GOCE

Gravity and steady-state Ocean Circulation Explorer

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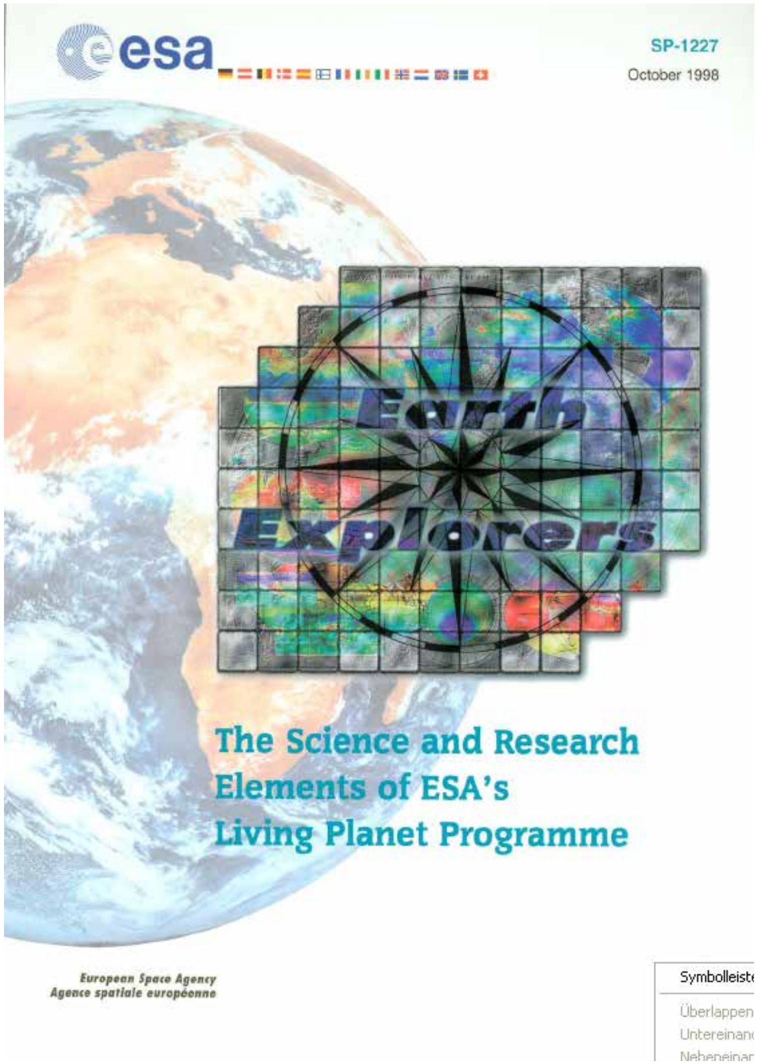
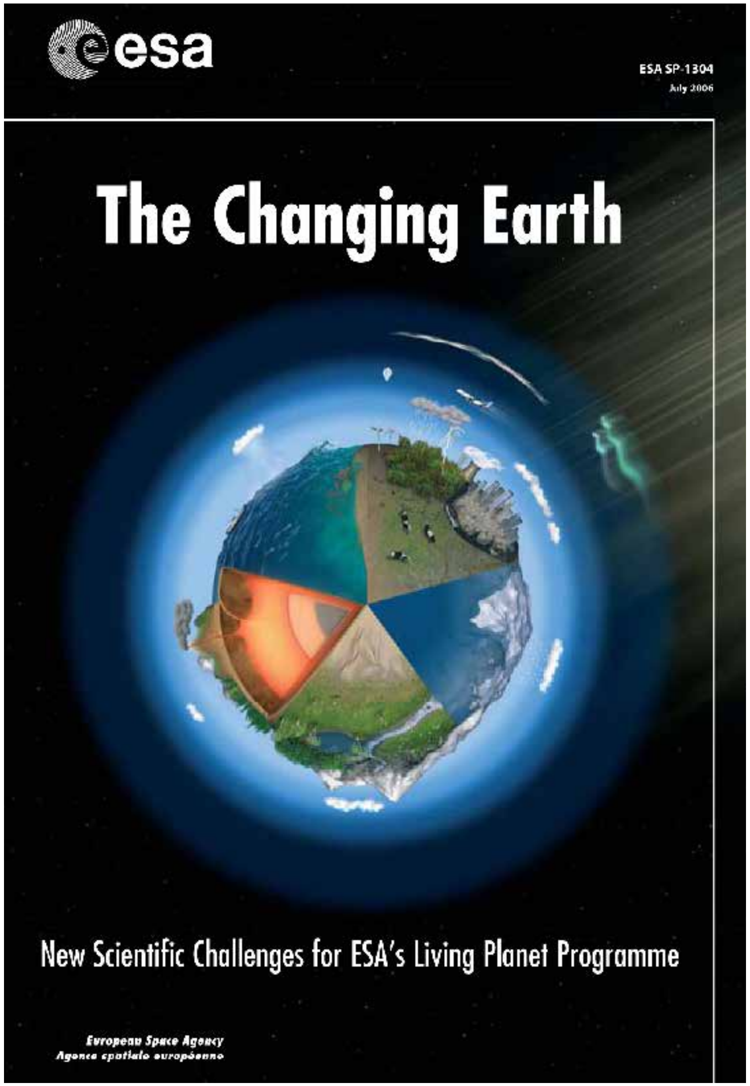
Three Lectures:

One	ESA explorer mission GOCE: earth gravity from space
Two	Signal processing on a sphere
Three	Gravity and earth sciences

ESA: Living Planet Programme



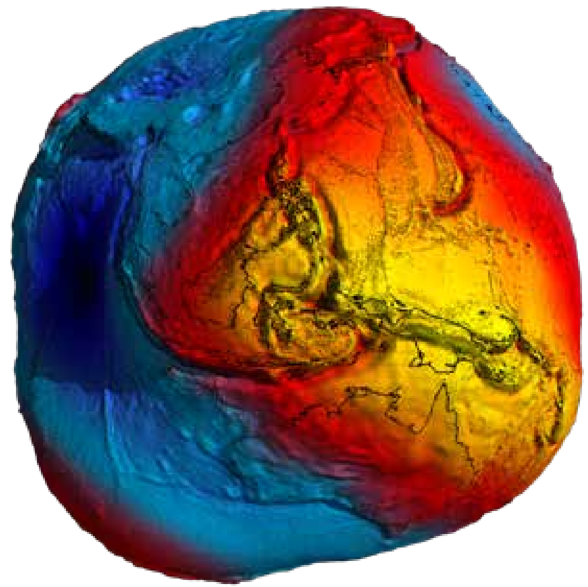


the team

earth potential fields space

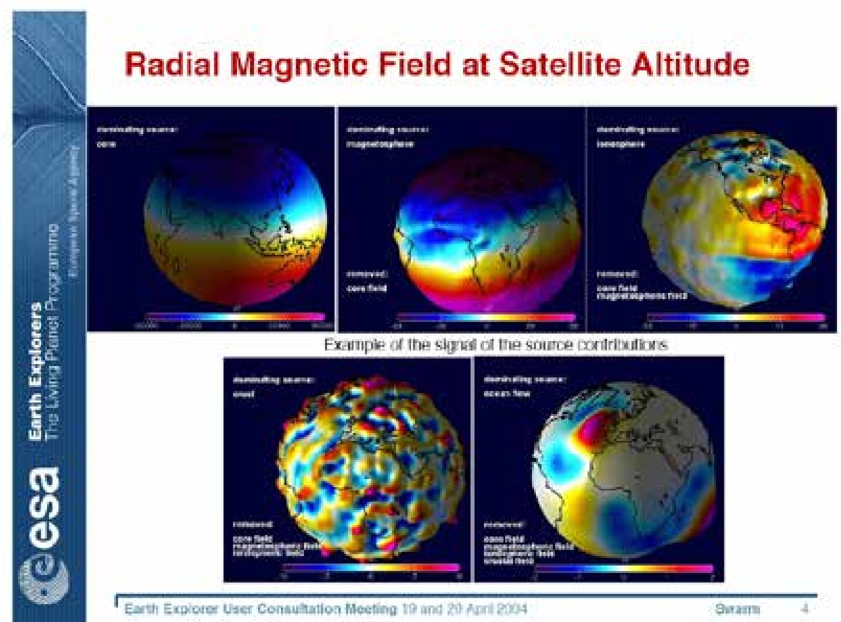
gravitational field

GOCE

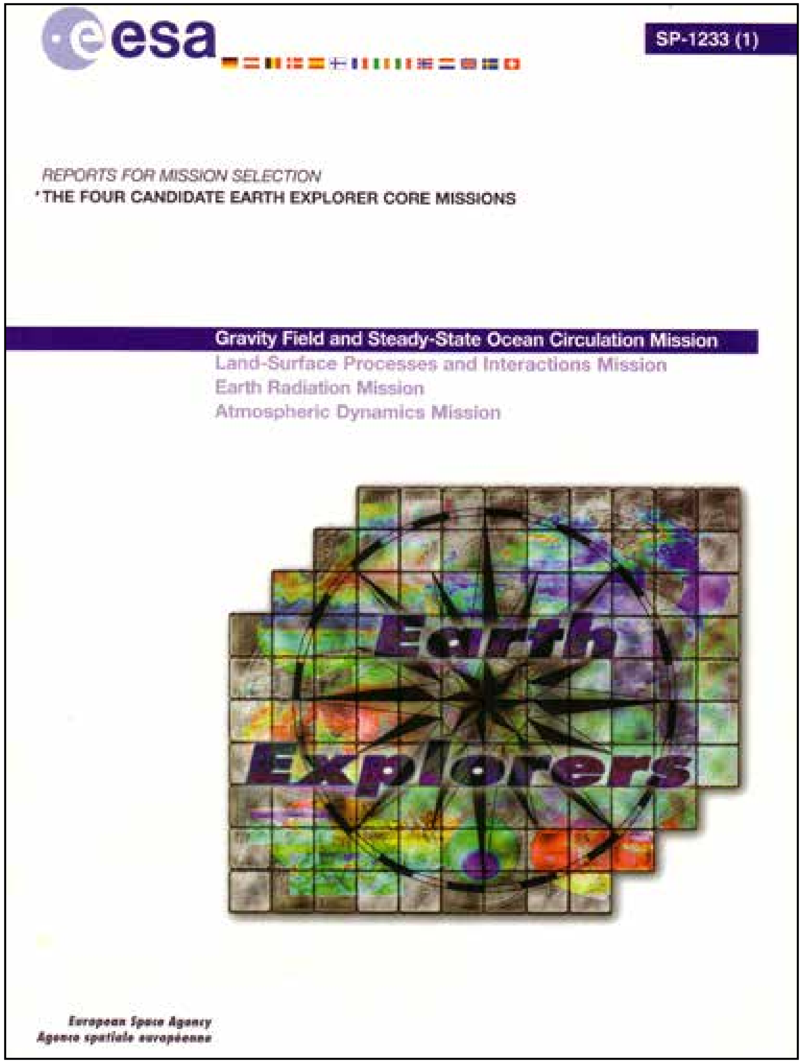


magnetic field

Swarm



The four candidate earth explorers



„Granada Report“ ESA 1999

GOCE basic facts

Gravity and steady-state Ocean Circulation Explorer

- launched on March 11, 2009 (now 3½ years in orbit)
- first mission of ESA's "Living Planet programme"
  (followed by SMOS and CRYOSAT)
- mission goals:
  gravity with 1 ppm (1 mGal) accuracy
  geoid with 1 to 2 cm accuracy
  spatial resolution 100km
  (equivalent to degree/order = 200 in spherical harmonics)
- orbit characteristics
  inclination 96.5° (sun-synchronous) → polar data gaps
  circular
  altitude 265km !
- mission extension till end of 2013
- currently re-processing of data up to July 2012

size of gravity signals

gravity (in laboratory at TU München)
9.807 246 72 m/s^2

stationary	10^{0}	spherical Earth
	10^{-3}	flattening & centrifugal acceleration
	10^{-4}	mountains, valleys, ocean ridges, subduction
	10^{-5}	density variations in crust and mantle
	10^{-6}	salt domes, sediment basins, ores
variable	10^{-7}	tides, atmospheric pressure
	10^{-8}	temporal variations: oceans, hydrology
	10^{-9}	ocean topography, polar motion
	10^{-10}	general relativity

introduction to gravitation

Newton's law of gravitation:

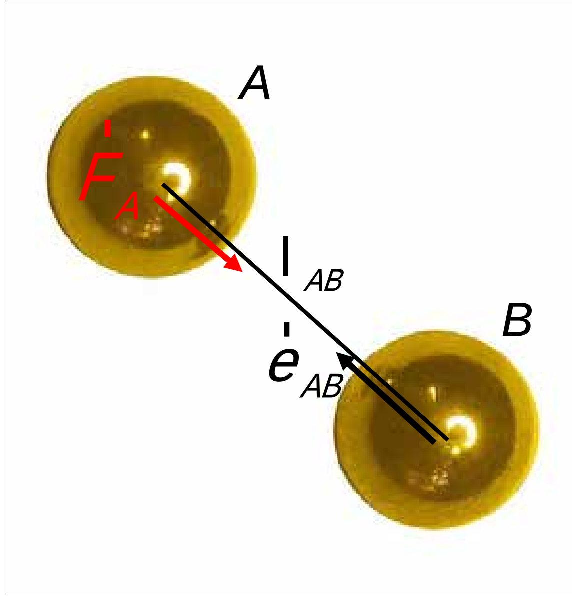
$$\vec{F}_A = -G\,\frac{m_A m_B}{l_{AB}^2}\,\vec{e}_{AB} = -G\,\frac{m_A m_B}{\left|\vec{x}_A - \vec{x}_B\right|^3}\left(\vec{x}_A - \vec{x}_B\right)$$

Newton's second law:

$$\vec{F}_A = m'_A\,\vec{a}_A$$

gravitational acceleration:

$$\vec{a}_A = -G\,\frac{m_A m_B}{m'_A\,l_{AB}^2}\,\vec{e}_{AB}$$



Gravitational Law of Newton

Why is it denoted gravitational gradiometry ?

