GRACE-FO in Differential Mode

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1. Introduction

Low Earth Orbit (LEO) satellites have been proven extremely useful for the detection and monitoring of the Earth system dynamic processes. A wide spectrum of geoscience applications, such as ice mass change and water circulation monitoring have been possible since the advent of satellite gravity missions, three specially designed missions to measure the Earth's gravity field. Two of them, namely the Gravity Recovery and Climate Experiment (GRACE) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE) missions have been undoubtedly valuable missions that allowed the monitoring of the Earth's dynamic and static gravity field, respectively.

GRACE mission's (2002-2017) primary objective was to measure the temporal variations of the gravity field (Tapley et al., 2004) from two identical spacecraft separated by about 220 kilometres, placed in a near polar orbit at an altitude of 500 km. Throughout its mission lifetime, Precise Orbit Determination (POD), inter-satellite range measurements and non-gravitational accelerations observed by GRACE (Touboul et al., 2004) have been used to model the Earth's gravitational field and detect and monitor various time-varying mass changes. Continuing the success of the GRACE, a nearly identical follow-on mission namely, the GRACE Follow-On (GRACE-FO, or GFO) has been planned to be launched on May 19, 2018.

GOCE mission (2009-2013) on the other hand, was a single spacecraft that orbited the Earth at almost half the GRACE altitude i.e. ~250km. Its scientific payload comprised, among many others, a 3D gradiometer and a GPS receiver that made possible the determination of the Earth's gravitational gradient tensor (GGT) (Rummel et al., 2011; Stummer et al., 2012a) leading to a large number of geoscience applications (see e.g., Bouman et al., 2015; Fuchs et al., 2013; Knudsen et al., 2011).

GOCE and GRACE mission data are very rich for continued Earth system studies that will further be reinforced by the upcoming GRACE-FO, particularly regarding studies of the impact of space weather dynamics on LEO satellite gravity missions (direct problem) and the determination of space weather and ionospheric dynamics (inverse problem). In this study, we develop a method that uses GRACE accelerometer and POD data to derive differential accelerations, similar to those of GOCE. An elegant combination of Level 1B data from both GRACE satellites, which we name 'differential mode' or 'GRACE DM method' is shown to produce common and differential mode accelerations (CM and DM, respectively) that closely resemble those of GOCE. We use GOCE CM- and DM-derived accelerations (Level 1b) to validate the GRACE DM method for a time period that the two missions were operating simultaneously. We expect that the new method will be directly applicable to GRACE-FO with many new benefits in geoscience applications.

2. The concept of GRACE Differential Mode

In this study, Level 1B data, specifically in GNV1B, ACC1B and SCA1B data files (Case et al., 2010), are used to retrieve information about POD, non-gravitational accelerations and spacecraft attitude, respectively. Acceleration measurements are bandpass filtered in the design band of the instrument (10^{-4}~10^{-1} Hz) with a Gaussian filter.

To generate Differential Mode (DM) 'measurements' from GRACE, we use the original generic accelerometer measurements from both satellites. This can be achieved by computing the time Δt the trailing satellite (hereafter B) takes to be as close as possible, position-wise, to where A was Δt seconds earlier. This means that A(t) and B(t+Δt) will be nearly at the same position. Afterwards, we compute the separation vector between A(t) and B(t+Δt) using precise orbits. We then transform the accelerometer measurements of B(t+Δt) into the accelerometer frame of A(t) via the attitude angle differences that occur in the time interval Δt, according to Bandikova & Flury, (2014). Once the accelerations of B(t+ Δt) are in the reference frame of A(t), they can be differenced in all three directions using POD solutions. The equations that give respectively the common and differential modes in the *x*-direction. All quantities in the equations are referenced to the satellite (accelerometer) reference frame (SRF):

$$\boldsymbol{\alpha}_c(t) = \frac{1}{2}(\boldsymbol{a}_B(t+\Delta t) + \boldsymbol{a}_A(t)) \quad (1)$$

