Highlights of Spanish Astrophysics XI, Proceedings of the XV Scientific Meeting of the Spanish Astronomical Society held on September 4–9, 2022, in La Laguna, Spain. M. Manteiga, L. Bellot, P. Benavidez, A. de Lorenzo-Cáceres, M. A. Fuente, M. J. Martínez, M. Vázquez- Acosta, C. Dafonte (eds.), 2023

Increasing the technological maturity of a low-noise magnetic measurement subsystem with IOD/IOV CubeSat Platforms.

Mateos, I.[1], Maria-Moreno, C.[1], Pacheco-Ramos, G.[2], Quirós-Olozábal, A.[1], Guerrero-Rodríguez, J.M. [1], Cifredo-Chacón, M.A. [1], Del Sol, I.[1], Cobos-Sánchez, C.[1], Vílchez-Membrilla, J.A.[1], and Rivas, F.[3]

[1] Escuela Superior de Ingeniería, Universidad de Cádiz, 11519 Cádiz, Spain
[2] Dpto. de Ingeniería Aeroespacial y Mecánica de Fluidos, Universidad de Sevilla, 41092 Sevilla, Spain
[3] Universidad de Loyola, 41704 Sevilla, Spain

Abstract

With the purpose of advancing the technological maturity of novel magnetic sensing techniques, in-orbit platform opportunities (IOD/IOV experiments) offer the possibility to assess their in-flight capabilities. Magnetic Experiments for the Laser Interferometer Space Antenna (MELISA) are a series of in-flight demonstrators that intend to characterize the low-frequency noise behavior of a magnetic measurement system under the harsh space environment. One of these undergoing experiments developed by the University of Cádiz is MELISA-III, an improved payload based on magnetoresistive sensors embarked on the first CubeSat mission of the Horizon 2020 IOD/IOV program with the support of the European Space Agency (ESA). After the successful environmental test campaign on the Qualification Model and the acceptance-level testing, the MELISA-III Flight Model was delivered to the prime contractor in February 2022 for its integration into a 6U CubeSat. A review of the main performances of the payload, the test campaigns, and the planned scientific operations at LEO will be described in this paper.

1 Introduction

LISA (Laser Interferometer Space Antenna) is the future space-borne gravitational wave (GW) observatory under the lead of the European Space Agency (ESA) in collaboration with NASA [1]. LISA will be constituted by three drag-free spacecraft forming a laser interferometer with 2.5-million-kilometer optical arms. Each spacecraft contains free-floating test masses (TMs) that behave as inteferometer end mirrors and follow a Geodesic trajectory. Hence, GWs passing through the LISA costellation will slightly change the distances between TMs shifting the inter-satellite optical arms of the laser interferometer. The top-level requirement for the LISA scientific payload is defined in terms of free-fall noise density as

$$S_{\delta a,\mathrm{LISA}}^{1/2}(\omega) \leq 3\times 10^{-15}\left\{\left[1+\left(\frac{\omega/2\pi}{8\ \mathrm{mHz}}\right)^4\right]\left[1+\left(\frac{0.1\ \mathrm{mHz}}{\omega/2\pi}\right)\right]\right\}^{\frac{1}{2}}\ \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}} \tag{1}$$

in the frequency band between $0.1\,\mathrm{mHz} \leq \omega/2\pi \leq 100\,\mathrm{mHz}$. One of the non-gravitational forces that can disturb the free-fall requirement is the magnetic environment caused by the interplanetary magnetic field and the spacecraft's magnetic sources, such as the electronics units or the solar panels. Therefore, to allow the accurate functioning of the GW detector, proper low-noise magnetometers are required to discern the magnetic contribution from the total acceleration budget.

2 CubeSat mission for in-orbit demonstration

To increase the technological maturity of chip-scale magnetic sensing techniques under harsh conditions in space, further experiments with In-orbit Demonstration and Validation (IOD/IOV) platforms need to be done for future space-based GW observatories. For this end, MELISA (Magnetic Experiments for the Laser Interferometer Space Antenna) are a series of compact magnetic measurement payloads with a detectivity capable of distinguishing interplanetary magnetic field fluctuations down to 100 μHz [2, 3].

MELISA-III is a technology demonstrator that intends to characterize the low-frequency noise behavior of a magnetic measurement system based on anisotropic magnetoresistive (AMR) sensors by applying low-noise bias fields with a built-in Printed Circuit Board (PCB) coil. With this purpose, the environmental magnetic field fluctuations will be diminished during in-flight operations by using a cylindrical shield with three concentric mu-metal layers enclosing the triaxial AMR sensors.

