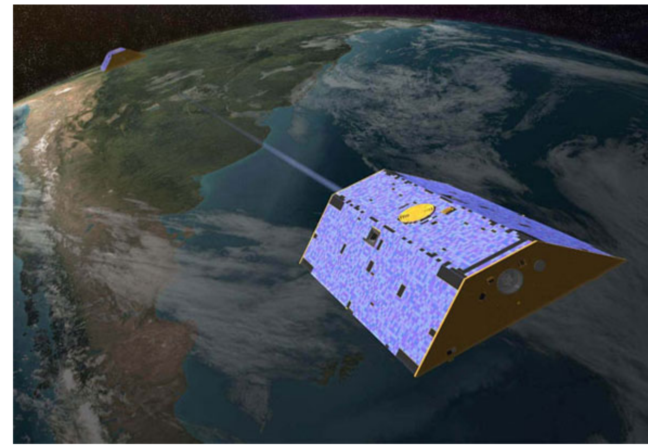
Low degree terms are of prime interest for CHAMP

GRACE:
Gravity Recovery And Climate Experiment



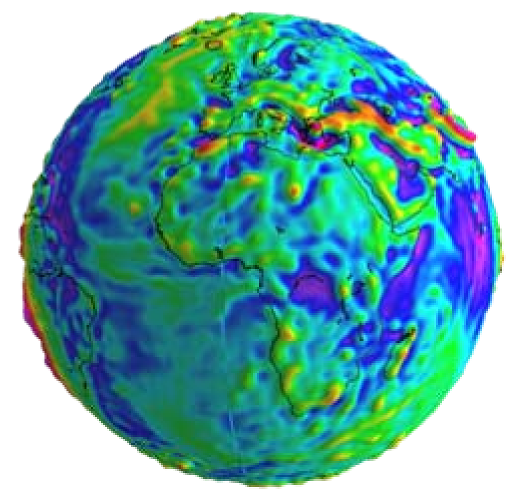
The GRACE Twin Satellites

Satellite Orbits



- Launch: 17. March 2002
- Inclination: 89°
- Initial Altitude: 485 km; today: 470 km
- Distance between the satellites: 220 km

Mission Goals

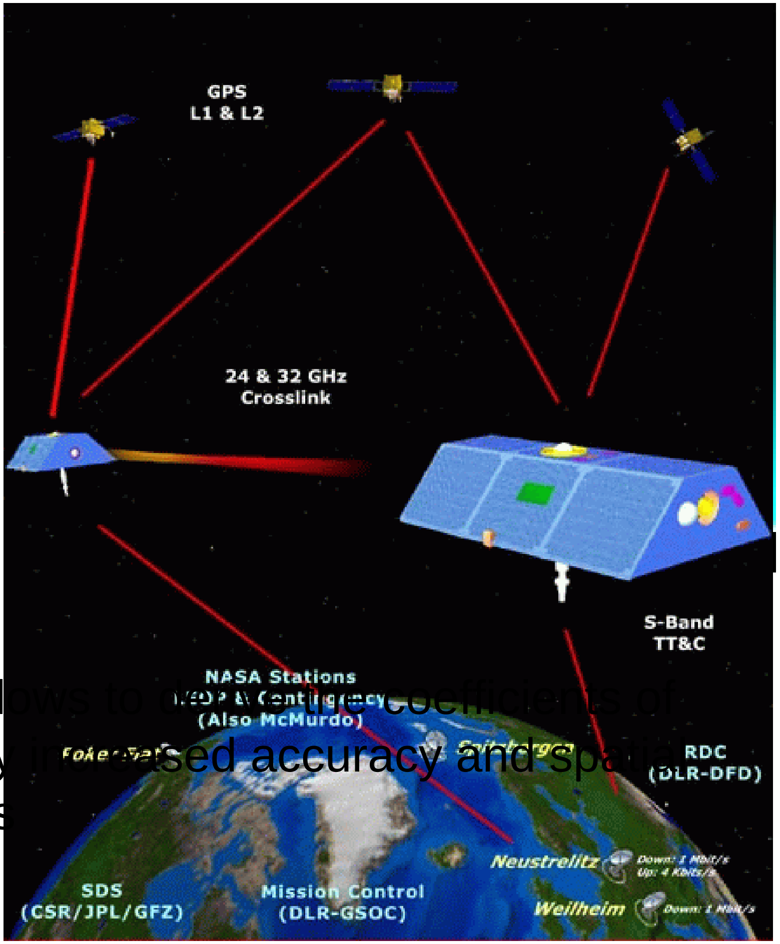


- Global models of the gravity field up to about degree 150
- Temporal variations of the gravity field (hydrology, ice masses, …)
- Atmosphere sounding

