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CONSTRAINTS ON EARTH'S CORE PROCESSES BY SPACE GRAVIMETRY

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Abstract. Space gravimetric missions such as GRACE and GRACE Follow-On (hereafter denoted as GRACE) have been measuring the temporal mass variations within the Earth since 2002. GRACE products have been widely used to study continental water mass redistributions bringing additional constraints to hydrological models. GRACE solutions have also enabled to study internal mass redistributions before, during and after large earthquakes, putting some new constraints on the seismic cycle. In the deeper Earth's interior, the core also possesses a broad range of dynamical mechanisms involving mass variations. We compute the gravity perturbations expected for several core processes using the gravito-elastic equations governing the Earth's response to any internal forcing. We focus on the interannual signals generated by the dynamic pressure changes at the Core Mantle Boundary (CMB) associated with core flows reconstructed from geomagnetic observations, the reorientation of the inner core controlled by gravitational coupling with the Earth's mantle and time-varying topography changes at the CMB associated with dissolution and crystallization processes for instance. We then confront the predicted signatures with the current uncertainties linked to the GRACE data. New constraints on these core processes are finally obtained from space gravimetry. Some of the current limitations in the search for Earth's core signatures in space gravity records could be lifted with the future space gravimetric missions.

Keywords: time-variable gravimetry, Earth's core

1 Introduction

The Earth's core possesses a large part of complexity, that only a multi-disciplinary approach can resolve. While seismology provides fundamental information about the Earth's structure and composition, dynamical processes at play in the Earth's deep interior are hardly accessible. Geomagnetism and magneto-hydro-dynamic (MHD) simulations provide information about the core flow dynamics at time-scales longer than a few years. Despite the progress made to reach Earth's like conditions in MHD simulations and to inverse core flows from observed variations of the Earth's magnetic field, provided at a global scale by satellites carrying magnetometers, we still lack information about the density properties inside the core and about the coupling processes acting at its boundaries with the mantle and solid inner-core. Geodesy has here a complementary role to play.

Dynamical processes acting in the Earth's core give rise to mass redistributions and elastic deformation that perturb the gravity field. Space gravimetry measurements provide a global image of the time-varying gravity field at the Earth's surface. Earth's gravity field fluctuations are obtained from precise orbit determination by tracking satellites orbiting the Earth (Satellite Laser Ranging technique - SLR) or by accurate measurement of the distance between two satellites on the same orbit, like for the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (-FO) satellites, after correcting from non-gravitational motions.

Since 2002, GRACE and GRACE-FO missions have been recording the gravity field fluctuations (Tapley et al. 2004; Landerer et al. 2020) associated with a wide range of processes (Fig. 1), which signatures are superposed on various spatial and temporal scales. The main sources of gravity changes are tidal effects, post-glacial rebound (Purcell et al. 2011), hydrology (Rodell et al. 2018), atmospheric (Kusche & Schrama 2005) and oceanic (Dobslaw et al. 2017) loading, water mass redistribution (Pfeffer et al. 2022), pre-seismic (Bouih et al. 2022), co-seismic and post-seismic (Deggim et al. 2021) mass redistributions, seismic pre-cursors (Panet

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et al. 2018; Bouih et al. 2022), sea-level changes (Peltier 2009; Adhikari et al. 2019; Horwath et al. 2022) and core processes (Dumberry 2010b; Dumberry & Mandea 2021; Lecomte et al. 2023). Separation between these contributions is a very challenging task.

In this work, we review the precision of gravity field solutions in terms of dispersion of the existing gravity field products proposed by various analysis centers, in terms of dispersion of the surface mass loading models, with respect to predicted gravity changes produced by major core processes. Most of the results shown here can be found in Lecomte et al. (2023) but we consider an additional core process not included in the later work, which is topographic loading at the core-mantle boundary (CMB). We first start by a review of the precision of space gravity solutions and loading models. Then, predicted gravity perturbations for major core processes are presented. We finally conclude by some perspectives related to the future space gravimetric missions like the Mass-change And Geosciences International Constellation (MAGIC) in the frame of NASA's Mass Change Designated Observable (MCDO) and ESA's Next Generation Gravity Mission (NGGM) (Haagmans & Tsaoussi 2020).

