

# Analysis of spatial correlations between satellite-measured gravity anomalies and geological structures of the Earth's mantle

**Dimitris Tsoulis**<sup>(1)</sup>, Jérôme Verdun<sup>(2)</sup>, José Cali<sup>(2)</sup>, Frédéric Durand<sup>(2)</sup>, Frédéric Masson<sup>(3)</sup>

- 1: Aristotle University of Thessaloniki (AUTH) - Department of Geodesy and Surveying  
Univ Box 440, 54 124 Thessaloniki (Greece)
- 2: National Conservatory of Arts and Crafts (Cnam) - Geomatics, Planning and Land Law  
Lab (GeF) ESGT Le Mans (France)
- 3: Institute of Physics of the Earth of Strasbourg (IPGS) - EOST Strasbourg (France)



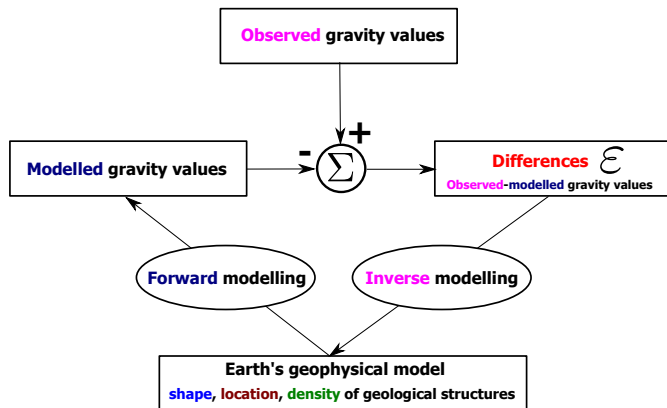
le cnam  
Laboratoire  
Géomatique et Foncier G&F

EOST  
Ecole et Observatoire  
des Sciences de la Terre



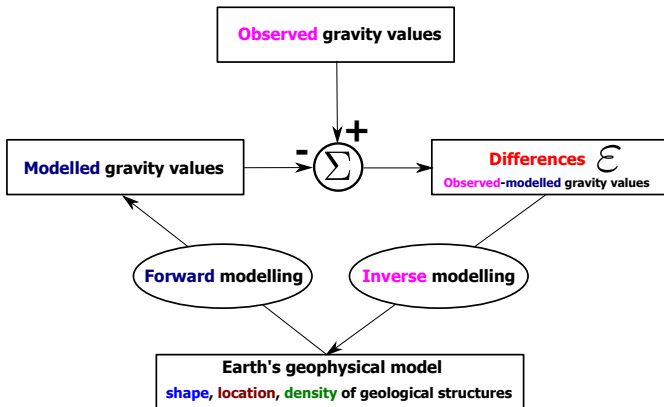
## Why such an analysis ?

- Basic idea: the use of satellite gravity observations to refine Earth's geophysical models



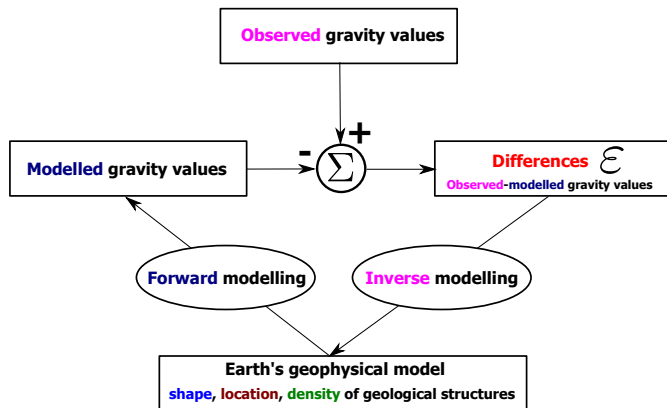
## Why such an analysis ?