The GRACE Twin Satellites

Measurement principle

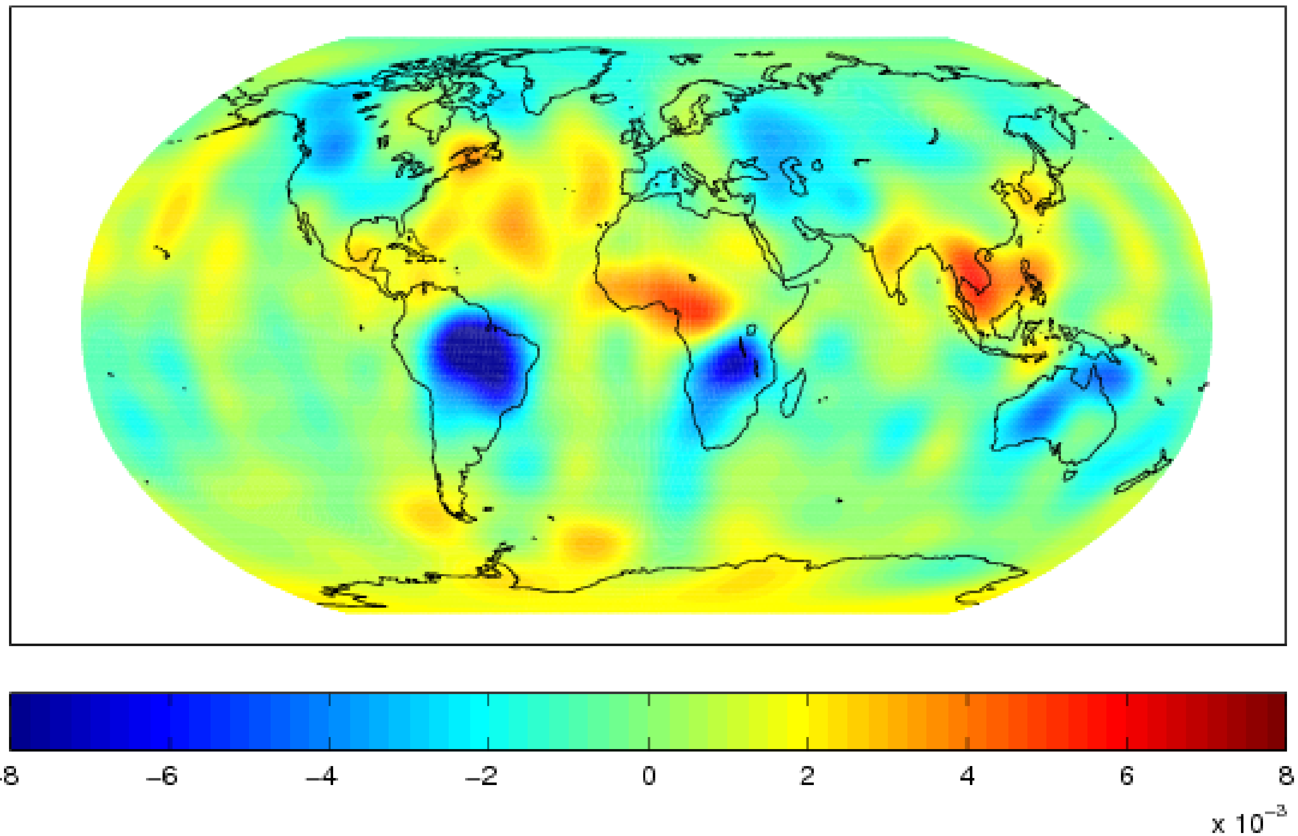
- The distance variations between both satellites are measured with micrometer-accuracy using a microwave crosslink
- In analogy to CHAMP, the GRACE satellite positions are determined by GPS in an absolute sense with an accuracy of a few centimeters
- Combining both measurement types allows to determine coefficients of the Earth‘s gravity field with significantly increased accuracy and spatial resolution than from GPS-only solutions