2 Precision of time-variable gravity field measurements vs amplitude of core processes

Core-induced gravity perturbations are the largest for the degree-2 spherical harmonic component (Dumberry 2010a). In the following, we then focus only on the degree-2 component of the perturbed gravity field.

2.1 Precision of gravity field measurements

Lecomte et al. (2023) have estimated the dispersion for GRACE solutions as about 0.34 cm of equivalent water height (EWH) or 20% of the total signal, 0.2 cm for the degree 2 alone. Moreover, they have shown that the largest uncertainty in loading models comes from hydrology with a dispersion as large as 0.89-2.10 cm of EWH and 0.37 cm for the degree 2 alone.

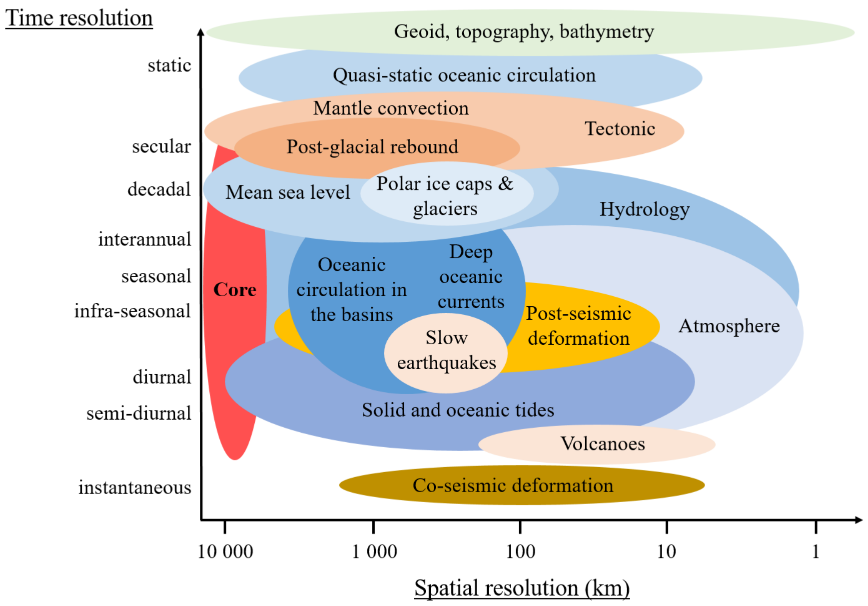

Fig. 1. Spatio-temporal fluctuations of the Earth's gravity field (after Lecomte et al. 2023).

2.2 Earth's core processes

Computation of the gravity field perturbation by core processes is performed using the classical Love numbers approach by integration of the gravito-elastic equations (Greff-Lefftz et al. 2004; Dumberry & Bloxham 2004) for a spherically symetric radial Earth's PREM (Dziewonski & Anderson 1981) model. We consider three core processes: density and pressure anomalies associated with core flows, mass redistribution and deformation associated with the inner-core rotation, topographic loading at the CMB associated with cristallization-dissolution for instance.

Core flows Core flows are associated with density anomalies at the order of 10^{-5} kg.m^3, as an upper bound, (Dumberry 2010b) and pressure anomalies at the CMB between 20 to 100 Pa from a few years to decadal timescales (Gillet et al. 2020). Degree-2 Stokes coefficient variation for a 10^{-5} kg.m^3 density anomaly is 2×10^{-11} or 0.1 cm EWH. For inter-annual and decadal pressure anomalies of 20 and 100 Pa, the respective degree-2 Stokes coefficient variations are 2×10^{-12} or 0.1 cm EWH and 3×10^{-11} or 0.5 cm EWH (Lecomte et al. 2023).

Reorientation of the inner core When the inner core is tilted by an angle α, it creates a variation on the Stokes coefficient approximated by $\Delta S \approx 10^{-10} h\alpha$ under the hypothesis of a non-convecting inner core and with a density almost uniform at hydrostatic equilibrium (Dumberry 2010a). h is the degree-2 topography of the inner core. Dumberry & Mandea (2021) have estimated $\alpha = 0.4^\circ$ and $h = 18$ m on decadal time scales. It gives a degree-2 Stokes coefficient variation of 10^{-11} or 0.2 cm EWH (Lecomte et al. 2023).