$$\vec{a} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} = \begin{pmatrix} \partial V / \partial x \\ \partial V / \partial y \\ \partial V / \partial z \end{pmatrix} = \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix}$$

$$M = \begin{pmatrix} \partial a_x / \partial x & \partial a_x / \partial y & \partial a_x / \partial z \\ \partial a_y / \partial x & \partial a_y / \partial y & \partial a_y / \partial z \\ \partial a_z / \partial x & \partial a_z / \partial y & \partial a_z / \partial z \end{pmatrix} = \begin{pmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{pmatrix}$$

Gravitational Law of Newton

Gravitational potential:
(extends over all masses)
(scalar field)

$$V_P = G \iiint_{\Sigma} \frac{\rho_Q}{\ell_{PQ}} \, d\Sigma_Q$$

[m^2 /s^2]

Gravitational acceleration:
(vector field)

$$\vec{a}_P = \nabla_P V = G \iiint_{\Sigma} \rho_Q \left\{ \nabla_P \frac{1}{\ell_{PQ}} \right\} d\Sigma_Q$$

[m /s^2]

Gravitational gradients:
(tensor field)

$$M_P = \nabla \otimes \nabla V = G \iiint_{\Sigma} \rho_Q \left\{ \nabla \otimes \nabla \frac{1}{\ell_{PQ}} \right\} d\Sigma_Q$$

Units:
1E = 1Eötvös Unit = 10^{-9} s^{-2}

[s^{-2}]

Gravitational Law of Newton

properties

Gravitational gradients:

Nine second derivatives

$$M = \partial_{ij} V = \begin{pmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{pmatrix}$$

M is a secod-order tensor:

(transformation property)

$$\Gamma^{*} = R\,\Gamma\,R^{T}$$

M is symmetric:

$$\nabla \times \nabla V = 0$$

= conservative

(the stationary part)

M is trace free (in vacuum)

LAPLACE condition

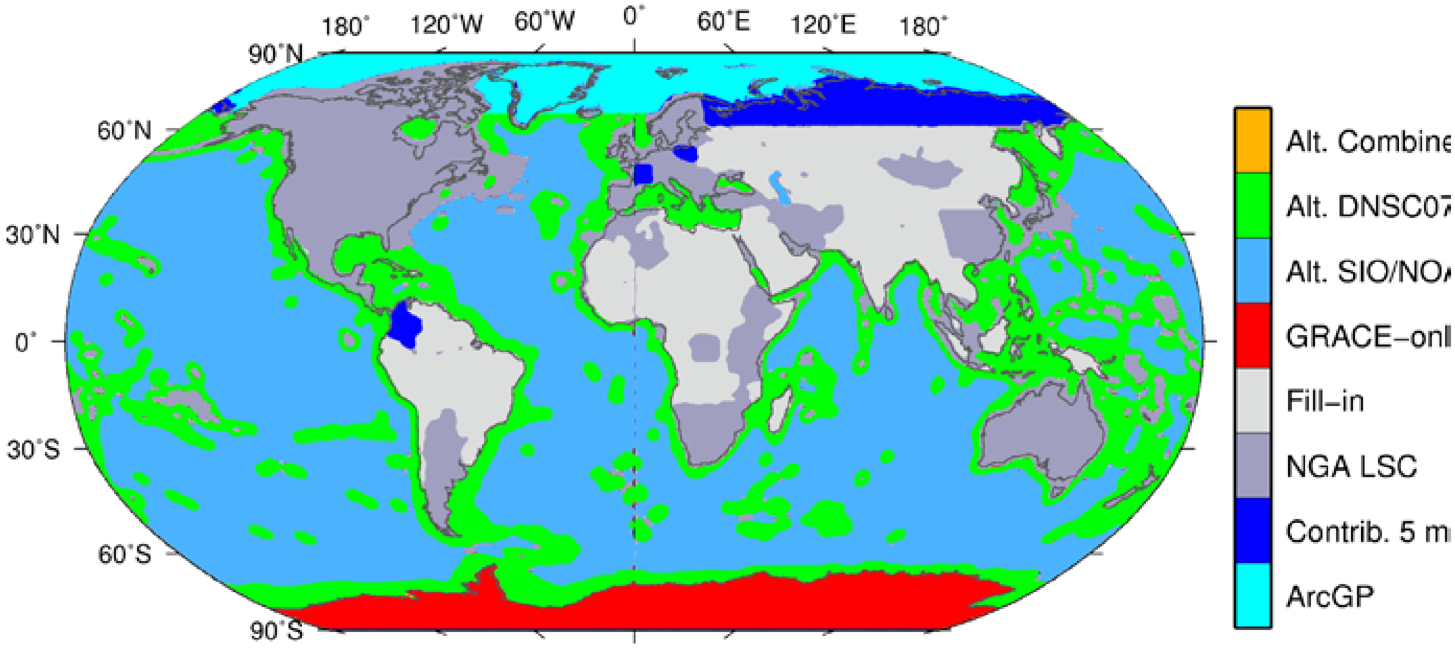
$$\nabla \cdot \nabla V = \nabla^2 V = -4\pi G \rho \approx 0$$

introduction to gravitation

satellite gravimetry:

- global
- uniform
- fast
- repeatedly (time series)

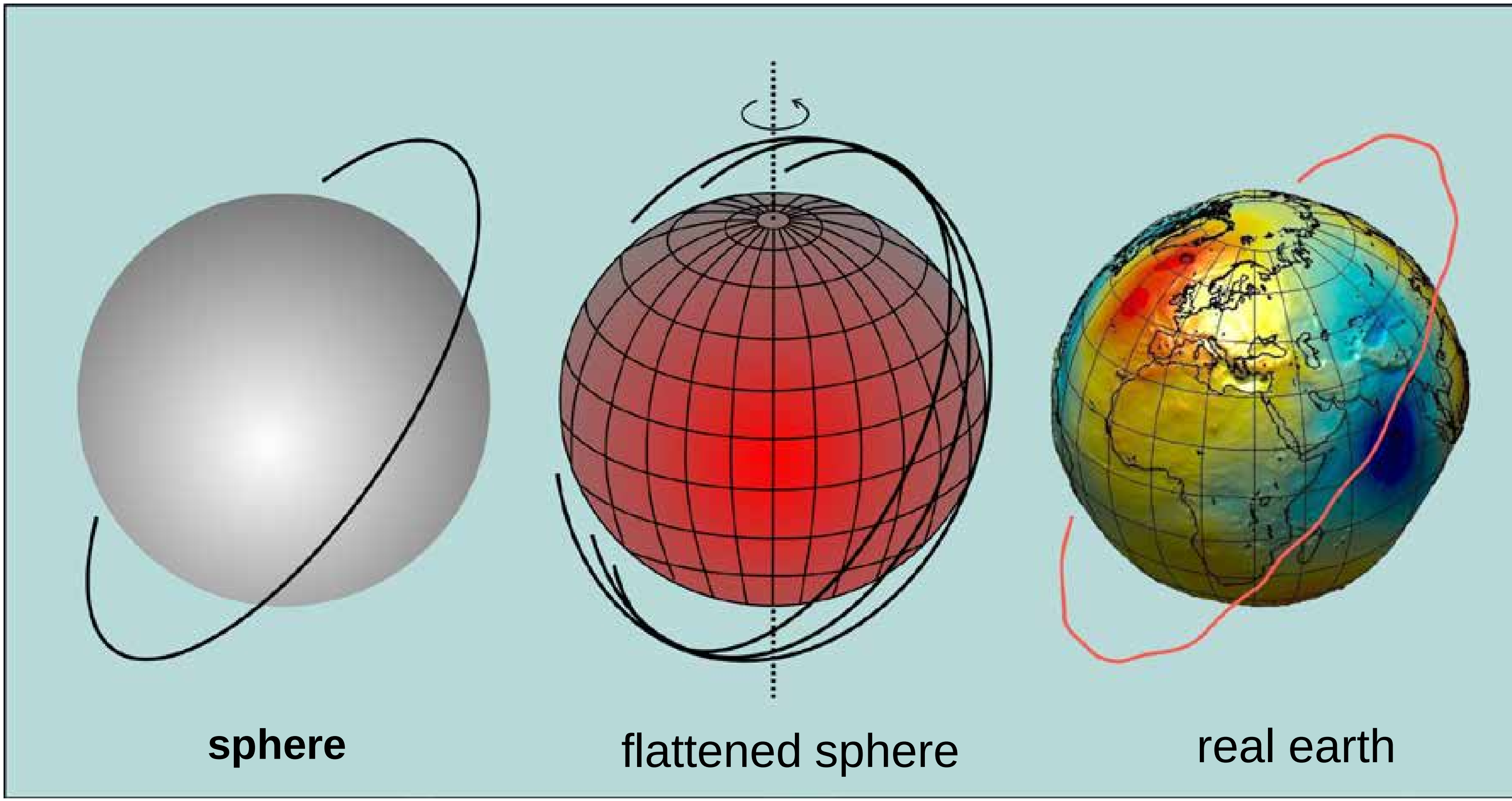
terrestrial gravity data sources of model EGM2008



Pavlis N, et al. JGRred 2012

principle of satellite gravimetry

a satellite is a test mass in free fall in the Earth‘s gravitational field



Kelplerian ellipse

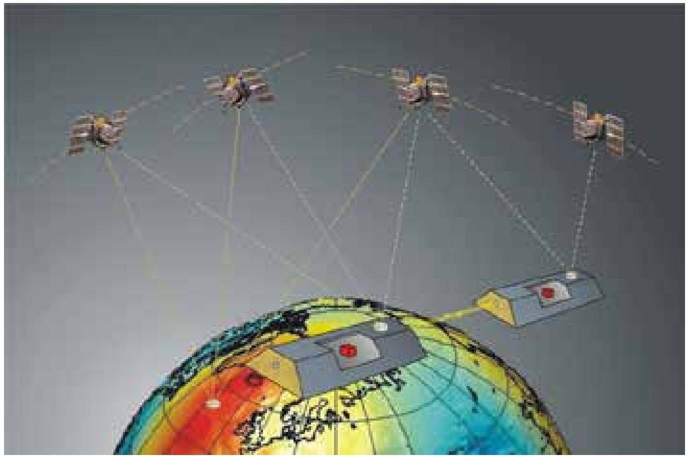
precessing ellipse

precessing ellipse
plus „gravitational code“

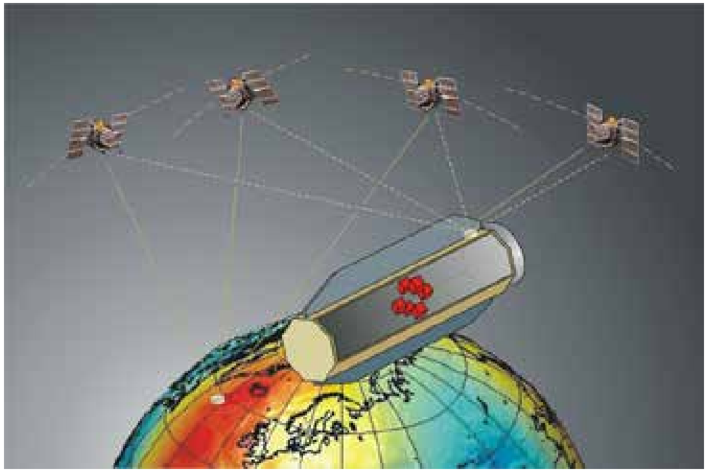
principle of satellite gravimetry

acceleration of
free falling test mass in gravitational field:

- from measurement of absolute motion of single mass to
- measurement of relative motion between test masses
- why?
- how many test masses?



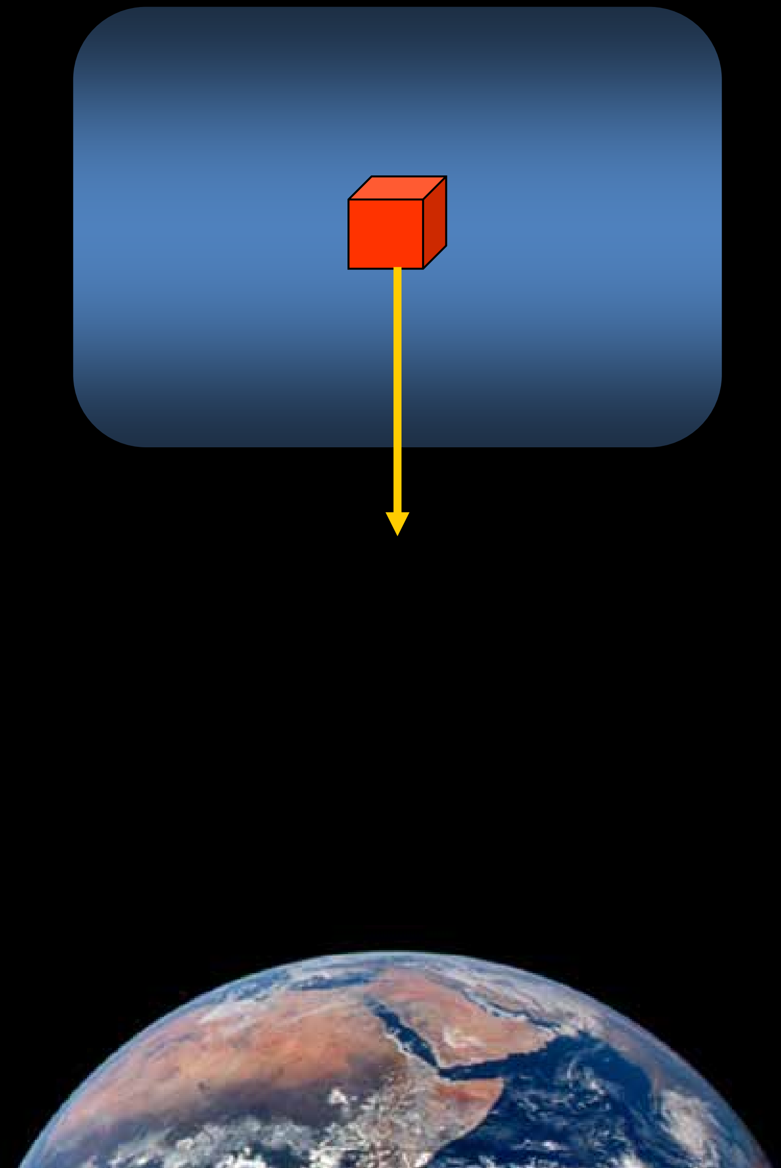
Concept: GRACE



Concept: GOCE

principle of satellite gravitational gradiometry

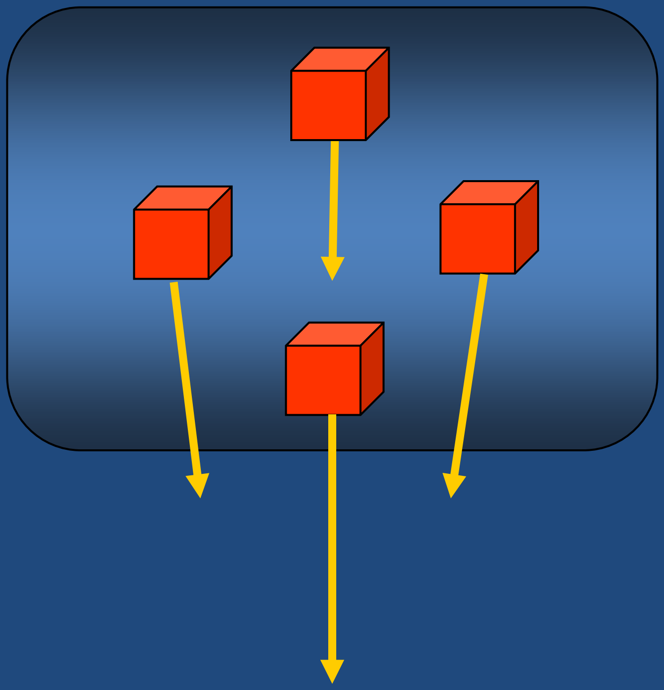
single test mass located of center of mass (CoM)



acceleration difference:
zero (= zero-g)

