GALILEO GALILEI (GG)

EXPERIMENT CONCEPT AND REQUIREMENTS DOCUMENT

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1. INTRODUCTION

1.1 Scope

This document is submitted in partial fulfilment of Work Package 1A-ADB of the GG Phase A2 Study. It provides a systematic statement of the science and payload requirements of the GG satellite experiment.

1.2 Background

The Galileo Galilei (GG) mission is a part of the Cosmology and Fundamental Physics project of the ASI Unit on Observation of the Universe, the purpose of which is providing support to the Italian Scientific Community in its participation in the European and worldwide development of knowledge in this field, both by independent projects and by international collaboration.

GG participates in the worldwide programme of verifying the founding principles of physics by means of groundbreaking experiments, which can only be performed in the space environment. The goal of GG is to test the “Equivalence Principle” (EP) to 1 part in 10^{17}, more than 4 orders of magnitude better than today’s ground experiments. As an EP experiment, GG shares the same goal as the STEP experiment of NASA and the Microscope experiment of CNES. Its contribution to the field consists in an original and innovative experiment concept, which promises an accuracy and precision unparalleled by any other experiment.

A one-g version of the differential accelerometer designed to fly onboard the GG satellite, called the GGG experiment, is currently operational in the INFN laboratory in San Piero a Grado, Pisa. It is designed to test the main features of the space instrument in a laboratory experiment. The GGG experiment is carried out with Istituto Nazionale di Fisica Nucleare (INFN) funding and ASI support.

The GG mission and satellite have already been studied at both scientific and industrial level. Between 1997 and 2000, a mission based on an equatorial orbit was studied under ASI contract [RD01]. In 2001, adaptation of the mission to a sun-synchronous orbit, driven by launcher availability, was addressed [RD02, RD03]. The successful launch of *Agile* has now demonstrated the feasibility for ASI of launching, at low cost, a small satellite into near perfectly equatorial orbit. Thus the equatorial orbit, which was preferred anyway because of simplicity of design and operation, can be taken again as the GG baseline.

The GG project of ASI is carried out in tight collaboration with INFN. ASI and INFN have signed an agreement for collaboration in a number of scientific projects. In the implementation phases of GG, if approved, ASI and INFN will sign a specific agreement, which will define the contributions by each institution to the mission.

1.3 Requirements Identification

The requirements in Chapter 5 and following of this document are classified according to the following categories:

- R: Mandatory requirements, to be complied with, and verified, by the Contractor. They are further classified according to the following codes:
  - EDR-X1: Experiment Driving Requirement
    - EDR-X1.X2: Requirement derived from one Experiment Driving Requirement, at the first level of branching
      - EDR-X.X1….XN Requirement derived from one Requirement of the N-1 level of branching from one Experiment Driving Requirement
- G: Performance goals, to be subject to cost/benefit analysis by the Contractor and ASI
- D: Descriptive text, providing supporting information/background about a set of requirements or goals.

2. DOCUMENTS

2.1 Applicable Documents

[AD 1] ASI, "Progetto Galileo Galilei-GG Fase A-2, Capitolato Tecnico", DC-IPC-2007-082, Rev. B, 10-10-2007 and applicable documents defined therein

2.2 Standards

[SD 1] ECSS-M-00-02A, Space Project Management – Tailoring of Space Standards, 25 April 2000

[SD 2] ECSS-E-ST-10C, Space Engineering - System Engineering General Requirements, 6 March 2009

[SD 3] ECSS-E-10-02A, Space Engineering – Verification

[SD 4] ECSS-Q-00A, Space Product Assurance - Policy and Principles, and related Level 2 standards.

2.3 ASI Reference Documents

[RD 1] GG Phase A Study Report, Nov. 1998, revised Jan. 2000, available at: http://eotvos.dm.unipi.it/nobili/ggweb/phaseA/index.html

[RD 2] Supplement to GG Phase A Study (GG in sun-synchronous Orbit) "Galileo Galilei-GG": design, requirements, error budget and significance of the ground prototype", A.M. Nobili et al., Physics Letters A 318 (2003) 172–183, available at: http://eotvos.dm.unipi.it/nobili/documents/generalpapers/GG_PLA2003.pdf

[RD 3] A. Nobili, DEL001: GG Science Requirements, Pisa, September 2008

2.4 GG Phase A2 Study Notes

[RD 4] SD-RP-AI-0625, GG Final Report / Satellite Detailed Architecture Report, Issue 1

[RD 5] SD-RP-AI-0626, GG Phase A2 Study Executive Summary, Issue 1

[RD 6] SD-TN-AI-1163, GG Experiment Concept and Requirements Document, Issue 3

[RD 7] SD-RP-AI-0620, GG System Performance Report, Issue 2

[RD 8] SD-TN-AI-1167, GG Mission Requirements Document, Issue 2

[RD 9] SD-RP-AI-0590, GG System Concept Report (Mission Description Document), Issue 3

[RD 10] SD-SY-AI-0014, GG System Functional Specification and Preliminary System Technical Specification, Issue 1

[RD 11] SD-RP-AI-0631, GG Consolidated Mission Description Document, Issue 1

[RD 12] SD-TN-AI-1168, GG Mission Analysis Report, Issue 2

[RD 13] DTM, GG Structure Design and Analysis Report, Issue 1

[RD 14] SD-RP-AI-0627, GG Thermal Design and Analysis Report, Issue 1

[RD 15] SD-RP-AI-0268, GG System Budgets Report, Issue 1

[RD 16] SD-RP-AI-0621, Technical Report on Drag and Attitude Control, Issue 2

[RD 17] TL25033, Payload Architectures and Trade-Off Report, Issue 3

[RD 18] SD-RP-AI-0629, Technical Report on Simulators, Issue 1

[RD 19] ALTA, FEEP Thruster Design and Accommodation Report, Issue 1

[RD 20] TASI-FI-44/09, Cold Gas Micro Thruster System for Galileo Galilei (GG) Spacecraft - Technical Report, Issue 1, May 2009

[RD 21] SD-RP-AI-0630, Spin Sensor Design, Development and Test Report, Issue 1

[RD 22] SD-TN-AI-1169, GG Launcher Identification and Compatibility Analysis Report, Issue 1

[RD 23] ALTEC-AD-001, GG Ground Segment Architecture and Design Report, Issue 1

[RD 24] SD-TN-AI-1218, GG Preliminary Product Tree, Issue 1

[RD 25] SD-PL-AI-0227, GG System Engineering Plan (SEP), Issue 2

[RD 26] TAS-I, Payload Development and Verification Plan, Issue 1

[RD 27] SD-PL-AI-0228, GG System Verification and Validation Plan, Issue 1

[RD 28] SD-TN-AI-1219, Report on Frequency Management Issues, Issue 1

[RD 29] SD-RP-AI-0632, GG Mission Risk Assessment And Mitigation Strategies Report, Issue 1

[RD 30] SD-RP-AI-0633, Report on Mission Costs Estimates, Issue 1

3. MISSION AND EXPERIMENT CONCEPT

3.1 Scientific Objectives

The goal of GG is to test the "Equivalence Principle" (EP) to 1 part in 10^{17}, more than 4 orders of magnitude better than today's laboratory experiments. As a consequence of this "Principle" all bodies in the gravitational field of a source mass should fall the same (in vacuum), regardless of their mass and composition. This phenomenon goes under the name of "Universality of Free Fall" (UFF).

The goal of GG to test the Equivalence Principle to 10^{-17} has to be compared with the current state of the art: 10^{-12} achieved with rotating torsion balances at the University of Washington in Seattle, US (recent improvement to about 10^{-13} announced). Lunar Laser Ranging (LLR) has provided a test (for the Earth and the Moon in the gravitational field of the Sun) to 10^{-13}, though it does not allow the sensitivity of the experiment to be tested with proof masses of the same composition.

In both cases an intense research activity is carried out to further improve the sensitivity of the test. However, the difficulties of torsion balance tests explain the slow improvement of their results over the years and indicate that considerable progress beyond the current level is extremely hard to achieve. Only experiments designed to be performed inside a spacecraft to fly in low Earth orbit can aim at testing the Equivalence principle to very high accuracy.

As compared to proof masses suspended on torsion balances in the lab, the driving signal in space is about 3 orders of magnitude stronger. As compared to free falling proof masses on the ground, the experiment can last as long as the satellite keeps orbiting the Earth (in the conditions required by the experiment..), certainly much much longer than 1 second or less available on ground; in a 1 year measurement the statistical error would decrease by more than a factor 5000!

