# Mapping and analyzing Earth's gravity gradients using Microscope data: interests and feasibility

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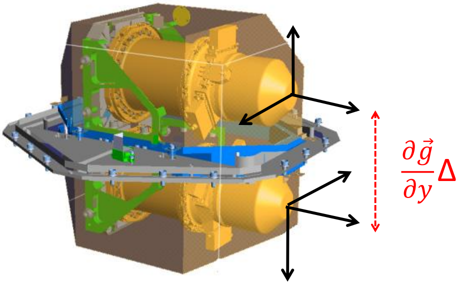
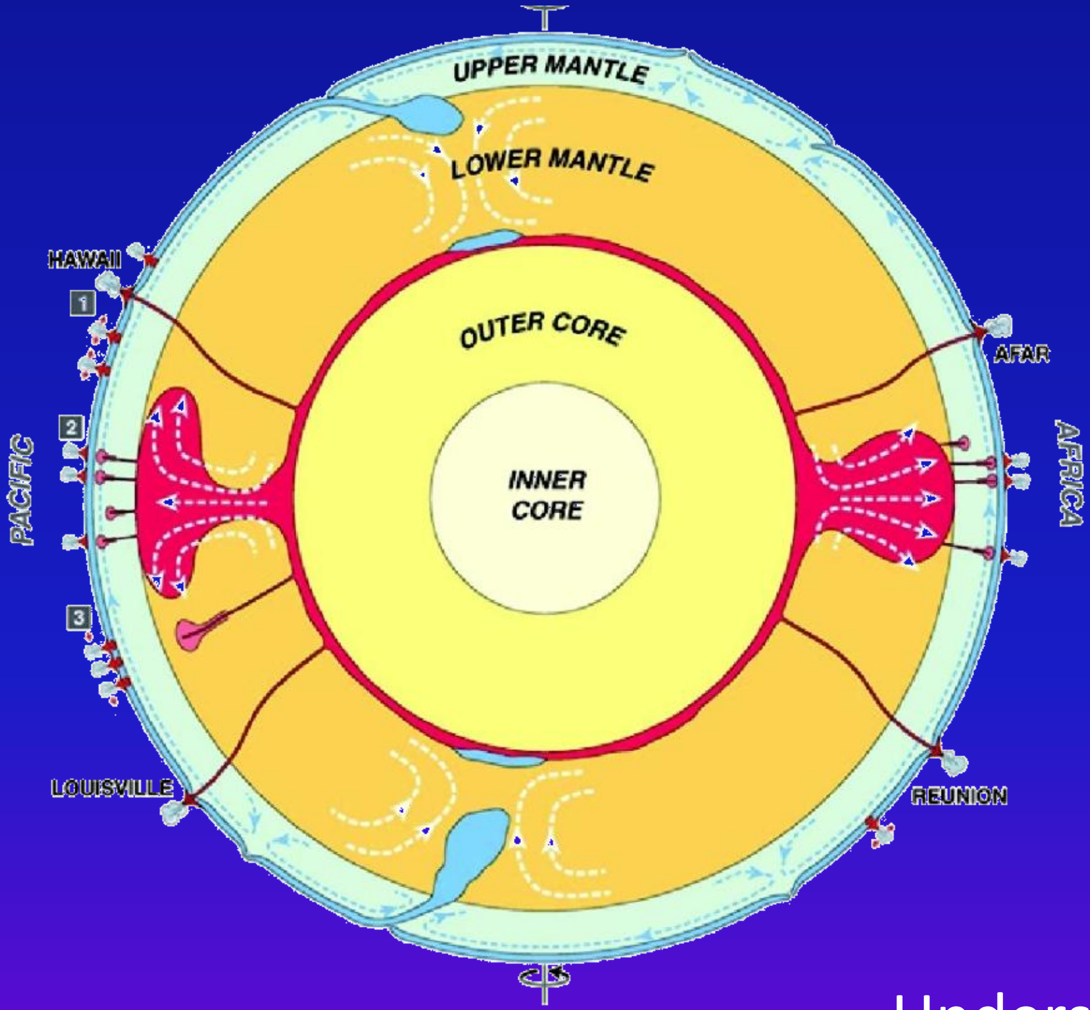
retour sur innovation

## Why gradiometry?

- The MICROSCOPE experiment contains 2 accelerometers (EP sensor unit and REF sensor unit), separated by an arm of 17 cm length
- We can therefore measure a gravitational gradient!



# Earth’s mass distribution is not homogeneous



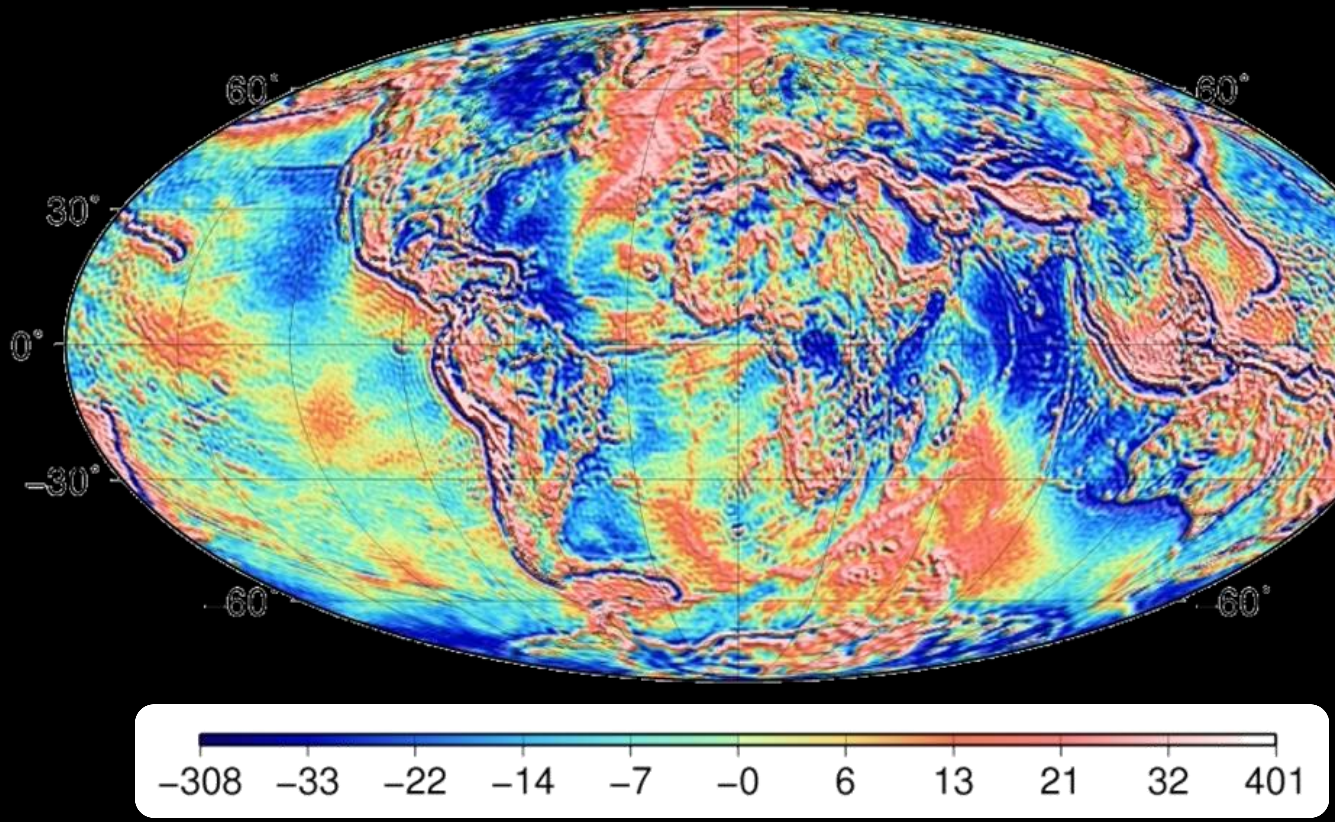

Courtillot et al. (2003)