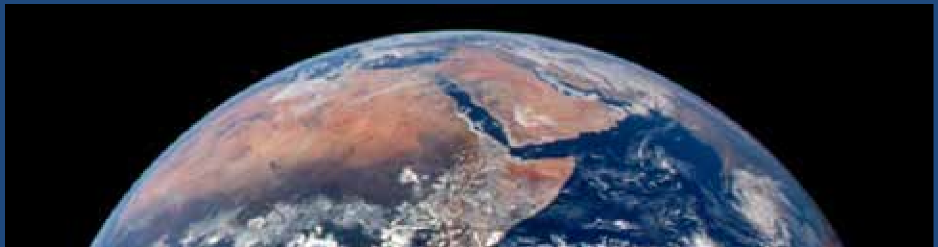
principle of satellite gravitational gradiometry

differences of gravitational acceleration of 4 test masses



acceleration differences:

1 millions of g (= micro-g)



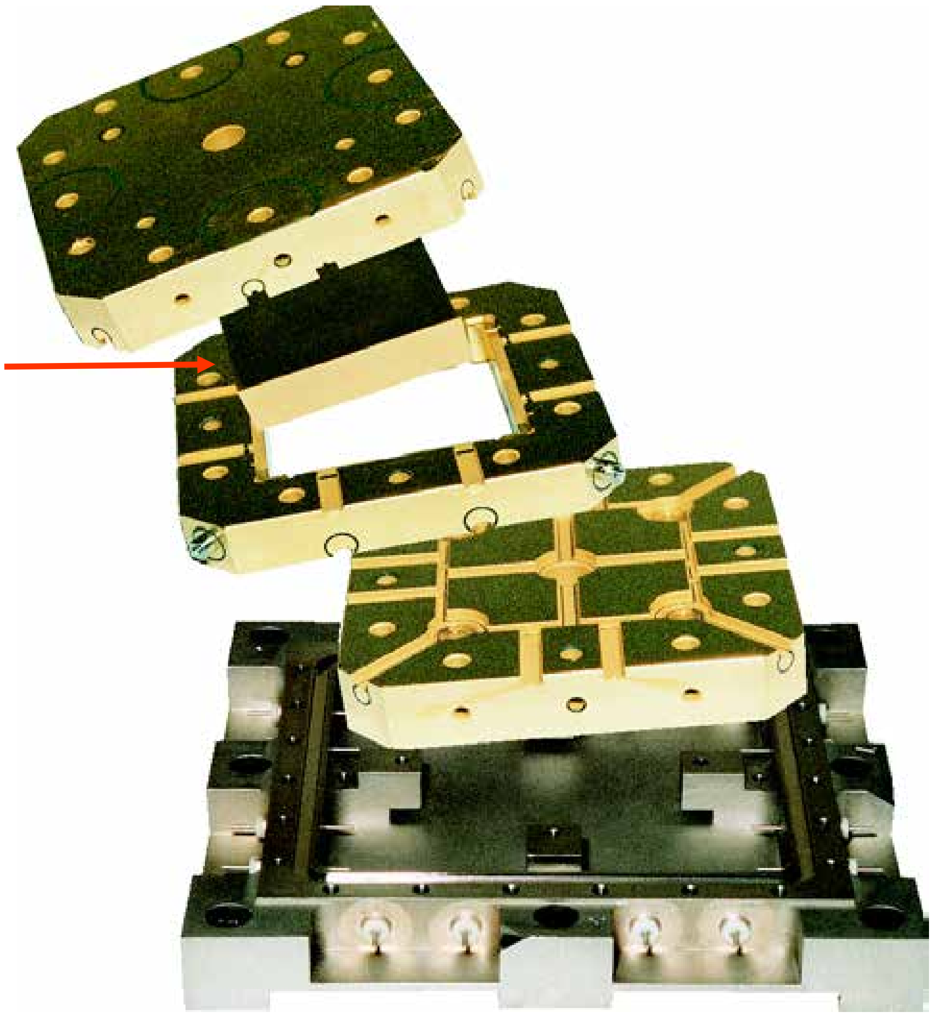
principle of GOCE gradiometry

single accelerometer

upper electrode

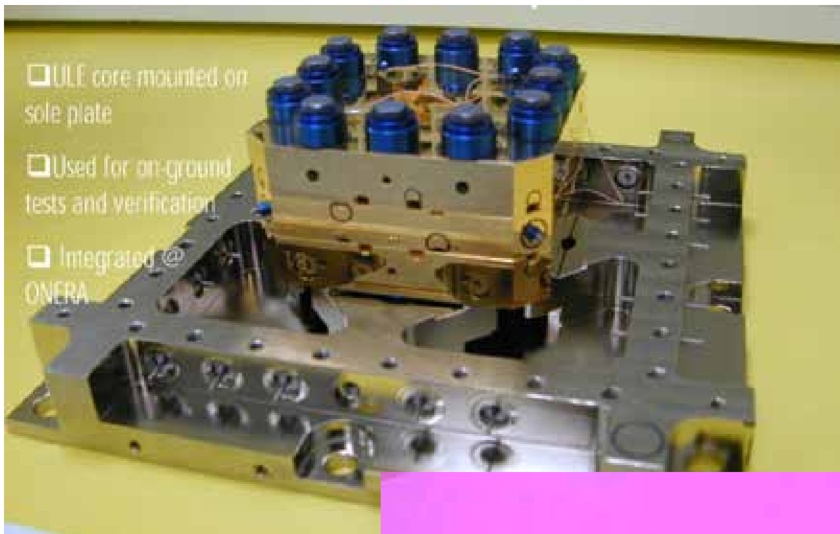
test mass
4cm x 4cm x 1cm
platinium-rhodium
320 g

cage
ULE-ceramics
gold electrodes



GOCE gravitational gradiometry

single accelerometer



one axis gradiometer

three axes gradiometer consisting of 6 accelerometers

GOCE gravitational gradiometry

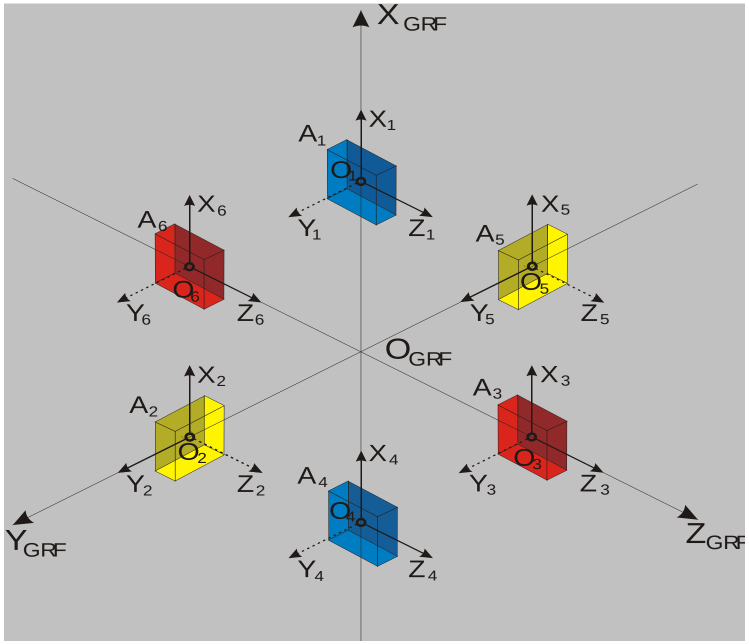
measurement in a rotating frame

gravitation tensor | centrifugal part (angular velocities) | angular accelerations

$$
\begin{pmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{pmatrix}
+
\begin{pmatrix} -\omega_y^2-\omega_z^2 & \omega_x\omega_y & \omega_x\omega_z \\ \omega_y\omega_x & -\omega_z^2-\omega_x^2 & \omega_y\omega_z \\ \omega_z\omega_x & \omega_z\omega_y & -\omega_x^2-\omega_y^2 \end{pmatrix}
+
\begin{pmatrix} 0 & \dot{\omega}_z & -\dot{\omega}_y \\ -\dot{\omega}_z & 0 & \dot{\omega}_x \\ \dot{\omega}_y & -\dot{\omega}_x & 0 \end{pmatrix}
$$