In space, absence of weight allows the proof masses to be suspended from the spacecraft much more gently than on ground, where suspension must withstand the local acceleration of gravity; in space they are close to free proof masses, and therefore can be extremely sensitive to external effects.

Finally, the spacecraft in orbit around the Earth and enclosing the EP testing instrument, is an isolated system. This is an extremely favourable condition when performing a small force experiment, and it is utterly impossible to achieve on ground where: a) the vacuum chamber enclosing the instrument is subjected to terrain tilts and seismic noise; b) any rotation of the apparatus (required to modulate the signal and reduce electronic noise, as in the best tests performed with rotating torsion balances) needs motor and bearings whose noise can be reduced but not eliminated altogether; c) nearby mass anomalies not rotating with the instrument would compete an EP violation signal from the Earth.

It is therefore no wonder that satellite experiments aiming at high accuracy tests of the Equivalence Principle have been proposed and studied by scientists both in the US and in Europe, with support and funding by major space agencies such as NASA, ESA, CNES and ASI.

CNES, with support from ESA, has approved and is completing construction of the μSCOPE satellite, to fly in the near future with the goal of performing an EP test to 10^{-15} (room temperature experiment, about 200 kg total mass at launch)

NASA has been the first space agency to investigate and support an experiment to test the Equivalence Principle in space proposed by Stanford University; the mission, still under investigation, is STEP (Satellite Test of the Equivalence Principle), has been studied also in Europe in collaboration with ESA, is a precursor of μSCOPE with a cryogenic payload, a large total mass (1 ton at launch) and the goal of reaching 10^{-18}.

GG, so far supported by ASI and INFN, has a conceptually different design with respect to STEP and μSCOPE: it does not require cryogenics, has a total mass comparable to that of μSCOPE (250 kg total mass at launch) and aims at an EP test to 10^{-17}.

3.2 Experiment Concept

Two proof masses of different composition form the GG **differential accelerometer**. The proof masses are heavy (10 kg each) concentric, co-axial, hollow cylinders. The two masses are mechanically coupled by attaching them at their top and bottom to two ends of a coupling arm, using flexible lamellae. The coupling arm is made of two concentric tubes similarly attached at their midpoints to a single shaft. This assembly preserves the **overall symmetry** of the apparatus, when the two parts of the arm are taken together.

The masses are mechanically coupled through the balance arm such that they are free to move in the transverse (XY) plane. A differential acceleration acting on the masses gives rise to a displacement of the equilibrium position in the XY plane. The displacement of the proof masses is sensed by two sets of capacitance plates located between the test cylinders, one set for each orthogonal direction (X and Y). Each set forms an **AC-bridge** so that a displacement of the masses causes an unbalance of the bridge and is converted into a voltage signal. When the physical system is mechanically well balanced, it is insensitive to `common-mode' accelerations. Moreover, the capacitance bridges are inherently sensitive to differential displacements. Thus, the differential nature of the accelerometer is ensured both by the dynamics of the physical system, and by the displacement transducer.

Testing the EP to 1 part in 10^{17} in the gravitational field of the Earth at 520 km altitude requires detection of a differential acceleration $\mathbf{a_{EP} \approx 8.4 \cdot 10^{-17}\ m/s^2}$. To achieve this sensitivity, the proof masses must be very weakly coupled, otherwise the displacement signal resulting from such tiny acceleration is too small to detect. Moreover, the signal (at the orbital frequency) must be up-converted to higher frequency, the higher the better, to reduce 1/f noise.

In the GG accelerometer, the natural period of the differential mode will be designed to be about 545s. At that natural frequency, the EP acceleration signal a_{EP} will produce a displacement $\Delta \mathbf{x_{EP}}$ **≈ 0.6 pm always in the direction of the centre of the Earth**. By spinning the satellite and the accelerometer, with its displacement transducer, around their common symmetry axis, the EP violation displacement signal is **modulated at the spin frequency** of the system relative to the centre of the Earth.

Once the spacecraft has been given the required rate of rotation at the beginning of the mission (1 Hz with respect to the centre of the Earth), no motor or ball bearings are needed inside the satellite. In fact, all parts of the apparatus and the satellite co-rotate around a common symmetry axis. Since the satellite is not constrained to spin slowly, a spin speed which optimizes the stability of the experiment and satellite can be chosen. Due to the very weak coupling between the masses and rapid spin, the GG system is **a rotor in supercritical regime** and supercritical rotors are known to be self-centring even if fabrication and mounting errors give rise to departures from ideal cylindrical symmetry. Moreover, the spacecraft too is passively stabilized by rotation around its symmetry axis and no active attitude control is required for the entire duration of the space mission.

The only disadvantage of spinning at frequencies above the natural oscillation frequencies of the rotor is the onset of **whirl motions**. These occur at the natural frequencies of the system as “orbital” motion of the masses around their equilibrium position. Whirl arises due to energy losses in the suspensions: the smaller the losses, the slower the growth rate of whirl. It must be damped to prevent instability. Provided the **quality factor** Q of the suspensions is at least 20,000 (which laboratory tests have shown to be achievable), whirl growth is so slow that experiment runs can be performed between successive damping cycles, thus avoiding any disturbance from damping forces.

The largest disturbing accelerations experienced by the accelerometer are due to residual air drag and other non-gravitational forces such as sun and Earth radiation pressure. Such inertial accelerations act on the spacecraft and not on proof masses suspended inside it, and are, in principle, the same on both the test bodies. Ideally, common mode effects do not produce any differential signal; in reality, they can only be partially rejected. The approach taken in GG calls for surface accelerations to be partially compensated by a **drag free control system**, and partially abated by the accelerometer’s own **common-mode rejection**. Drag compensation requires the spacecraft to be equipped with **proportional thrusters** and a control system to force the spacecraft to follow the motion of an undisturbed proof mass inside it at (and close to) the frequency of the signal.

Another potential threat is due to temperature effects. **Temperature differences can give rise to differential accelerations** via (a) the “radiometer effect”, (b) differential elongation of the coupling arms, (c) differential changes in the stiffness of the suspensions, (d) expansion of the proof masses leading to change of their position w.r.t. the capacitance sensors. The temperature requirements derived in the 1998-2000 study were as follows: 0.2°C/day proof mass temperature stability; 1°C axial gradient across the test bodies and the coupling arms. Such performance, which was shown feasible by passive thermal insulation alone, allows 20 days of data taking before rebalancing the test bodies, and at least 15 days before rebalancing the read-out capacitance bridge.

3.3 System Description

3.3.1 *System Elements*

The GG system consists of the following segments:

- Space Segment, consisting of the GG satellite and its payload instruments
- Launch Service Segment
- Ground Segment.

3.3.2 *Payload*

The GG payload is constituted by the PGB (Pico Gravity Box) laboratory, enclosing

- The two cylindrical proof masses
- Capacitance plates for “science-level” sensing of proof mass relative displacements
- Small capacitance sensors/actuators for sensing relative displacements and damping the whirl motions
- Shaft connected to the coupling arm and U shaped flexible lamellae
- Inchworms and piezo-ceramics for fine mechanical balancing and calibration
- Launch-lock mechanisms, associated to all suspended bodies.

The PGB also carries a small mirror, in correspondence of a photo-detector mounted on the inner surface of the spacecraft, for measuring small residual phase lags with respect to the spacecraft.

The payload electronics include:

- The PGB Control and Processing Electronics (CPE), located on the spacecraft platform, managing PGB motion control (whirl sensing, whirl damping and drag-free control) and processing of all signals coming from the proof masses (motion control and EP sensing).
- The Experiment Control Electronics (ECE), housed inside the PGB, and communicating with the CPE via an optical link. The ECE locally manages whirl sensing and damper activation, under control by the CPE processor, and readout of the EP chain.

The payload apparatus further includes the necessary electrical harness and connectors and the thermal insulation.

3.4 Mission Overview

The GG mission is devoted to a single experiment that, once initialized, runs to the end of the scientific data collection. After the launch and early orbit phase, experiment set-up and first calibration operations are executed. Thereafter, the experiment is run in 7-day long data collection intervals. Calibration sessions are regularly interspersed with the measurement intervals. The nominal duration of the mission is 1 year.

