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Satellite-to-satellite attitude control of a long-distance spacecraft formation for the Next Generation Gravity Mission

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ABSTRACT

The paper presents the design and some simulated results of the attitude control of a satellite formation under study by the European Space Agency for the Next Generation Gravity Mission. The formation consists of two spacecrafts which fly more than 200 km apart at an altitude from the Earth's ground of between 300 and 400 km. The attitude control must keep the optical axes of the two spacecraft aligned with a microradian accuracy (pointing control). This is made possible by specific optical sensors accompanying the inter-satellite laser interferometer, which is the main payload of the mission. These sensors allow each spacecraft to actuate autonomous alignment after a suitable acquisition procedure. Pointing control is constrained by the angular drag-free control, which is imposed by mission science (Earth gravimetry at a low Earth orbit), and must zero the angular acceleration vector below 0.01 $\mu\text{rad/s}^2$ in the science frequency band. This is made possible by ultrafine accelerometers from the GOCE-class, whose measurements must be coordinated with attitude sensors to achieve drag-free and pointing requirements. Embedded Model Control shows how coordination can be implemented around the embedded models of the spacecraft attitude and of the formation frame quaternion. Evidence and discussion about some critical requirements are also included together with extensive simulated results of two different formation types.

1. Introduction

The Next Generation Gravity Mission (NGGM) under study by the European Space Agency will take advantage of the previous gravimetry missions GOCE [15] and GRACE [26]. It will consist of a long-distance formation of two satellites as in GRACE ($d_{nom} \geq 200$ km), where each spacecraft (S/C) will be controlled to be drag-free as in GOCE [1,2]. As a significant advancement, satellite-to-satellite distance fluctuations will be measured by laser interferometry with an accuracy improvement of at least three orders of magnitude with respect to GRACE (see Table 1, row 3). The formation will fly in a polar orbit at an altitude of between 330 and 420 km, depending on the formation type, either inline or pendulum. The satellites $k=1,2$ ($k=1$ denotes the leader and $k=2$ the follower) fly on the same orbit in the inline formation, whereas, in the pendulum formation, they fly on slightly separated and crossing orbits. The range of the orbit altitude requires drag cancellation and formation control. Drag-free control is ensured by the ultrafine accelerometers of the GOCE mission.

The paper focuses on the formation attitude control during the science phase, whose requirements are demanding because of several reasons. Intersatellite distance fluctuations must be measured along the satellite-to-satellite line (SSL) which is defined as the line joining the satellite centers-of-mass (CoM) C_1 and C_2 in Fig. 1. In a low-Earth orbit, the SSL can be materialized – it becomes a measurable physical object – by differential global navigation system instruments (GNSI). For the same purpose, NGGM will also employ interferometry.

One property of laser interferometry is that any direction inside a laser beam, which is launched by either satellite and is imaged by the receiving optics of the companion satellite, materializes the SSL (see Fig. 1). The receiving optics fixes the first axis $\vec{c}_{k1}$ of the kth satellite, which must be perfectly aligned to the SSL by a 2D attitude control referred to as pointing control.

Materialization errors occur because the SSL and the laser optical path do not coincide. An offset exists between CoM and optics, and the error magnitude can be shown to be of the order of the offset length ρ_k times the tilt q_k between $\vec{c}_{k1}$ and the SSL. Error fluctuations limit the accuracy of the intersatellite distance measurement, which thus demands an upper bound to $|q_k|$. Assuming $|\rho_k| \leq 0.001$ m and nanometric distance accuracy, the spectral density of q_k must be of the order of 1 $\mu\text{rad}/\sqrt{\text{Hz}}$ as in Table 1, row 8. This is the first challenging requirement of NGGM

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Table 1
Required bounds on attitude fluctuations of gravimetry missions.

No.	Requirements	GOCE	GRACE	NGGM
1	Orbit altitude [km]	250	500	330 (inline), 420 (pendulum)
2	Formation	None, single satellite	Two inline S/C 220 km apart	Two S/C 200 km apart
3	Intersatellite distance accuracy	None	10 μm [18]	0.005 $\mu\text{m}/\sqrt{\text{Hz}}$
4	3D angular acceleration max value [$\mu\text{rad/s}^2$]	1 [25]	1	1
5	3D angular acceleration spectral density $\left[\mu\text{rad}/s^2/\sqrt{\text{Hz}}\right]$	0.1 [25]	None	0.01
6	3D attitude max value [mrad]	150 [25]	4 [18]	See rows 7–10
7	2D pointing max value (pitch and yaw) [mrad]	See row 6	See row 6	0.02
8	2D pointing spectral density $\left[\text{mrad}/\sqrt{\text{Hz}}\right]$	None	None	0.001
9	Roll max value [mrad]	See row 6	See row 6	2
10	3D angular rate spectral density $\left[\text{mrad}/s/\sqrt{\text{Hz}}\right]$	0.01 [25]	None	0.001

The term ‘spectral density’ stands for ‘root of unilateral Power Spectral Density’ (PSD).Spectral density bounds refer to the MBW.