$$\boldsymbol{\alpha}_d(t) = \frac{1}{2}(\boldsymbol{a}_B(t+\Delta t) - \boldsymbol{a}_A(t)) \quad (2)$$

where $\boldsymbol{\alpha}_c(t)$ denotes the common mode and $\boldsymbol{\alpha}_d(t)$ denotes the differential mode; $\boldsymbol{a}_A(t)$, $\boldsymbol{a}_B(t+\Delta t)$ represent the linear accelerations of A(t) and B(t+Δt), respectively. The above are valid under the following realistic assumptions:

a) The distance between A(t) and B(t+Δt) is very small, compared with the size of the orbit. Analysis of more than 5000 orbits indicates that the typical distance in *x* and *y* directions (horizontal distance in the SRF) is of the order of a few hundred metres, whereas along the *z*-axis (vertical) is about 500*m* in extreme cases.
b) Satellite B is Δt≈26*s* on average behind A during which time the gravitational field does not change. Thus, the principle of Eq. (2) is not violated and differencing the acceleration measurements between A(t) and B(t + Δt) at the position of A(t), when Δ$x(t) \rightarrow 0$, results in realistic differential accelerations.
c) The dynamic regime in the thermosphere remains unchanged within the 20-40*s* interval between A and B and within a few hundred metres. This is a very realistic assumption since an average spatiotemporal homogeneity of external atmospheric dynamics (i.e., neutral winds and plasma flux) is roughly 300*km* in extent and lasts several minutes (Zhang et al., 2003).

3. Results from GRACE Differential Mode

GOCE mission orbited the Earth in a nearly polar sun-synchronous orbit (Rummel et al., 2002), designed to cross the equator at 6:00 hours (dawn-dusk orbit) or 18:00 hours (dusk-dawn orbit). GRACE mission had also a nearly polar orbit though, as opposed to GOCE, it was not a sun synchronous orbit. To be able to compare GOCE and GRACE DM estimates, we separate all the GRACE tracks in ascending and descending and we further classify them as daytime and nighttime, respectively. To remove any non-linear accelerometer behaviour, we filter GRACE accelerations in the passband of the instrument (0.1-100mHz) and the GOCE measurements in the gradiometer's passband (5~100 mHz). In both cases we use a simple Gaussian filter. Finally, to be able to compare results of the two missions, we note that the reference frames of the measurements should be the same for both GOCE and GRACE DM accelerations. GOCE Level 1B measurements are referred to Local Orbital Reference Frame (LORF) (ESA, 2006) and GRACE Level 1b measurements are referred to the so-called Satellite Reference Frame (SRF) (Case et al., 2010). As GRACE and GOCE had both a nearly polar orbit, differences between GRACE SRF and GOCE LORF are or the order of the difference between the two orbit inclinations and thus negligible, at least for this conceptual study. Therefore, all the results are kept to each satellite's frame. We calculate GRACE DM accelerations from more than 5000 orbits over the period of 1 year, namely 2010. After filtering the measured accelerations, we apply the GRACE DM method as described in Section 2 and then we use GOCE gradiometer measurements for the same period to test and validate the newly introduced method.

3.1 GRACE and GOCE DM

At the first stage of this investigation, we explore the capability of GRACE DM method to obtain differential accelerations (cf., Eq. (2)) by employing non-gravitational accelerations measured by the two GRACE spacecraft during 2010. Derived GRACE DM maps (Fig. 1) show a strong presence of the magnetic inclination signal over the equatorial region. Additionally, Fig. 1b shows a linear negative to positive trend close to $\phi = 60^o$N, evident only in the ascending nighttime DM accelerations. This linear perturbation drops in $\lambda = [-180^o, -120^o]$ and we believe that it is induced by the Birkeland currents which are highly correlated with the Sun's magnetic field activity (Friis-Chistensen & Lassen, 1991; Friis-Chistensen et al., 2017). The interaction of the Earth's magnetic field with solar winds, induces a wide range of dynamic phenomena one of them being the Birkeland currents that are mainly present at local nighttime and they get stronger when the radial component of the Interplanetary Magnetic Field (IMF) field (B_z) becomes strongly negative (see Fig. 1b; ibid., 2017). Contrary to GRACE, GOCE followed sun-synchronous dawn-dusk orbit that did not allow for ascending nighttime measurements thus, the Birkeland currents are not evident in GOCE DM accelerations.