No orbital change manoeuvres are required after acquisition of the operational orbit, approximately 1.5 hours after lift-off. The Spinup operations at beginning of life will take on the order of 1 week. Thereafter, no other attitude manoeuvres are required.

The processing of scientific data is done in bulk; therefore no scientific quick-look is required. All scientific operations are autonomous, executed on the basis of time-tagged operation sequences that are loaded at least one day in advance. Given the high level of autonomy, the tasks of the ground control are essentially limited to:

- Commanding and monitoring of the attitude manoeuvres (spin-up and spin axis orientation)
- Generation and transmission of command sequences and parameters
- Analysis of satellite data to establish that the satellite is operating correctly.

The mission is performed in equatorial circular orbit. The dedicated ground station is San Marco, Malindi, Kenya. The ground passes occur according to the sequence described in Section 4. Support by other stations in the early orbit phase may be considered.

As it is customary, the ground segment will include, besides the ground station, an Operational Control Centre (OCC), responsible of the execution of the mission operations, and an Operational Scientific Centre (OSC), responsible of the generation of the scientific operation sequences. There is no special requirement for real-time interaction between the on-board payload and the OSC, or, in general, between the satellite and the OCC.

4. BASIC DEFINITIONS

4.1 Reference Frames

The GG satellite will fly in a near-circular, near-equatorial, low Earth orbit. The reference frames relevant for the GG mission are defined as follows.

4.1.1 Inertial Reference Frame (IRF)

The fundamental inertial reference frame of the mission is currently realised by the J2000 Equatorial Reference Frame (JERF), which is a Cartesian frame defined as follows (see Figure 4.1-1):

- Origin, O_{J2000}, located at the centre of the Earth
- X_{J2000} axis at the intersection of the mean ecliptic plane with the mean equatorial plane at the date of 01/01/2000 and pointing positively towards the vernal equinox
- Z_{J2000} axis orthogonal to the mean equatorial plane at the date 01/01/2000
- Y_{J2000} axis completing a right-handed reference frame.

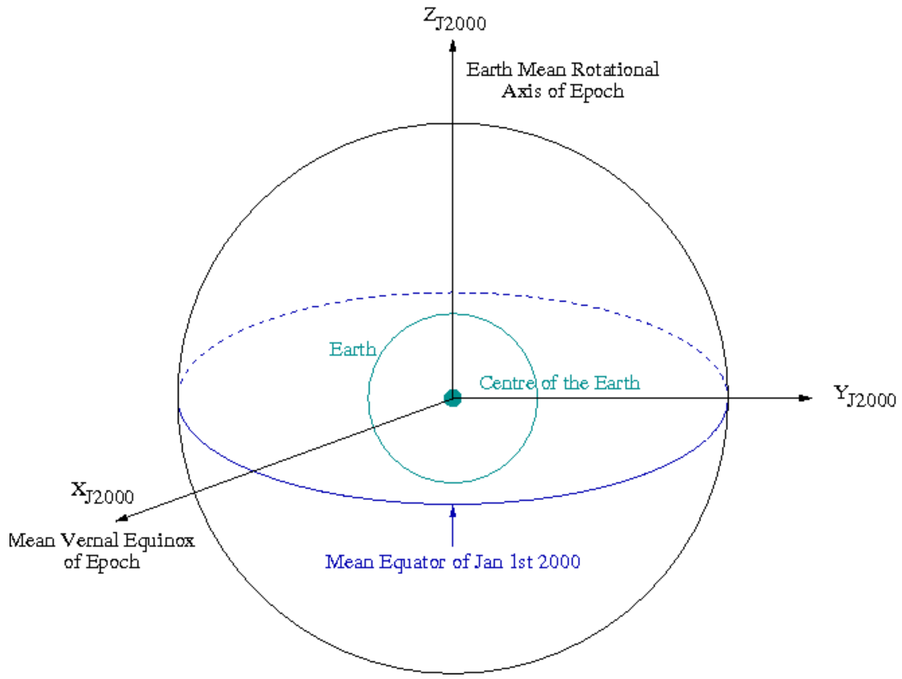

Figure 4.1-1: The Inertial Reference Frame is the J2000 Equatorial Reference Frame.

The centre is coincident with the Earth centre, the X axis is at the intersection of the mean ecliptic plane with the mean equatorial plane (at the date Jan 1st 2000), the Z axis is perpendicular to the mean equatorial plane (at the date Jan 1st 2000), and the Y axis completes a right-handed reference frame.

4.1.2 Local Vertical Local Horizontal Reference Frame (LVLH)

The LVLH reference frame is another fundamental frame: in this frame the EP violating signal always appears along a fixed direction (in case of a perfect circular orbit, the Earth is fixed in this reference and the EP violating signal appears as a DC effect). In order to have the EP violating signal along the XLVLH axis, this reference frame is so defined (see Figure 4.1-2):

- Origin, O_{LVLH}, located at the satellite centre of mass (COM)
- X_{LVLH} axis directed from the centre of mass of the Earth to the satellite centre of mass (X_{LVLH} axis identifies the local vertical from the point of view of the satellite COM)
- Y_{LVLH} axis points toward the direction of motion (it identifies the local horizontal projection of the velocity)
- Z_{LVLH} axis is perpendicular to the orbital plane and completes the right-handed coordinate system.

Notice that because the velocity vector rotates, to remain tangential to the orbit, the LVLH system also rotates about the Earth and that it does not take into account the GG spinning about its symmetry axis.

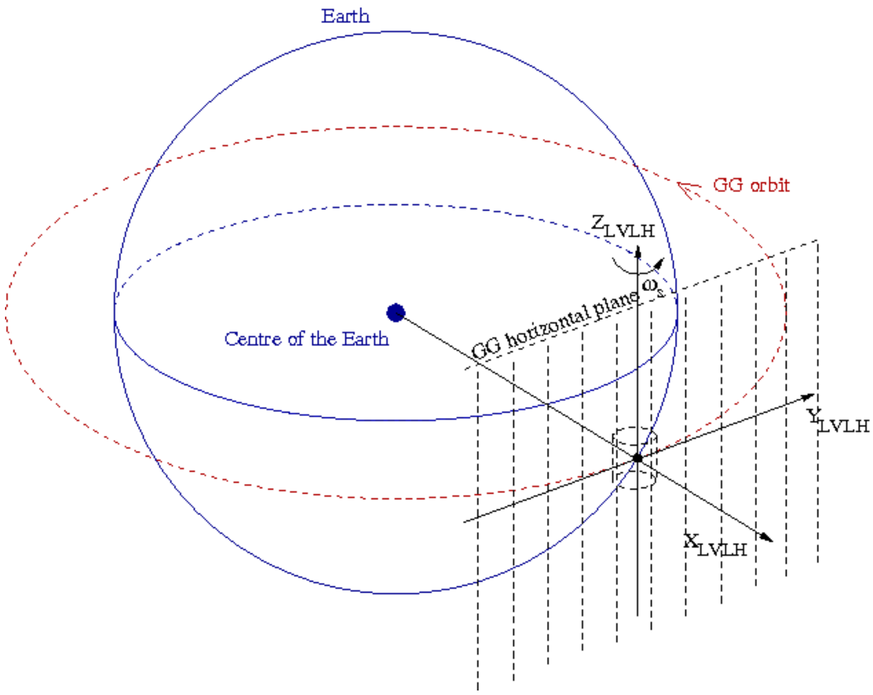

Figure 4.1-2: The Local Vertical Local - Horizontal Reference Frame

The LVLH frame is defined such that its origin is coincident with the satellite COM, its X axis is always from the Earth centre of mass to the centre of mass of the satellite, Y is pointing in the direction of orbit motion (it identifies the local horizontal plane) and its Z axis is perpendicular to the orbital plane and completes the right-handed coordinate system.

4.1.3 Body Fixed Reference Frame (BF)

The Body Fixed reference frame is the frame "attached" to the spinning satellite and defined by means of physical markers. The markers are placed when PGB and test masses are locked with respect to the satellite. The choice of the assuming spacecraft fixed reference frame with respect to PGB or proof masses fixed one is dictated by the fact that DFC sensors and actuators are fixed with respect to the satellite structure (PGB and test masses are mechanically suspended and during science operations are not fixed with respect to the satellite structure).