Main advantage

Short data spans of one month are already sufficient to derive solutions of respectable quality, which opens the door to solve for time-variability

Time-variable gravity from GRACE

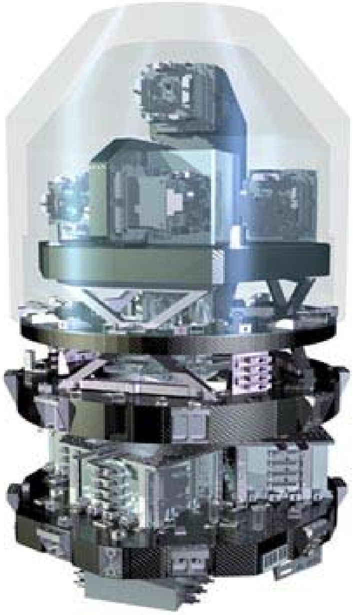


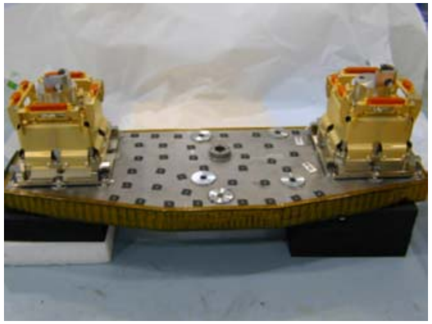
Strong signals of time-variable gravity are mainly observed over large river basins of the world, e.g., over the amazon basin, and mainly reflect the hydrological cycle

The GOCE Satellite

Satellite Orbit

- Launch: 17. March 2009
- Inclination: 96.5°
- Initial altitude: 283 km; today: 255 km