Leakages from the Earth's magnetic field fluctuations are also evident in GRACE DM ascending tracks during nighttime (Fig. 1b) at the North Pole. GOCE DM accelerations also demonstrate a strong signal induced by the Earth's magnetic inclination. We note that the GOCE DM accelerations have been low-pass filtered (Bouman et al., 2011) and thus, they appear much cleaner than the GRACE equivalents (cf., Fig. 1). The presence of the Earth's magnetic field dominates both GOCE and GRACE DM accelerations and as such it does not allow the extraction of geophysical signals. Further band-pass filtering must be applied. Interestingly, the inclination signal in GOCE measurements shows a latitudinal displacement between ascending and descending tracks whereas this is not observed in GRACE. Additionally, as GRACE DM method implies, the distance between the two spacecraft is highly variable and considerably longer than that of GOCE accelerometers separation (0.5m). As a result, GRACE DM accelerations are expected to have higher magnitude than that of GOCE (see Figs. 1-2).

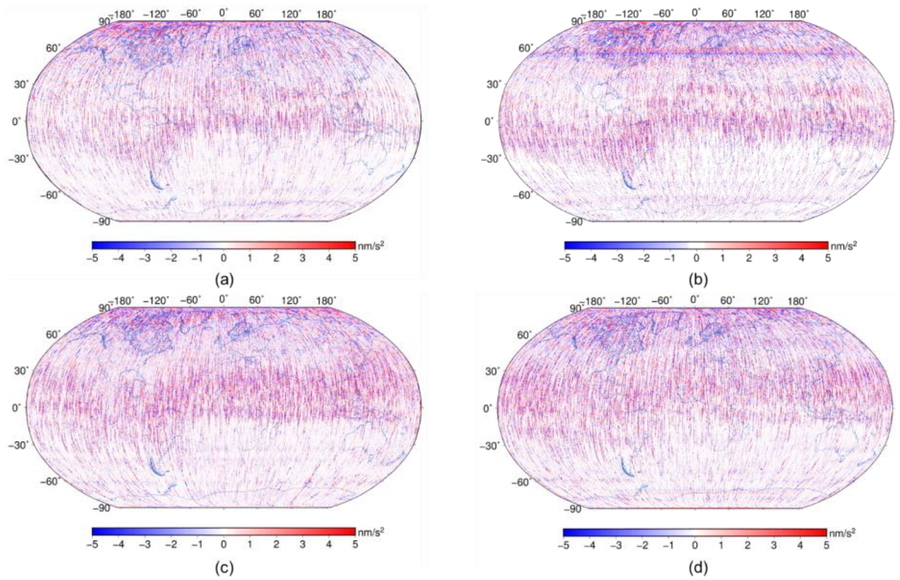

Fig. 1: a) DMx ascending daytime during 2010; b) DMx ascending nighttime during 2010; c) DMx descending daytime during 2010; DMx descending nighttime during 2010. Data have not been low-pass filtered along the tracks.