- Z_{BF} axis, corresponding to the central axis of the PGB connecting cylindrical tube (when the PGB is locked to the satellite). It is nominally the spinning axis of the satellite, and the positive direction is the same of the angular rate vector
- Origin, O_{BF}, located on the Z_{BF} axis. When PGB and test masses are locked with respect to the satellite, the origin marker is placed in order to individuate the position along the Z_{BF} axis of the test masses equatorial plane. O_{BF} is nominally coincident with the satellite centre of mass (when PGB and proof masses are locked)
- X_{BF} and Y_{BF} axes lie on the plane containing O_{BF} and perpendicular to the Z_{BF} axis. Each axis passes through the median plane of the two pairs of capacitance plates in between the test masses. A dedicated marker identifies the axes X_{BF} and Y_{BF}, which are chosen to complete with the Z_{BF} axis a right-handed coordinate system

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4.2 Satellite Spin Definition

The nominal equatorial orbit described by the GG spacecraft is such that it is counter clock wise with respect to the IRF (see Figure 4.2-1).

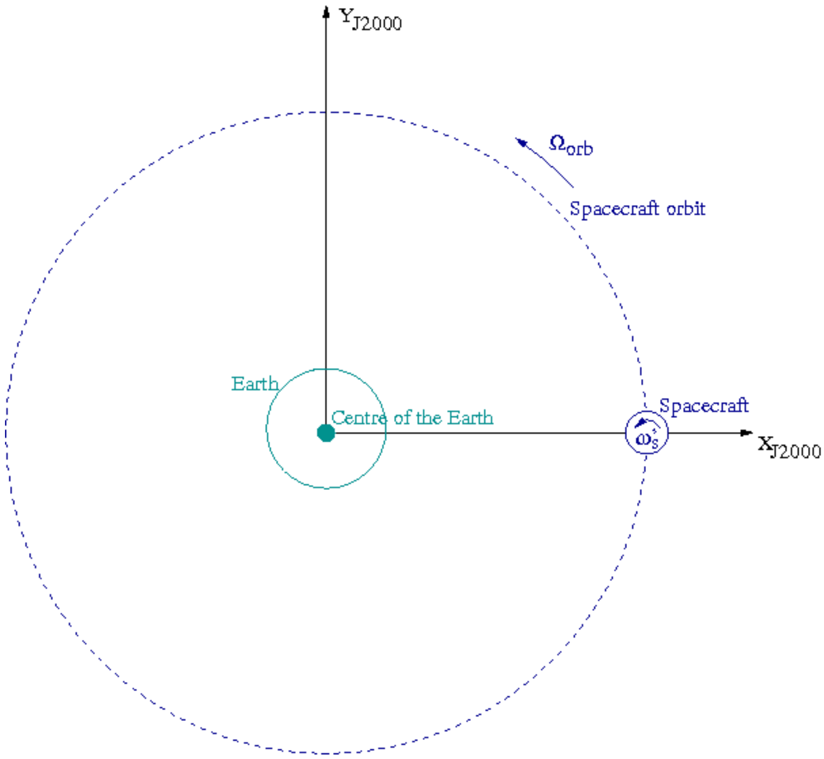

Figure 4.2-1: Satellite nominal circular orbit and spinning direction with respect to IRF

ω_s and Ω_{orb} are nominally parallel (they are parallel to the Z_{J2000} axis) and have the same orientation.

The satellite spin frequency is operatively defined with respect to the IRF (the spin-up of the satellite is performed with respect to the IRF by means of thrusters). From the science point of view, it is instead useful to define the satellite spin wrt the LVLH: the spinning frequency wrt LVLH is in fact the modulating frequency of the EP violating signal. According to Figure 4.2-1, it is assumed that Ω_{orb} and $\omega'_s = 2 \cdot \pi \cdot \nu'_s$ are the satellite orbit and the spin angular rate with respect to the IRF. Nominally, Ω_{orb} and ω'_s are parallel to the Z_{J2000} axis, with the same versus.

This means that an observer fixed with respect to the LVLH origin measures a satellite spin angular rate $\omega_s = 2 \cdot \pi \cdot \nu_s = \omega'_s - \Omega_{orb}$. This means that a satellite with null spin (fixed attitude) wrt LVLH has $\omega'_s = \Omega_{orb}$, i.e. its spin angular rate wrt IRF is equal to the orbit angular rate.

5. EXPERIMENT REQUIREMENTS

5.1 Introduction

The experiment requirements are organised by stating the Principal Drivers of the Experiment, and describing all their derived branches (which appear as bulleted list of requirements). See the figure below.

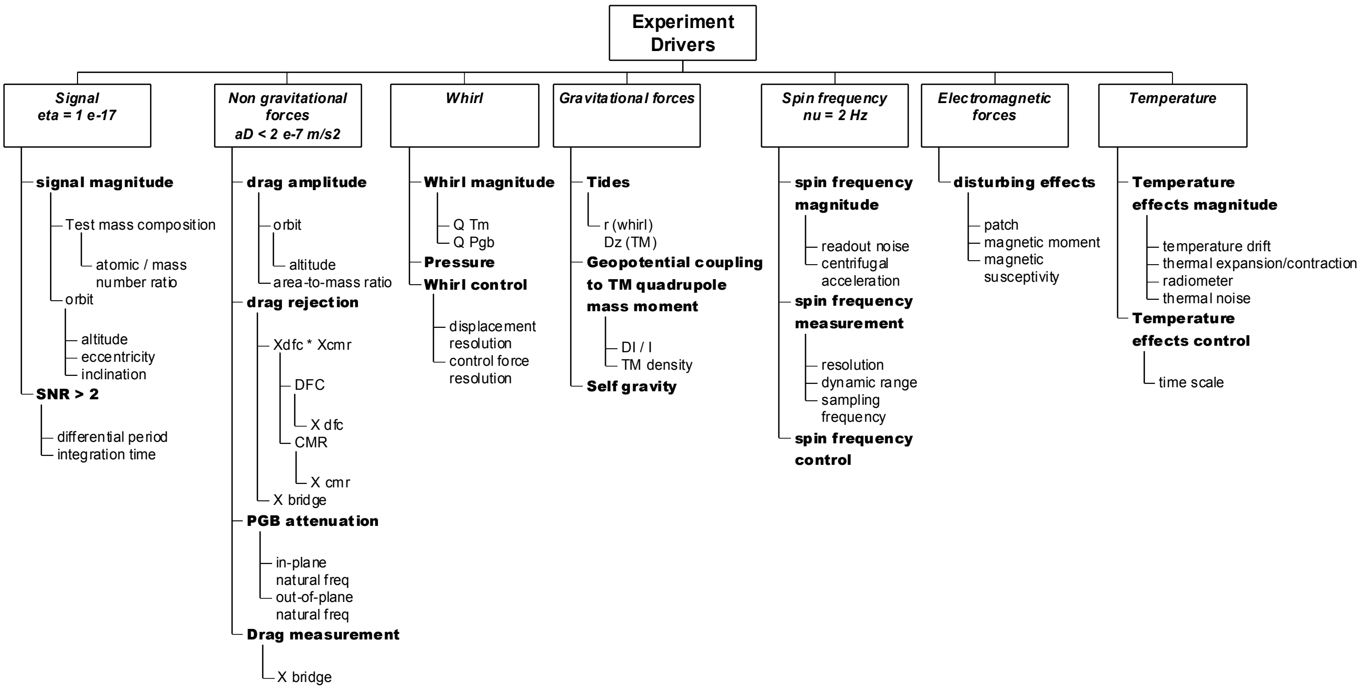

Figure 5.1-1: Experiment drivers

5.2 The Signal

5.2.1 Science objective definition

[EDR-1] (R) The science objective of GG is to test the "Equivalence Principle" (EP) to ***1 part in 10^{17}***.

5.2.2 Signal optimization: choice of the test mass material

[EDR-2] (R) In order to maximise the EP violating signal, the test masses material shall be chosen in order to maximise the difference between the ratio of atomic number (number of atom protons) over mass number (atomic number + number of atom neutrons).

5.2.3 Signal optimization: choice of the orbit

(D) In order to maximise the EP violating signal, the orbit altitude has to be chosen as low as possible. Practically, the desired driving signal is $g(h) > 8$ m/s^2. The best suitable orbit is the equatorial one:

- no regression of the nodes
- spin axis nominally aligned with the orbit angular rate (signal optimisation).

In practice, the expected orbit inclination will be about 5° (since the orbit inclination depends on the launch site latitude, and the selected launch site is the space centre of Kourou). The realised GG orbit cannot be exactly circular, and its eccentricity cannot be smaller than $e \approx 0.01$.

