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

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1 Introduction: science case
2 Measurement principle
3 Preliminary study
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

- 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?

_Courtillot et al. (2003)_
As a result, Earth’s gravity intensity varies in space...

contribution from a homogeneous ellipsoidal Earth removed
Gravity varies in time as these masses move

- Evolution of polar ice caps
- Visco-elastic deformation & mantle viscosity
- Global water cycle
- Seismic cycle
- Mantle convection & interaction with the lithosphere
- Origin of the volcanism
- Subduction zones dynamics
- Core dynamics & geodynamo
- Moutain building & evolution, sinking plate

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.**
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

  $\rightarrow$ Gravity gradients
Gravity vector deflections

In addition to modifying its intensity, density heterogeneities slightly deflect the gravity vector towards the source.

Case of a mass excess
Source

\[ \Delta \rho = 10 \text{ kg/m}^3 \]

60 km

160 km

1000 km

Shallower source: gradients tensor

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

\[ T_{ij} = \frac{\partial}{\partial i} g_{ij} \]

Geometry of masses

High resolution

rr, \(\phi\phi\), \(r\theta\), \(r\phi\), \(\theta\theta\), \(\theta\phi\), TT, PP, TP

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

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

Reference:
- PREM radial structure
- Hydrostatic self-gravitating equilibrium of a rotating spheroid
YY gradients

Seismic velocities

Complementarity with seismology to image the deeper mantle

mEötvös

900-1600 km depth

1700-2600 km depth

dVs/Vs (%)
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.
Measurement principle

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:

$$2\Gamma_d = \Gamma_{EP,I} - \Gamma_{REF,I}$$

$$= ([T] - [In]) \Delta - 2[\Omega] \dot{\Delta} - \ddot{\Delta}$$
How to measure a gradient with MICROSCOPE?

Two possibilities:

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

\[
\Gamma_{d,x}^g = \frac{1}{2} \Delta_y \left( T_{xy} - \Omega_x \Omega_y + \dot{\Omega}_z \right)
\]  

(1)

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

\[
\Gamma_{d,y}^g = \frac{1}{2} \Delta_y \left( T_{yy} + \Omega_x^2 + \Omega_y^2 \right)
\]  

(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...
Measurement principle

How to measure a gradient with MICROSCOPE?

MICROSCOPE: 700 km altitude and inertial pointing... or spin mode
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 $T^b_{bb}$ (ITRF), as a linear combination depending on time. Example of $T_{xy}$ in the instrument frame:

$$T_{xy} = -\frac{1}{2} (\sin 2\omega_e \sin I) T_{xx}^b + \frac{1}{2} ((\cos 2\omega_e + 1) \sin I) T_{yy}^b + (\cos 2\omega_e \sin I) T_{xy}^b - (\cos \omega_e \cos I) T_{xz}^b - (\sin \omega_e \cos I) T_{yz}^b$$

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

$I$: orbit inclination
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 study

Preliminary simulations

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

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.
Preliminary study

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Does the instrument distinguish between the signals associated with these different model? We compare them with the instrumental noise level of the differential acceleration.
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 $dx = 6.8 \text{ km/f}$). 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!

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Appendix

$T_{yy}$ simulations

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

\( T_{yy} \) simulations

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