- The rigid crust floats on a mantle which behaves as a highly viscous fluid at « long » time scales.

- The internal convection releases Earth’s internal heat to the surface and the outer space

- Understand current structure and Earth’s evolution in time?

# As a result, Earth’s gravity intensity varies in space…




x $10^{-6}$ g

*contribution from a homogeneous ellipsoidal Earth removed*

# Gravity varies in time as these masses move

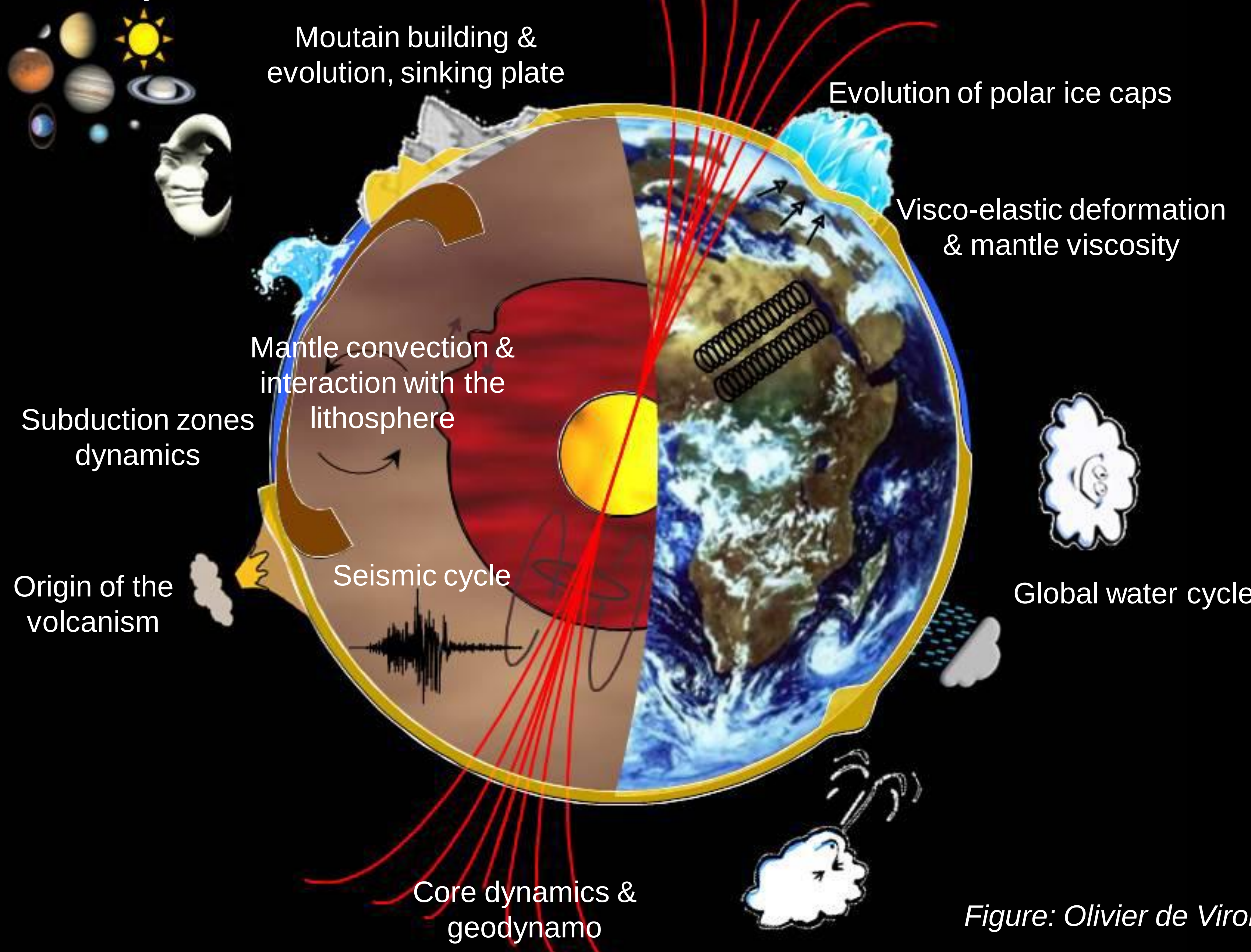
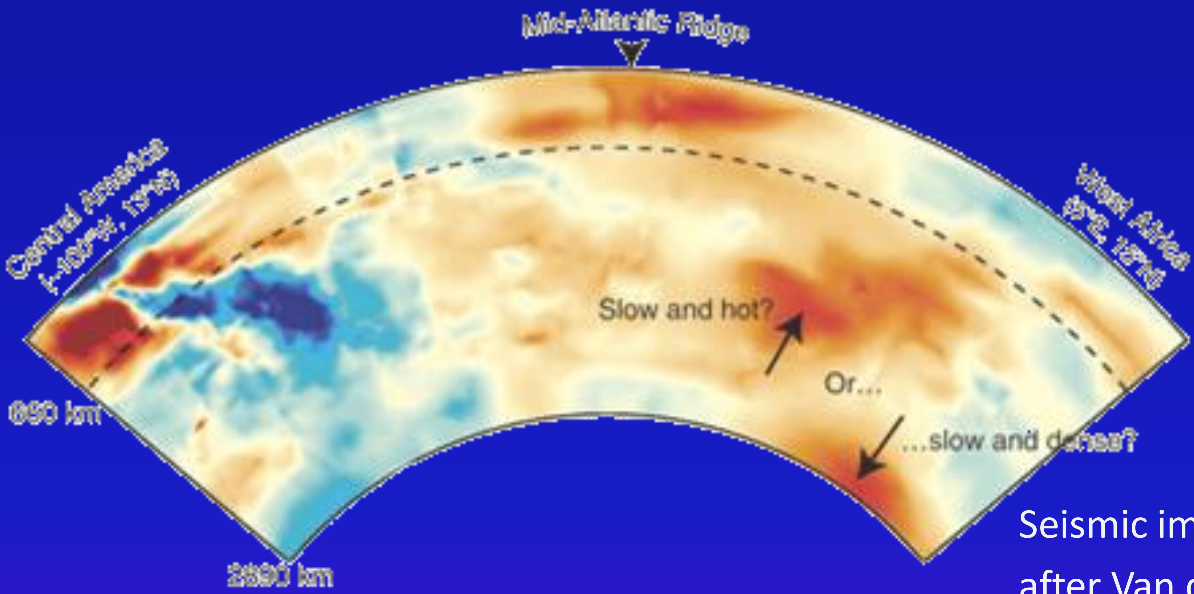