symmetric | symmetric | skew symmetric

GOCE gravitational gradiometry



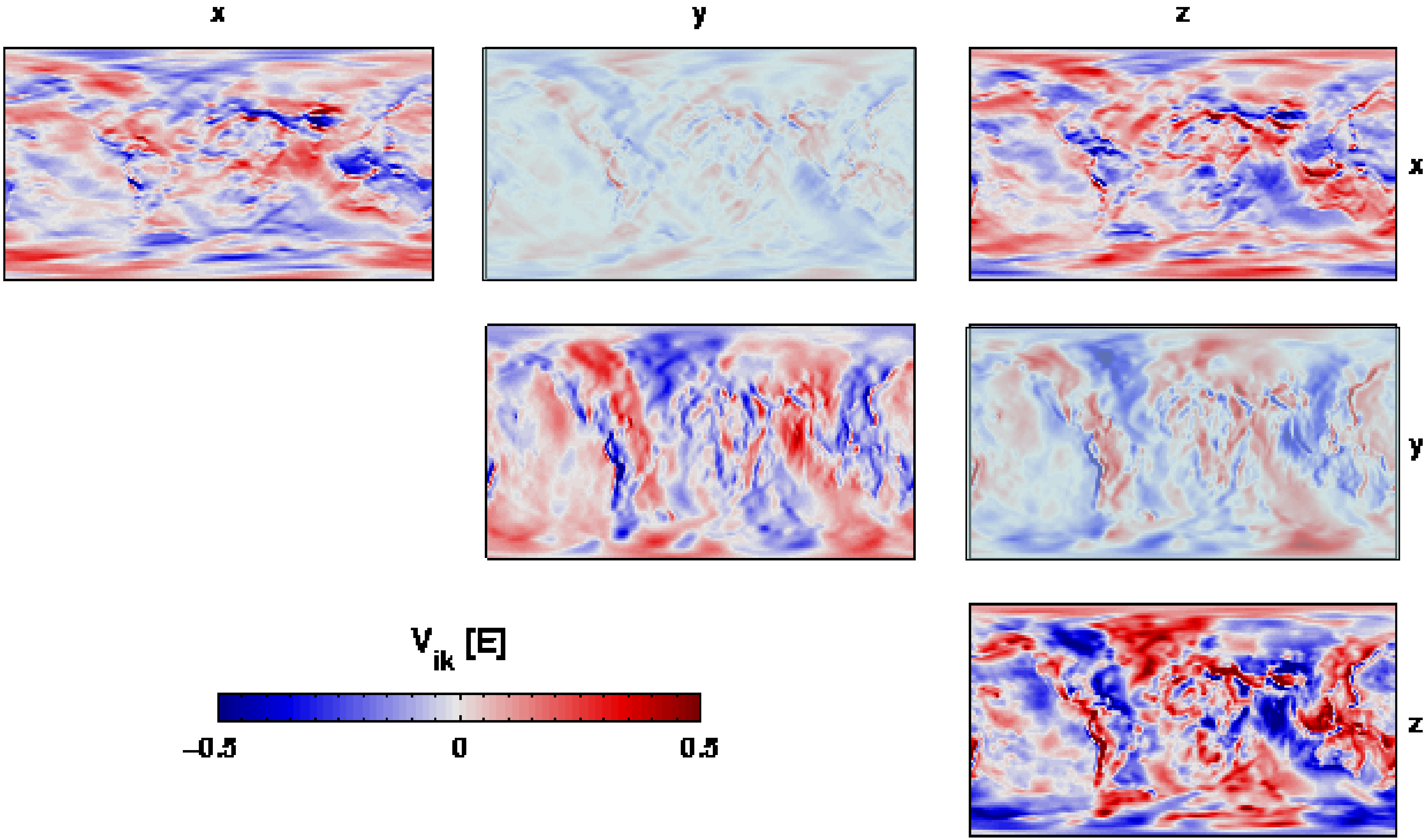
two sensitive and

one less sensitive

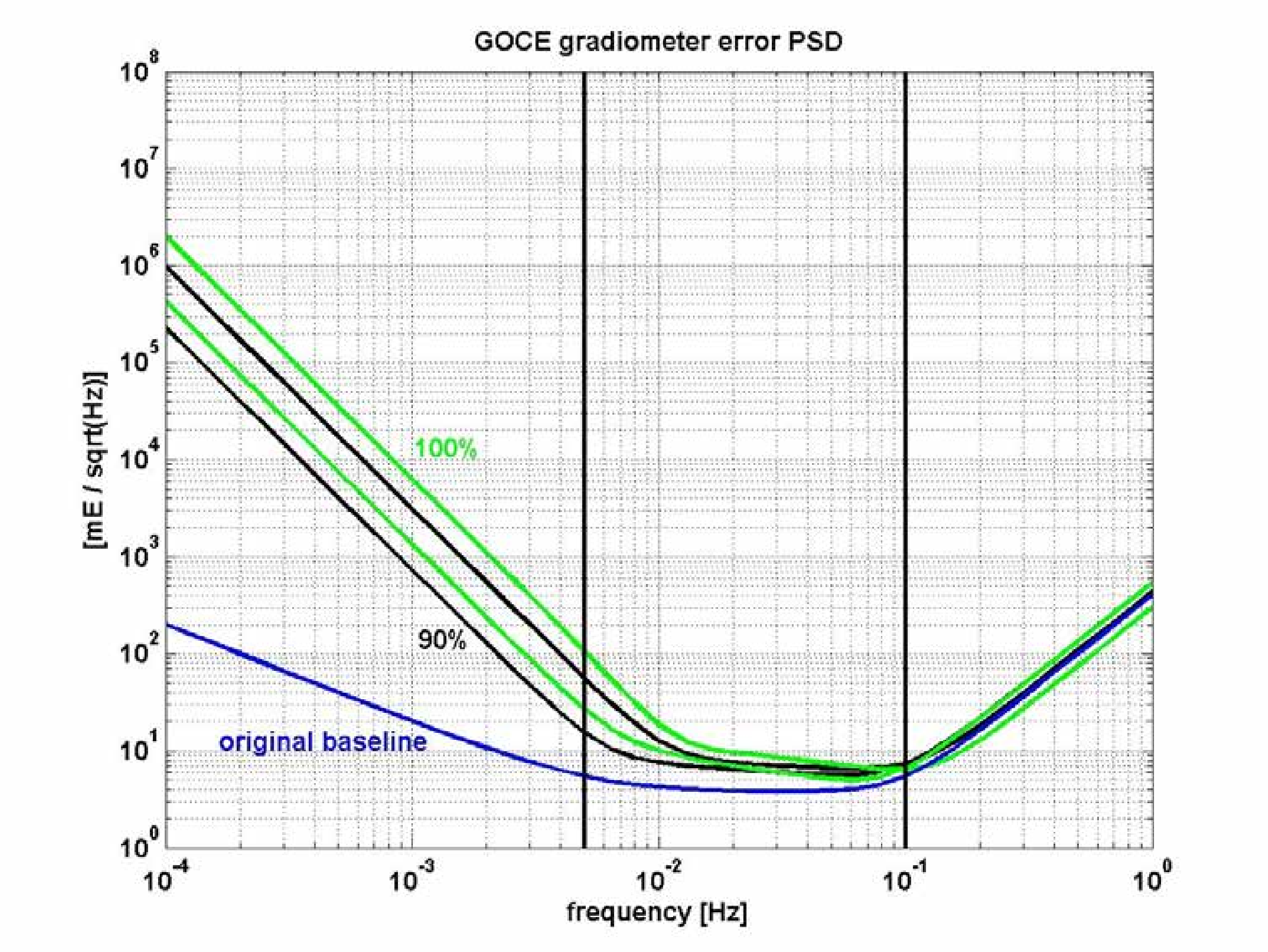
direction

$$\begin{pmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{pmatrix} + \begin{pmatrix} -\omega_y^2 - \omega_z^2 & \omega_x\omega_y & \omega_x\omega_z \\ \omega_y\omega_x & -\omega_z^2 - \omega_x^2 & \omega_y\omega_z \\ \omega_z\omega_x & \omega_z\omega_y & -\omega_x^2 - \omega_y^2 \end{pmatrix} + \begin{pmatrix} 0 & \dot{\omega}_z & -\dot{\omega}_y \\ -\dot{\omega}_z & 0 & \dot{\omega}_x \\ \dot{\omega}_y & -\dot{\omega}_x & 0 \end{pmatrix}$$

GOCE gravitational gradiometry



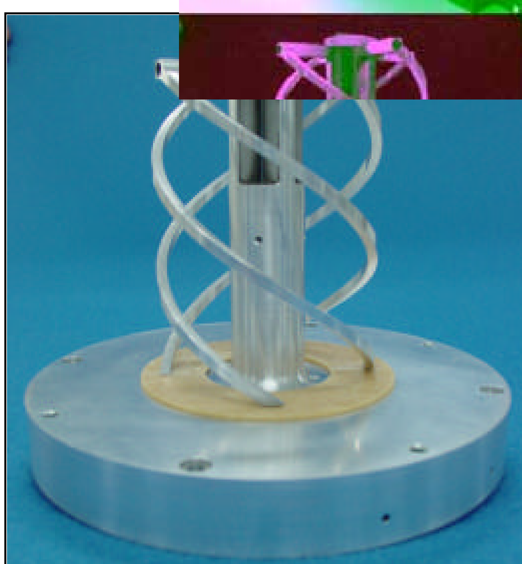
principle of GOCE gradiometry



GOCE sensor concept

orbit and gravity field determination from GPS

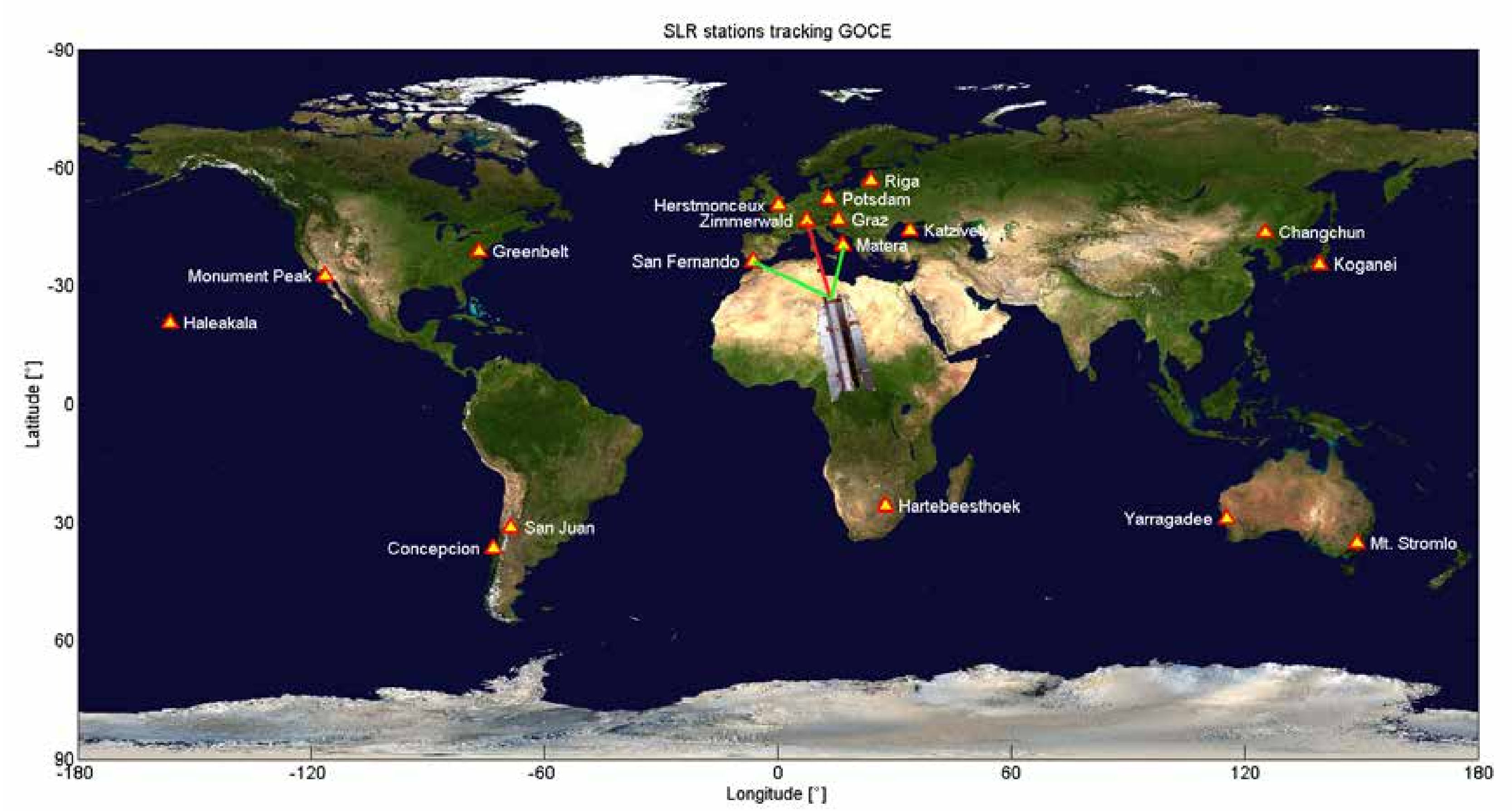
independent control via satellite laser ranging (SLR)



