Temperature coefficient improvement for low noise magnetic measurements in LISA

I. Mateos¹, M. Diaz-Aguiló¹, F. Gibert¹, I. Lloro¹, A. Lobo¹, M. Nofrarias¹ and J. Ramos-Castro¹,²
¹ Institut de Ciències de l’Espai (CSIC-IEEC), Barcelona, Spain
² Departament d’Enginyeria Electrònica, Universitat Politècnica de Catalunya, Barcelona, Spain
E-mail: mateos@ice.csic.es

Abstract. Previous research with Anisotropic Magnetoresistive sensors (AMR) have shown significant improvements for weak magnetic field applications using dedicated noise reduction techniques in the signal conditioning circuit. However, an important source of error that must be addressed is the thermal dependence of the sensor system, more significant in the AMR sensitivity. The external temperature fluctuations affect the output of the sensors due to the temperature coefficient of the magnetoresistors, which may cause an increase of the estimation of the noise spectral density at low frequencies. Ongoing research using a low noise/low temperature coefficient current source to supply the sensor’s bridge enhances the thermal performance of the sensors at the lower end of the LISA bandwidth. Preliminary results are shown in this paper.

1. Introduction
LISA (Laser Interferometer Space Antenna) is planned to be the first space-based gravitational wave detector with the main goal of detecting and observing gravitational waves within the frequency range between 0.1 mHz to 0.1 Hz. The required acceleration noise for the LISA mission is set at:

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

in the frequency band between 0.1 mHz ≤ ω/2π ≤ 100 mHz. For LISA Pathfinder, a technology precursor of LISA, the acceleration noise budget has been relaxed (30 fm\text{s}^{-2} \text{Hz}^{-1/2}) in the frequency band between 1 mHz ≤ ω/2π ≤ 30 mHz [1]. These noises are the result of various disturbances which limit the performance of the instrumentation onboard. Magnetic disturbances are foreseen to contribute a significant fraction of the total acceleration budget, which takes place as a consequence of the magnetic properties of the test masses (TMs).

The onboard LISA Pathfinder magnetometers are fluxgate technology, which were chosen on grounds of their excellent sensitivity, low noise and availability for space applications [2]. Nevertheless, a number of drawbacks have been later identified which point to the need of a different technology more suitable for LISA [5].

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We are currently investigating alternative magnetic sensing techniques for LISA, based on magnetoresistive sensors [4] where previous research has shown significant improvements for weak magnetic field applications using dedicated noise reduction techniques in the signal conditioning circuit [6].

An important issue to take into account with respect to the magnetic sensor is its temperature coefficient (TC). The main concern comes from the thermal dependence of the sensor’s bridge sensitivity, which may cause an increase of the noise spectral density in the bandwidth of interest. This paper describes a preliminary research and results to improve the thermal performance of the sensor at submilli-Hertz frequencies. In sections 2, 3 and 4 a brief description of the electronic chain is shown. In section 5 the noise results and TC obtained for different configurations are presented, and section 6 summarises the main conclusions and further work.

2. Influence of the temperature coefficient of the magnetoresistor

Temperature fluctuations of the resistors forming the Wheatstone bridge show up as an error in the measurements; assuming the worst-case condition, the thermal sensitivity of the bridge output voltage (in V K$^{-1}$) is

$$\alpha_b(T) = 2V_b \left[ \frac{R_1 R_2}{(R_1 + R_2)^2} + \frac{R_3 R_4}{(R_3 + R_4)^2} \right] \cdot \alpha_R$$

(2)

where $V_b$ is the bridge voltage, $R_{i=1,2,3,4}$ are the magnetoresistances shown in Figure 3, and $\alpha_R$ its TC, whose maximum permitted value in the desired bandwidth can be calculated by

$$\frac{\alpha_b(T)}{s_b, \text{AMR}(B)} \cdot S_{1/2} \cdot S_{1/2} \leq S_{1/2} \cdot S_{1/2} \cdot S_{1/2}$$

(3)

The TC of the magnetoresistor needed for the magnetic stability requirements$^1$ depends on the temperature spectral density of the Front-End Electronics. Assuming $S_{1/2, \text{FEE}} \leq 0.1 \text{KHz}^{-1/2}$, comfortably met in the satellite, this leads to maximum values of $\alpha_b \leq 14 \mu\text{V/K}(100 \text{nT/K})$ and $\alpha_R \leq 1.6 \text{ppm/K}$. In view of these demanding values, research on dedicated techniques in the signal conditioning circuit to reduce the thermal dependence of the magnetometer is necessary. A common method is to supply the sensors’ bridge by means of a low noise/low TC current source, as explained in the next sections.