- The best model is obtained when  $\|\varepsilon\|$  is minimal



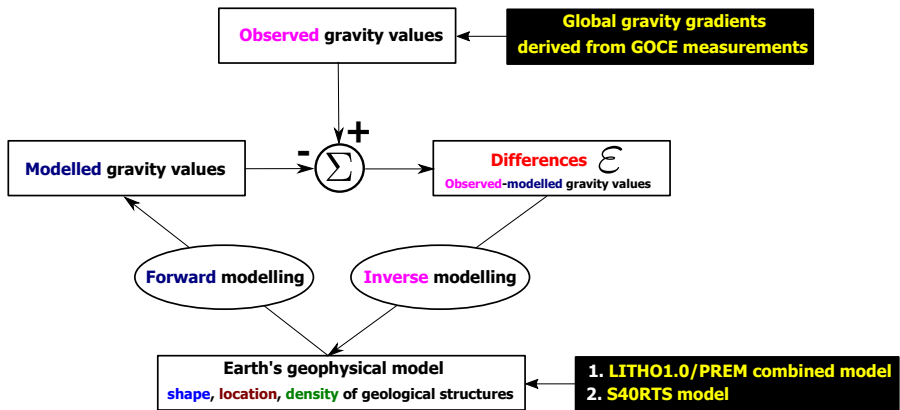
## Why such an analysis ?

- For inversion to be possible from an initial model,  $\|\varepsilon\|$  must not be too large

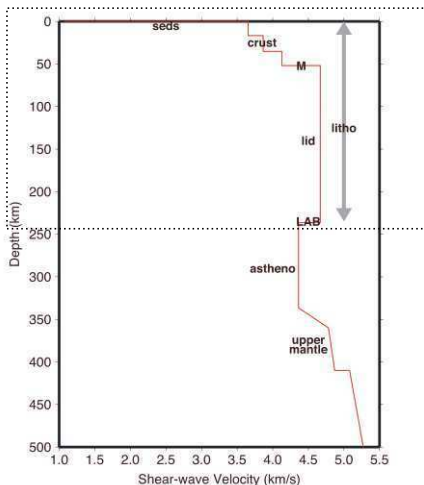


## Our own experiments

- Comparison of GOCE-derived gravity gradients at GOCE altitude with their modelling values from two Earth's geophysical models



# 1<sup>st</sup> Earth's geophysical model: LITHO1.0

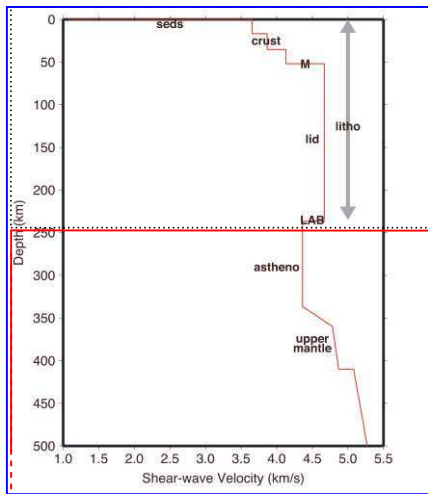


## LITHO1.0

Available at 1°x1° resolution

Pasyanos, M. E., Masters, T.G., Laske, G. and Z. Ma (2014). LITHO1.0: An update crust and lithospheric model: *J. Geophys. Res. Solid Earth*, 119, 2153-2173, doi: 10.1002/2013JB010626

# 1<sup>st</sup> Earth's geophysical model: LITHO1.0~PREM



## LITHO1.0

Available at  $1^\circ \times 1^\circ$  resolution

## PREM

Dziewonski and Anderson, 1981

## Combined model

Pasyanos, M. E., Masters, T.G., Laske, G. and Z. Ma (2014). LITHO1.0: An update crust and lithospheric model: *J. Geophys. Res. Solid Earth*, 119, 2153-2173, doi: 10.1002/2013JB010626

## LITHO1.0: physical parameters

num	layer	parameters
1	ice	(thickness), (vp), (vs), ( $\rho$ ), (Q)
2	water	(thickness), (vp), (vs), ( $\rho$ ), (Q)
3	sediment layer 1	(thickness), (vp), (vs), ( $\rho$ ), (Q)
4	sediment layer 2	(thickness), (vp), (vs), ( $\rho$ ), (Q)
5	sediment layer 3	(thickness), (vp), (vs), ( $\rho$ ), (Q)
6	upper crust	thickness, vp, vs, $\rho$ , (Q)
7	middle crust	thickness, vp, vs, $\rho$ , (Q)
8	lower crust	thickness, vp, vs, $\rho$ , (Q)
9	lithospheric mantle (lid)	thickness, vp, vs, ( $\rho$ ), (Q)
10	asthenospheric mantle	vp, vs, ( $\rho$ ), (Q)

Surface

Basement

Moho  
LAB

ak135

<sup>a</sup>Parameters unmodified from the starting model are shown in parentheses.