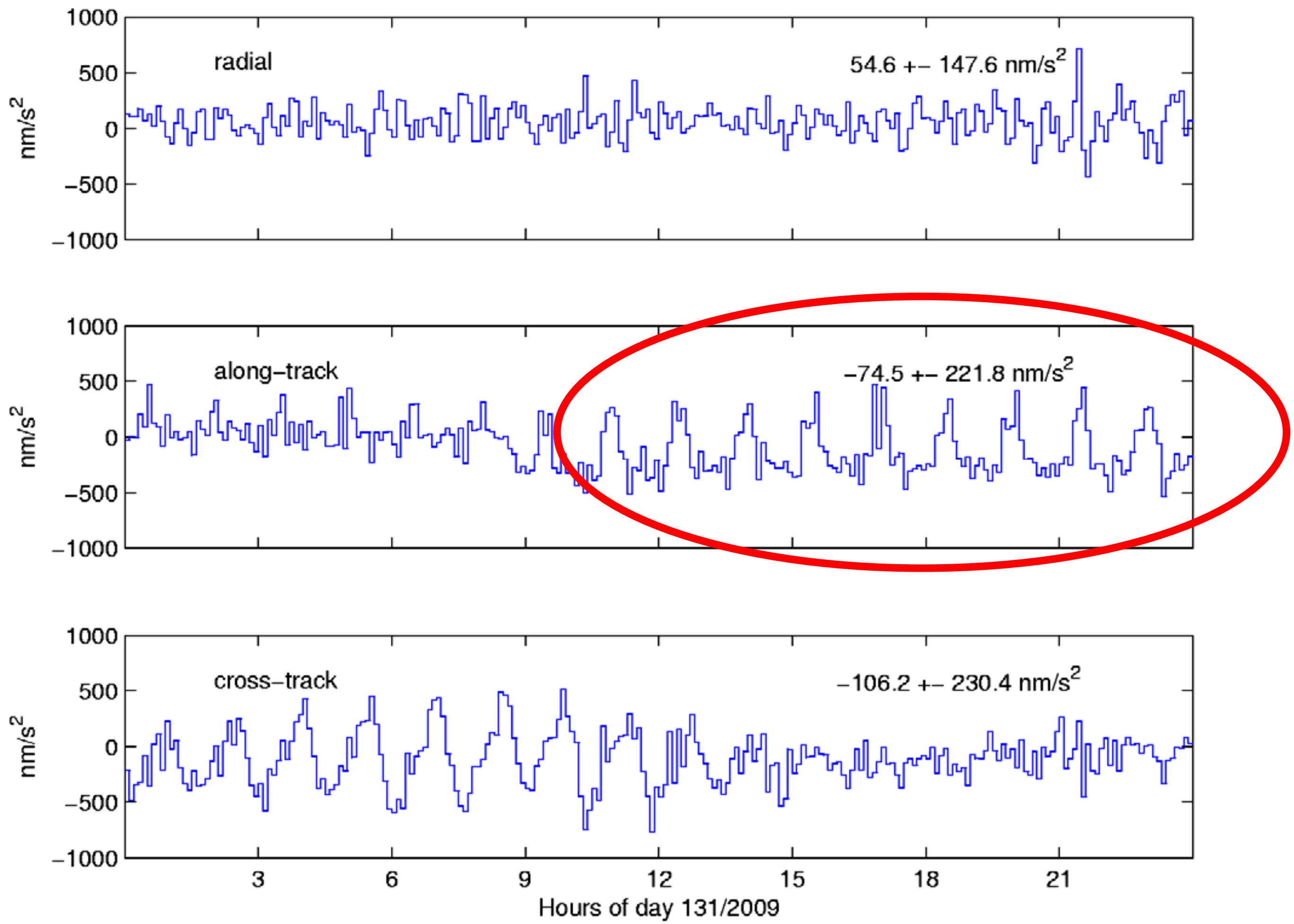




Innovations

- Gradiometer (used for the first time)
- Extremely low altitude
- Active compensation of air-drag