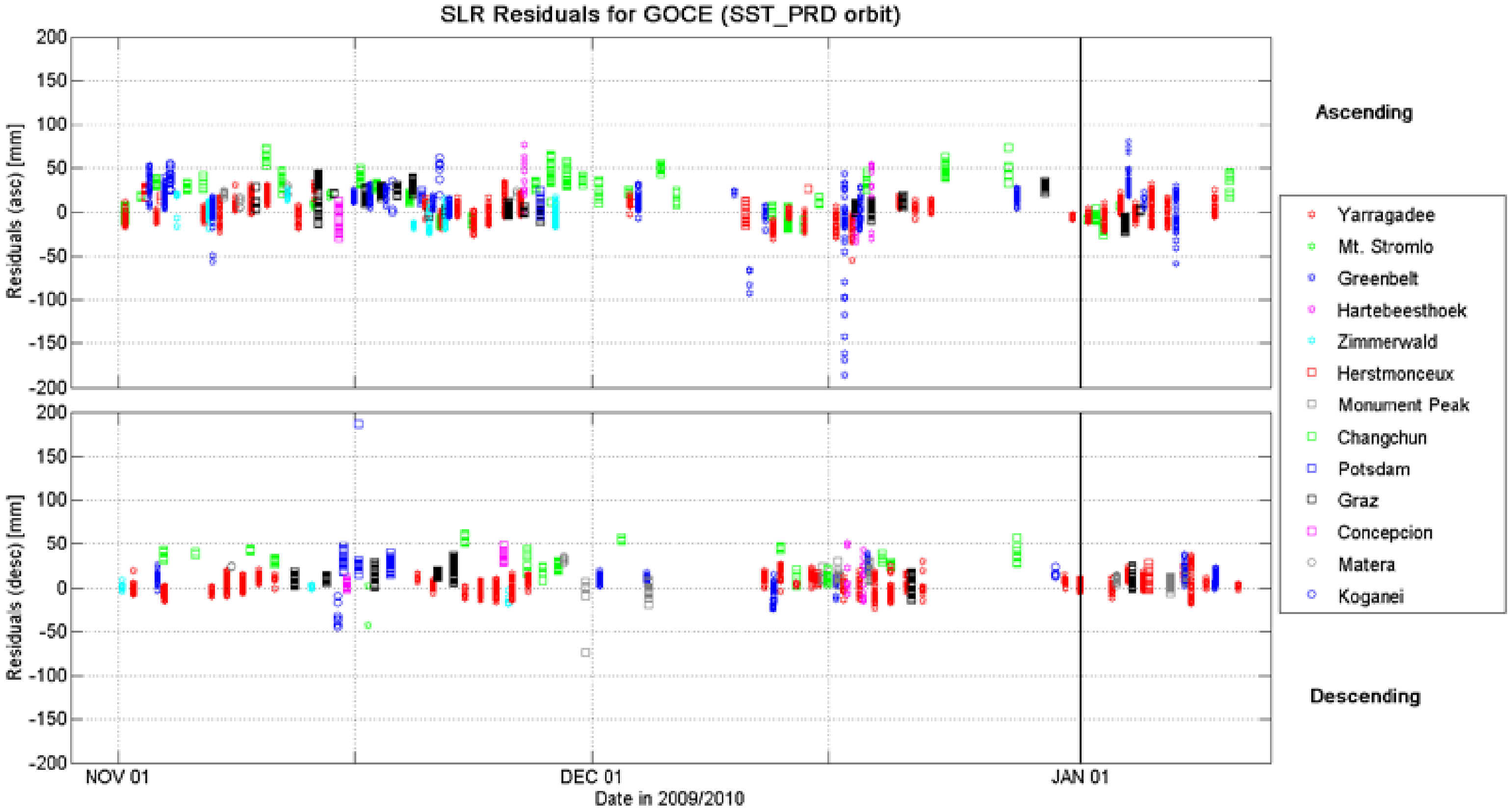
newly developed European GPS receiver

laser retro-reflectors

comparison with satellite laser ranging



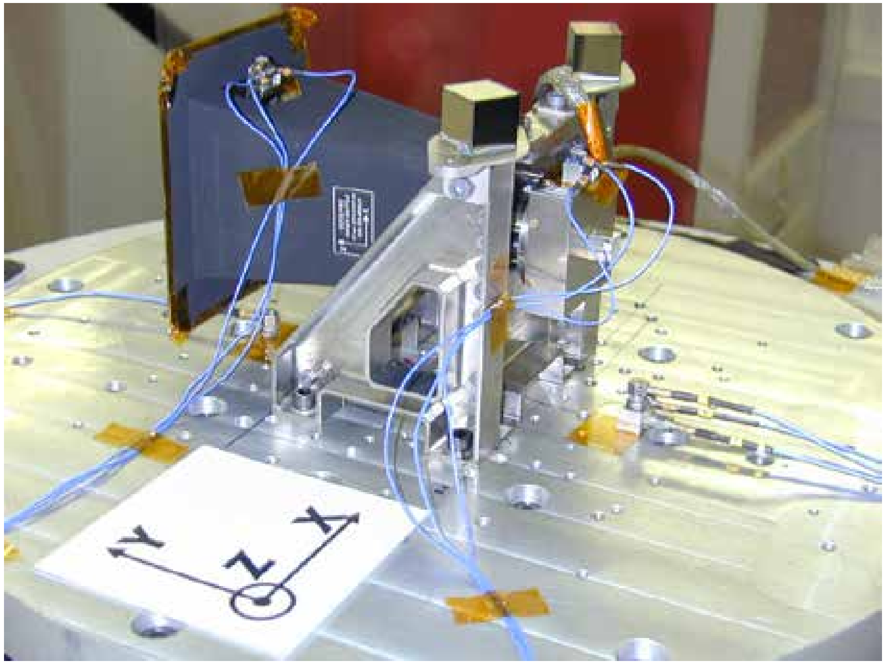
GOCE orbits

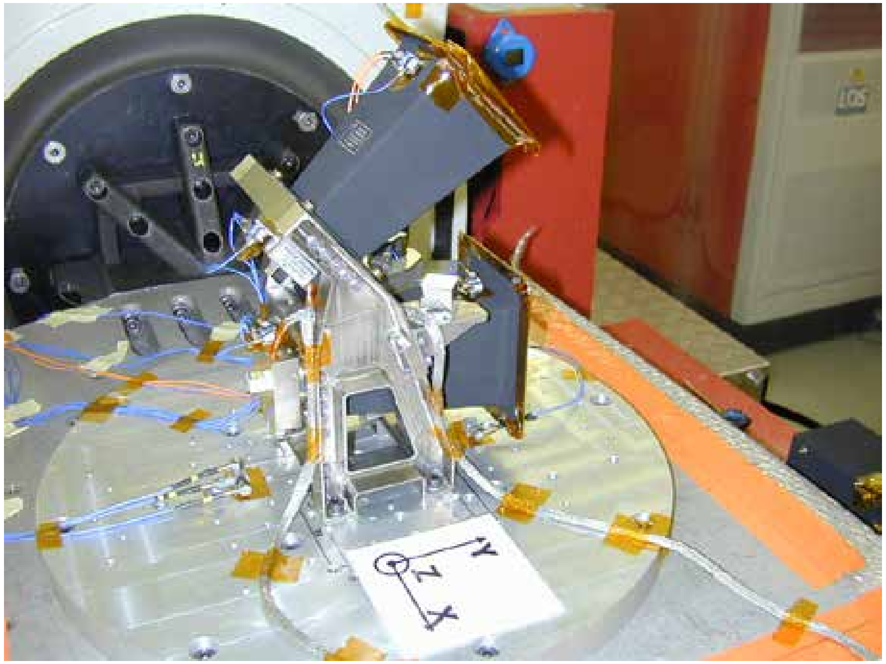


RMS differences 2cm

GOCE sensor concept

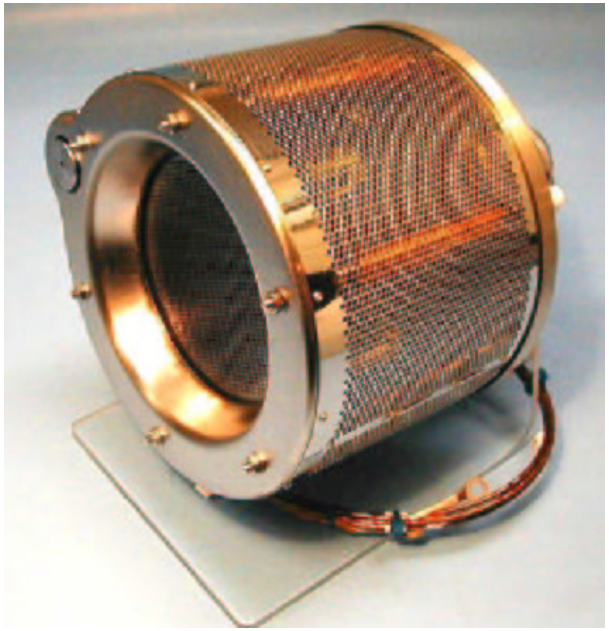
star sensors
DTU Copenhagen

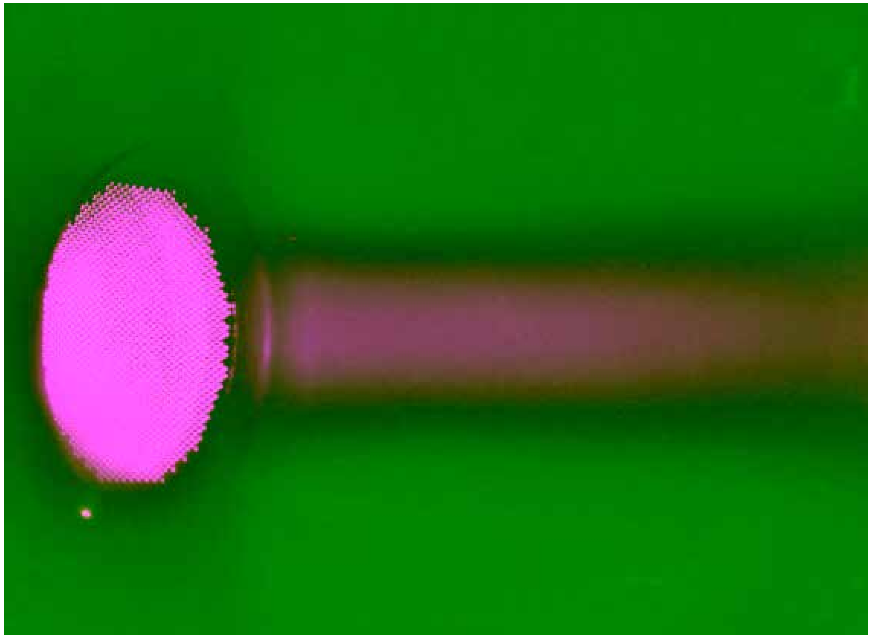




GOCE sensor concept

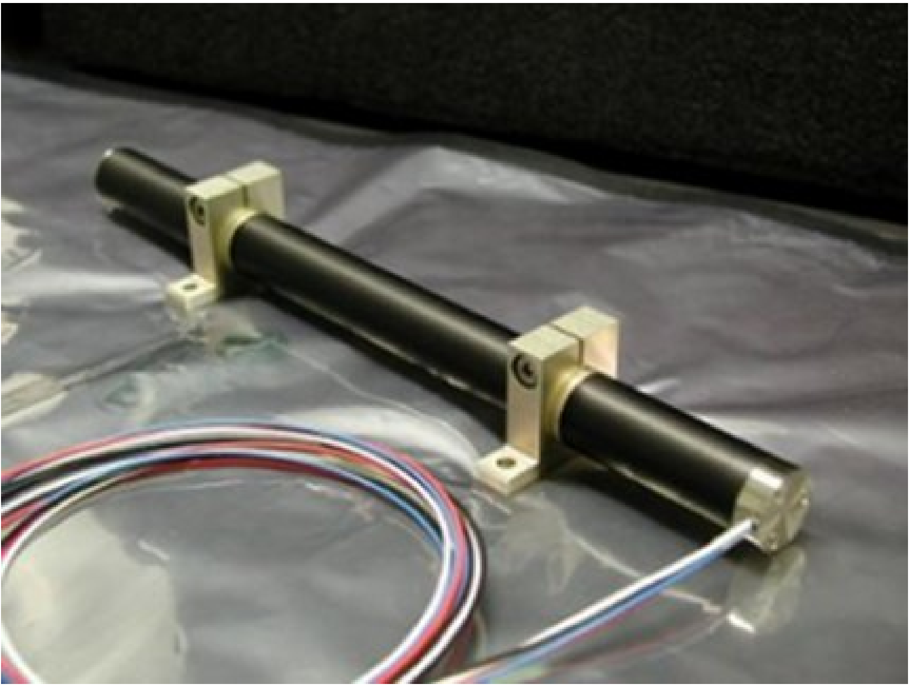
proportional air drag compensation in flight direction
by ion thrusters