Pasyanos et al., 2014

### Starting models

#### CRUST1.0

Laske et al., 2012

#### LLNL-G3D

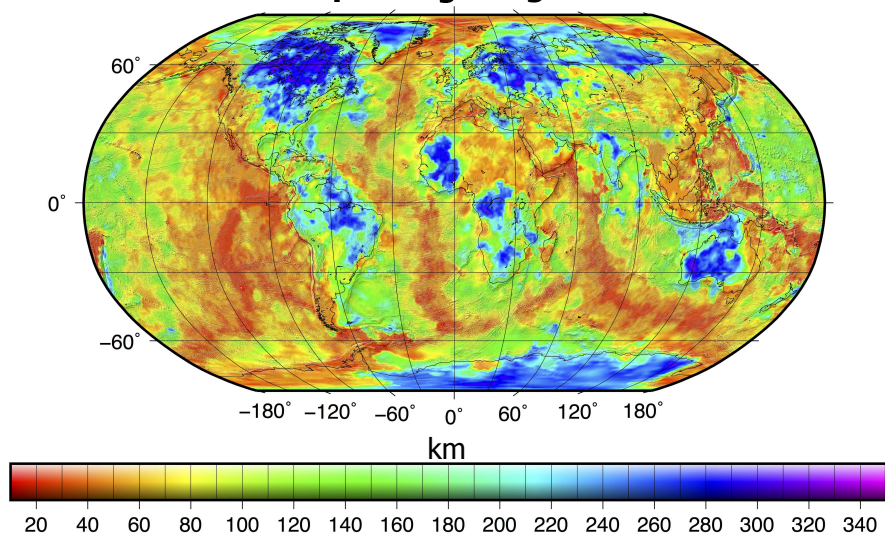
Simmons et al., 2012

Pasyanos, 2010 (thickness)

Kennett et al., 1995



## Maximum depth of geological structures



## Software used: **Tesseroids**<sup>1</sup>

- 1: Uieda, L., V. Barbosa, and C. Braitenberg (2016), Tesseroids: Forward-modeling gravitational fields in spherical coordinates, GEOPHYSICS, F41-F48, doi:10.1190/geo2015-0204.1

## Software used: **Tesseroids**<sup>1</sup>

1: Uieda, L., V. Barbosa, and C. Braitenberg (2016), Tesseroids: Forward-modeling gravitational fields in spherical coordinates, GEOPHYSICS, F41-F48, doi:10.1190/geo2015-0204.1

- Numerical integration based on the Gauss-Legendre quadrature

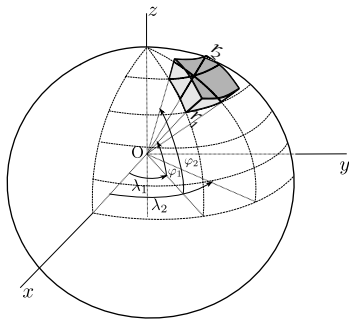
## Software used: **Tesseroids**<sup>1</sup>

1: Uieda, L., V. Barbosa, and C. Braitenberg (2016), Tesseroids: Forward-modeling gravitational fields in spherical coordinates, GEOPHYSICS, F41-F48, doi:10.1190/geo2015-0204.1

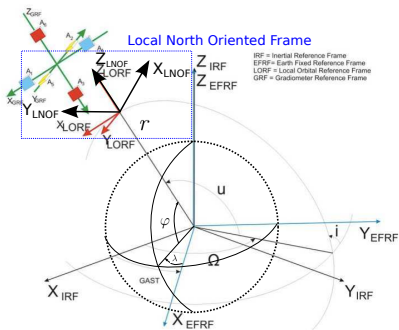
- Numerical integration based on the Gauss-Legendre quadrature
- Earth's solid body decomposed into *spherical prisms*

# Computation of gravity gradients

- Direct computation of the gravity gradients induced by each constant density ( $\rho$ ) prism in the LNOF associated with GOCE
- $\lambda_2 - \lambda_1 = 1^\circ$  ;  $\varphi_2 - \varphi_1 = 1^\circ$  ;  $\rho, r_2 - r_1 \leftarrow \text{LITHO1.0}$
- Computation by means of analytical formulas for PREM (ellipsoidal concentric layers)



Spherical prism



Original figure from: GOCE Level 2 Product Data Handbook, EGG-C, 2014

# Computation of gravity gradients

## Computational considerations

# Computation of gravity gradients

## Computational considerations

- LITHO1.0 → **447 824** tesseroids (spherical prims)