[EDR-3] (R) The GG orbit shall be equatorial and its altitude h shall be chosen to guarantee a local gravity acceleration $g(h) > 8$ m/s^2 (i.e. $h \leq 700$ km).

[EDR-3.1] (R) The maximum orbit inclination shall be $i \approx 5°$.

[EDR-3.2] (R) The maximum orbit eccentricity shall be $e \approx 0.01$.

[EDR-3.3] (R) The maximum error on the knowledge of the orbit inclination shall be $\delta i \approx 1°$.

5.2.3.1 Measurement of the Direction of the Earth

(D) The LVLH frame is a fundamental reference frame for the science post processing, and its axes have to be known all along the science mission.

[EDR-4] (R) The direction of an axis pointing at the centre of the Earth shall be known to better than 0.05 radians in a suitable local rotating frame.

5.2.4 Signal to Noise Ratio: SNR ≥ 2

(D) The science objective and the requirement of a Signal to Noise Ration SNR ≥ 2, together to the definition of the differential period (**T_{diff}**) of test mass oscillation and the duration of the fundamental science integration time slot (**T_{int}**) provide the following fundamental requirements and their derived branches.

[EDR-5] (R) The GG differential capacitance read-out shall be able to detect a test mass differential acceleration, with period T_{diff}, and smaller than $a_{EP} = 10^{-17} \times g(h)$ m/s², over the fundamental measurement interval T_{int}. In the IRF this signal is sensed in the test masses XY plane and has a period of 1 orbit. In the LVLH, in case of the nominal equatorial circular orbit, this acceleration is a DC effect along the X_{LVLH} axis.

[EDR-6] (R) In the LVLH, the test masses relative displacement due to the EP violating signal is $\Delta x_{EP} = a_{EP} \times (T_{diff})^2/(4 \times \pi^2)$. The capacitance read-out shall be capable (after calibration) to detect the displacement Δx_{EP} (in the test masses XY plane) in one fundamental science integration time slot **T_{int}**. The overall noise (mechanical thermal noise is here included) affecting the science measurement shall be such that in one fundamental science integration time slot **T_{int}** the Signal to Noise Ratio is SNR ≥ 2.

5.2.4.1 Differential period of oscillation and science integration time slot

(D) The ground laboratory prototype experience has demonstrated that a differential period of test mass oscillation **T_{diff} = 540 s** is feasible. This value is assumed here as an input, a provided number, not a parameter to be derived.

[EDR-7] (R) The test masses differential period **T_{diff}** shall not be shorter than 540 s.

[EDR-8] (R) The fundamental science integration time slot **T_{int}** shall not be longer than a week.

5.2.5 Payload Operation Requirements

5.2.5.1 Science Mission Duration

[EDR-9] (R) The in-orbit lifetime of the GG spacecraft shall be at least 1 year after the end of the initial commissioning.

[EDR-10] (G) The in-orbit lifetime of the GG spacecraft shall be at least 2 years after the end of the initial commissioning.

5.2.5.2 *Payload Operations Modes and Autonomy*

(D) After commissioning at the beginning of life, the main operational modes of the satellite are:

- Experiment Set-up and Calibration Mode
- Normal mode (scientific operation of the experiment)
- High-rate Data Collection Mode
- Safe (Hold) Mode.

The minimum set of scientific and auxiliary data to be made available to ground is in Appendix 2.

[EDR-11] (R) In normal science mode, whirl control shall be off for the duration of the fundamental measurement interval.

[EDR-12] (R) The experiment design and operations shall allow taking science data while whirl control is on.

[EDR-13] (R) All scientific operations shall be autonomous, executed on the basis of time-tagged operation sequences that shall be loaded at least one day in advance.

[EDR-14] (R) The scientific data set sent to ground shall consist of a suitable subset of non-demodulated science data.

[EDR-15] (R) In the High-rate Data Collection Mode, an extended set of raw (non demodulated) data shall be collected, for special checkout, parameter identification, and troubleshooting.

[EDR-16] (R) The High-rate Data Collection Mode shall be commanded by ground.

[EDR-17] (R) The duration the high rate data collection periods shall not exceed 10 minutes.

[EDR-18] (R) The satellite shall autonomously detect its status, basing on automatic self-check procedures and programmable decision tables.

[EDR-19] (R) On detection of an anomaly, the satellite shall suspend the scientific operations.

[EDR-20] (R) Resumption of the scientific operations shall be commanded by the ground.

5.2.5.3 Mission Timeline

[EDR-21] (R) The GG satellite shall be spin stabilized at the nominal spin rate within 1 week of the launcher separation.

[EDR-22] (R) The fist experiment set-up shall be concluded within 1 month of the launcher separation.

[EDR-23] (R) The nominal mission timeline shall consist of experiment data collection intervals, of the duration specified by [EDR-8], interspersed with short intervals during which whirl control is on.

5.2.5.4 In-Orbit Set-up and Calibration

[EDR-24] (R) The set-up sequence of the GG experiment consists of the following operations:

- Balancing of the proof masses
- Balancing of the capacitance sensors
- TBD

[EDR-25] (R) The calibration sequence of the GG experiment consists of the following operations:

- TBD

[EDR-26] (R) Set-up and calibration sessions shall be repeated at intervals of TBD days.

[EDR-27] (R) Set-up and calibration operations shall be based on automatic procedures, with minimal interaction with the ground control.

5.2.6 Payload Electronics

5.2.6.1 Payload Electronics Functions and Location

[EDR-28] (R) The PGB Control and Processing Electronics (CPE), shall manage PGB motion control (whirl sensing, whirl damping and drag-free control) and processing of all signals coming from the proof masses (motion control and EP sensing).

[EDR-29] (R) The CPE shall be located on the spacecraft platform.

[EDR-30] (R) The Experiment Control Electronics (ECE) shall locally manage whirl sensing and damper activation, under control by the CPE processor, and readout of the EP chain.

[EDR-31] (R) The ECE shall be housed inside the PGB and communicate with the CPE via an optical link.

5.3 The Non-Gravitational (Surface) Forces

5.3.1 Non gravitational acceleration amplitude in the XY plane

(D) In the IRF, the amplitude of the overall external non-gravitational forces (drag, albedo, solar radiation pressure, etc.) affecting the spacecraft motion at the orbit frequency (i.e. at the same frequency of the EP violating signal) in the XY plane shall produce an acceleration $a_{NG}^{ext} = 2\times10^{-7}$ m/s². This level of acceleration corresponds to the situation for which drag acceleration and solar radiation pressure have almost the same magnitude (choosing a higher altitude does not provide a much more comfortable environment). The GG Drag Free Control, and its sensors and actuators, shall be designed assuming this reference value for the main external disturbing acceleration.

[EDR-32] (R) In the IRF, the amplitude of the acceleration in the XY plane due to the overall external non-gravitational forces affecting the GG satellite shall be $a_{NG\,xy}^{ext} = 2\times10^{-7}$ m/s² at the orbit frequency.

[EDR-32.1] (R) The altitude of the GG orbit and the satellite A/M ratio shall be selected in order to guarantee that the spacecraft altitude shall be within the range specified by [ERD-3] and the amplitude of the a_{NG}^{ext} acceleration at the orbit frequency in the IRF shall be not greater than $a_{NG\,xy}^{ext} = 2\times10^{-7}$ m/s².

[EDR-32.1.1] (R) The 95% NASA solar activity forecast published in October 2008 shall be used for the purpose of predicting atmospheric density.

5.3.2 Non gravitational acceleration rejection in the XY plane

(D) The acceleration in the XY plane due to the overall external non-gravitational forces affecting the spacecraft motion is several order of magnitude greater than $a_{EP} = 10^{-17} \times g(h)$ m/s². This acceleration is sensed from the test masses as inertial force, and so it is a pure common mode for them. It is necessary to reduce this common mode acceleration for mainly three reasons:

- The common mode acceleration displaces each test mass, and this displacement has a limited range: the gap of the science capacitance plates
- The common mode rejection of the test masses mechanical suspension is not ∞ (i.e. a fraction of the common mode acceleration is transformed into differential acceleration, which competes with the interesting signal)
- The capacitance read-out, which is in charge of detecting the test masses relative displacement due to an EP violation, is sensitive to both common and differential mode. Hence (a) Its dynamic range must be not saturated, (b) Its rejection of the common mode is limited.

