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Low-frequency noise characterization of a magnetic field monitoring system using an anisotropic magnetoresistance

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ABSTRACT

A detailed study about magnetic sensing techniques based on anisotropic magnetoresistive sensors shows that the technology is suitable for low-frequency space applications like the eLISA mission. Low noise magnetic measurements at the sub-millihertz frequencies were taken by using different electronic noise reduction techniques in the signal conditioning circuit. We found that conventional modulation techniques reversing the sensor bridge excitation do not reduce the potential $1/f$ noise of the magnetoresistors, so alternative methods such as flipping and electro-magnetic feedback are necessary. In addition, a low-frequency noise analysis of the signal conditioning circuits has been performed in order to identify and minimize the different main contributions from the overall noise. The results for chip-scale magnetoresistances exhibit similar noise along the eLISA bandwidth (0.1 mHz – 1 Hz) to the noise measured by means of the voluminous fluxgate magnetometers used in its precursor mission, known as LISA Pathfinder.

1. Introduction

eLISA (evolved Laser Interferometer Space Antenna) is a space-based observatory proposed as a large space mission of the European Space Agency (ESA) and conceived to directly detect low-frequency gravitational radiation between 0.1 mHz and 1 Hz. This bandwidth, which is not observable from Earth, is expected to reveal some of the most exciting gravitational wave (GW) sources, such as massive black hole coalescence, compact binaries, and extreme mass ratio inspirals [1]. eLISA will consist of three drag-free spacecraft in an equilateral triangle configuration with one-million-kilometer sides. The spacecraft constellation forms a two-link interferometer between freely floating test masses (TMs) that act as the geodesic reference mirrors for the gravitational wave measurement. Hence, the changes between the TM distances caused by a GW shift the phase readout of inter-satellite laser interferometer. However, the weakness of GWs distort in a very small manner the geometry of space-time, therefore, measurements of exceedingly small displacements between the two TMs are necessary for their detection.

For this reason, the environment surrounding the TM must be shielded from non-gravitational forces, which can perturb the geodesic motion of the bodies preventing the GW detection. Consequently, environmental conditions such as thermal, magnetic and random charging fluctuations need to be under stringent control [2]. Among the residual disturbance sources, a significant fraction is due to the magnetic environment created by the interplanetary magnetic field, electronic units, and other components of the satellite such as the micro-thrusters and the solar panel cells. The non-gravitational force induced by the magnetic field $\mathbf{B}$ and its gradient is caused by the magnetic properties of the TM, i.e., the magnetization $\mathbf{M}$ and susceptibility χ. This spurious force on the TM volume V is given by [3]

$$\mathbf{F} = \left\langle \left[\left(\mathbf{M} + \frac{\chi}{\mu_0}\mathbf{B} \right) \cdot \nabla \right] \mathbf{B} \right\rangle V, \quad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ m kg s^{-2} A^{-2}, and $\langle\rangle$ denotes TM volume average of the enclosed quantity. This leads to keeping the magnetic background below certain values in order to ensure proper science operation of the GW observatory. Due to the important role that magnetic effects play in eLISA, a set of magnetic sensors will be placed in key locations with the purpose of quantitatively identifying the magnetic contributions that couple to the TM motion. To that end, magnetometers are aimed at reconstructing an accurate map of the magnetic field and gradient in the region occupied by the TM.

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The point of the magnetic sensing in eLISA has obviously been addressed first in its technology demonstrator called LISA Pathfinder [4]. As a consequence, the selection criteria to identify the applicable magnetometer technology is performed in view of the previous experience with the design of the LISA Pathfinder magnetic subsystem [5], in which the selected scheme was a set of four tri-axial fluxgate magnetometers. This technology was chosen on grounds of its long heritage in space applications and the low noise along the LISA Pathfinder measurement bandwidth ($1\,\text{mHz} \le \omega/2\pi \le 30\,\text{mHz}$). Looking toward eLISA, a number of further improvements need to be taken into account [6,7], which have derived in the study of alternative technologies to fluxgate magnetometers. Consequently, the main sensor characteristics that need to be addressed are: (i) compactness, so as to allow more of them to be incorporated in the spacecraft, and moreover, improve the spatial resolution; (ii) sufficiently low magnetic and thermal back-action effects on the spacecraft environment to avoid disturbances, so that they can be placed closer to the TM [8]; and (iii) low noise performance down to 0.1 mHz. In particular, the main purpose of this work is the development of a system capable of monitoring the slow drifts of the environmental magnetic field in eLISA by using chip-scale magnetometers.

Regarding the noise performance for the lower end of the eLISA bandwidth, magnetic field fluctuations across the TM are expected to be dominated by a time-varying interplanetary magnetic field no lower than $100\,\text{nT}\,\text{Hz}^{-1/2}$ [9,10], while the spacecraft's magnetic sources are expected to be the main contributors to the magnetic field gradient fluctuations [11]. Therefore, to be on the safe side, although eLISA requirements at subsystem level and the distribution of the magnetic sources in the spacecraft are still not formally defined, the noise performance of the magnetic measurement system should be at least one order of magnitude less noisy than the expected interplanetary magnetic noise to be measured. This implies a sensitivity in the measurement system of

$$S^{1/2}_{B,\text{system}} \le 10\,\text{nT}\,\text{Hz}^{-1/2}, \quad \omega/2\pi = 0.1\,\text{mHz}. \tag{2}$$

The work presented here has been proposed as well as part of the magnetic field monitoring system within the STE-QUEST mission concept [12], a high-precision experiment of the weak equivalence principle using space atom interferometry.