# Computation of gravity gradients

## Computational considerations

- LITHO1.0 → **447 824** tesseroids (spherical prims)
- Worldwide  $1^\circ \times 1^\circ$  grid at GOCE altitude (255 km a.s.l) → **64 800** computation points



# Computation of gravity gradients

## Computational considerations

- LITHO1.0 → **447 824** tesseroids (spherical prims)
- Worldwide  $1^\circ \times 1^\circ$  grid at GOCE altitude (255 km a.s.l) → **64 800** computation points
- **6** gravity gradients per point

# Computation of gravity gradients

## Computational considerations

- LITHO1.0 → **447 824** tesseroids (spherical prims)
- Worldwide  $1^\circ \times 1^\circ$  grid at GOCE altitude (255 km a.s.l) → **64 800** computation points
- **6** gravity gradients per point

= **174 113 971 200** computations based on Gauss quadrature

# Computation of gravity gradients

## Computational considerations

**174 113 971 200** computations based on Gauss quadrature performed in **8** hours using a computing cluster consisting of **5** computing servers (nodes) totalling:



# Computation of gravity gradients

## Computational considerations

**174 113 971 200** computations based on Gauss quadrature performed in **8** hours using a computing cluster consisting of **5** computing servers (nodes) totalling:

- **200** cores



# Computation of gravity gradients

## Computational considerations

**174 113 971 200** computations based on Gauss quadrature performed in **8** hours using a computing cluster consisting of **5** computing servers (nodes) totalling:

- **200** cores
- **336** GB of memory



# Computation of gravity gradients

## Computational considerations

**174 113 971 200** computations based on Gauss quadrature performed in **8** hours using a computing cluster consisting of **5** computing servers (nodes) totalling:

- **200** cores
- **336** GB of memory
- **36.1** TB of storage capacity in a gigabit network



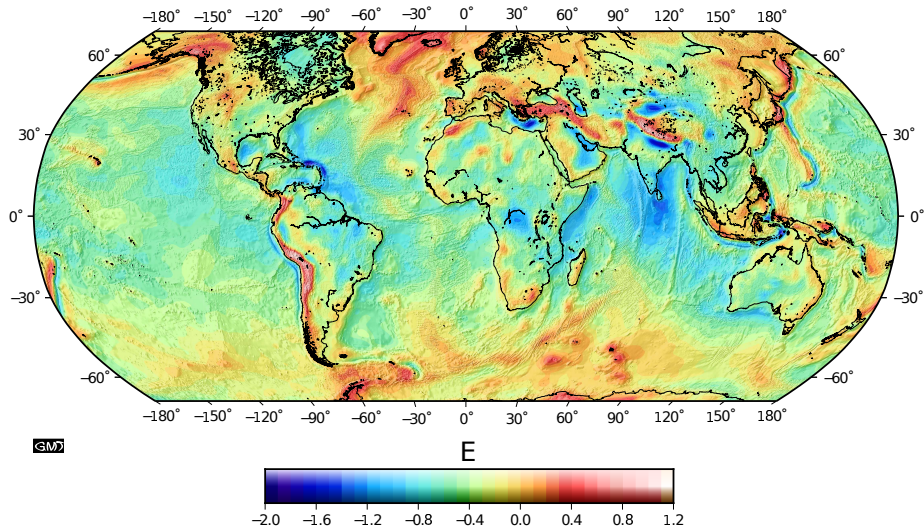
Anomaly of gravity gradient  $V_{ij}$ ,  $i, j = x, y, z$

$$\Delta V_{ij\text{EM}} = V_{ij\text{EM}} - V_{ij\text{PREM}}$$

$$\Delta V_{ij\text{GOCE}} = V_{ij\text{GOCE}} - V_{ij\text{PREM}}$$

where EM = "Earth's geophysical Model", GOCE = "GOCE data" and PREM = "PREM model"