*Figure: Olivier de Viron*

- *Density is a key parameter to model Earth's internal structure and dynamics*

*Buoyancy forces driving the motions*
*Light: moves up ; heavy: moves down*




Seismic image of Earth's interior, after Van der Hilst (2004)

- *Interpreting seismic velocities in terms of density variations requires independent data.*

Gravity

# What kind of gravity data?

- Even if differential measurements of gravity are an early concept (Cavendish, Eötvös), analyzing the field intensity is more usual

**Easier to measure**

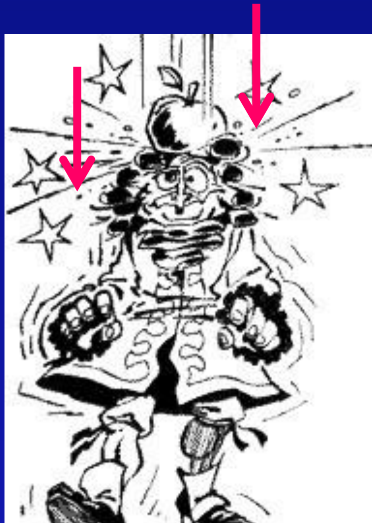
**Easier to interpret**

- However, separating signals from superimposed sources in gravity data is a crucial step, that benefits from a directional information

**Identify sources geometries**

⟶ ***Gravity gradients***

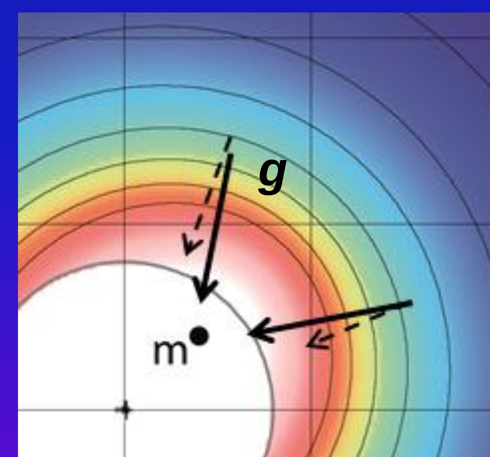
# Gravity vector deflections



Gottlieb

In addition to modifying its intensity,

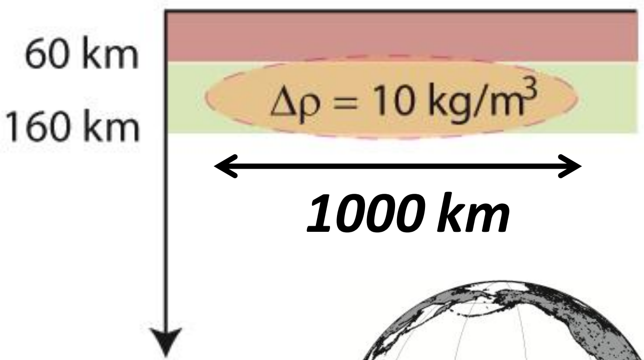
density heterogeneities slightly deflect the gravity vector towards the source