MELISA-III was selected by the European Union on the H2020 IOD/IOV mission, a 6U CubeSat with the support of ESA called CSC-2. The mission goal is to provide flight heritage to MELISA-III and two other selected experiments.

3 MELISA-III Payload: design and analysis

3.1 Analog signal conditioning circuit

The output from a full Wheatstone bridge of AMR elements is modulated at 5 Hz to reduce the $1/f$ noise of the sensor and electronics. The signal then goes through a precision instrumentation amplifier and is synchronously demodulated. Once the signal is integrated, a feedback controller helps to minimize the thermal dependence of the payload. This will decrease the excess noise in the lower end of the frequency bandwidth that is coupled to the long-term thermal drifts [2, 3]. Figure 1 displays the physical architecture of the experiment.

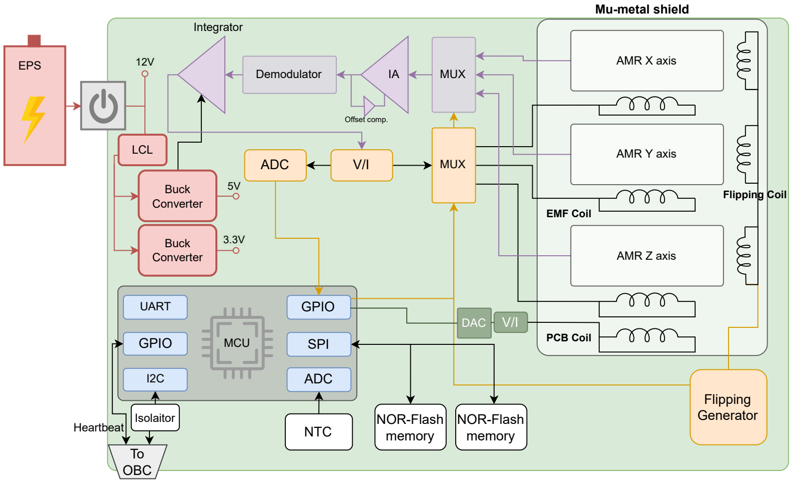

Figure 1: Block diagram of MELISA-III.

3.2 Compact PCB coil optimization

A transducer coil is built into the inner layers of the PCB to inject ultra-stable magnetic fields in the three axes of the AMR sensors. The purpose is to obtain noise curves along the whole magnetic field range of the payload during the in-flight scientific operations. The circuit that produces the current to feed the PCB coil contains a Digital-to-analog converter (DAC) followed by a low-noise floating current source. The DAC that sets the amplitude of the current applied to the coil is configured with bipolar operation.

An adapted Inverse Boundary Element Method (IBEM) has been utilized to optimize the multilayer PCB coil considering different geometrical and performance constraints, such as magnetic field maximization in the region where the AMR sensitive axes are located. The theoretical results were compared to numerical simulations using COMSOL Multiphysics and experimental measurements. Those results were deemed to be in good agreement [4].

3.3 Structural assessment

The design of MELISA-III is analyzed and validated from the structural point of view by means of Finite Element Analysis (FEA) using Ansys. The loading scenarios considered include: quasi-static loading, sine vibrations, random vibration, and shock response spectrum. The load levels are established according to the information supplied by the prime contractor. Moreover, a lower limit of 135 Hz is established for the first natural frequency. Given the dynamic nature of the loads, the numerical analyses are carried out based on modal decomposition and all the vibration modes within range of interest are considered. Based on the CAD, a simplified geometrical model is developed where design details not impacting structural analysis are removed. The geometrical entities and parts considered are showed in Fig. 2. Additionally, punctual and distributed masses are included to compensate the mass neglected due to geometry simplifications and modeling approach. A 3D finite element mesh-

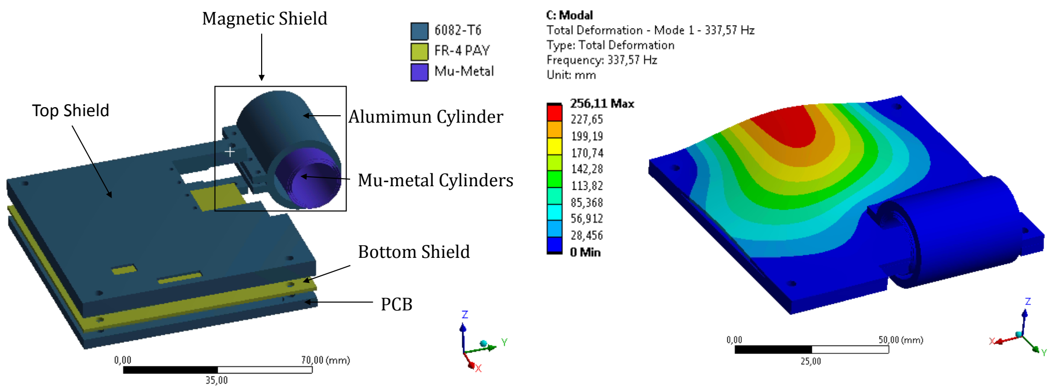

Figure 2: Left: MELISA-III geometry description. Exploded view. Right: First natural mode.