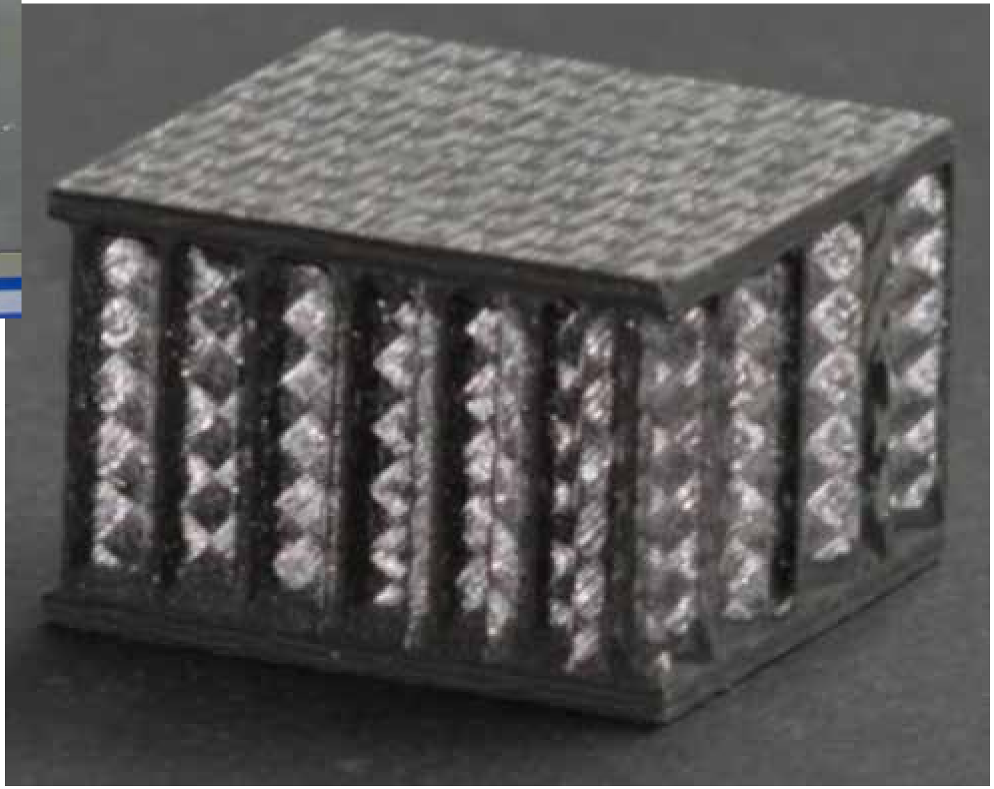
GOCE sensor concept

angular control via magnetic torquing



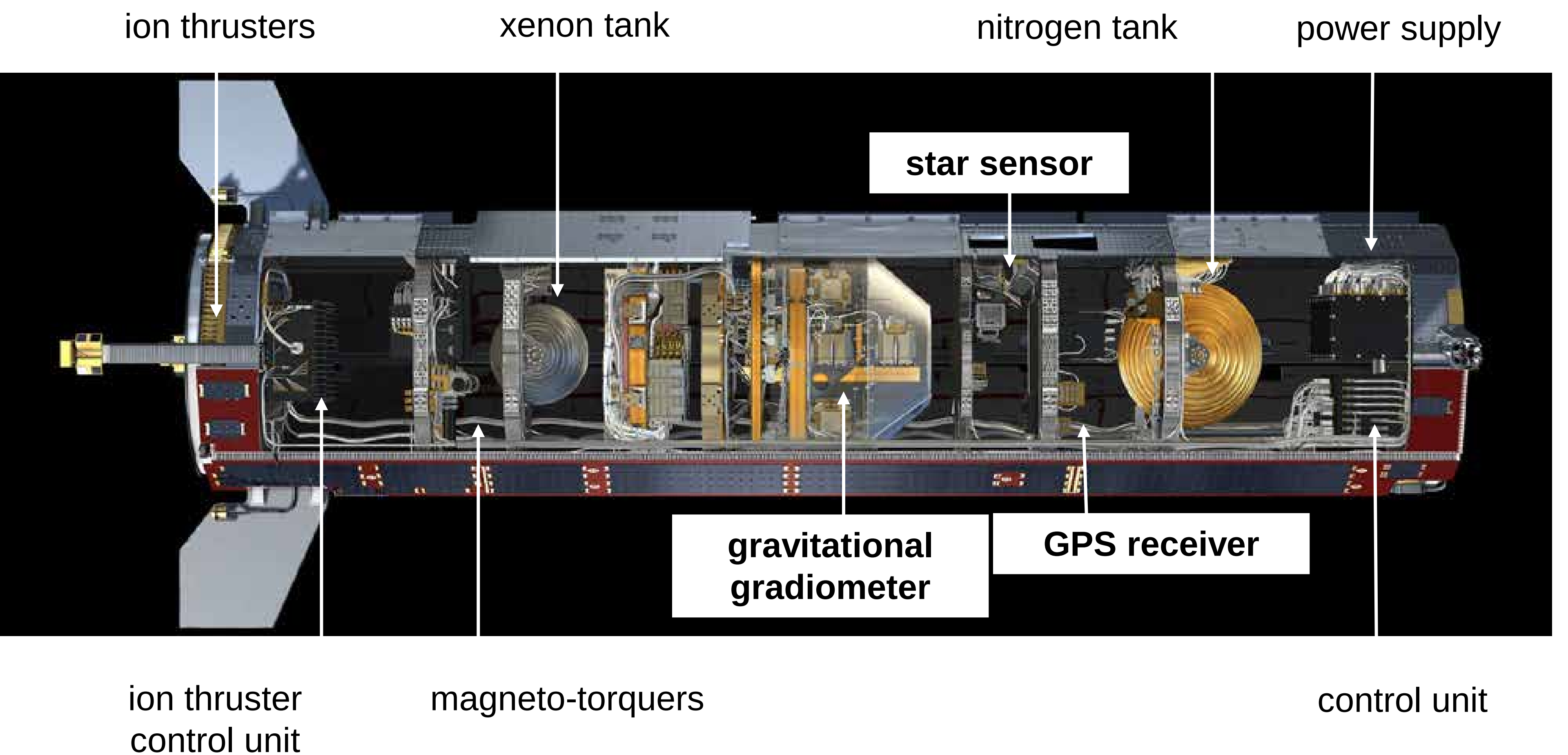
GOCE sensor concept

thermo stabilisation
of the gradiometer



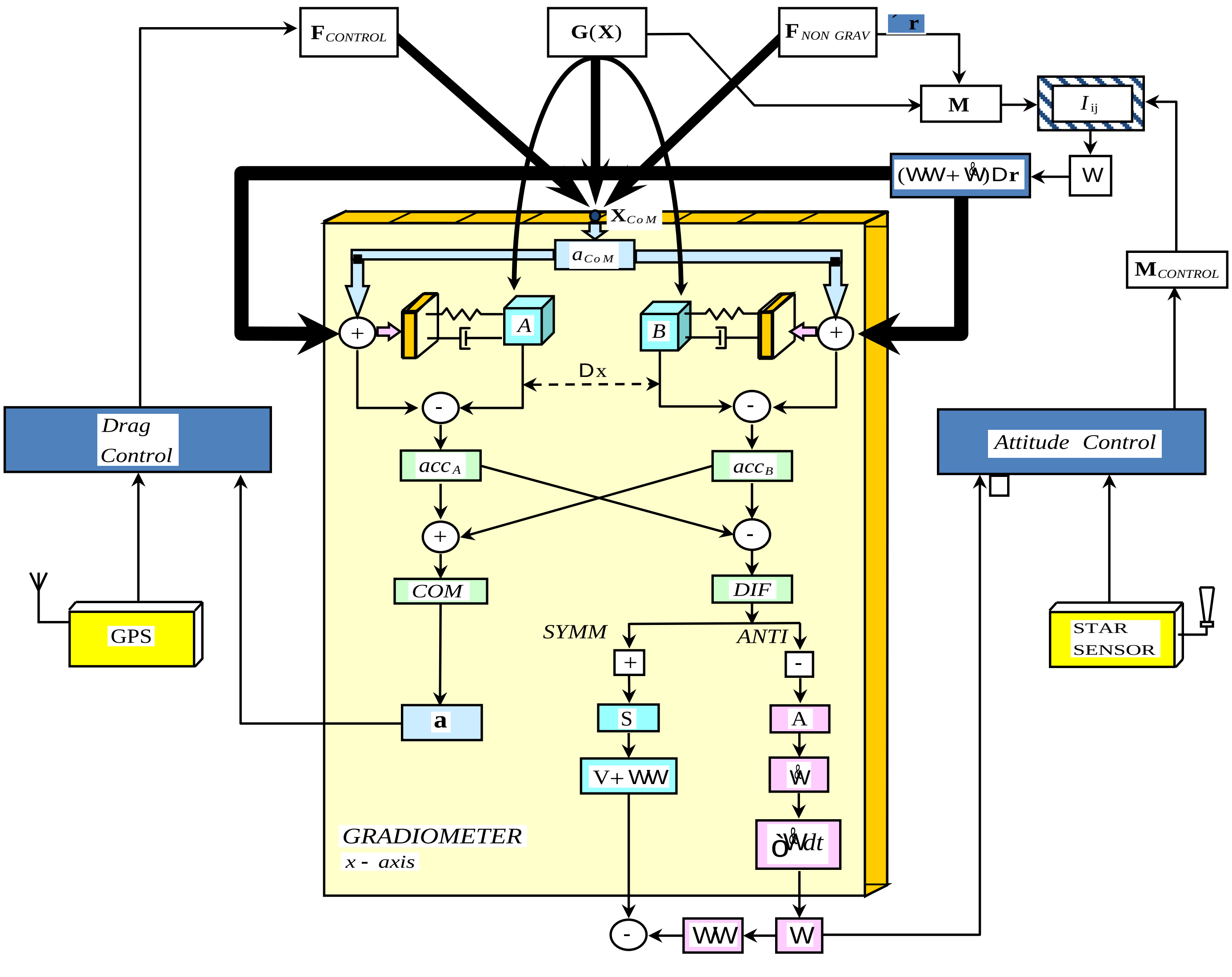
Carbon
sandwich structure

GOCE sensor system

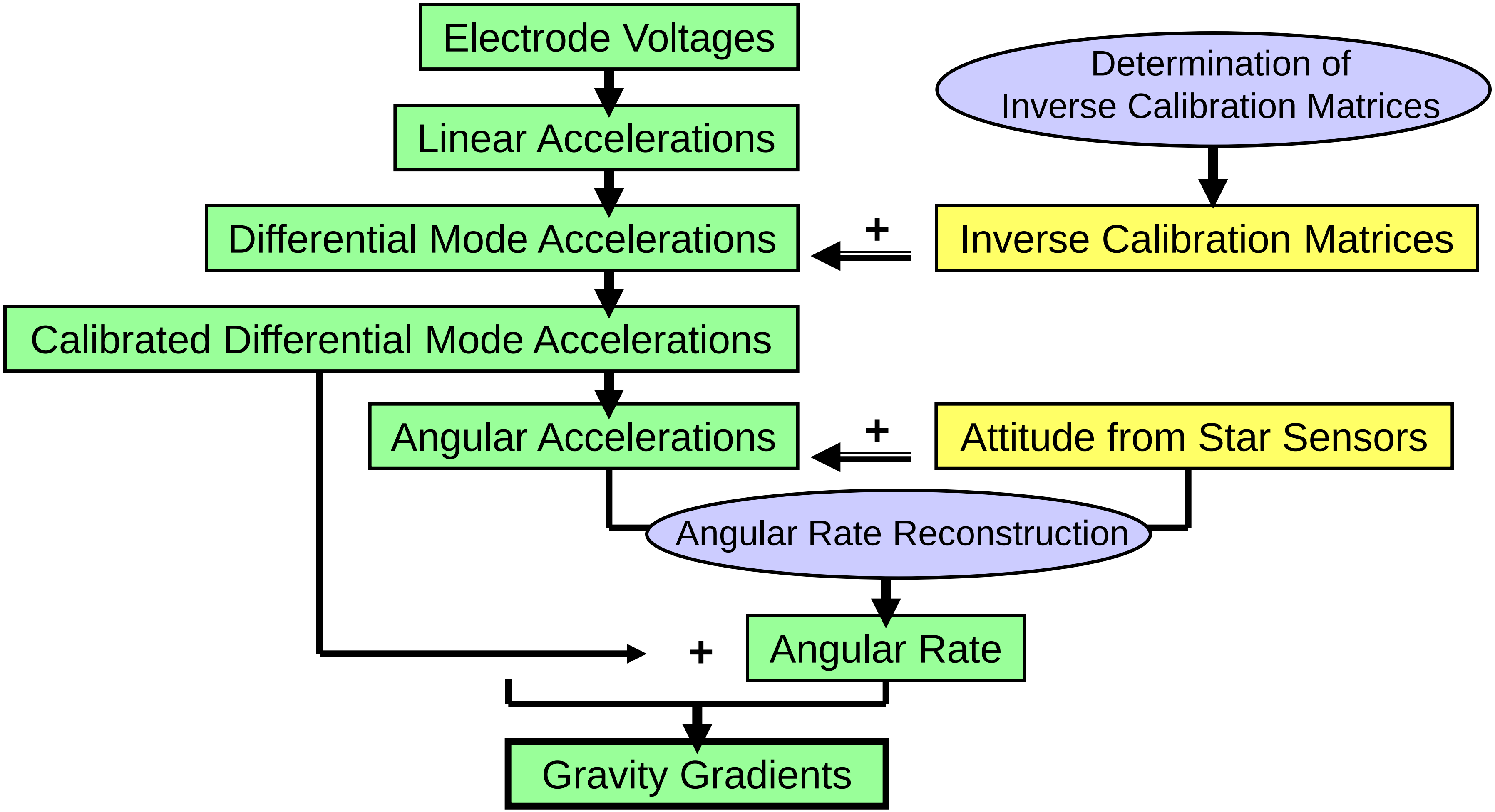


- an orbiting gravitational laboratory
- high performance of all sensors
- very different from „typical“ remote sensing satellites

GOCE End-to-End Simulation Scheme



Level 1: from sensor data to gravity gradients

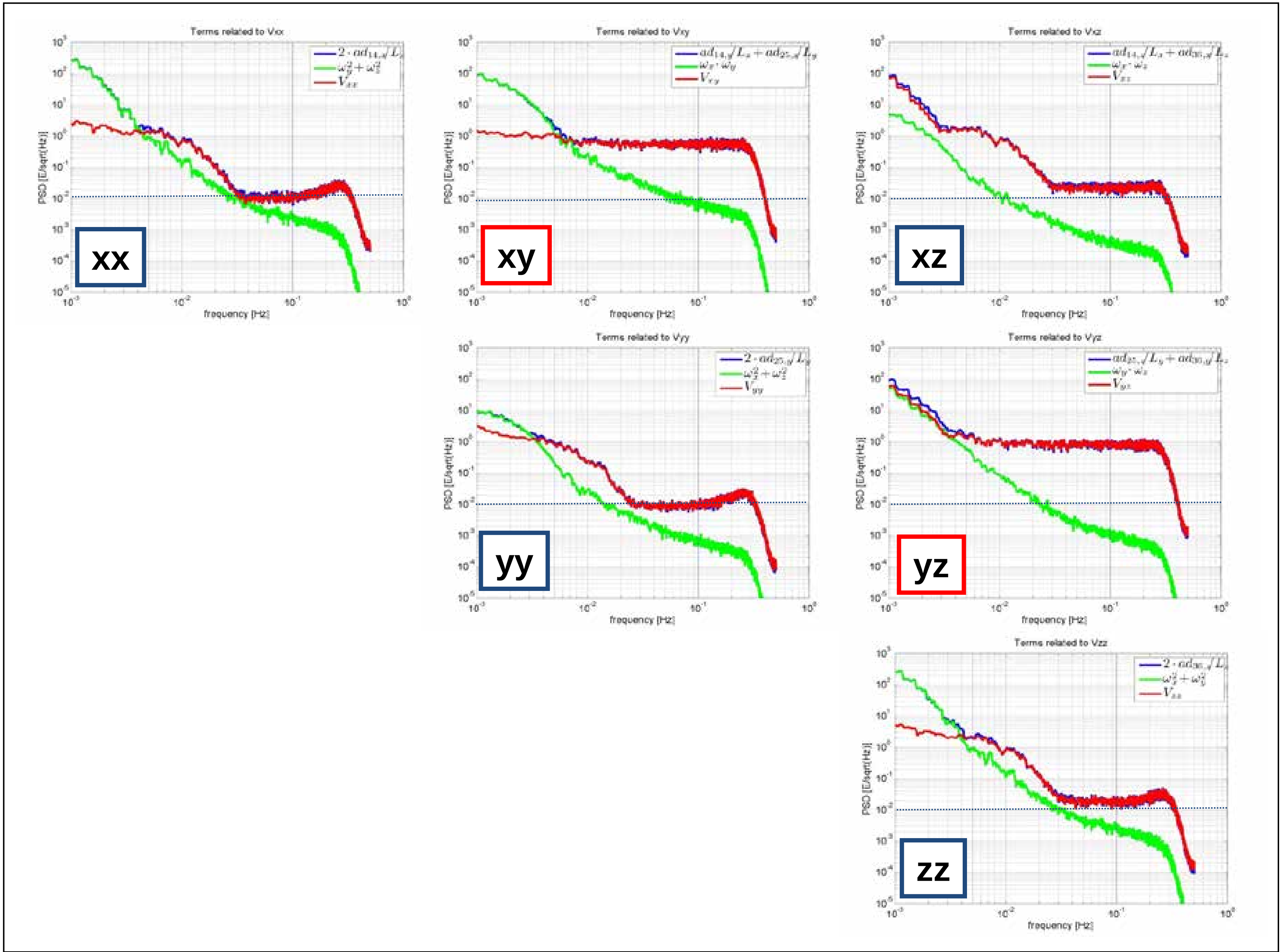


GOCE status

mission operation and special events

before September 2009	commissioning / calibration
September 2009	data to be reprocessed
October 2009	outage and calibration
November & December 2009	first 2 months cycle
January to February 11, 2010	nominal operation
February 12 – March 2	outage and calibration
March 3 to July 1	nominal operation
July 2 to September 25	outage and re-initialization
from September 25 on	nominal operation