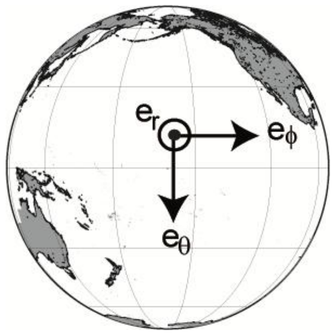



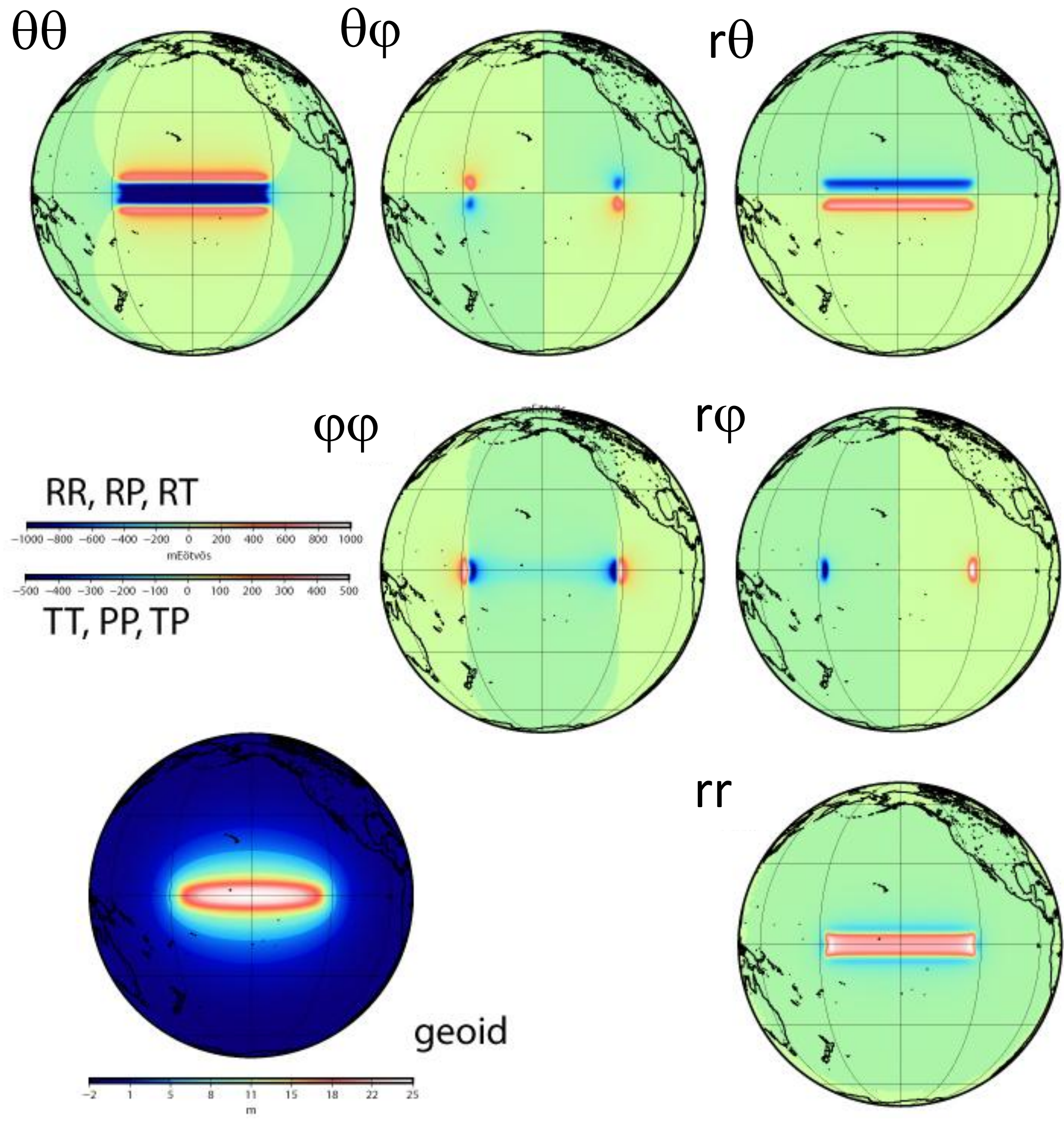

*Case of a mass excess*

# *Shallower source: gradients tensor*

Source



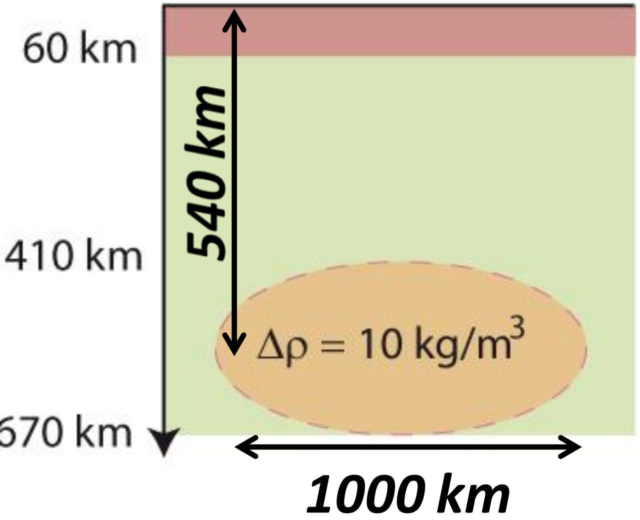

***Geometry of masses***

***High resolution***

$$T_{ij} = \frac{\partial}{\partial i} g_j$$

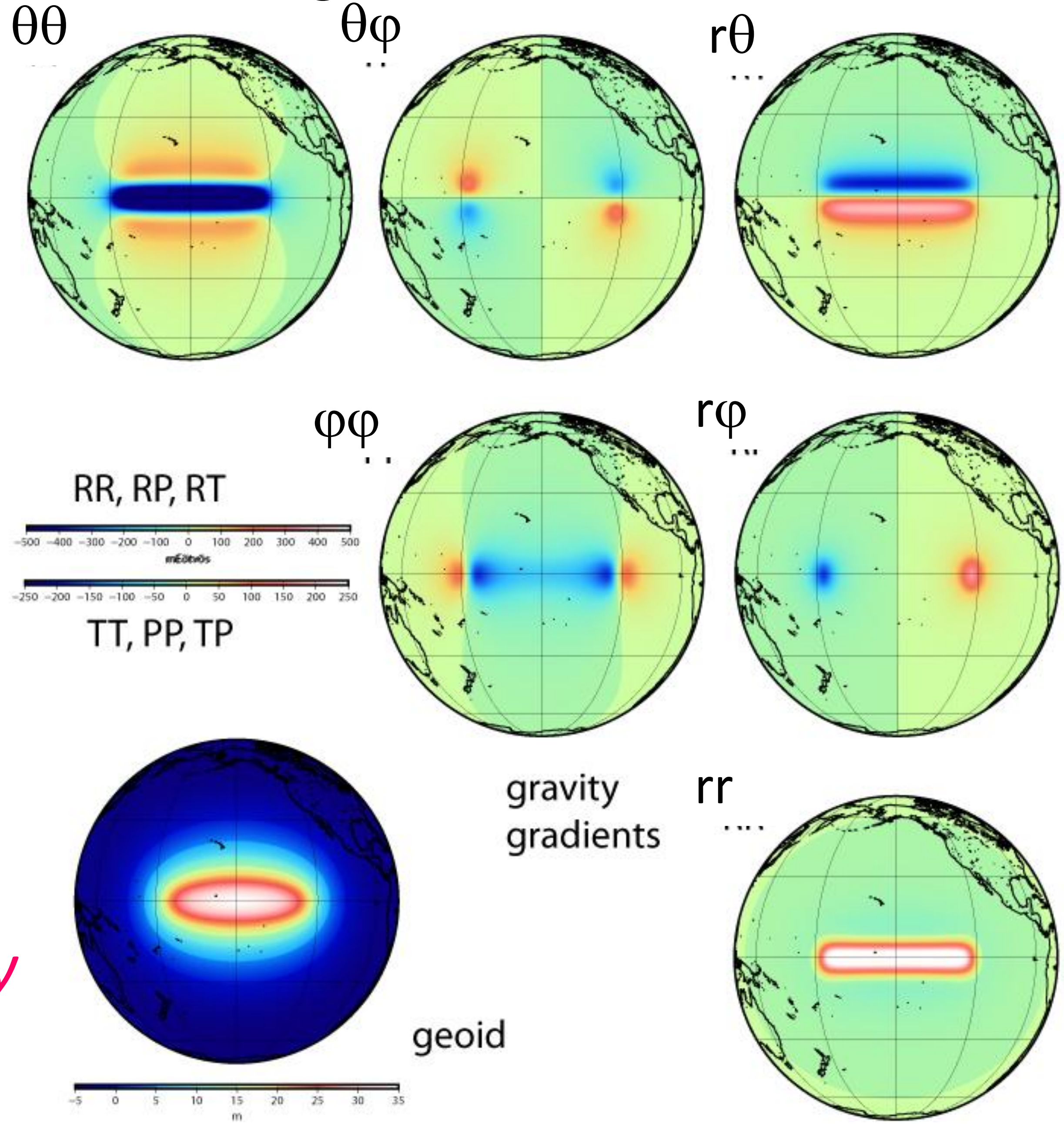
$$\Delta T = T_{xx} + T_{yy} + T_{zz} = 0$$

# *Deeper source: gradients tensor*

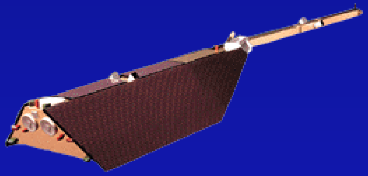
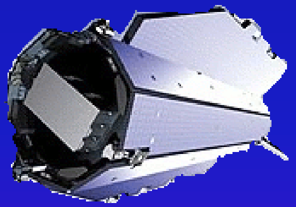



