Magnetic field measurement using chip-scale magnetometers in eLISA

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Abstract. Magnetic sensors are necessary devices to map the magnetic field and gradient at eLISA test masses location. Their primary goal is assessing the contribution of the magnetic effects to the acceleration noise budget. Our experience, accumulated during the magnetic diagnostics system design for LISA Pathfinder, indicates that the accuracy of the magnetic field map interpolation at the test mass is critical issue. Therefore, taking into consideration eLISA increased performance demands, an enhancement of the LISA Pathfinder magnetic subsystem is deemed necessary. A goal pursued by using alternative magnetic sensing techniques. In this study, the accuracy improvements in the magnetic field map reconstruction obtained with the currently conceived instrumental layout are demonstrated.

1. Introduction

The evolved Laser Interferometer Space Antenna (eLISA) is a dedicated space-based gravitational wave observatory proposed as a large science mission to ESA [1]. In its current design, the noise requirement in terms of free-fall accuracy is \( \sqrt{2 \cdot 3 \text{fm s}^{-2} \text{Hz}^{-1/2}} \) in a measurement bandwidth between 0.1 mHz and 1 Hz. Among the main contributions to the total noise budget are the magnetic fields and gradients present within the spacecraft, which are mostly generated by different units such as the micro-thrusters. Hence, eLISA will include a set of magnetic sensors for magnetic environment monitoring which will allow discerning the magnetic noise contribution from the overall measured acceleration noise.

The current eLISA magnetic measurement subsystem is based on LISA Pathfinder’s where mature fluxgate magnetometers were selected due to their proven sensitivity and actual availability for space applications. However, their use for magnetic field estimation at the test mass (TM) position present a few drawbacks driven by the following two basic factors:

- Permalloy-core magnetometers are able to disturb their magnetic surroundings due to the employed measurement principle.
- Sensors of large size conflict with the possibility of having a sufficient number of them to properly map the magnetic field around the TMs.

In LISA Pathfinder, these factors limited the total number of tri-axial sensors to just four which, moreover, had to be placed somewhat far from the TMs (\( \geq 18.85 \text{ cm} \)). As a consequence, ¹ Deceased
classical interpolation methods led to unsatisfactory magnetic field estimations which forced using alternative approaches which required magnetic environment previous knowledge [2]. In order to mitigate the aforementioned limitations and to ensure a more robust magnetic field reconstruction for eLISA purposes, a sufficient number of smaller sensor devices with lower magnetic back-action effects are required.

2. Interpolation method: Multipole expansion
The magnetic field at the TM location must be estimated only with the information given by the magnetometer located around the region of interest. Since the magnetic field surrounding the TM is considered to be mostly a vacuum field ($\nabla \times \mathbf{B} = \nabla \cdot \mathbf{B} = 0$), the estimated magnetic field $\mathbf{B}_e$ inferred from the magnetic field readings can be approached by a multipole expansion, where the order of the series is determined by the number of magnetometer data channels $N$. The magnetic field can therefore be expressed as

$$\mathbf{B}_e(\mathbf{x}) = \nabla \Psi(\mathbf{x}) = \sum_{l=1}^{L} \sum_{m=-l}^{l} M_{lm}(t) \nabla [r^l Y_{lm}(\mathbf{n})],$$

where $r \equiv |\mathbf{x}|$ and $\mathbf{n} \equiv \mathbf{x}/r$ are the spherical coordinates of the field point $\mathbf{x}$. $M_{lm}$ and $Y_{lm}$ are the multipole coefficients and the standard spherical harmonics of degree $l$ and order $m$, respectively.

3. Magnetic sources and sensor layout
Since the magnetic environment and requirements are not yet known for eLISA, the algorithm performance verification has been based on the distribution of LISA Pathfinder known magnetic sources (modeled as magnetic dipoles). Therefore, the magnitude and location of the sources have been fixed but the dipoles orientation were randomly set (using a normal distribution) in order to evaluate the robustness of the algorithm. According to this, a series of $10^3$ different magnetic scenarios have been considered for the present analysis.

The key aspect of the study is the use of sensors based on the anisotropic magnetoresistance (AMR) principle to replace the fluxgate magnetometers used in LISA Pathfinder shown in Figure 1. These sensors use a different physical principle to operate, but they both include a magnetic core as sensor head. However, for the purpose of maintaining the magnetic cleanliness needed for eLISA, the use of AMRs pose a clear advantage over fluxgate magnetometers due to the fact that the amount of ferromagnetic material present in their cores is much smaller. Therefore, AMR magnetometers can be placed closer to eLISA TM because of their inherently lower magnetic moment, which has been verified by measurement in a superconducting quantum interference device (SQUID) [3].

Figure 1. Fluxgate magnetometer used in LISA Pathfinder and AMR sensor proposed for eLISA.
For the present analysis, the magnetometers have been symmetrically placed on the wall of the vacuum chamber, which encloses the TM in order to meet the strict vacuum requirements. Figure 2 displays the the magnetic sources distribution and the location of the eight sensors. The exact magnetic field map for a given source distribution is shown in Figure 3, where the magnetometers and the test mass positions are also represented.

Figure 2. Left: Views of the 29 measured dipole magnetic sources in LISA Pathfinder (green dots: size is proportional to their magnetic moment), the test mass (red dot) and the 8 AMR magnetometers (black triangles). Right: Sensor array configuration on the vacuum enclosure (Units are in mm).

Figure 3. Magnetic field contour plot ($B_x$ and $|B|$) of the magnetic field for a specific source configuration.

4. Results: Magnetic field reconstruction
The proposed number of sensors allows resolving the magnetic field using multipole expansion up to the hexadecapole order approximation. The resultant reconstructed field, shown in figure 4, reveals a clear resemblance to the exact one shown in the previous section.

The estimation errors at the TM location for LISA Pathfinder and for two possible configurations for eLISA (equipped with AMRs) are displayed in figure 5. The improvement with the 8-AMR configuration is encouraging and reaches mean errors lower than 1% and 2% for the magnetic field and magnetic field gradient, respectively. The reader will find detailed information on this matter in [4].
Figure 4. Contour plot of the estimated field ($B_x$ and $|B|$) using multipole expansion with 8 magnetometers.

Figure 5. Relative errors of the estimated magnetic field at the position of the TM using different sensor arrangements (4 fluxgates used in LISA Pathfinder, 4 AMRs and 8 AMRs as shown in figure 2).

5. Conclusion

Multipole expansion with the suggested sensor configuration has consistently produced reliable results in estimating the magnetic field at the positions of the TM. Hence, the proposed magnetic measurement subsystem for eLISA represents a considerable improvement in the magnetic field estimation accuracy compared to LISA Pathfinder. It shall be remarked that this improvement has been achieved due to the small size and low magnetic back-action offered by AMRs which enables the possibility of not only installing more sensors but also placing them closer to the TMs. Future work will include the analysis taking into account extra details such as readout noise, unexpected offset and spatial resolution of the sensor head.

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