Estimated Accelerations

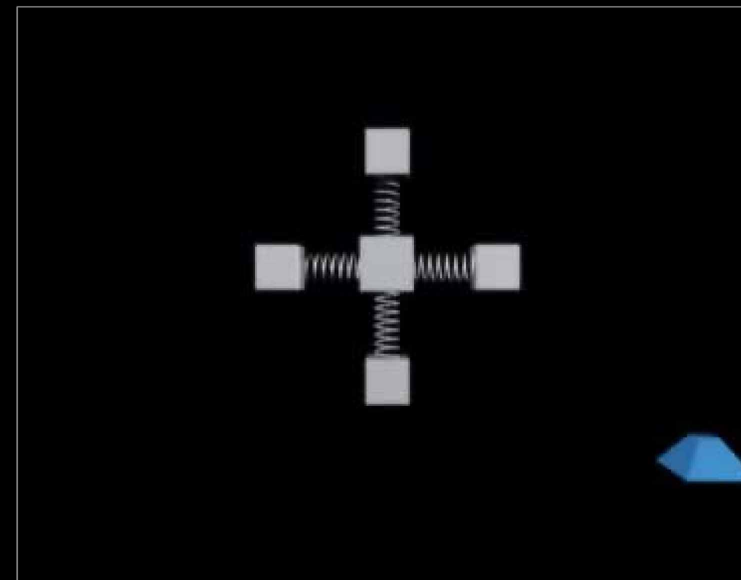


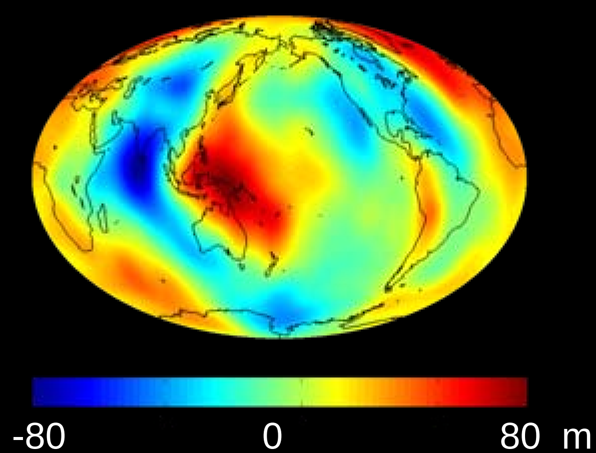
First drag-free flight on 7. May, 2009

The GOCE Satellite

GPS Data

Gradiometer Data





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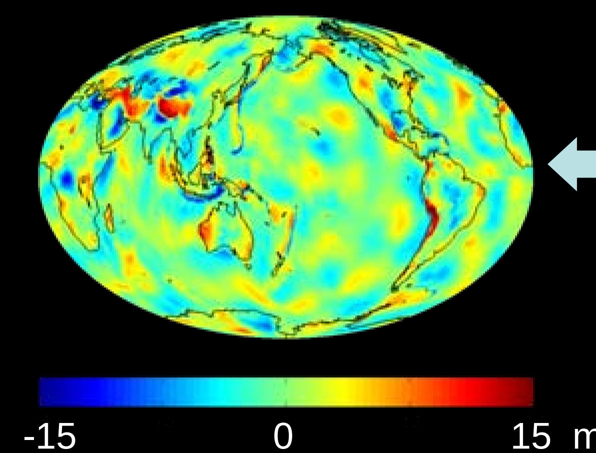
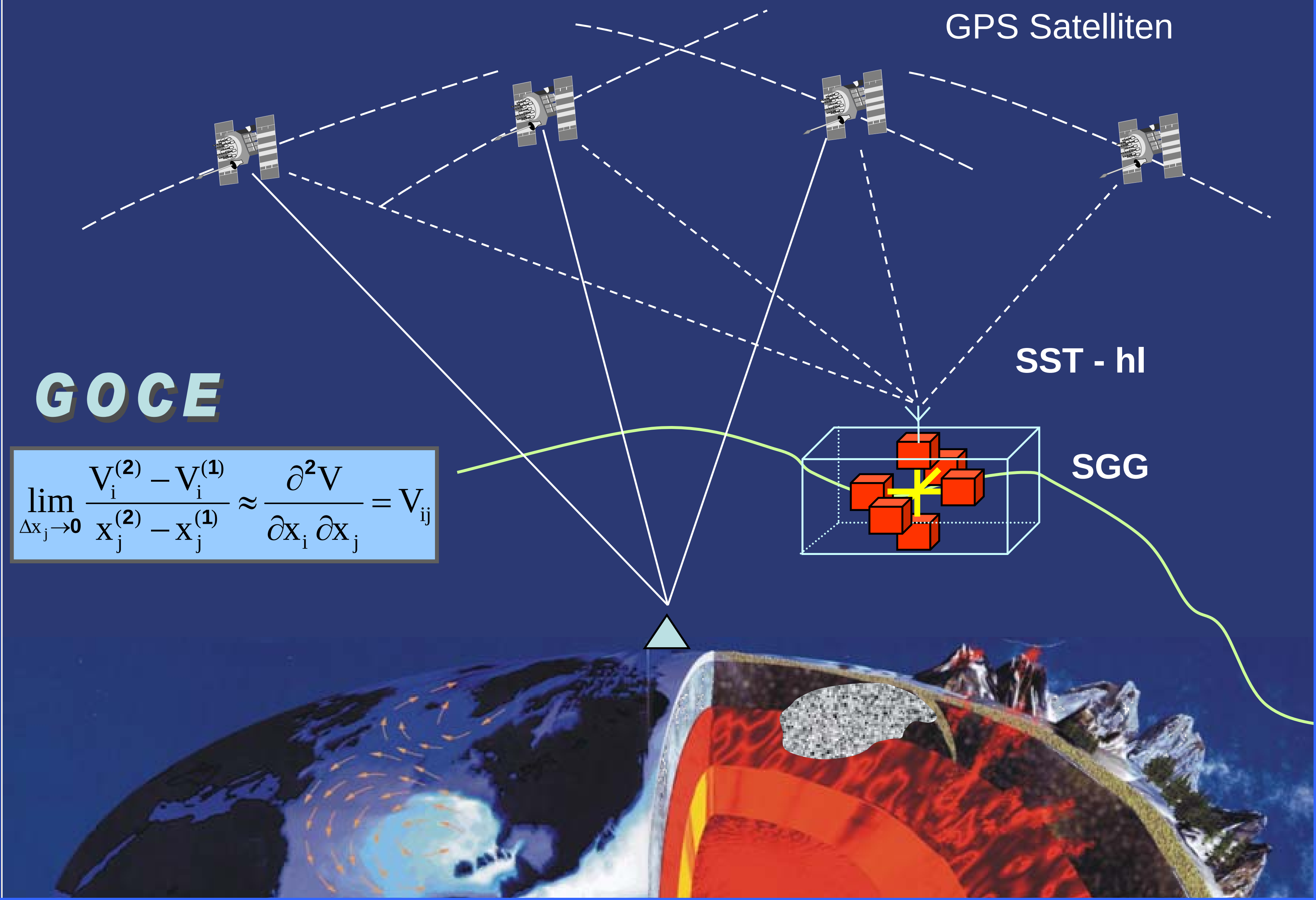