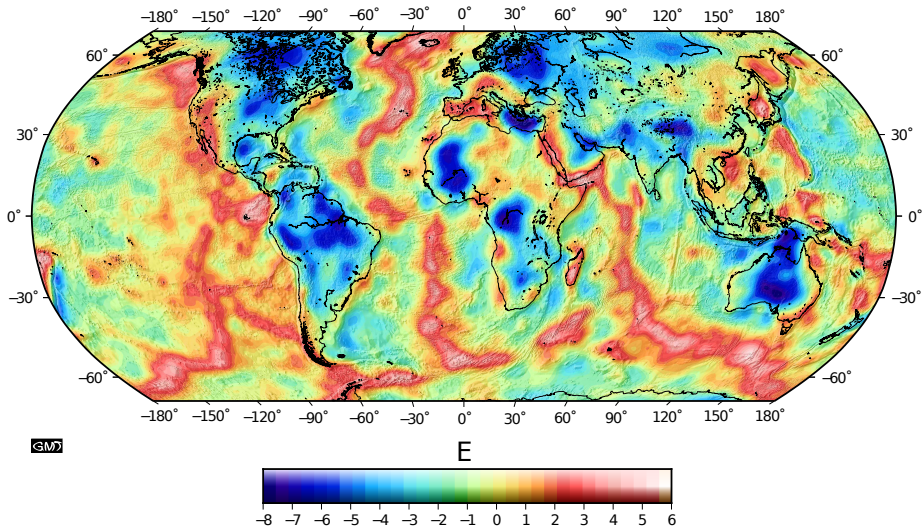
# Anomaly of GOCE $V_{zz}$ measurement/PREM (255 km a.s.l.)



BOUMAN J., EBBING J., FUCHS M., SEBERA J., LIEB V., SZWILLUS W., HAAGMANS R., NOVAK P.: Satellite gravity gradient grids for geophysics. Nature Scientific Reports, 6:21050, 10.1038/srep21050, 2016



# Anomaly of $V_{zz}$ computed from the combined model LITHO1.0~PREM/PREM (255 km a.s.l)



- The variation range of the calculated gravity gradient values is about **5** times greater than that of the GOCE-derived values

- The variation range of the calculated gravity gradient values is about **5** times greater than that of the GOCE-derived values
- $\Rightarrow$  The differences ( $\varepsilon$ ) between observed gravity gradient values and modelled ones are too high for performing an inversion

- The variation range of the calculated gravity gradient values is about **5** times greater than that of the GOCE-derived values
- $\Rightarrow$  The differences ( $\varepsilon$ ) between observed gravity gradient values and modelled ones are too high for performing an inversion
- $\Rightarrow$  Substantial adjustments of the model first have to be done before going further in model refinement

- The variation range of the calculated gravity gradient values is about **5** times greater than that of the GOCE-derived values
- $\Rightarrow$  The differences ( $\varepsilon$ ) between observed gravity gradient values and modelled ones are too high for performing an inversion
- $\Rightarrow$  Substantial adjustments of the model first have to be done before going further in model refinement
- Critical issue: regardless of model accuracy in terms of density values, the coordinates of the points limiting the geological structures must be expressed in the same reference frame as the one used to define GOCE-derived gravity gradients

## 2<sup>nd</sup> Earth's geophysical model: S40RTS

Ritsema, J. , Deuss, A. , van Heijst, H. J. and Woodhouse, J. H. (2011), S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements.

Geophysical Journal International, 184: 1223-1236. doi:10.1111/j.1365-246X.2010.04884.x

## 2<sup>nd</sup> Earth's geophysical model: S40RTS

- Model of shear-velocity variations in Earth's mantle deduced from seismic data

Ritsema, J. , Deuss, A. , van Heijst, H. J. and Woodhouse, J. H. (2011), S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements.

Geophysical Journal International, 184: 1223-1236. doi:10.1111/j.1365-246X.2010.04884.x

## 2<sup>nd</sup> Earth's geophysical model: S40RTS

- Model of shear-velocity variations in Earth's mantle deduced from seismic data
- Extended from 100 km to 2836 km depth

Ritsema, J. , Deuss, A. , van Heijst, H. J. and Woodhouse, J. H. (2011), S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements.

Geophysical Journal International, 184: 1223-1236. doi:10.1111/j.1365-246X.2010.04884.x