***Source resolved if width/depth ratio is large enough***

*A high accuracy description of gravity variations*

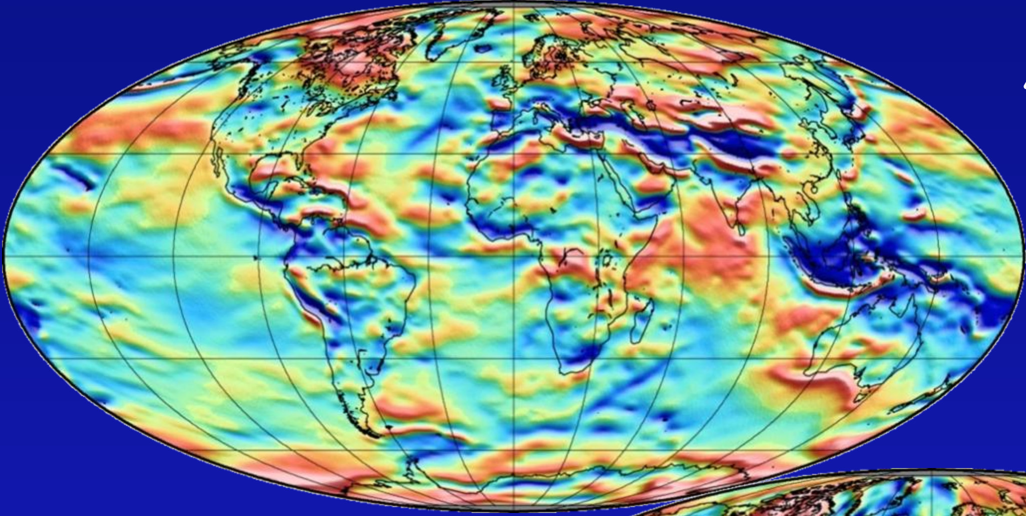


# *GOCE changes the way we look at gravity*

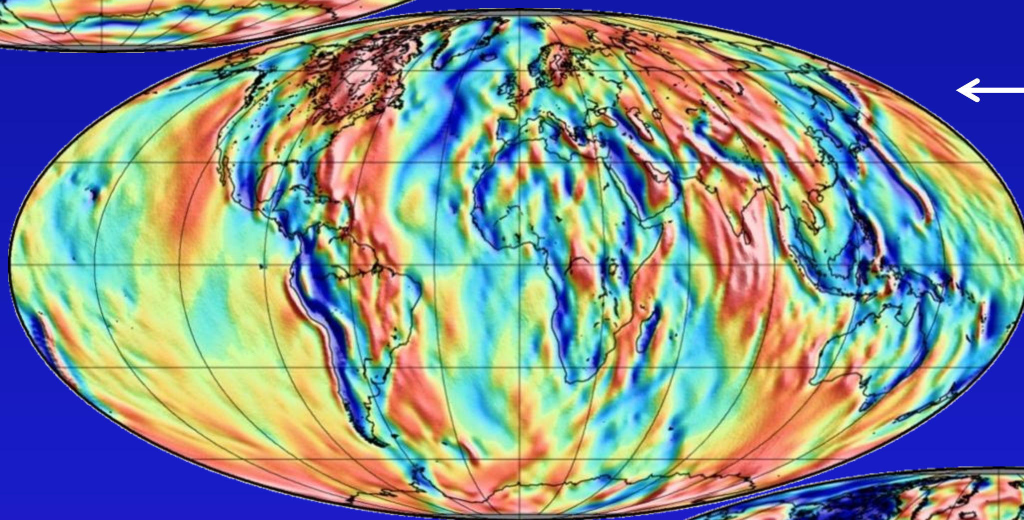
| | | |
|---|---|---|
| *CHAMP* | $g$ |  |
| *GRACE* | $g(t)$ |  |
| *GOCE* | $\vec{g}$ |  |

For the first time, GOCE makes us look at the gravity vector variations at a planetary scale