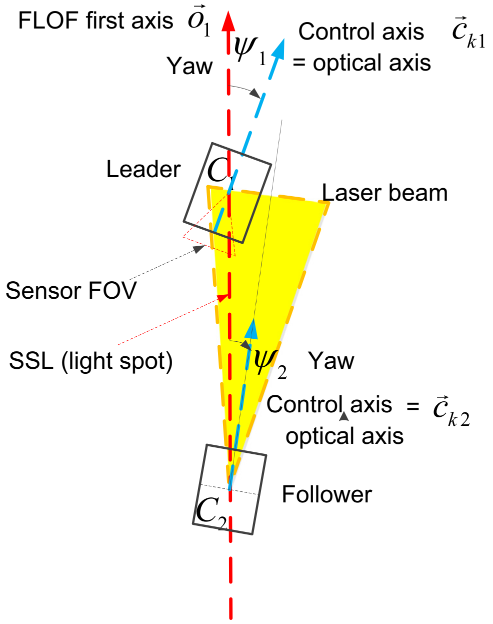

Fig. 1. Sketch (not in scale) of the satellite-to-satellite line and of the laser beam.

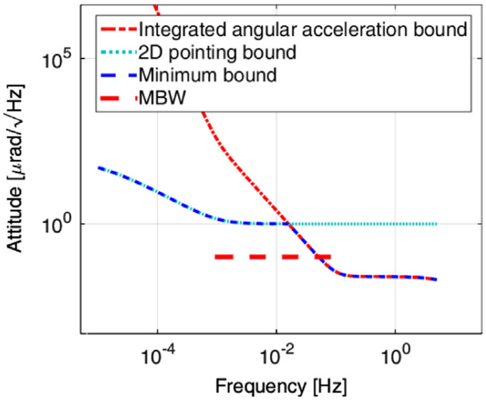

Fig. 2. Spectral density bound of the 2D pointing control.

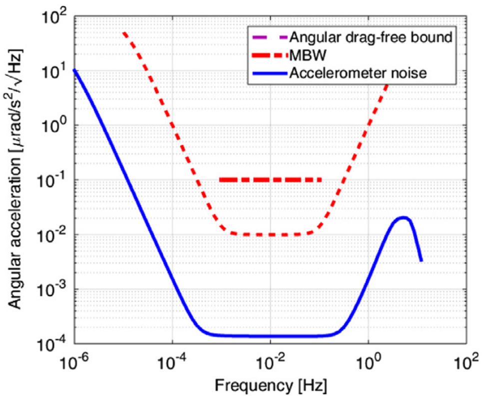

Fig. 3. Drag-free bound and accelerometer noise.

with respect to previous missions as reported in Table 1. Fig. 2 shows the spectral bound (solid line) of the 2D pointing control, and the so-called science measurement bandwidth (MBW)

$$\boldsymbol{M} = \{f_0 = 1\ \text{mHz} \le f \le f_1 = 100\ \text{mHz}\}, \quad (1)$$

where intersatellite distance measurement requires the highest accuracy. Here the term ‘measurement’ refers to science measurements during the mission, and not to attitude control measurements. Science data requirements demand formation attitude to be the most accurate in the MBW as shown by the ‘minimum bound’ in Fig. 2 and by the ‘drag-free bound’ in Fig. 3. Outside the MBW, science data accuracy progressively relax and consequently attitude requirements. The angular accuracy around $\vec{c}_{k1}$ (the roll φ_k) is of the same order as in GRACE, but fluctuations must be rather slow in order to respect the angular-rate spectral bound of Table 1, row 10.

SSL materialization and fine pointing can be obtained if the axis of the launched beam is more closely aligned with the SSL than the laser beam divergence, which is around 0.1 mrad. This alignment cannot be achieved by star trackers because of their bias which is of the same order or even larger. Optical sensors capable of measuring the beam tilt are mandatory [9]. If each satellite can image the incoming beam of the companion satellite, it becomes capable of autonomous alignment once the incoming laser spot has been located and held in the optics field-of-view. Optical tilt sensors are complemented with a pair of star trackers for implementing optical link acquisition and providing roll measurements. Gyroscopes are shown to be of scarce help.

A second set of requirements concerns the inertial angular acceleration (Table 1, rows 4 and 5) and the angular rate with respect to the local orbital frame of the mission, the so-called Formation Local Orbital Frame (FLOF), whose first axis $\vec{o}_1$ is directed along the SSL (see Fig. 1). Their spectral density bounds in the MBW (Table 1, rows 5 and 10) are of one order of magnitude less than in GOCE.

The spectral bound (angular drag-free bound, dashed line) is shown in Fig. 3 until the attitude control Nyquist frequency $f_{max} = 0.5/T = 5$ Hz, where T is the control time unit. The bound has been designed to limit the errors of the accelerometer package