## 2<sup>nd</sup> Earth's geophysical model: S40RTS

- Model of shear-velocity variations in Earth's mantle deduced from seismic data
- Extended from 100 km to 2836 km depth
- The relationship between the relative variation in shear-velocity ( $V_s$ ) and density ( $\rho$ ) is given by:

$$\frac{\Delta\rho}{\rho} = a \frac{\Delta V_s}{V_s}$$

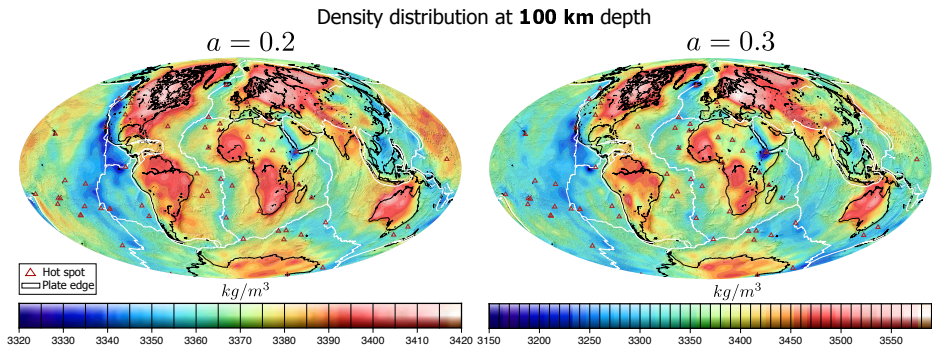
where  $a = 0.2$  or  $0.3$  according to Karato's estimates (1993, 2001)

Ritsema, J. , Deuss, A. , van Heijst, H. J. and Woodhouse, J. H. (2011), S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements.

Geophysical Journal International, 184: 1223-1236. doi:10.1111/j.1365-246X.2010.04884.x

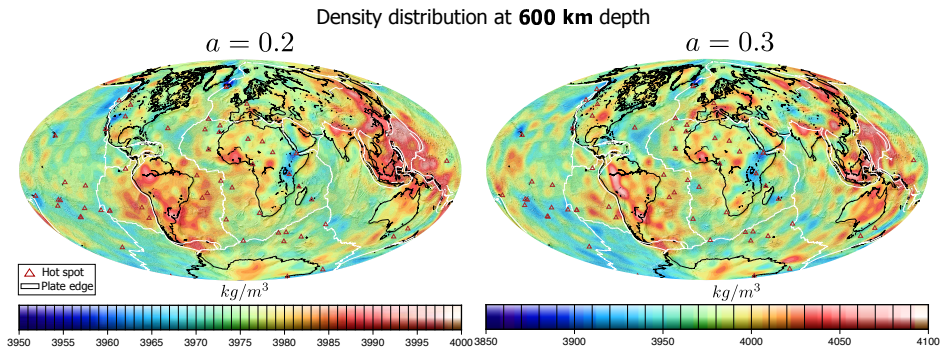
# 2<sup>nd</sup> Earth's geophysical model: S40RTS

Density distribution as a function of depth



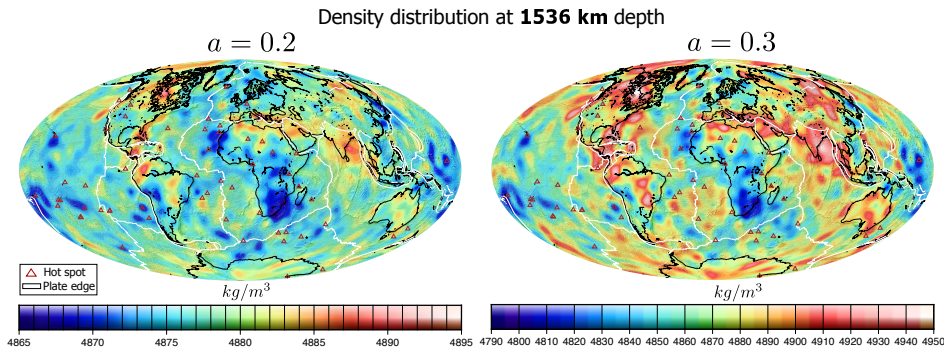
# 2<sup>nd</sup> Earth's geophysical model: S40RTS

Density distribution as a function of depth



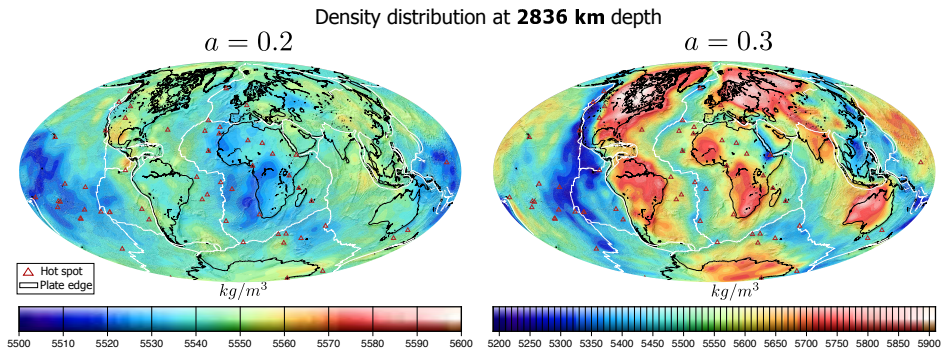
# 2<sup>nd</sup> Earth's geophysical model: S40RTS