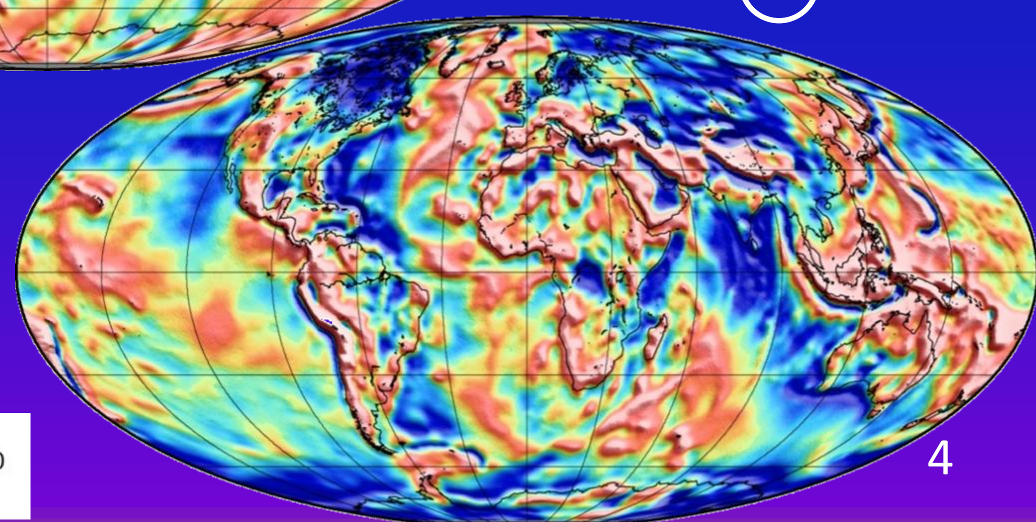
# Gradient anomalies at GOCE altitude



*XX*



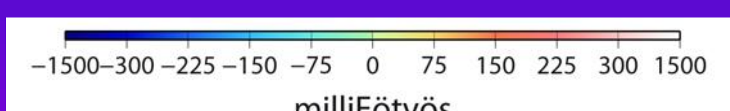
*YY*



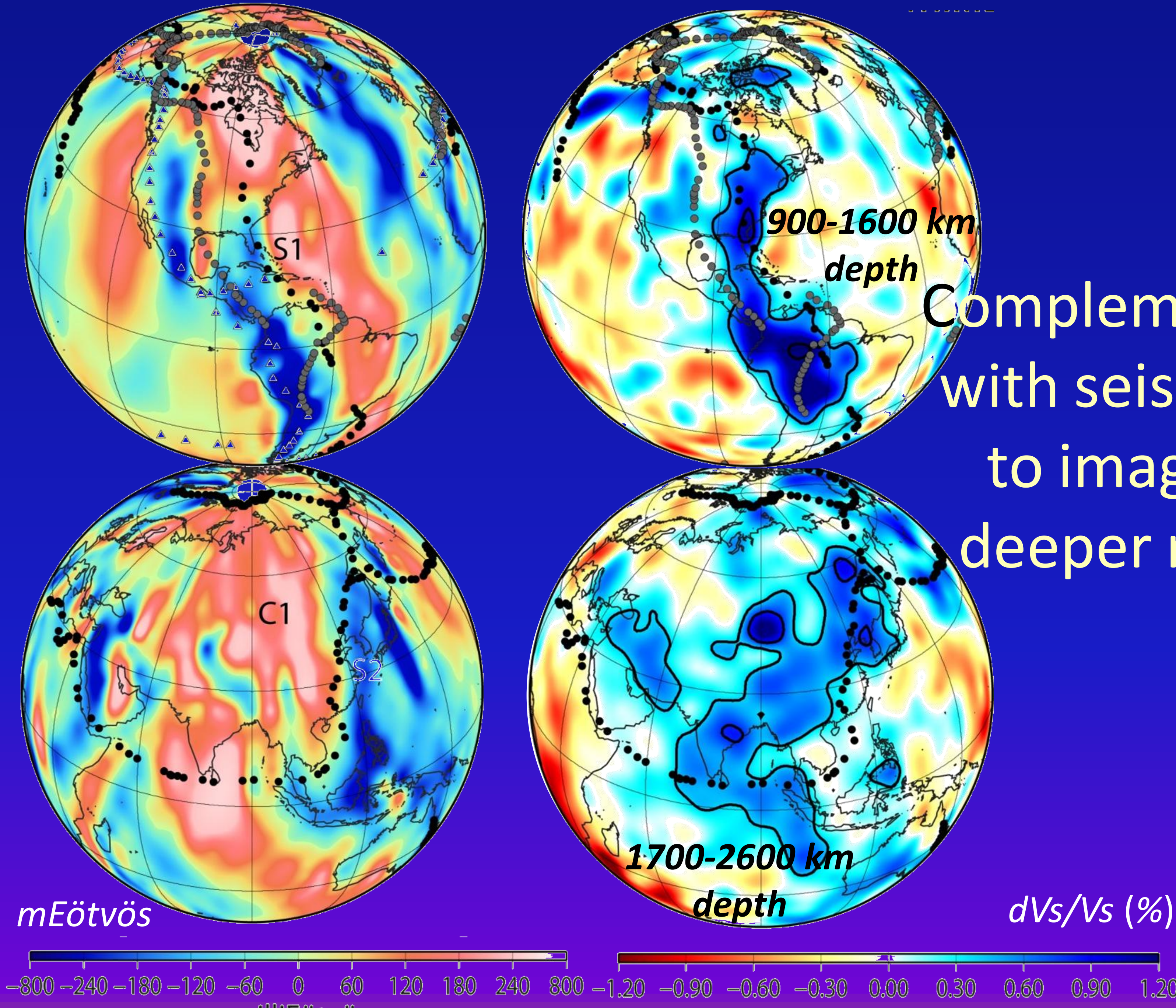
*ZZ*

Reference:

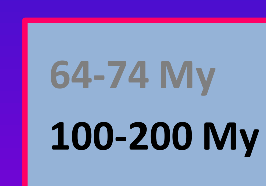
- PREM radial structure
- Hydrostatic self-gravitating equilibrium of a rotating spheroid



*YY gradients* | *Seismic velocities*




Complementarity with seismology to image the deeper mantle



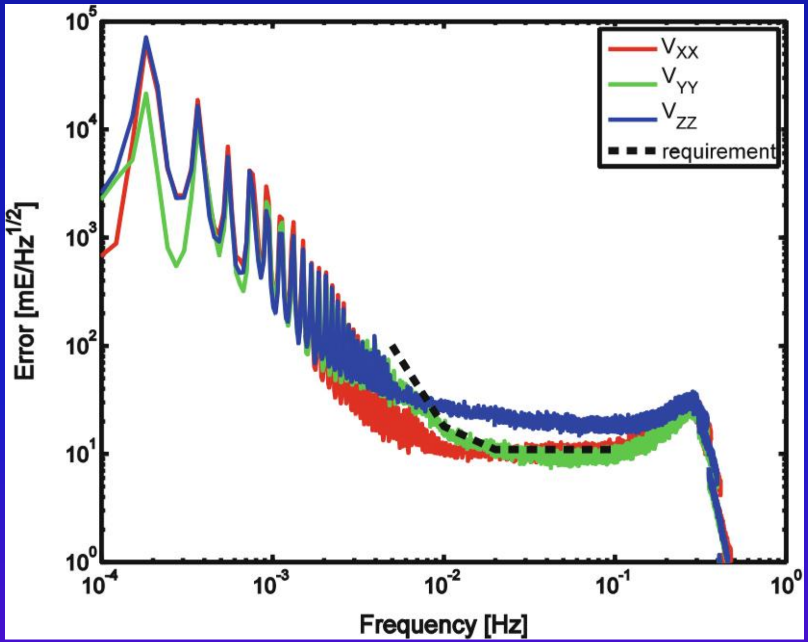
# Measuring or filtering?

Beyond the gradiometer measurement bandwidth, the large-scale gravity gradients are reconstructed from GRACE / orbit data

***5-100 mHz bandwidth (Rummel et al., 2011)***

***~40 – 740 km resolution***

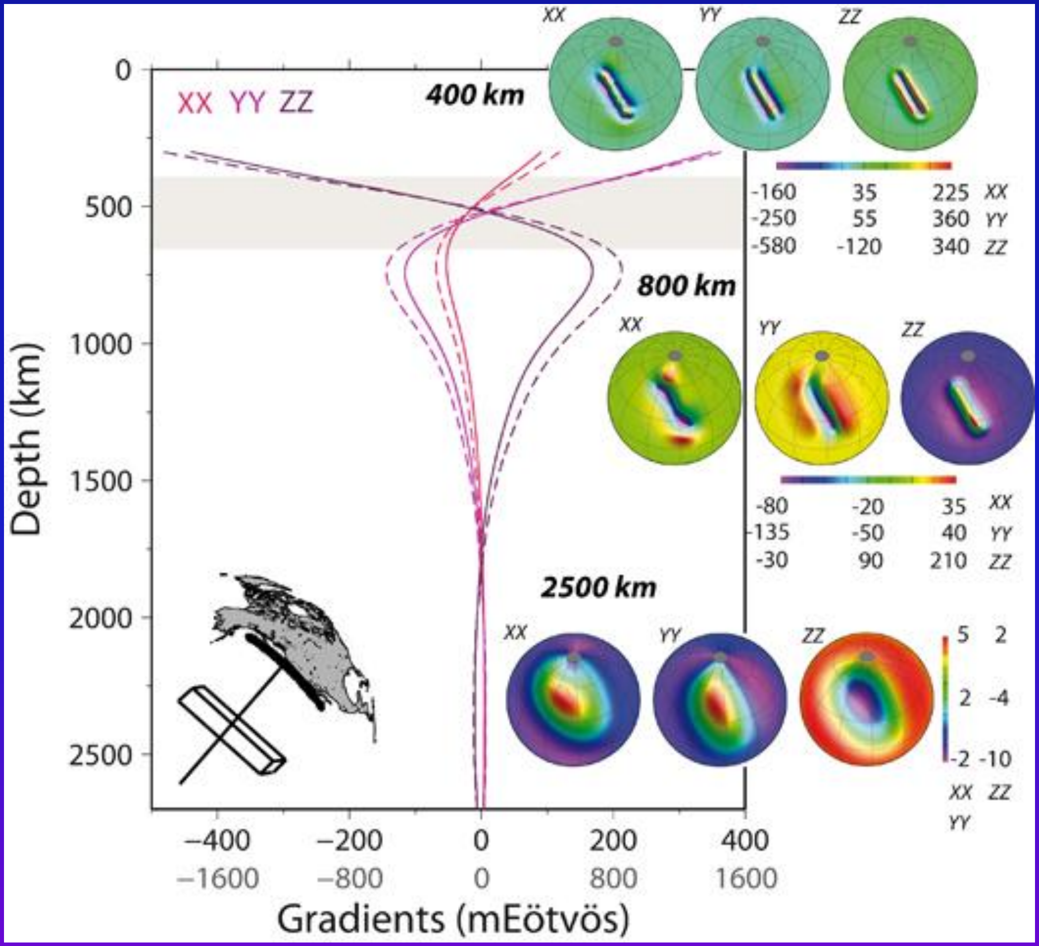
Bouman et al. (2011)




Their accuracy is not optimal – we work « as if applying a directional filter to a GRACE-based geoid ».