Topographic loading Dissolution and crystallization processes have been proposed to continuously reshape the topography of the CMB on a decadal time period (Mandea et al. 2015). Such processes would give rise to surface gravity perturbation through a density load $V^{c,s}_{n,m} = \frac{4\pi G b}{2n+1}\Delta\rho \times h^{c,s}_{n,m}$ at the CMB computed as

$$\Delta C, S_{n,m} = -\frac{a}{GM}\left[\left(\frac{b}{a}\right)^{n+1} + k'_n\right] V^{c,s}_{n,m}, \tag{2.1}$$

where $k'_2 = -0.2$, $\Delta\rho \approx 5 \times 10^3$ kg.m^{-3} the density jump at the CMB, $h^{c,s}_{n,m}$ the harmonic coefficient of the topography at the CMB, b and a are respectively the CMB and Earth's surface radii. We have noted $C_{n,m}$ and $S_{n,m}$ the degree$-n$, order$-m$ fully normalized Stokes coefficients of the spherical harmonic representation of the Earth's gravitational potential. A degree-2 topographic loading of 1 cm would induce a Stokes coefficient variation of 2×10^{-11} or 0.1 cm EWH (Fig. 2).

3 Conclusions

Earth's core processes affect the Earth's gravity field at time-scales ranging from a few years to a few decades. These perturbations occur under various mass redistributions associated with inner-core reorientation, topographic loading at the core interfaces or dynamic core flows. The surface effect increases with the time-scales. Decennal time-varying gravity records are then required to better constrain density anomalies associated with such core processes. The continuity of space gravimetric observation after GRACE-FO will be reached with the Next Generation Gravity mission (Cesare et al. 2016). The MAGIC mission is a planned National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) joint venture. The MAGIC mission will provide greater temporal resolution with a substantial reduction in spatial and temporal aliasing (Haagmans & Tsaoussi 2020), and better determination of the low-degree Stokes coefficients (Technische Universität München & et al. 2023). If high accuracy (signals amplitude of 0.1 cm EWH in 10 years) can be reached at long wavelengths (thousands km) and decadal timescales, on-going deep Earth dynamics may become observable (Fig. 2). Continuity in time of the monitoring of the time-variable Earth's gravitational field is essential to constrain deep Earth's dynamics.

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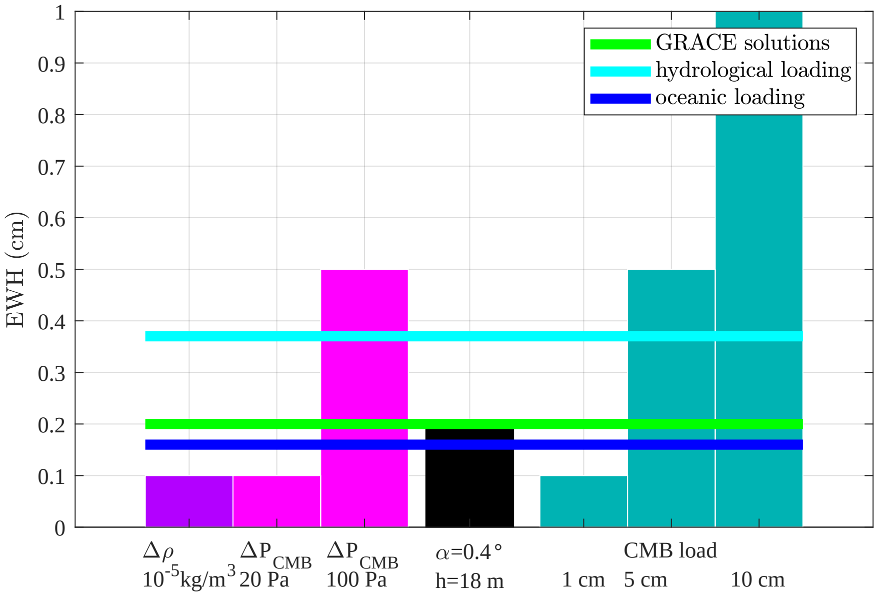

Fig. 2. Uncertainties of degree-2 GRACE solutions (green) and of hydrological (cyan) and oceanic (blue) loading with respect to expected degree-2 surface gravity perturbations by some dynamical core processes: density anomalies and pressure anomalies at the CMB associated with core flows (magenta and pink color), reorientation of the inner core (black) and topographic loading at the CMB for various degree-2 topographic heights (1, 5 and 10 cm) (turquoise). Amplitudes are given in Equivalent Water Height (EWH) in cm.

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