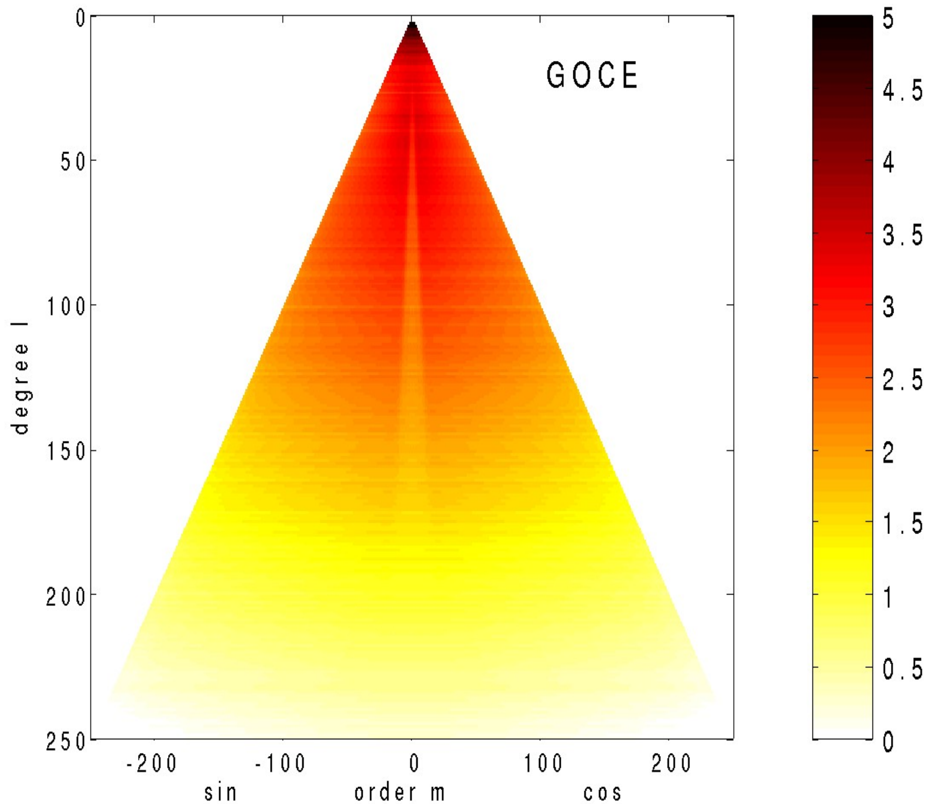


$$\lim_{\Delta x_j \to 0} \frac{V_i^{(2)} - V_i^{(1)}}{x_j^{(2)} - x_j^{(1)}} \approx \frac{\partial^2 V}{\partial x_i \, \partial x_j} = V_{ij}$$