3. Low noise/Low temperature coefficient current source

The floating load current source topology has been the preferred option because of its lower noise in the very low frequency range [5]. The theoretically expected total noise for the current source is calculated as

$$S_{I_o}(\omega) = S_{I_o, \text{noise}}(\omega) + \alpha_{\text{theoretical}}^2 S_T(\omega)$$

(4)

where $S_{I_o, \text{noise}}(\omega)$ is the current noise density excluding random temperature fluctuations and $\alpha_{\text{theoretical}}$ is the global TC of the current source.

Figure 1 shows the equivalent circuit for noise analysis purposes. Noise contributions due to the operational amplifier in the model are:

- Equivalent noise sources: $e_n, i_{n1}, i_{n2}$
- Thermal drift caused by the input bias current $I_b$, input offset current $I_{os}$ and input offset voltage $V_{os}$

$^1$ The magnetic stability required for LISA is still not formally defined, but it will likely be one order of magnitude more demanding in frequency than in LISA Pathfinder, i.e. $S_{B, \text{system}}^{1/2} \leq 10 \text{nT Hz}^{-1/2}$ at 0.1 mHz.
The latter introduce a negligible effect, which is not so critical in terms of temperature
dependence, specially if the temperature of the environment is stable in the MBW (≤
1 K Hz$^{-1/2}$). Getting into numbers, the TC due to $I_b$, $I_{os}$, $V_{os}$ and their thermal
dependences is 0.1 nA K$^{-1}$.

Figure 1: Noise model of the floating current source, which uses the load itself as the feedback
element.

To sum up, using high stability resistors (0.6 ppm K$^{-1}$), the current source has a theoretical
$\alpha_{global} = 2.4$ nA K$^{-1}$ (assuming a worst-case condition). Combining thermal and noise model
terms, equation 4 gives the overall equivalent current noise density of the bridge, which yields
$\sim 25$ nA Hz$^{-1/2}$ at 0.1 mHz. Putting this number in context, the current noise of the designed
floating load source is more than one order of magnitude lower than the Howland current source
used in LISA Pathfinder to generate a controlled magnetic field by onboard induction coils [3].

Figure 2 shows theoretical and measured amplitude spectral noise densities of the current source.

Figure 2: Current noise measurement for floating load source is compared with the theoretical
prediction considering the measured temperature fluctuations, showing good agreement between
both. Discrepancy between prediction and measurements above 100mHz is due to the noise
spectral density of the ADC. The green line shows the small thermal contribution to the noise.
4. Front-End Electronics for AMR sensor
The analog signal conditioning for the magnetic field sensing is shown in Figure 3. The signal output from the bridge is modulated using a flipping technique [6], amplified and low-pass filtered. Once the signal has been sampled by the ADC, the demodulating process of the signal $d[n]$ is done digitally.

Figure 3: Analog signal processing scheme with flipping technique. For further details see [6].

In order to reduce the temperature dependence of the magnetometer response, the Wheatstone bridge circuit is powered with the floating load current source as explained in the previous section. The input voltage of the current source ($V_i$ in Figure 1) is the analog-to-digital converter (ADC) voltage reference, permitting a voltage reference-independent conversion (ratiometric conversion) [7].

5. Experimental test results
5.1. Equivalent Magnetic field noise spectral density
Magnetic measurements have been done in suitable conditions of magnetic shield, placing the sensor inside a small Mu-metal chamber. Constant current source and voltage source for bridge supply have been compared. The results in Figure 4 show a significant decrease of the noise in the LISA Bandwidth when the AMR’s bridge is powered with the designed current source.