5.3.2.1 Maximum differential acceleration in the XY plane due to limited rejection of the non-gravitational forces

[EDR-33] (R) In the IRF, the residual (due to limited rejection of common mode) external non-gravitational acceleration sensed from each test mass in the XY plane shall cause no differential acceleration of the proof masses greater than $0.5 \times a_{EP}$ m/s² at the orbit frequency, and 3×10^{-15} m/s^2/√Hz in a bandwidth of 2×10^{-4} Hz around the orbit frequency.

5.3.2.2 Overall DFC and mechanical suspension rejection in the XY plane of the non-gravitational forces

[EDR-34] (R) In the IRF, the product of the DFC rejection χ_{DFCxy} and of the mechanical suspension Common Mode Rejection Ratio χ_{CMRRxy} shall be such that in the test masses XY plane and at the orbit frequency, $\chi_{DFCxy} \times \chi_{CMRRxy} = 0.5 \times a_{EP} / \ a^{ext}_{NG\,xy} = 2 \times 10^{-10}$.

5.3.2.3 DFC compensation of non-gravitational forces in the XY plane

(D) The DFC is in charge of partially compensate the acceleration due to the overall external non-gravitational forces affecting the spacecraft motion. The action of the DFC is different with respect to that of the mechanical suspension because it actually reduces the common mode acceleration sensed from the PGB and test masses: the required elongation of the suspension “springs” on the test masses equatorial plane depends on the inertial residual acceleration $\chi_{DFCxy} \times \ a^{ext}_{NG}$.

[EDR-35] (R) In the IRF, the DFC shall provide a rejection $\chi_{DFCxy} = 2 \times 10^{-5}$ in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency, in the XY plane of the test masses.

[EDR-35.1] (R) The drag free control authority shall be sufficient to meet or exceed the worst case external disturbance forces over at least 98% of the operational science mission duration.

5.3.2.4 Mechanical suspension rejection in the XY plane of common mode forces

(D) The residual external non gravitational forces acting on the spacecraft (after DFC compensation) are transferred to the PGB via its suspension springs and, from the PGB, via the U shaped flexible lamellae connecting the PGB to the coupling arms of the test bodies, to the test masses themselves. The residual inertial acceleration filtered through the PGB that is acting on the test masses mechanical suspension, $\chi_{DFCxy} \times \ a^{ext}_{NG\,xy}$, is in principle a perfect common mode acceleration (it is the same for the two test masses). The imperfections of the test masses mechanical suspension transform a fraction (Common Mode Rejection Ratio, χ_{CMRR}) of this acceleration into a differential acceleration. The gap between science capacitance plates and test mass surface requires a limited common mode motion. The test mass differential displacement depends on the square of the period of differential oscillation.

[EDR-36] (R) In the IRF, the test masses mechanical suspension shall provide a rejection $\chi_{CMRRxy} = 10^{-5}$ in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency, in the XY plane of the test masses.

[EDR-37] (R) In the IRF, the natural frequency of the common mode oscillations of the proof masses in the XY plane shall be within the range [1/100 1/30] Hz.

[EDR-38] (R) In the IRF, the natural frequency of the differential oscillations of the proof masses in the XY plane shall be $1/T_{diff}$ Hz, with $T_{diff} = 540$ s.

5.3.2.5 Mechanical balancing of the science read-out capacitance bridge

[EDR-39] (R) The mechanical balancing of the capacitance bridge χ_{bridge} shall allow the measurement of a differential displacement Δx_{EP} (in the test masses XY plane) in the presence of a larger test masses common mode displacement Δx_{CM}. The balancing shall be $\chi_{bridge} \le \Delta x_{EP}/\Delta x_{CM}$ with $\Delta x_{EP}/\Delta x_{CM} = (T_{diff})^2 \times a_{EP} / \left(a_{NG\,xy}^{ext} \times \chi_{DFCxy} \times (T_{CM})^2 \right)$, T_{CM} being the test masses common mode period of oscillation. The requirement reads: $\chi_{bridge}(T_{CM} = 100\text{ s}) = 6\times10^{-4}$ (i.e. 3 μm over a gap of 5 mm), $\chi_{bridge}(T_{CM} = 30\text{ s}) = 6.5\times10^{-3}$ (i.e. 32 μm over a gap of 5 mm).

5.3.3 The PGB

5.3.3.1 Pico Gravity Box suspension frequencies

(D) The Pico Gravity Box (PGB) provides a low vibrational noise platform for the test masses mechanical suspension, and at the same time it can be used as magnetic shield and faraday cage. It is an intermediate stage in between the spacecraft and the mechanical balance suspending the test masses. In the IRF, the PGB provides attenuation above its natural oscillation frequency; for a BF observer, it provides attenuation but at the spin frequency. Moreover, the relative motion of the PGB wrt the spacecraft is used to feed the DFC.

[EDR-40] (R) In the IRF, the PGB residual acceleration in the test masses XY plane shall be no greater than 4×10^{-12} m/s² at the orbit frequency and 3×10^{-10} $m/s^2/\sqrt{Hz}$ Hz in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

[EDR-41] The PGB shall provide passive attenuation of mechanical noise in both the BF XY plane and along the BF Z symmetry axis.

[EDR-41.1] (R) The first natural frequency of the oscillations of the satellite/PGB system in the XY plane, as measured in the IRF, shall be 1/360 Hz. In the IRF, this is the cutting frequency of the mechanical suspension.

[EDR-41.2] (R) In the IRF, the first natural frequency of the oscillations of the PGB in the Z direction shall be 1/30 Hz .

5.3.3.2 Limitations on Pico Gravity Box / Spacecraft relative motion

(D) The relative motion of PGB vs spacecraft must be limited due to the finite mechanical suspension dynamics range and due to the limited gaps of the capacitance sensors/actuator. This motion takes into account also differential angular rate due, for example, to variations of the inertia moments induced by thermal expansion/contraction of the structure.

[EDR-42] (R) The phase lag of the spacecraft relative to the PGB shall be detected to better than TBD rad.

[EDR-43] (R) The maximum phase lag of the spacecraft relative to the PGB shall not exceed TBD rad, at any time during the scientific mission, either by design or by active control.

5.3.3.3 Limitations on Pico Gravity Box / External Test Mass relative motion (D)

[EDR-44] (R) The phase lag of the PGB relative to the external proof mass shall be detected to better than TBD rad.

[EDR-45] (R) By design, the phase lag of the PGB relative to the external proof mass shall not exceed TBD rad over the scientific mission lifetime.

5.3.3.4 PGB Locking/Unlocking mechanism

[EDR-46] (R) The PGB shall be designed to be clamped during launch with a locking/unlocking mechanism.

5.3.3.5 Test Masses Locking/Unlocking mechanism

[EDR-47] (R) The test masses shall be designed to be clamped during launch with a locking/unlocking mechanism.

5.4 The Whirl

(D) The whirl motion, i.e. the very slow transformation of the spin kinetic energy into relative growing orbital motion between spacecraft and PGB (and between PGB and each test mass), is due to the unavoidable dissipation of the mechanical connections (U shaped springs). The whirl motion drives towards the realisation of the mechanical suspension with small dissipation and the implementation of one active control, which aims to make this motion limited and as small as possible during the science data measurements.

5.4.1 Dissipation requirements

[EDR-48] (R) The mechanical quality factor Q of the mechanical springs connecting the PGB to the spacecraft, measured at the s/c spin frequency (i.e. measured in the BF) shall be $Q_{PGB}(@\nu'\ Hz) \approx 90$.

[EDR-49] (R) The mechanical quality factor Q of the test masses mechanical suspension, measured at the s/c spinning frequency (i.e. measured in the BF) shall be be $Q_{TM}(@\nu'\ Hz) \approx 20000$.

[EDR-50] (R) The residual pressure acting on the test masses shall be $\leq 10^{-5}$ torr, in order to have not air damping in between test masses and science capacitance plates.

5.4.1.1 Drag compensation at the frequency of the differential mode

(D) Due to the high Q value of the mechanical suspension, if a line of the external non-gravitational forces appears at the same frequency of the test masses common and differential mode, there is an amplification of the acceleration by a factor Q. The common mode is attenuated by the PGB, the differential mode not.

[EDR-51] (G) In the IRF, in case the differential mode of the test masses shall be close to a mode of the external non-gravitational forces, the common mode rejection ratio of the drag free control shall be better than 1 part in 100, in the XY plane, in a bandwidth of 2×10^{-4} Hz centred at the differential mode frequency.