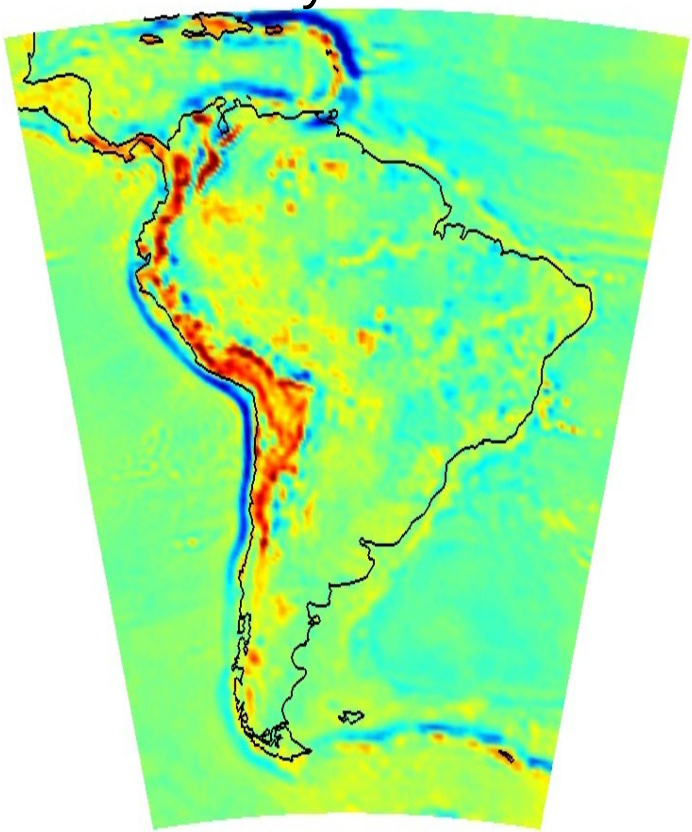
Improved Spatial Resolution

$$V(r,\theta,\lambda) = \frac{GM}{R}\sum_{l=0}^{l_{\max}}\left(\frac{R}{r}\right)^{l+1}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)\cdot\left[\overline{C}_{lm}\cos(m\lambda)+\overline{S}_{lm}\sin(m\lambda)\right]$$

Significant digits of coeff.