ing, based on tetrahedral/hexahedral SOLID185 elements, is created with the help of ANSYS meshing tools. With regards to properties, with the exception of FR4, which is modeled as an orthotropic material, isotropic properties are considered and applied to the modeled parts. In reference to connection, Multi Point Constraint (MPC) elements are used in order to model mechanical connections such as the bonding between cylinders or the connections to the PCB stack rods. Bolted joints are modeled as a combination of MPC and bar elements.

The results obtained from analysis allow to conclude the fulfilment of the structural requirements: i) the minimum natural frequency computed is 337.57 Hz, represented in Figure 2; ii) the stress levels and displacements obtained provide positive Margins of Safety for both metallic and FR4 parts, being the shock loading the most critical case.

4 Qualification and acceptance tests

The model and test philosophies were agreed upon with ISISpace as the System Integrator and ESA. The Qualification Model (QM) and Flight Model (FM) approach was selected for the MELISA-III payload. An overview of the required tests that were successfully performed at subsystem level is shown in Table 1. The environmental tests (EMC, TVAC/Bakeout, Vibration, and shock) were carried out in collaboration with ALTER Technology at their facilities.

5 Low-frequency environmental noise contributions at LEO

5.1 Magnetic impact of LEO environment

The LEO magnetic fluctuations that the magnetic shielding can not cancel out will be perceived by the measurement system. Therefore, the subtraction of these contributions must be applied during postprocessing. As a result, a simulation of the in-orbit environment is

Table 1: Qualification and acceptance tests performed in MELISA-III QM and FM.

Test	QM	FM
Functional and performance	✓	✓
EMC	✓	✓
Bakeout/TVAC	✓	
Thermal ambient		✓
Burn-in		✓
Vibration	✓	
Shock Response Spectrum	✓	

needed in order to foresee the influence of these conditions in the magnetic measurements, and elaborate an approach for the subtraction [5].

The LEO orbit is simulated in GMAT (General Mission Analysis Tool), providing the position of the satellite during a number of days. The orbital parameters are implemented according to the current information about the Sun-synchronous orbit provided by the CubeSat Operator. From these data, the magnetic environment that the CubeSat will experience is calculated during that time using the World Magnetic Model in MATLAB. The attitude, which will be nadir pointing, is simulated by applying a rotation matrix

$$R_Z = \begin{bmatrix} \cos(\omega) & -\sin(\omega) & 0 \\ \sin(\omega) & \cos(\omega) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

while $\omega = 7.66$ deg. On-ground triaxial Helmholtz coils are fed using controlled currents that provide the previously-determined magnetic field. MELISA-III is placed inside these coils along with an unshielded fluxgate magnetometer.

The in-orbit fluctuations are simulated in the three axes, while the scientific data of MELISA-III is produced at 5 Hz for 42 hours. The results are displayed in Figure 3, with and without the environment simulation. In this Amplitude Spectral Density (ASD), the fundamental frequency appears at approximately 93 min, which is the period of the orbit. Besides, the peak at $\approx$ 100 mHz is associated to the quantization noise due to the control of the currents through the Helmholtz coils. Eventually, ongoing postprocessing techniques will allow to disentangle these contributions from the scientific data provided in orbit through correlation with measurements of the platform's magnetometers.

5.2 Excess noise caused by temperature fluctuations

Variations in the ambient temperature may result in changes in the magnetic field generated by other components of the satellite, impacting the measurements of sensors. For instance, a rare-earth magnet is located in the same platform as MELISA-III for other experimental purposes. A test was performed in order to assess the magnetic field generation of that magnet based on the in-orbit temperature fluctuations. Thus, variations of approximately 20°C in the magnet conditions were induced by a heater with the aim of assessing the magnetic influence on MELISA-III.

The results of the test are shown in Figure 3. The peak located at 0.35 mHz corresponds to the fundamental frequency of the thermal cycle of the magnet. Therefore, results provided by MELISA-III at mHz frequencies are significantly influenced by the temperature of this magnet, resulting in a possible in-orbit surpassing of the mission requirements. A suitable magnetic shielding for the payload is required for the mitigation of these contributions, otherwise postprocessing techniques are also needed.