# Why measuring gravity gradients with high accuracy over the whole spectrum?

Because we can better identify and separate mass signals based on shape/pattern recognition, as their gravity signature may be small (also true for time-varying signals).




*Example of slab elements at various depths*

# Gravity gradients from Microscope?

1) Can Microscope data complement GOCE to measure Earth's gravity gradients:

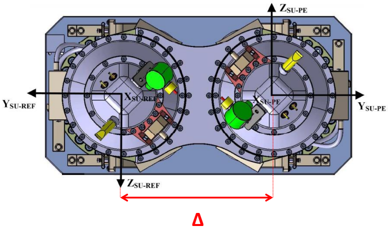
- large scales (> 800 km), beyond GOCE bandwidth
- 2 components of the tensor are not well determined from GOCE

2) Can we improve the quality of GOCE-based gravity gradients by a joint analysis with Microscope data?

*Here we consider the 'static' gravity field as time-varying signals would have a much smaller amplitude.*

## How to measure a gradient with MICROSCOPE?

- One ultra-sensitive axis (but three-axis accelerometer): X, where the EP test is performed
- Only one arm: along Y-axis, perpendicular to the orbital plane




Use the two accelerometers SU-EP and SU-REF, which are $\Delta = 17$ cm apart:

$$2\overrightarrow{\Gamma^{g}_{\mathrm{d}}} = \overrightarrow{\Gamma_{\mathrm{EP,I}}} - \overrightarrow{\Gamma_{\mathrm{REF,I}}}$$
$$= ([T] - [\mathrm{In}])\,\overrightarrow{\Delta} - 2[\Omega]\dot{\overrightarrow{\Delta}} - \ddot{\overrightarrow{\Delta}}$$

## How to measure a gradient with MICROSCOPE?

Two possibilities:

- use the X-axis: the most sensitive, but presence of angular accelerations to be estimated

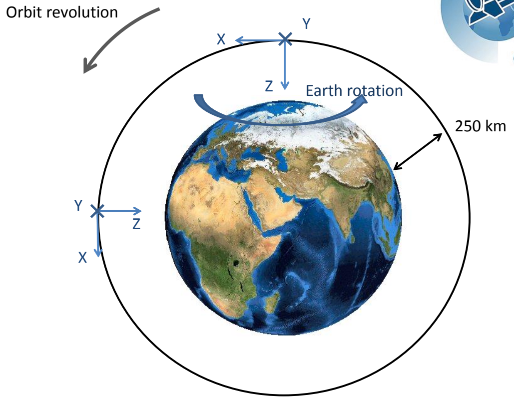
$$\Gamma^{g}_{\mathrm{d,x}} = \frac{1}{2}\Delta_y \left(T_{xy} - \Omega_x\Omega_y + \dot{\Omega}_z\right) \tag{1}$$

- use the Y-axis: less sensitive, but no need to estimate the angular accelerations

$$\Gamma^{g}_{\mathrm{d,y}} = \frac{1}{2}\Delta_y \left(T_{yy} + \Omega_x^2 + \Omega_y^2\right) \tag{2}$$

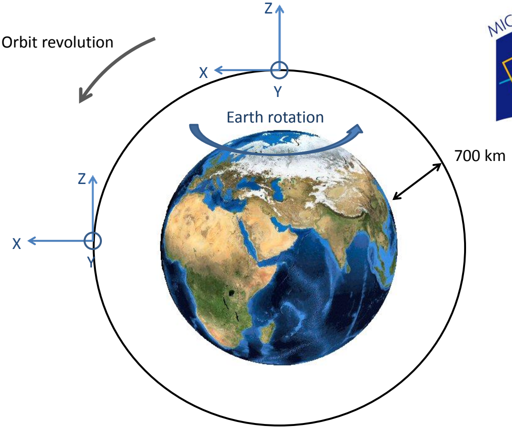
## How to measure a gradient with MICROSCOPE?

Orbit altitude and attitude control different from GOCE (= Nadir pointing)



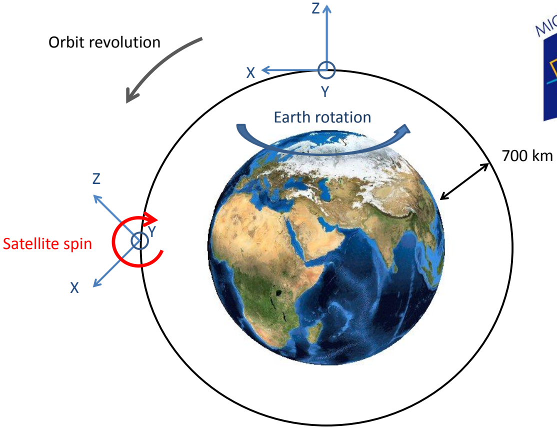

## How to measure a gradient with MICROSCOPE?

MICROSCOPE: 700 km altitude and inertial pointing...



## How to measure a gradient with MICROSCOPE?

MICROSCOPE: 700 km altitude and inertial pointing... or spin mode



## How to measure a gradient with MICROSCOPE?

As a result of this particular pointing, the gradients measured in the reference frame of the instrument "see" different components of the gradient in the Earth reference frame $T^b$ (ITRF), as a linear combination depending on time. Example of $T_{xy}$ in the instrument frame:

$$\begin{aligned} T_{xy} \quad = \quad & -\frac{1}{2}\left(\sin 2\omega_e \sin I\right) T^b_{xx} + \frac{1}{2}\left(\left(\cos 2\omega_e + 1\right) \sin I\right) T^b_{yy} \\ & + \left(\cos 2\omega_e \sin I\right) T^b_{xy} - \left(\cos \omega_e \cos I\right) T^b_{xz} - \left(\sin \omega_e \cos I\right) T^b_{yz} \end{aligned}$$

| | |
|---|---|
| $\omega_e = \Omega - \theta$: | difference between argument of the ascending node and Earth rotation |
| $I$: | orbit inclination |