Density distribution as a function of depth



# 2<sup>nd</sup> Earth's geophysical model: S40RTS

Density distribution as a function of depth

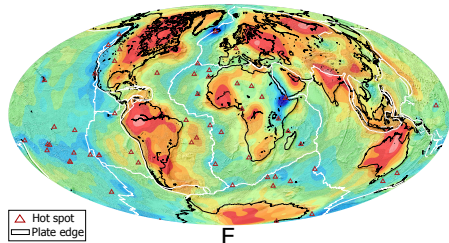


⇒ The density distributions are significantly different depending on the value of the parameter  $a$

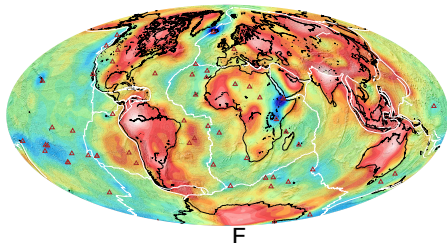
## 2<sup>nd</sup> Earth's geophysical model: S40RTS

$V_{zz}$  gravity gradient resulting from S40RTS-deduced density distribution

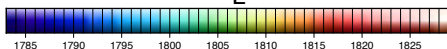
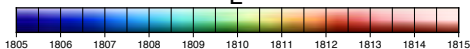
$a = 0.2$



$a = 0.3$



△ Hot spot  
— Plate edge

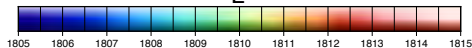
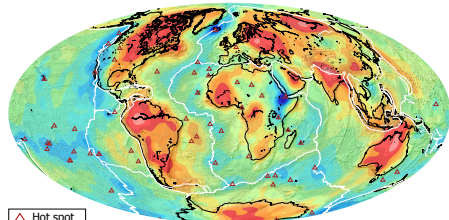


Computation involving **1 739 883** tesseroids, thus giving **676 466 510**  
**400** computations for calculating 6 gravity gradients worldwide  $\Rightarrow$   
computation time: **24** hours

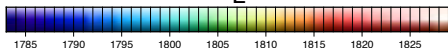
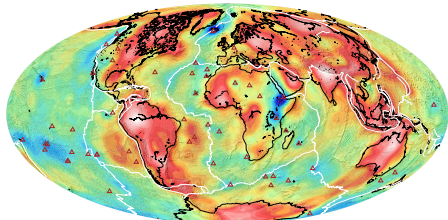
## 2<sup>nd</sup> Earth's geophysical model: S40RTS

$V_{zz}$  gravity gradient resulting from S40RTS-deduced density distribution

$a = 0.2$



$a = 0.3$



Major differences in the range of  $V_{zz}$  values:

$$|V_{zz}^{\text{Max}} - V_{zz}^{\text{Min}}| = 10 \text{ E } (a = 0.2) \text{ and } |V_{zz}^{\text{Max}} - V_{zz}^{\text{Min}}| = 46 \text{ E } (a = 0.3)$$

# Conclusions and prospects



- 1 Direct comparison of the worldwide gravity gradients calculated from Earth's geophysical models and those derived from GOCE measurements is to date still tricky

# Conclusions and prospects

- 1 Direct comparison of the worldwide gravity gradients calculated from Earth's geophysical models and those derived from GOCE measurements is to date still tricky
- 2 Geo-referencing of Earth's geophysical models is a fundamental issue in order to assimilate satellite-derived gravity gradients into the models

# Conclusions and prospects

- 1 Direct comparison of the worldwide gravity gradients calculated from Earth's geophysical models and those derived from GOCE measurements is to date still tricky
- 2 Geo-referencing of Earth's geophysical models is a fundamental issue in order to assimilate satellite-derived gravity gradients into the models
- 3 Close collaboration between geodesians and geophysicists must be initiated with a view to exploit all valuable gravity data acquired by satellites

Thank you for your kind attention!