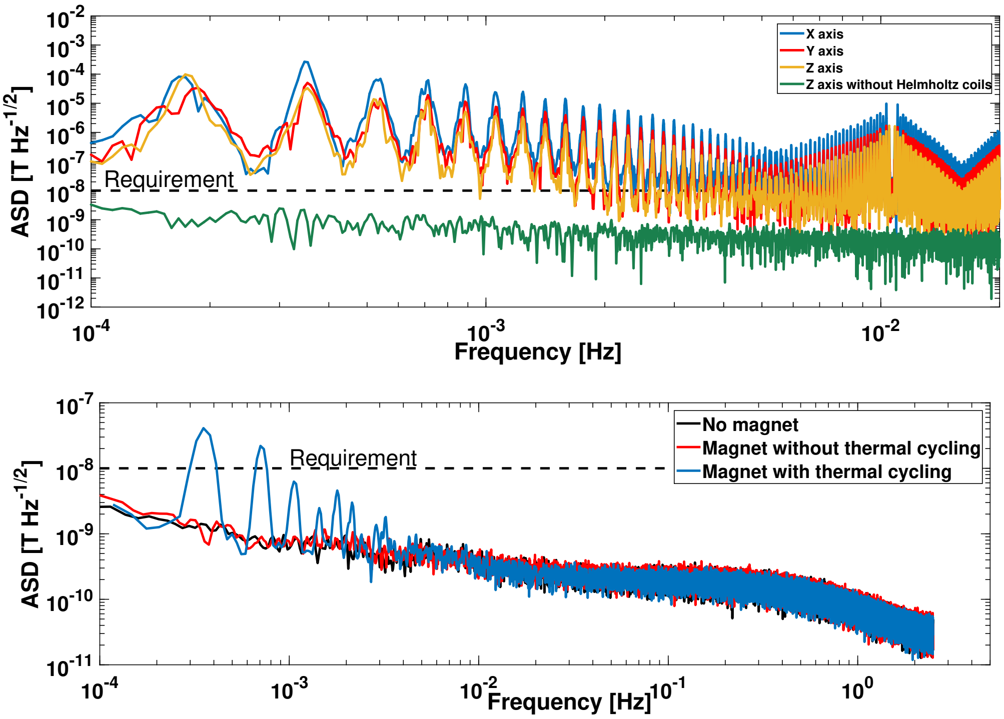

Figure 3: Top: ASD for the MELISA-III during the orbit simulation with the Helmholtz coils. The black dashed line indicates the instrument requirement. Bottom: Comparison between MELISA-III measurements with and without the influence of the magnet that is part of another on-board experiment.

6 Conclusions

MELISA-III, a low-noise magnetic measurement system based on AMR sensors with dedicated noise reduction techniques, has been designed, developed, and tested for a 6U CubeSat mission of the Horizon 2020 program. The MELISA-III payload has successfully passed the qualification and acceptance test campaigns at subsystem level before its final assembly, integration, and validation on the platform. The CubeSat is scheduled to be launched from Kourou in ESA's Vega-C rocket before mid-2023.

During scientific operations, ongoing post-processing analyses will enable discerning thermal and magnetic contributions from the scientific data provided in orbit. The in-flight characterization of MELISA-III will allow reaching an unprecedented noise performance and expand the frequency range for magnetic sensing in space-based gravitational wave detectors, pushing the technological discipline beyond its previous state of the art.

Acknowledgments

We wish to thank ALTER Technology for their collaboration during the environmental tests and Laboratorio de Corrosión y Protección (UCA) and Navantia for the black anodizing process of the MELISA-III shield. Support for this work came from the Department of Economy, Knowledge, Business and University of the Regional Government of Andalusia under Project P18-FR-2721 (PAIDI-2020 Programme), Project FEDER-UCA18-107380, and Project FEDER-UCA18-105867. The MELISA-III experiment will be embarked on the first mission of the H2020 IOD/IOV program of the EU.

References

[1] Amaro-Seoane P. et al. 2017, https://arxiv.org/abs/1702.00786

[2] Mateos I. et al. 2015, Sens. Actuator A-Phys., 224, 147

[3] Mateos I. et al. 2018, Sens. Actuator A-Phys., 273, 311

[4] Vilchez-Membrilla J. A. et al. 2022, IEEE Trans. Instrum. Meas., 71, 9512509

[5] Maria-Moreno C. et al. 2023, Zenodo, https://doi.org/10.5281/zenodo.7050680