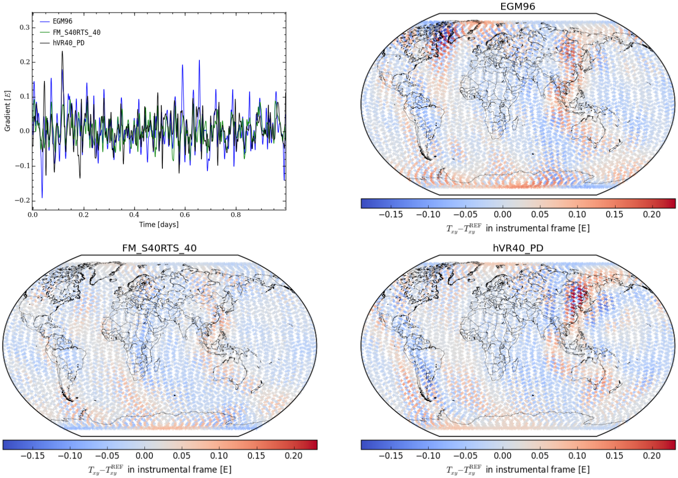
## Preliminary simulations

We simulate the observable $T_{xy}$ during an inertial measurement session of 120 orbits (approx. 8 days) for 3 models truncated at degree 12, to focus on large spatial wavelengths:

- EGM96: reference for "real" Earth potential (Lemoine et al., 1998)
- FM_S40RTS_40: model where the internal mass heterogeneity geometry is build from a joint analysis of geoid, gravity and gravity gradients with the seismic velocities (Greff-Lefftz et al, 2015)
- hVR40_PD: model where the internal mass heterogeneity geometry uses a reconstruction of the movement of tectonic plates from 200 Myr and also includes hot instabilities (Rouby et al., 2010)

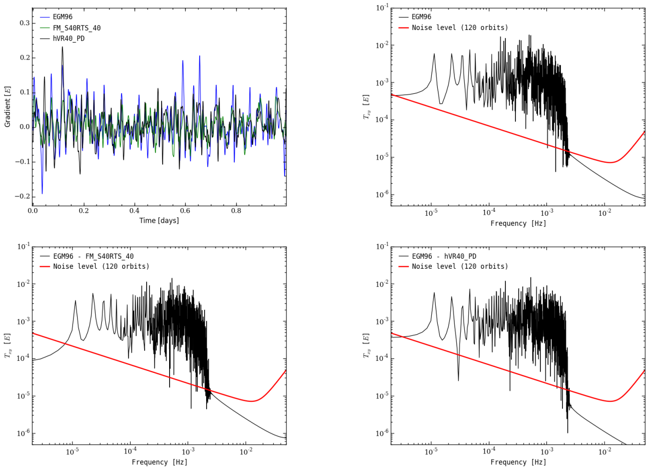
## Preliminary simulations

We simulate the observable $T_{xy}$ during an inertial of 120 orbits (approx. 8 days) for 3 models:



## Preliminary simulations

Does the instrument distinguish between the signals associated with these different model? We compare them with the instrumental noise level of the differential acceleration.



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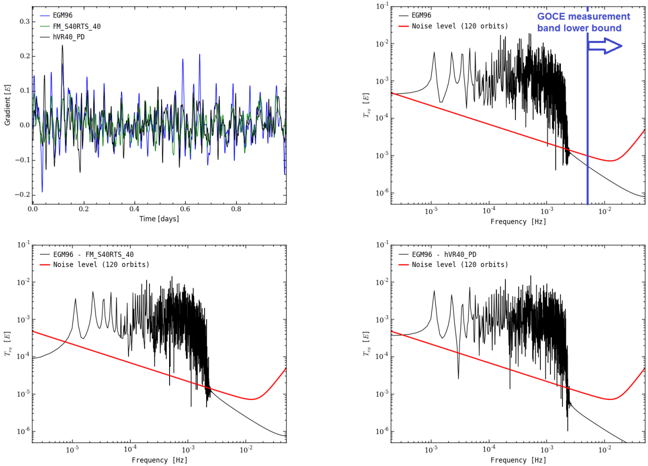

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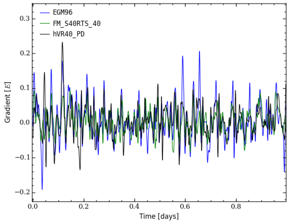
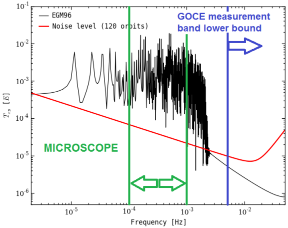
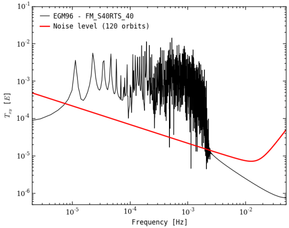
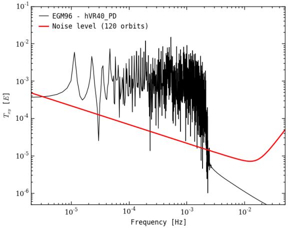


## Conclusion and perspectives

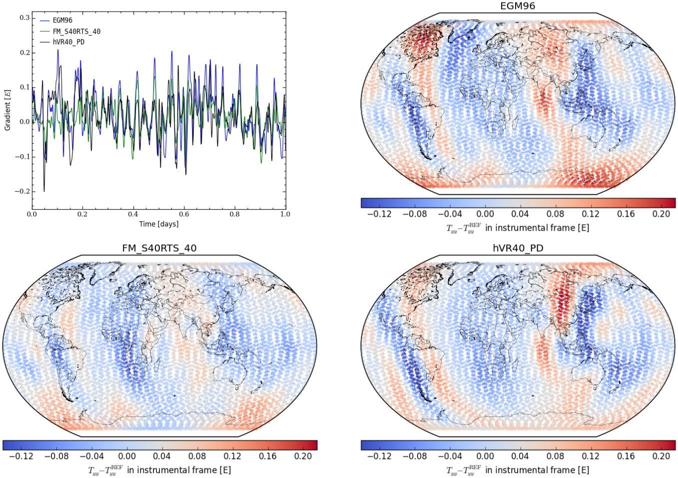
- Accurate gravity gradients below 800 km resolution are needed in order to decipher deeper from shallower sources and study the mantle dynamics from global to regional scales
- Can MICROSCOPE bring new complementary information to GOCE data in the low frequency band, below 5 mHz? (at MICROSCOPE altitude a temporal frequency $f$ correspond to a on-ground distance of $dx = 6.8$ km/f). Possibly: the sensitivity is optimized for lower frequencies than GOCE.
- Differences between Earth deep structures models are likely to be visible with MICROSCOPE
- More precise simulations remain to be done, especially about the restitution of angular rates and angular accelerations
- Calibration of the accelerometer: the use of the already existing calibration sessions is possible (preliminary study done)
- Prospects: perform comparisons with GOCE data on the same simulation cases


THANK YOU !

Appendix

# Appendix

# Maps of $T_{yy}$ in the instrument reference frame



# Appendix

## $T_{yy}$ simulations