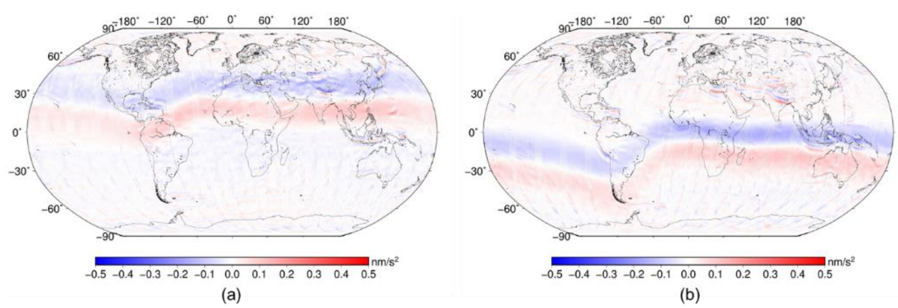

Fig. 2: a) Ascending tracks of GOCE DM along the x-axis during daytime; b) Descending tracks of GOCE DM along the x-axis during nighttime. Data used for these figures were taken from EGG_NOM_1b solutions.

3.2 GRACE and GOCE CM

Common mode accelerations (*cf*., Eq. (1)) are derived by averaging the non-gravitational accelerations to provide valuable information on the behavior and the structure of these accelerations. We calculate common mode accelerations (cf., Eq. (2)) for the year of interest and we further investigate the non-gravitational sources that dominate the CM signal. GRACE CM accelerations reveal strong fluctuations of the magnetic field over the North and South poles (see Fig. 3). Previous studies addressed magnetic fluctuations in GOCE CM accelerations (Ince & Pagiatakis, 2016). These fluctuations also known as magnetic ripples (Nakanishi et al., 2014) are perpendicular to the geomagnetic field and have a spatiotemporal variability (ibid, 2014). Perturbations of these fluctuations on LEO satellites highly depend on the local time that the satellite passes over (Aoyama et al., 2017; Nakanishi et al., 2014). GRACE CM accelerations demonstrate a strong presence of these fluctuations along track, which we attribute to the lack of drag compensation mechanism of GRACE. North and South Pole fluctuations (Fig. 3), result in stronger perturbations in GRACE CM accelerations during daytime. The magnetic inclination is also evident in GRACE CM solutions, especially in the ascending nighttime tracks (Fig. 3b). Additionally, the longitudinal linear feature at $\phi \approx 60^{o}$ that we attribute to Birkeland currents, peaks during ascending nighttime tracks as demonstrated in Fig. 3b. Fig. 4 reveals that the North and South Pole fluctuations evident in GRACE CM are also present in the cross-track measurements and mainly in the ascending GOCE CM tracks. Of note is that GOCE CM accelerations do not demonstrate any signal induced by the Earth's magnetic inclination. The different response of GOCE and GRACE CM accelerations might be attributed to technical specifications (i.e., mission's design and instrumentation) and to the different altitude of the two missions.

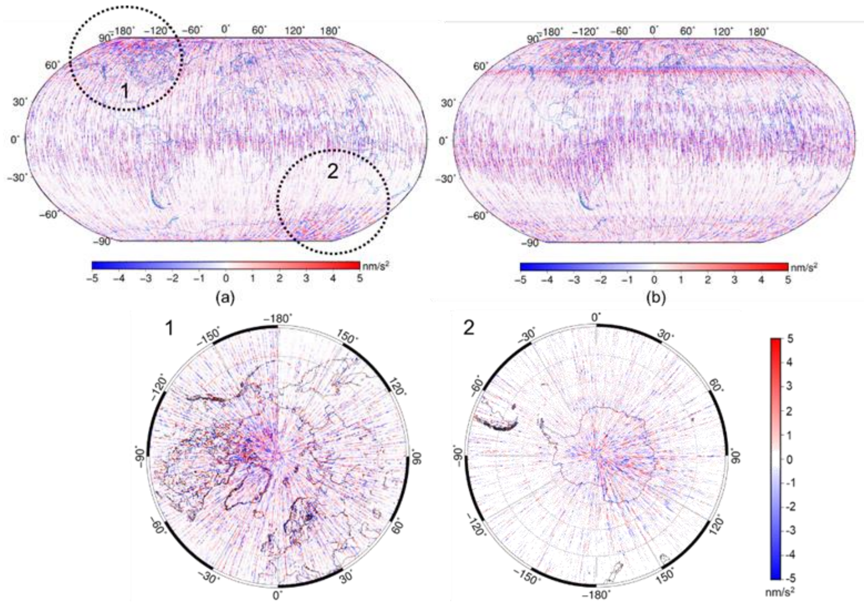

Fig. 3: a) CMx ascending daytime during 2010. Dashed circles indicate the areas 1 and 2 with magnetic fluctuations; b) CMx ascending nighttime during 2010. Data have not been low pass filtered.