GOCE mission performance

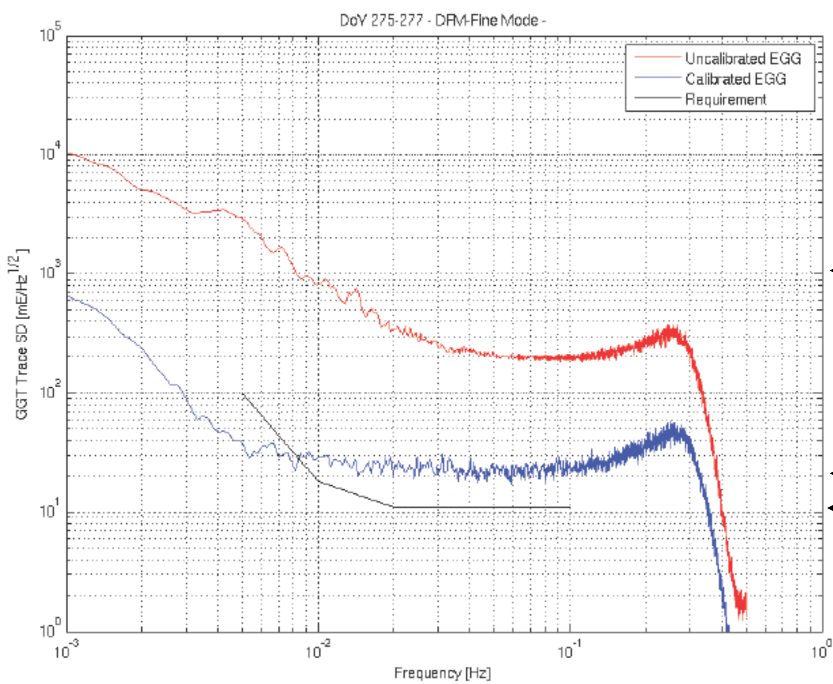


GOCE mission performance

trace condition (Laplace condition)

gradiometer performance
calibrated vs. uncalibrated gradio

esa

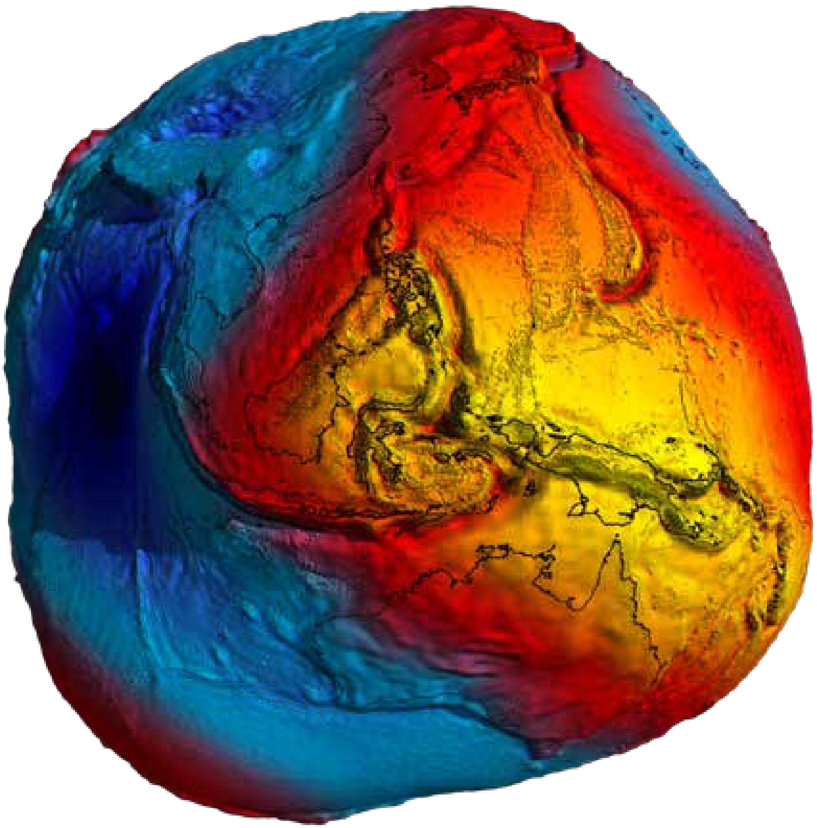


1E/sqrt(Hz)

20mE/sqrt(Hz)

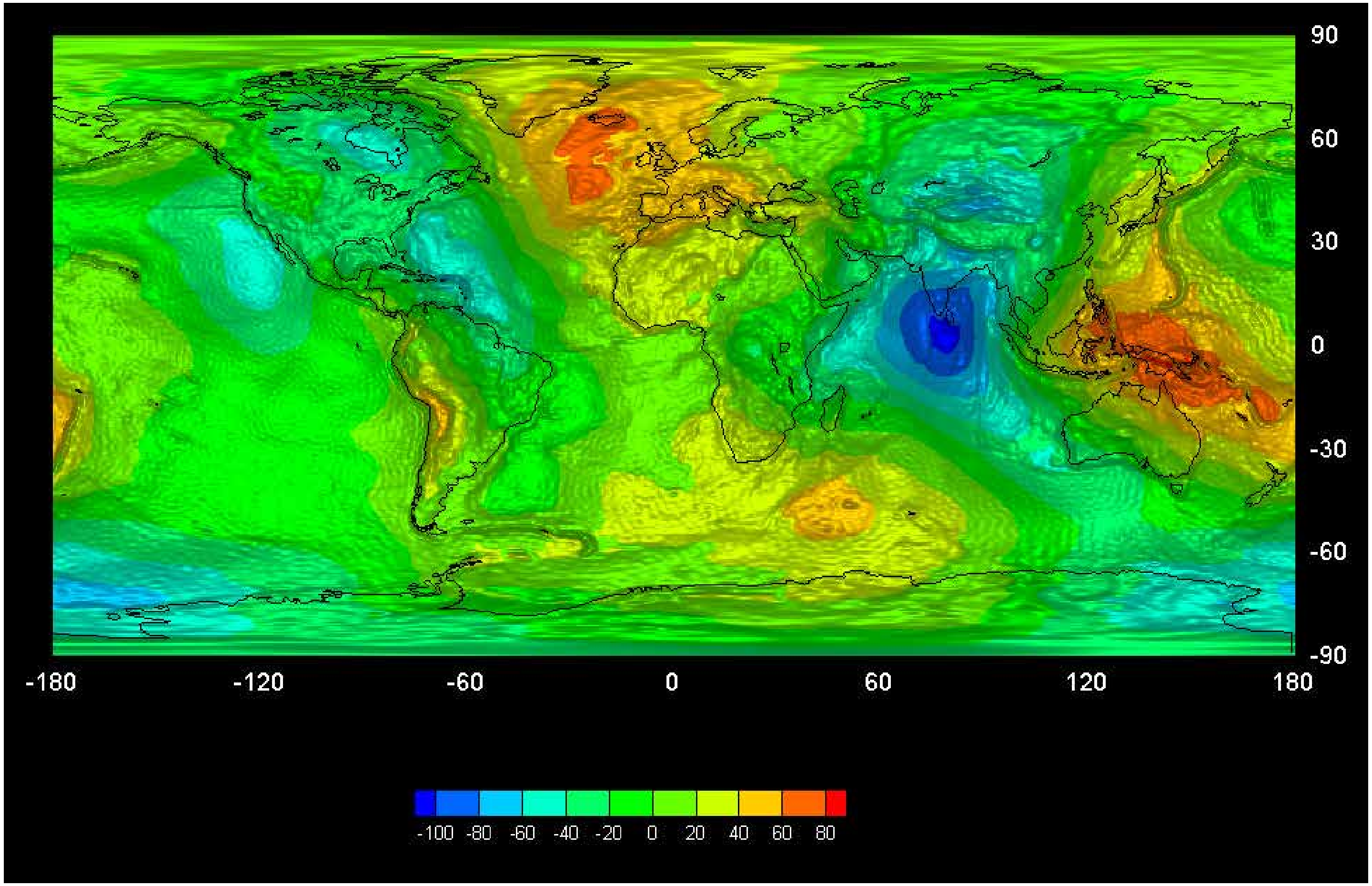
10mE/sqrt(Hz)

GOCE geoid



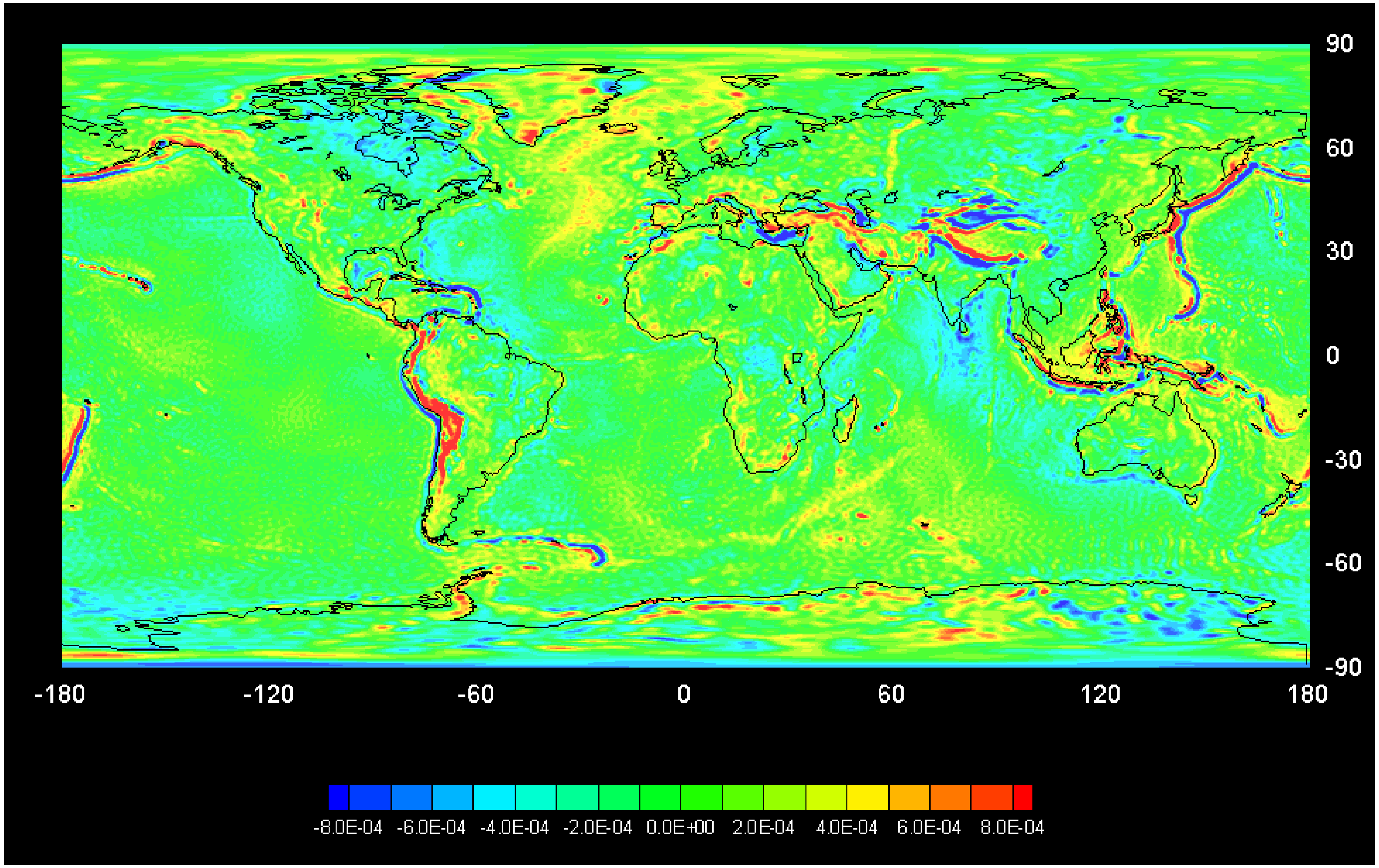
Source: ESA

GOCE geoid



global map of geoid heights from only two months of data

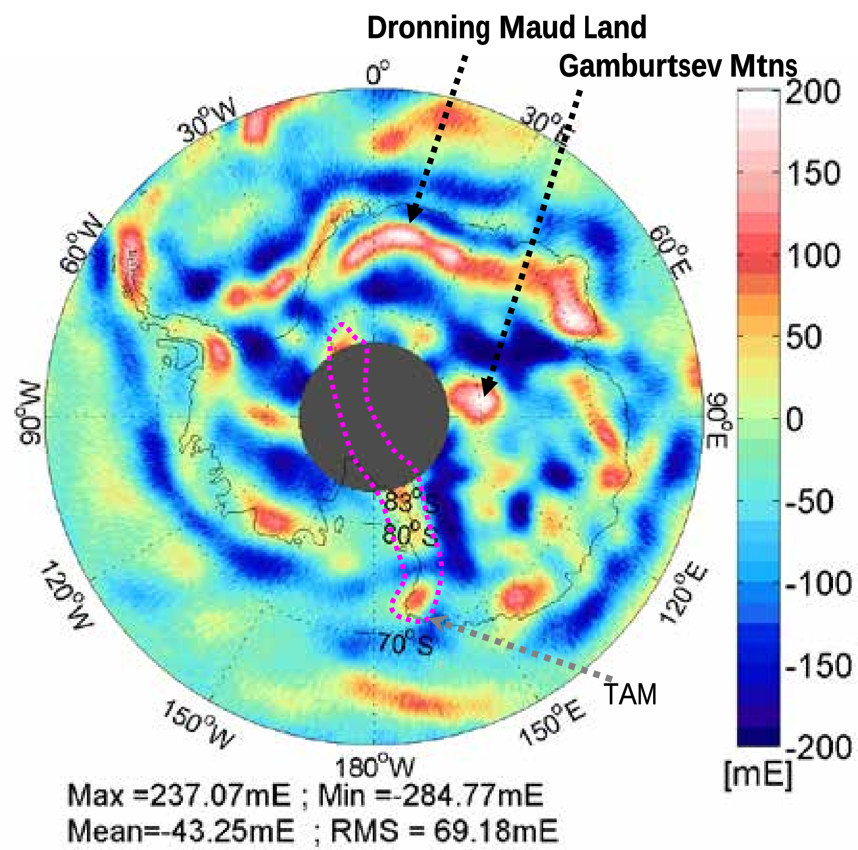
GOCE gravity



global map of gravity anomalies (1 ppm of “g”)

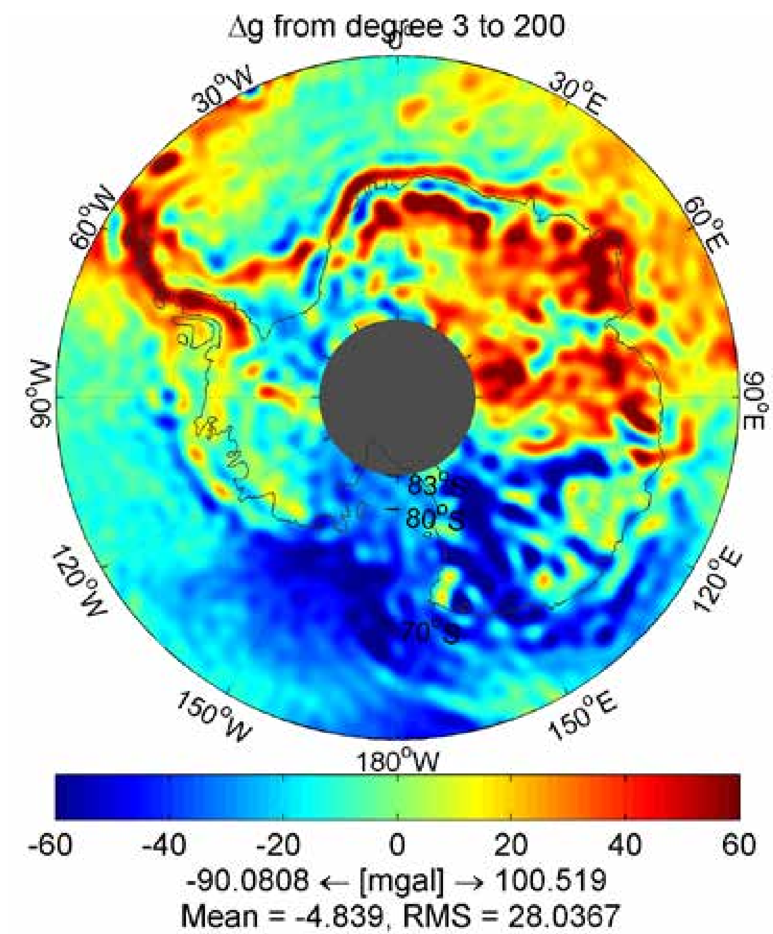
gravity field of Antarctica

raw measured gravitational gradients (z-component, filtered) and gravity anomalies in Antarctica