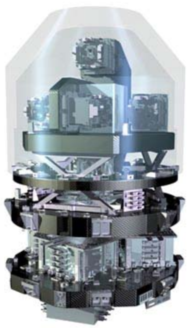


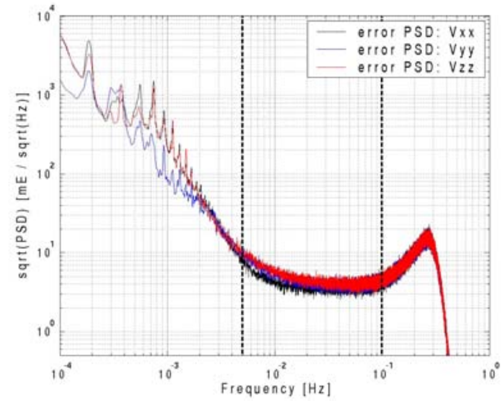
Gravity anomalies



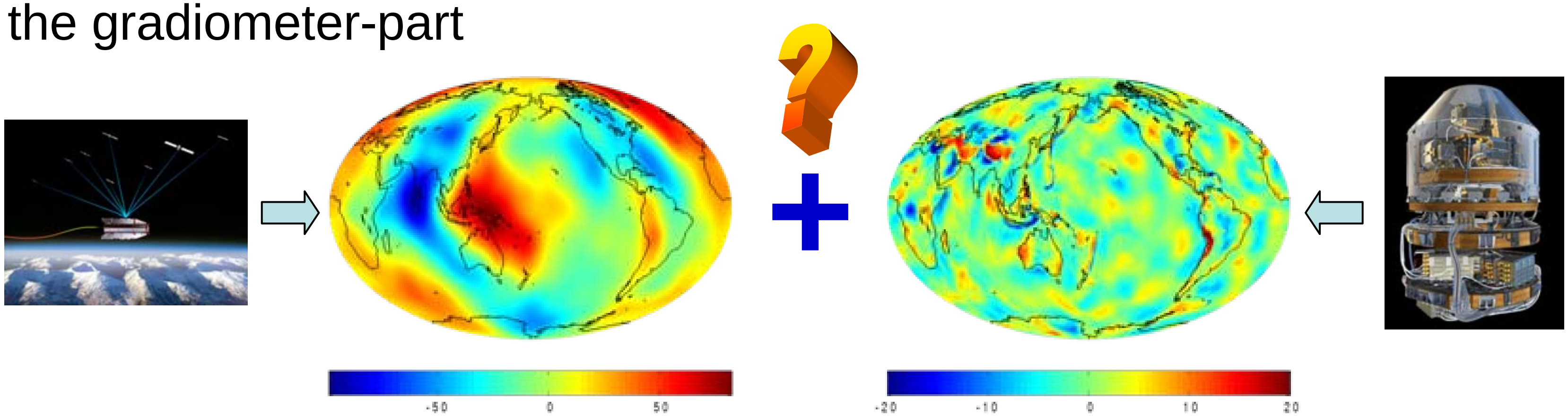
Challenges for GOCE Data Processing

- Solution of large equation systems
- Correct stochastic modeling of gradiometer observations

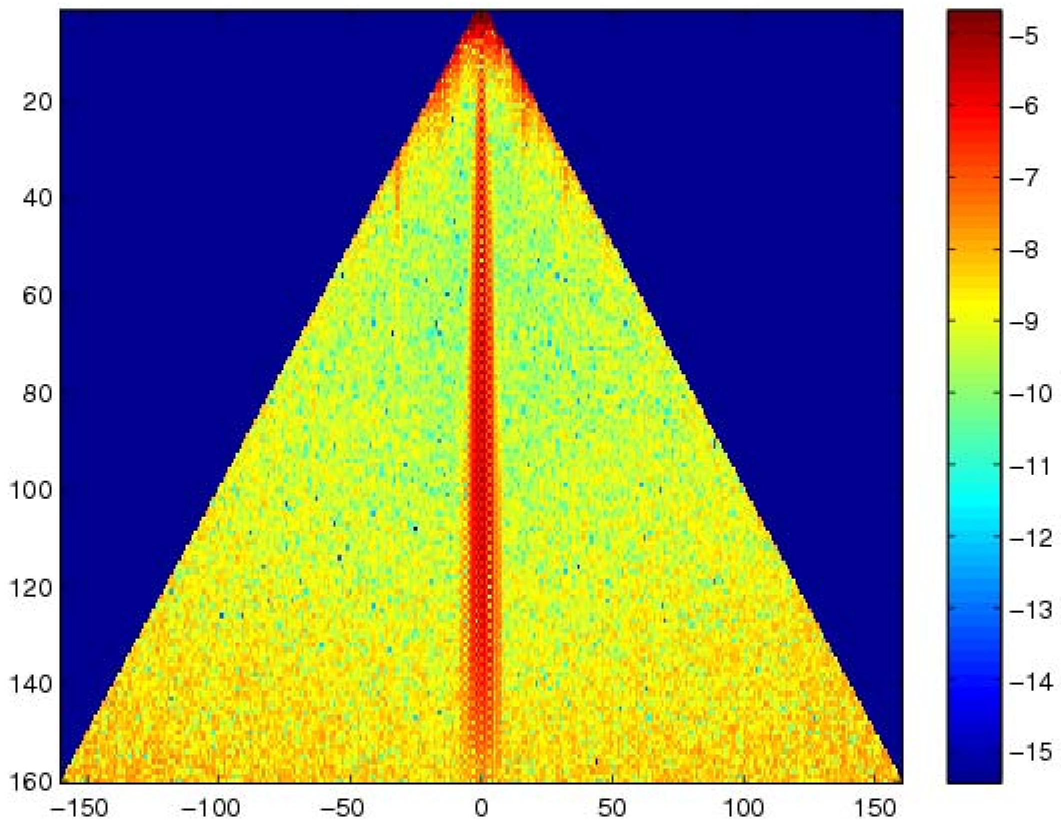




- Optimal combination of the GPS-part and the gradiometer-part



First GOCE Gravity Field Results



GOCE solutions show different characteristics than CHAMP or GRACE solutions. The quality is remarkable despite the short data spans used


Thank you for your attention