The reason for using anisotropic magnetoresistive sensors (AMR) as an alternative to the LISA Pathfinder scheme with fluxgate magnetometers, is their mass, size and power restrictions for space applications [13–15]. Besides, the AMR-type HMC1001 [20] presents the lowest noise level among different commercial magnetoresistive sensors [16]. Nevertheless, an important disadvantage of the AMR technology is the intrinsic $1/f$ noise that limits its use for applications requiring long integration time [17]. Extensive research was conducted on this topic at frequencies between 0.1 Hz and 10 kHz. However, to our knowledge, the noise performance of the sensor and its electronics has not yet been explored in the lower end of the eLISA bandwidth (0.1 mHz). A recent work has shown a noise level of $\simeq 100\,\text{nT}\,\text{Hz}^{-1/2}$ at 1 mHz [18], which clearly exceeds the value in Eq. (2). For these reasons, in this paper we study the low-frequency noise behavior of a prototype based on magnetoresistive sensors with dedicated noise reduction techniques, which are necessary to achieve the envisaged magnetic noise level for eLISA.[2] The paper is organized as follows. In Section 2 a brief overview of the noise reduction techniques is explained. In Section 3 we analyze the noise and thermal contributions of the sensor and signal conditioning circuits to the overall noise. The experimental results are presented in Section 4, and finally, the main conclusions are drawn in Section 5.

[2] For a more demanding scenario, a parallel study was performed using an atomic magnetometer [19].

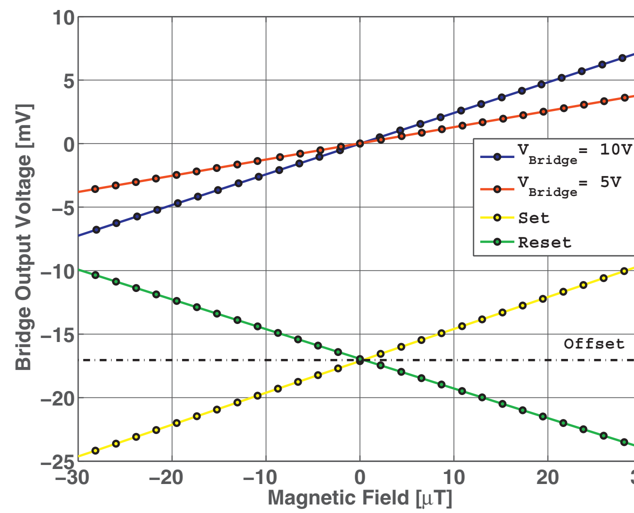

Fig. 1. Output characteristics as a function of the magnetic field after a *set* (yellow trace) and *reset* (green trace) pulse with $V_{\text{bridge}} = 10\,\text{V}$. Bridge offset extraction is performed for $V_{\text{bridge}} = 10\,\text{V}$ (blue trace) and $V_{\text{bridge}} = 5\,\text{V}$ (red trace). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Noise reduction techniques: flipping and electro-magnetic feedback

As detailed further on in the text, the intrinsic noise characteristics specified by the manufacturer of the magnetoresistors [20] are non-compliant with the requirements in Eq.(2). For this reason, different electronic noise reduction techniques need to be assessed in order to minimize the sensor noise level in the eLISA frequency band. This section describes the methods to be studied.

2.1. Flipping

AMR sensors contain a thin film composed of a nickel-iron alloy with magnetic anisotropy. They have a sensitive axis to the magnetic field, the *hard* axis, and another axis aligned with the sensor magnetization called the *easy* axis. Taking advantage of these properties, the flipping technique entails the periodic flip of the internal magnetization of the sensor strips by applying switching field pulses (*set*/*reset* pulses) generated by a thin film conductor, which is wound around the active area of the sensor [21]. The change of the magnetization direction induces the reversion of the output characteristic; as a result, the sensor output signal is modulated at the frequency of the switched pulses. Then, magnetic field measurements between each *set* and *reset* pulses are taken and subsequently demodulated. This sequence makes it possible to subtract the bridge offset, and its related temperature dependence, since the offset voltage remains unchanged while the sensor output reverses the polarity. Fig. 1 shows the opposite slopes in the output characteristics after the *set* and *reset* pulses, and the following offset voltage extraction for different bridge voltages. In addition, the main advantage of performing modulation techniques by using flipping pulses is the reduction of the $1/f$ noise within the desired bandwidth. Another advantage is the recovery of the output signal degradation induced from strong external magnetic fields (>300 µT), which resolves an important drawback of magnetometers that use ferromagnetic core, such as fluxgates.