5.4.2 Whirl active control

[EDR-52] (R) The capacitance sensors in between the PGB and the spacecraft shall provide the measurements (in the BF) of the relative displacement δr^{w}_{PGB} of these two bodies in the XY plane with the r.m.s. of 0.01 μm in a bandwidth of $\approx$ 20 Hz.

[EDR-53] (R) The capacitance sensors in between the PGB and the spacecraft shall provide the BF stabilizing not-rotating damping control force to nullify the PGB whirling motion, which is of the order of $k_{PGB} \times \delta r^{w}_{PGB}$ / Q_{PGB}, with k_{PGB} the stiffness of the mechanical spring suspending the PGB.

[EDR-54] (R) The science capacitance sensors in between the PGB and each test mass shall provide the measurements (in the BF) of the relative displacement δr^{w}_{TM} of the two bodies in the XY plane with the r.m.s. of 0.001 μm (TBC) in a bandwidth of $\approx$ 20 Hz.

[EDR-55] (R) The small capacitance sensors in between the PGB and each test mass shall provide the BF stabilizing not-rotating damping control force to nullify the test masses whirling motion, which is of the order of $k_{TM} \times \delta r^{w}_{TM}$ / Q_{TM}, with k_{TM} the stiffness of the mechanical spring suspending the test masses to the PGB.

5.5 The Spacecraft Spin Frequency ν

5.5.1 Nominal Spin Rate

(D) For an observer fixed wrt the LVLH, the GG spin ν provides the modulation of the EP violating signal. This modulation reduces the electronic noise affecting the science measurement. The spin frequency, being much higher than the natural frequency of oscillation of PGB wrt the spacecraft, and much higher than the natural frequency of oscillation of each test mass wrt the PGB, provides also the supercritical centring. On one side, the higher is the spin frequency, the better is the science; on the other side, the centrifugal acceleration sensed at the outer surface of the spacecraft from the DFC actuators may prevent their functionality.

[EDR-56] (G) The spin frequency ν of the GG spacecraft shall be 1 Hz ± 0.1 Hz wrt LVLH.

[EDR-57] (R) The maximum centrifugal acceleration sensed on the GG satellite shall not exceed 12 g (TBC).

5.5.2 Measurement of the Spin Rate

[EDR-58] (R) The spin rate of the GG spacecraft shall be measured in the IRF with a fractional accuracy better than $\Delta\omega'_s / \omega'_s = 10^{-5}$ (TBC).

[EDR-58.1] (R) The angular rate of the GG spacecraft shall be measured with resolution better than $10^{-6}\ \omega'_s$ rad/s (TBC).

[EDR-58.2] (R) The spin rate sensor dynamic range shall be ±1000 deg/s.

[EDR-58.3] (R) The measurement of the spin rate of the GG spacecraft shall be provided at > 1 (TBC) Hz frequency.

5.5.3 Orientation of the Spin Axis

(D) The precise direction of the spin axis in space does not matter because the active dampers act, by geometrical construction, in the plane perpendicular to the spin axis. The measurement requirement below shall not be a design driver.

[EDR-59] After in-orbit attitude acquisition, the spin axis of the GG spacecraft shall initially be pointed within 1 deg of the normal to the orbit plane.

[EDR-60] The maximum angle in between GG spin axis and normal to the orbit plane shall be less or equal to 15 deg in the worst case after 2 years of mission.

5.5.4 Measurement of the Direction of the Spin Axis

[EDR-61] The direction of the spin axis shall be known with an accuracy of 1 deg in a suitable inertial frame, all along the measurement phase.

5.5.5 Supercritical Rotation and Suspension Mounting Errors

(D) The spin frequency and the natural frequencies of oscillation of the PGB and test masses provides the requirements on the mounting errors for the mechanical suspension. The residual offsets after self-centring due to the supercritical rotation are fixed vector wrt the BF (ω_S rotating vectors wrt LVLH). The following requirements refer to $\nu_S = 1$ Hz.

[EDR-62] (R) The mechanical suspension mounting errors shall not affect the science measurements.

[EDR-62.1] (R) The total noise injected by the electronics into the position measurement shall not exceed 6.5×10^{-10} m/Hz$^{1/2}$ @ ν'.

[EDR-62.2] (R) The mounting errors of the PGB/spacecraft suspension points shall be $\leq$ 100 μm.

[EDR-62.3] (R) The mounting errors of the TM/PGB suspension points shall be $\leq$ 1 μm.

[EDR-62.3.1] (R) Each proof mass shall have its centre of mass within TBD 10^{-6} m RMS of its geometric centre.

5.6 The Gravitational Forces

(D) The test masses are not spheres, and their quadrupole mass moment coupling with the Earth monopole field is not negligible wrt a_{EP}.

[EDR-63] (R) The quadrupole mass moment Q_{2int} and Q_{2ext} of the inner and external test masses shall be almost the same, i.e. $Q_{2int} \approx Q_{2ext}$. The differential acceleration due to the coupling of the Earth monopole field with the test bodies quadruple mass moment shall be less than $0.1\times a_{EP}$.

[EDR-63.1] (R) Each proof mass shall be a right circular cylinder with principal moments of inertia equal to better than 2 parts in 10,000.

[EDR-63.2] (R) Each proof mass shall be made from a material of density uniform to better than TBD.

5.6.1 The Tides

(D) The Gravity Gradient Tensor sensed at the spacecraft centre of mass, which is about 2×10^{-6} $m/s^2/m$, gives rise to differential acceleration provided any relative displacement of the test masses (for both displacement on the sensing equatorial plane and along the BF z axis). The tidal signal is also function of the inclination angle θ between the spin axis and the orbit angular rate.

5.6.1.1 Maximum whirl radius in the XY plane to limit the tidal signal

[EDR-64] (R) In the BF, the maximum whirl radius permitted to each test mass during science measurement shall not be larger than r_w^*, with $2\times10^{-6} \times 2 \times r_w^* \leq 10 \times a_{EP}$.

5.6.1.2 Maximum test masses Z offset to limit the tidal signal

[EDR-65] (R) In the BF, the maximum relative vertical (along BF z axis) offset of the centre of mass of proof bodies during science measurement and after calibration shall not be larger than $\Delta z^* = 5\times10^{-10}$ m.

5.6.1.3 Mechanical suspension common mode along the Z axis

[EDR-66] (R) In the IRF, the natural frequency of oscillations of the proof masses along the symmetry axis Z shall be 1/30 Hz.

5.6.1.4 Overall DFC and mechanical suspension rejection along Z of the non-gravitational forces

(D) The acceleration along the Z axis due to the overall external non-gravitational forces affecting the spacecraft motion is $a^{ext}_{NG_z} \approx 5 \times 10^{-8}$ m/s². This acceleration is sensed from the test masses as an inertial force, and so it is a pure common mode for them. According to the requirement [EDR-65], the maximum common mode acceleration along Z acting on the test masses must not introduce a test masses offset greater than 5×10^{-10} m.

[EDR-67] In the IRF, the product of the DFC rejection χ_{DFCz} and of the mechanical suspension Common Mode Rejection Ratio χ_{CMRRz} shall be such that along the Z axis and at the orbit frequency, $\chi_{DFCz} \times \chi_{CMRRz} \leq \omega^2_{CMz} \times \Delta z^* / a^{ext}_{NG_z}$, with $\omega_{CMz} = 2 \times \pi \times 1/30$ rad/s

5.6.1.5 DFC compensation of non-gravitational forces along Z

[EDR-68] In the IRF, the common mode rejection ratio along Z of the drag free control, χ_{DFCz}, shall be better than 2.5×10^{-3}, in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

[EDR-68.1] (R) The drag free control authority shall be sufficient to meet or exceed the worst case external disturbance forces over at least 98% of the operational science mission duration.

5.6.1.6 Mechanical suspension rejection along Z of common mode forces

[EDR-69] (R) In the IRF, the test masses mechanical suspension shall provide a rejection $\chi_{CMRRz} = 2\times10^{-2}$ in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency, along the Z axis of the test masses.

5.6.2 Satellite Self-Gravity

(D) The gravity signal due to local mass anomalies of the structure (PGB, spacecraft inner equipment, spacecraft external equipment) surrounding the test masses has not to introduce differential acceleration acting at the same frequency of the EP violating signal.