Ambient temperature noise is about $2 \text{ KHz}^{-1/2}$ at 0.1 mHz for both topologies (voltage and current source), and the voltage noise is reduced from $\sim 1.3 \mu\text{V Hz}^{-1/2}$ to $\sim 0.5 \mu\text{V Hz}^{-1/2}$. Therefore, we can infer that using a voltage source, the excess noise is due to the greater thermal dependence of the AMR, which appears as error voltage fluctuations in the measurement. The value obtained in terms of equivalent magnetic field is about $4 \text{nT Hz}^{-1/2}$ at 0.1 mHz with a current source.

5.2. Noise and temperature coefficient in the presence of a static magnetic field
The test consisted in determining the experimental noise model and TC of the system under a constant magnetic field ($\sim 21 \mu\text{T}$), which is applied by a coil inside the Mu-metal shielding. The purpose is to unbalance the Wheatstone bridge, where the error due to the thermal dependence of the AMR’s sensitivity is greater. Test setup is shown in Figure 5.

Magnetic fluctuations created by the signal injection to the coil must be at least one order of magnitude less noisy than the required magnetic noise of the system, i.e $S_{B}^{1/2} \leq 1 \text{nT Hz}^{-1/2}$ within the MBW, which is mostly a requirement on the coil’s current. Considering a coil at a certain distance $x$, the coil’s magnetic field generated by a current is estimated with a simple
calculation based on Ampere’s Law. Thus the stability of the current injected by the source is given by:

\[ S_{I}^{1/2} \leq S_{Bz}^{1/2} \frac{2}{\mu_{0} N} \frac{(r^2 + x^2)^{3/2}}{r^2} \] (5)
Table 1: Comparison of the results at 0.1 mHz using voltage and current sources. A significant improvement of the TC is achieved with the current source topology.

| Bridge Source | $S_B^{1/2}$ [nT/√Hz] | $S_T^{1/2}$ [K/√Hz] | TC [nT/K] | [%/K] |
|---------------|------------------------|---------------------|-----------|-------|
| Voltage       | 150                    | 2.5                 | 60        | 0.3   |
| Current       | 33                     | 2                   | 16.5      | 0.08  |

Current stability obtained with the floating load source of section 3 at 0.1 mHz is perfectly compatible with the needed requirements for the test. Figure 6 shows the map of the estimated magnetic field noise, which has axial symmetry about the x-axis. From this Figure, we can infer the distance needed between the coil and the sensor, so that the applied magnetic field does not exceed the required noise level.

![Magnetic Field noise (nT/Hz^1/2)](image)

Figure 6: Magnetic noise applied by the coil at 0.1 mHz using the current source explained in the text. The sensor is placed at ~15 mm from the coil along the axis. $x$ and $\rho$ are the distances to the centre and to the longitudinal axis of the coil, respectively.

Test results are shown in Figure 7 and Table 1. In summary, due to the thermal sensitivity of the bridge output voltage $\alpha_b$, the greater the measured magnetic field, the greater the equivalent magnetic field noise at the frequency of the milli-Hertz. Therefore, techniques to reduce the thermal dependence of the system are totally necessary.

6. Conclusions

This paper shows how the temperature coefficient of the AMR using a current source for bridge excitation is improved by a factor of $\simeq 4$ compared with a voltage source. Hence, it helps to reduce the noise caused by thermal dependence of the AMR at the submilli-Hertz LISA band. Under an applied magnetic field, it has been observed that, across the MBW, the temperature drift of sensor sensitivity produces an extra noise, so the further from zero is the AMR bridge output, the larger the noise is.
Figure 7: Spectral density in terms of voltage, temperature and magnetic field using voltage and current sources to supply the AMR’s Wheatstone bridge. Green trace shows magnetic field noise generated by the coil at 15 mm from the sensor.

Further improvements involve using the AMR’s Offset strap as a feedback element in a closed loop circuit to operate the bridge in the balanced resistance mode, and thus minimise the effect of the gain temperature coefficient of the sensor. This method could produce desirable results for measuring magnetic fields at the LISA frequencies and can be useful in other applications beyond the scope of LISA.

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