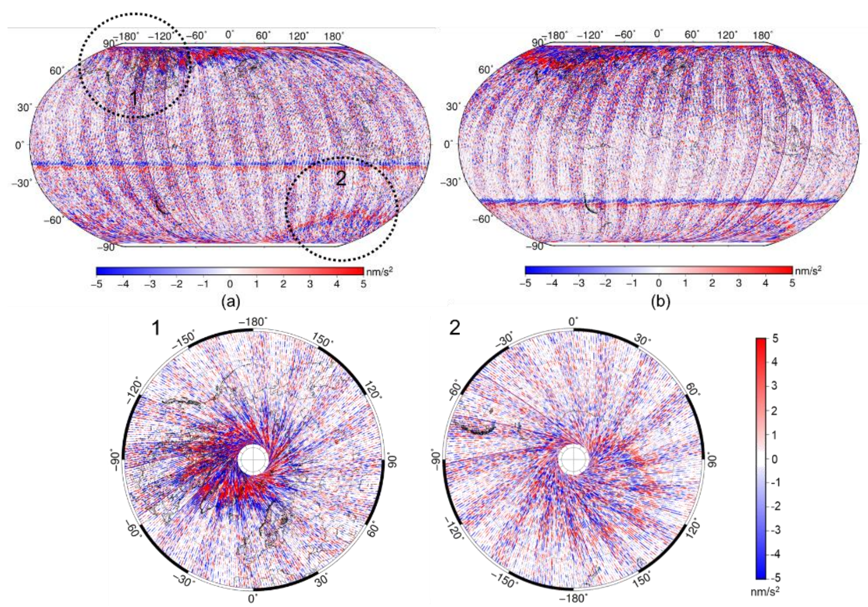

Fig. 4: a) Ascending daytime tracks of GOCE CM along the y-axis. Dashed circles indicate the areas 1 and 2 with magnetic fluctuations; b) Descending nighttime tracks of GOCE CM along the y-axis.

Overall, the impact of the Earth's magnetic field on the two LEO missions is stronger on GRACE CM/DM accelerations than in GOCE. The Earth's main magnetic field coming from the Earth's lithosphere and core, is relatively constant (timewise) compared to disturbances coming from external sources (Moldwin, 2008). The dynamic response of the Earth's magnetic field to these external sources, mainly coming from the Sun, affect the upper ionospheric layers and consequently the spacecraft (ibid, 2008). As these forces are external, the magnitude of their impact is proportional to the altitude above the Earth (ibid, 2008) and consequently the higher the altitude of a mission the more intense the disturbances to the spacecraft environment. To that end, we believe that GRACE CM/DM accelerations are stronger due to the altitude of the mission, which is nearly double than that of GOCE mission.

4. Conclusions

We have introduced a new method, called GRACE-DM, where we employed GRACE accelerometer observations and precise orbit determination to allow for the estimation of CM and DM accelerations. The GRACE DM results were assessed by employing GOCE CM/DM accelerations. Comparisons between the two mission differential accelerations demonstrated a strong similarity in the structure of GRACE and GOCE DM. GRACE and GOCE DM revealed a strong signal along the equatorial region attributed to the Earth's magnetic field inclination. CM accelerations of both LEO missions depict the magnetic field's fluctuations over the North and South poles with GRACE CM demonstrating a higher magnitude than that of GOCE. In the light of the almost identical GRACE-FO mission, GRACE-DM method could introduce a new approach on a wide spectrum of applications that require satellite gravity gradients.

5. References

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