[EDR-70] (R) In the LVLH, coupling of the satellite's gravity with the test masses displacement and moments of inertia shall cause no differential acceleration of the proof masses greater than $0.1 \times a_{EP}$ m/s².

5.7 The Electromagnetic Forces and Other Disturbing Effects

5.7.1 Electromagnetic forces

(D) Test masses material shall be chosen in order to maximise the difference between the ratio of atomic number (number of atom protons) over mass number (atomic number + number of atom neutrons). The charging of the test masses is avoided due to the conductive mechanical suspension and the (electrostatic) patch effect is mainly a DC effect in the BF. The magnetic coupling between test masses puts some limit on their magnetic impurities and susceptibility. The PGB could be used as magnetic shield in case the spacecraft electronics generates non-negligible magnetic fields.

[EDR-71] (R) In the IRF, the patch effect during science measurement shall generate a differential acceleration smaller than 0.1× a_{EP} in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

[EDR-71.1] (R) The proof mass design shall minimize charge accumulation from ionizing radiation.

[EDR-71.2] (R) The proof mass outer surfaces shall have dimensional accuracy better than 1 part in 10^4.

[EDR-72] (R) In the IRF, the acceleration due to the coupling of each test mass intrinsic magnetic moment (due to residual ferromagnetic impurities) with the gradient of the magnetic field sensed at the proof body location shall be less than 0.1× a_{EP} in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

[EDR-73] (R) In the IRF, the acceleration due to the coupling between the intrinsic magnetic moment of one test body and the magnetization induced on the other one by the magnetic field sensed at its location shall be less than 0.1× a_{EP} in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

[EDR-74] (R) The intrinsic magnetic moment (due to residual ferromagnetic impurities) of each test mass shall be less than 10^{-7} Am^2.

[EDR-75] (R) The magnetic susceptibility of each test mass shall be less than 10^{-6}.

5.7.2 Other Perturbations

5.7.2.1 Differential residual pressure

[EDR-76] (R) In the IRF, the differential acceleration between the proof masses due to residual gas pressure shall not exceed 10^{-17} × g(h) m/s², in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

5.8 The Temperature Variation

(D) The time scale of the thermal effects on board is very large due to the thermal capacitance and due to the isolation of the inner PGB environment wrt external world. The read-out capacitance bridge is also sensitive to thermal effects, which can change for example its mechanical balancing. The high spin frequency makes the temperature almost homogeneous in azimuth. This means that the differential accelerations due to both radiation pressure and radiometric effect are negligible on the test masses equatorial plane.

5.8.1 Time scale of thermal effects

[EDR-77] (G) The time scale of the thermal effects shall be much and much longer than the calibration one. The minimum elapsed time between two consecutive capacitance bridge calibration shall be 2 weeks.

5.8.2 Test Masses expansion

[EDR-78] (R) In the IRF, radial and longitudinal (along Z axis) thermal expansion/contraction of the mass surrounding the proof bodies shall cause no test masses differential acceleration greater than $10^{-17} \times g(h)$ m/s² in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency during each time slot in between two consecutive calibrations.

5.8.2.1 Thermal Effects on Test Masses Suspension

[EDR-79] (R) In the IRF, the temperature drift inside the PGB shall no larger than 0.2 °K/day.

[EDR-80] (R) In the IRF, variation of the suspension rigidity due to thermal effects shall cause no degradation of the χ_{CMRRxy} from 10^{-5} in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency in the period of two weeks.

[EDR-80.1] (R) In the IRF, the percent variation of each test mass suspension stiffness per deg shall be not larger that $\Delta K/K = 1/4000$ 1/°K in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency in the period of two weeks.

[EDR-80.2] (R) In the IRF, the differential variation of the test masses suspension stiffness due to thermal effects shall not be larger than $\delta(\Delta K/K) = 10^{-2}\times \Delta K/K$, in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency in the period of two weeks.

[EDR-81] (R) In the IRF, variation of suspension arm length due to thermal expansion/contraction shall not degrade of the χ_{CMRRxy} from 10^{-5} in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency in the period of two weeks.

[EDR-82] (R) In the IRF, variation of suspension arm length due to thermal expansion/contraction shall not degrade of the χ_{CMRRz} from 2×10^{-2} in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency the period of two weeks.

[EDR-82.1] Thermal gradients along suspension arms shall not exceed 1 °K the period of two weeks.

[EDR-82.2] Thermal dilation coefficient for the test masses suspension material shall not exceed 10^{-5} m/(°K m).

5.8.3 Radiation Pressure Acting on Test Masses

(D) If the two bases surfaces of one test cylinder have different temperatures they will emit differently, and this will result in a net force along the symmetry axis of the cylinder. This effect will be different for the two test masses, hence resulting in a differential acceleration.

[EDR-83] (R) In the IRF, the differential thermal radiation hitting the proof masses along Z shall no induce an offset larger than 5×10^{-10} m, in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

5.8.4 Thermal Noise

(D) The fluctuation-dissipation theorem states that the thermal noise affects the system such as a dissipation term. This noise has been already accounted for in [EDR-6]. The thermal noise depends on environment temperature and dissipation in the test masses suspension. The thermal noise directly affects the science measurement must be limited.

[EDR-84] (R) Temperature at the location of the proof masses and of test masses themselves shall not exceed 350 °K during 1 fundamental science time slot.

5.8.5 Thermal Gradients

(D) The temperature gradient are responsible of the radiometric effect. Due to negligible azimuthal temperature gradient, there is no radiometric effect in radial direction.

[EDR-85] (R) In the IRF, the radiometric effect along Z, with a maximum temperature gradient of 1 °K across the arm length, shall not induce a test masses offset larger than 5×10^{-10} m, in a bandwidth of 2×10^{-4} Hz centred at the orbit frequency.

6. SPACECRAFT SUPPORT REQUIREMENTS

6.1 Spacecraft Mass Properties

[EDR-86] (R) In the spacecraft as a whole, the moment of inertia *Jz* with respect to the symmetry/spin axis shall be the axis of maximum inertia.

[EDR-87] (R) In the PGB alone, the moment of inertia *Jz* with respect to the symmetry/spin axis shall be the axis of maximum inertia.

[EDR-88] (R) In the spacecraft as a whole, the fractional difference in the principal moments of inertia (moment of inertia *Jz* with respect to the symmetry/spin axis and the moment of inertia *Jx* with respect to any axis in the transversal plane) shall be comprised between the following limits:

$$0.2 < \frac{J_Z - J_X}{J_Z} \equiv \frac{\Delta J}{J} < 0.3$$

[EDR-89] (R) The uncertainty in measurement of the spacecraft mass properties shall be less than 1%.

[EDR-90] (R) The uncertainty in the transformation between attitude control reference frame and principal inertia reference frame shall be less than 0.5 degrees.

(D) The uncertainty on the transformation between attitude control reference frame and principal inertia reference frame depends on the inertia products amplitude and uncertainty. Taking into account EDR-85 and EDR-86, the following requirements are derived.

[EDR-91] (R) The cross product of inertia shall not exceed the following values wrt the axial and transverse principal axes of inertia:

$$|I_{XY}| \le 0.02\ I_t$$

$$|I_{XZ}| \le 0.00125\ I_a$$

$$|I_{YZ}| \le 0.00125\ I_a$$

ANNEX 1 – ACRONYMS

AD	Applicable Document
AOCS	Attitude and Control Subsystem
ASI	Agenzia Spaziale Italiana
BF	Body Fixed (Reference Frame)
CCSDS	Consultative Committee for Space Data Systems
COM	Centre of Mass
CNES	Centre National d'Etudes Spatiales
CPE	Control and Processing Electronics
ECE	Experiment Control Electronics
EP	Equivalence Principle
ESA	European Space Agency
G/S	Ground Station
GG	Galileo Galilei
HK	Housekeeping
INFN	Istituto Nazionale di Fisica Nucleare
IRF	Inertial Reference Frame
LEOP	Launch and Early Orbit Phase
LLR	Lunar Laser Ranging
LVLH	Local Vertical Local Horizontal (Reference Frame)
MRD	Mission Requirement Document
P/L	Payload
PA	Product Assurance
PGB	Pico Gravity Box
RD	Reference Document
SD	Standard Document
S/C	Spacecraft
S/S	Subsystem
SPF	Single Point Failure
TBC	To Be Checked
TBD	To Be Defined
TC	Telecommand
TM	Telemetry

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