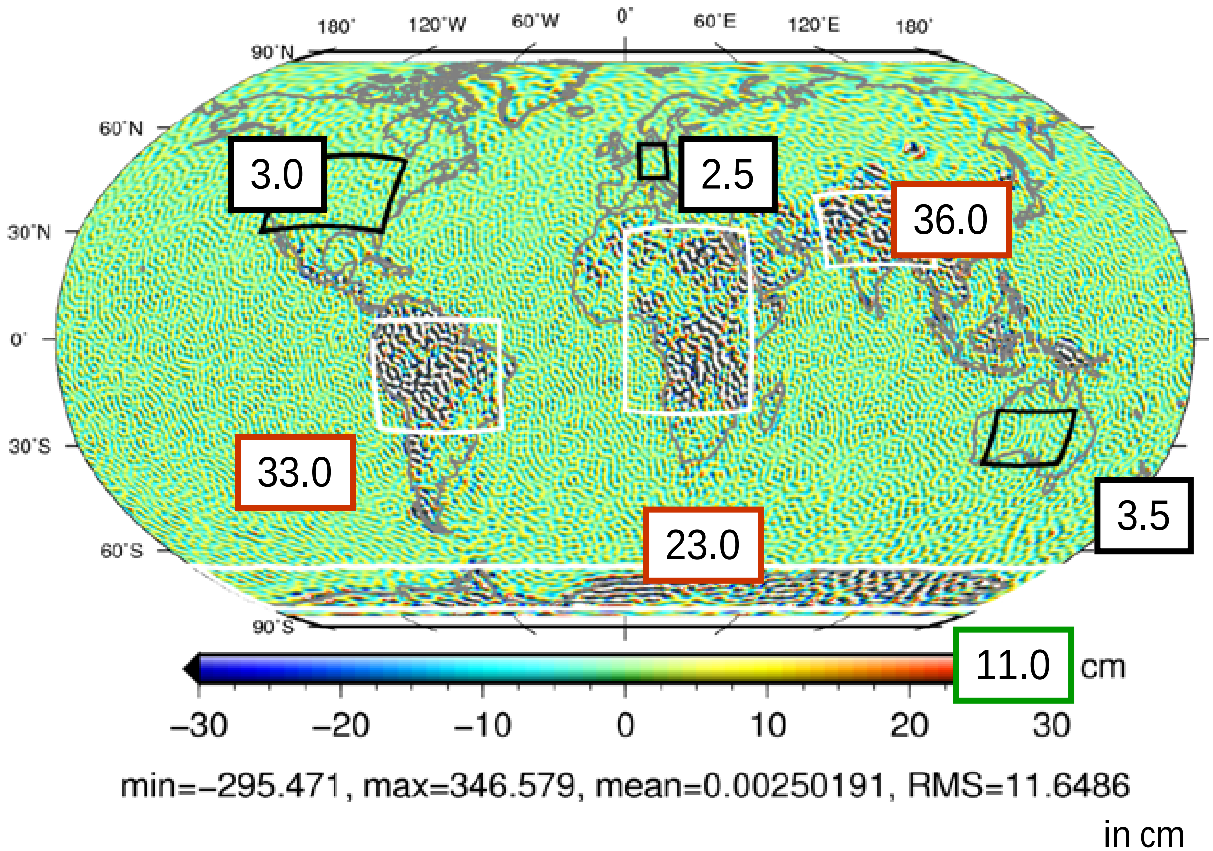
November to December 2009

Only ascending orbit arcs (polar gap in black)



Δg from 1.5 years of GOCE data

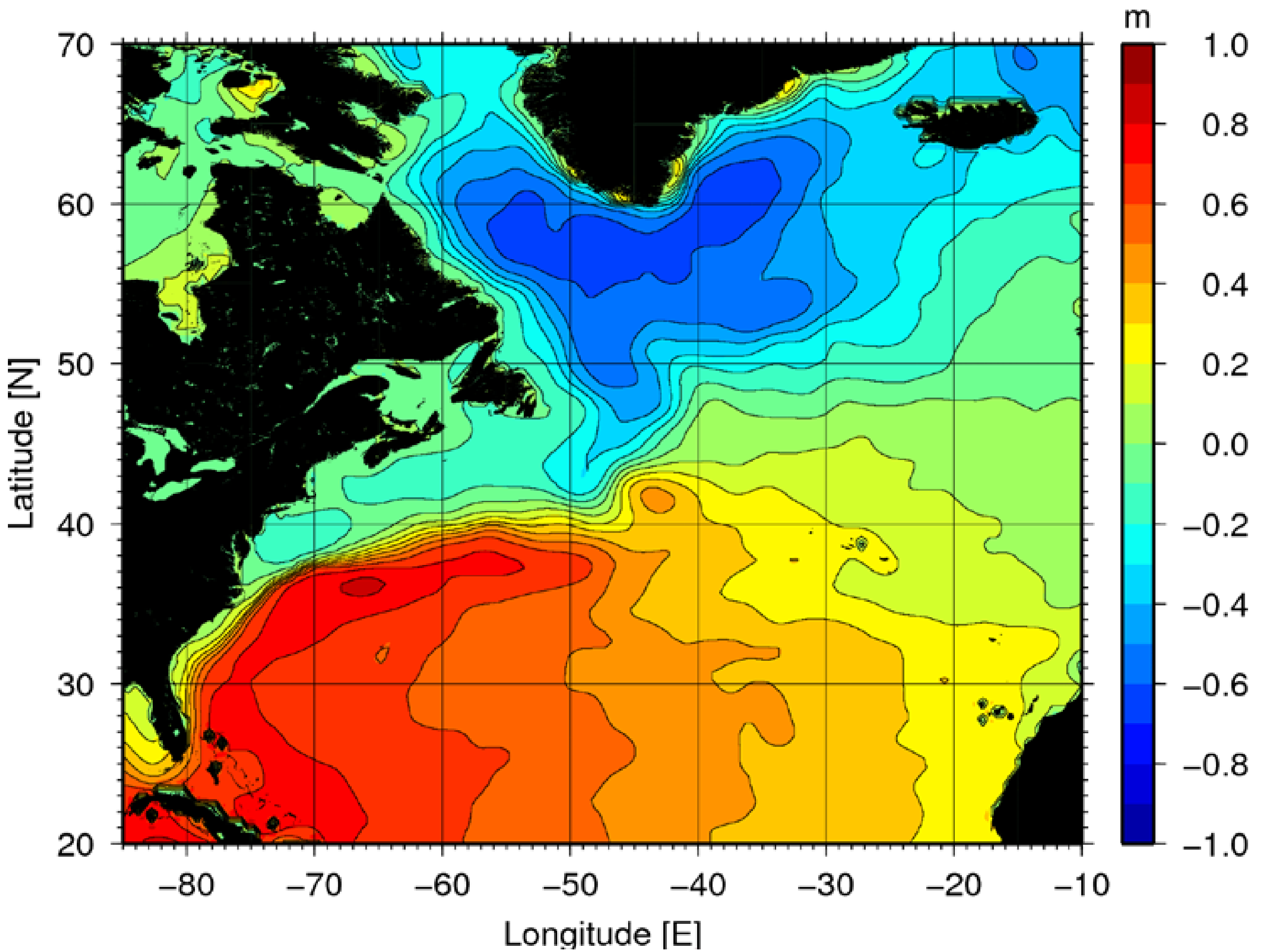
GOCE versus EGM2008



RMS geoid differences between EGM2008 and GOCE release-3

well surveyed regions (black), problematic regions (red) and Antarctica (green)

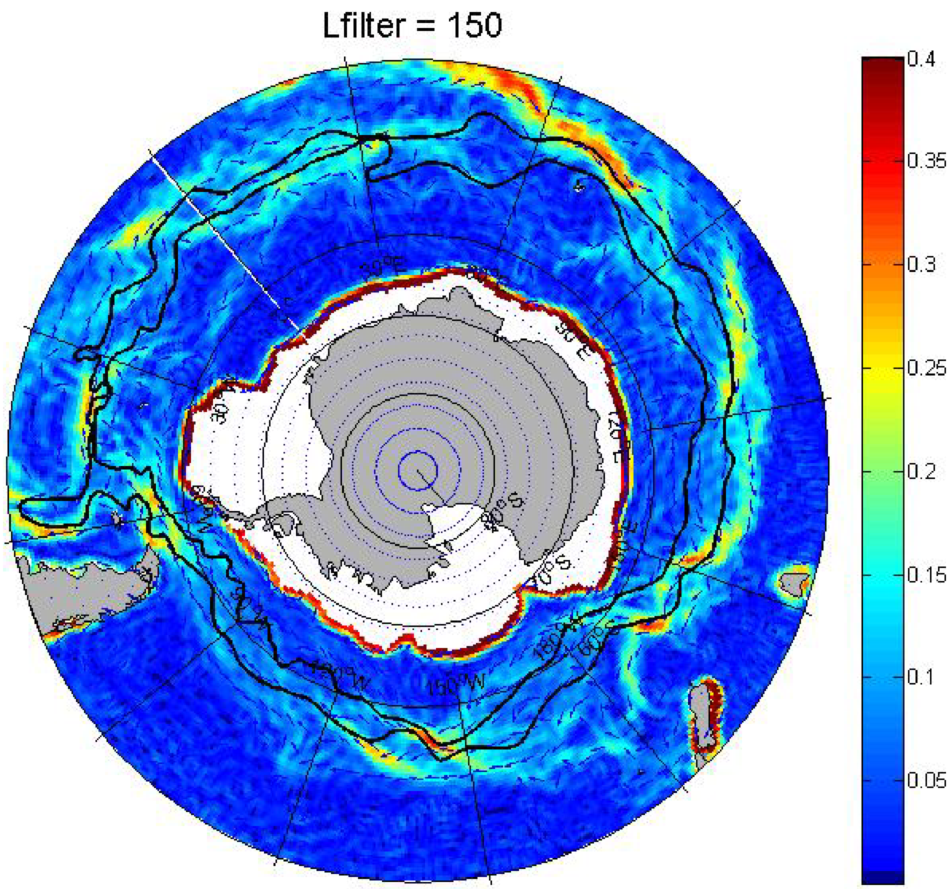
GOCE and oceanography



Bingham et al., 2011

mean dynamic ocean topography in North Atlantic

GOCE and oceanography



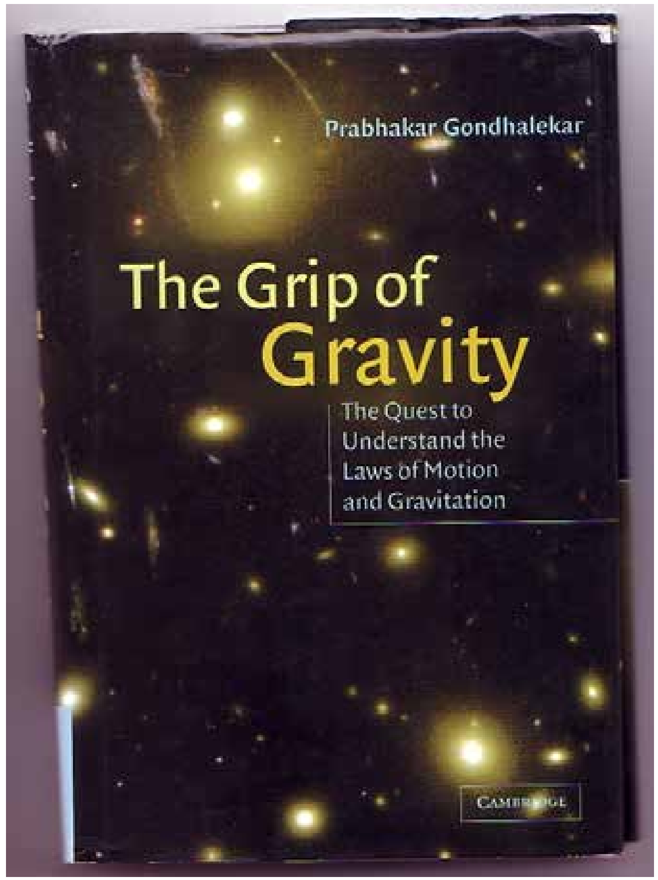
geostrophic ocean velocities

from GOCE and satellite altimetry [model: DGFI2010]

fronts (in black) from in-situ ocean measurements

conclusions

- GOCE is a gravitational field mission
- gravitation tells us about the geoid and about mass distribution
- it uses the principle of gradiometry (=acceleration differences) in order to counteract signal attenuation
- the gradiometer measures the components {xx}, {yy}, {zz}, {xz} in the instrument reference frame
- the gradiometer is embedded in a “laboratory”, with GPS-receiver, star trackers, drag free control, angular control, calibration by shaking and high stiffness and thermal stability
- all systems work well
- satellite will be put into an even lower orbit
- currently the data are re-processed
- GOCE serves geophysics, oceanography and geodesy


Prabhakar Gondhalekar
The Grip of Gravity
The Quest to Understand the Laws of Motion and Gravitation