Magnetic polarisation effects of temperature sensors and heaters in LISA Pathfinder

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Abstract. Temperature sensors and heaters belong in the diagnostics subsystem of the LISA Technology Package (LTP) on board LISA Pathfinder, the technology demonstrator for LISA. A number of these diagnostics items are placed at short distances from the LTP proof masses, and are negative temperature coefficient (NTC) thermistors. By design, these devices have tiny amounts of ferromagnetic materials which therefore constitute a potential source of disturbance to the performance of the LTP. We present a detailed magnetic characterisation of the NTC’s, and use the data to evaluate their impact on the acceleration noise budget of the LTP. The effect is seen to be small, and can be further reduced if the NTC’s are submitted to a demagnetisation process before they are attached. Re-magnetisation is unlikely, as rather strong fields (mili-Tesla) are required to re-magnetise the NTC’s.

1. Introduction

LISA Pathfinder [1] is a technological mission intended to demonstrate that two proof masses can be put into free-fall to a certain level of accuracy. This idea is reflected in the differential acceleration noise requirement for the LTP

\[ S_{\delta a}^{1/2}(\omega) \leq 3 \times 10^{-14} \left[ 1 + \left( \frac{\omega/2\pi}{3 \text{ mHz}} \right)^2 \right] \text{ m s}^{-2} \text{ Hz}^{-1/2} \]

in the frequency band between 1 mHz to 30 mHz.

This requirement implies stringent limitations on internal environment fluctuations. Specifically, thermal and magnetic fluctuations must be very low not to exert any noise force on the test masses (TM’s) [2].

The diagnostics subsystem [3] responsible of measuring such low temperature fluctuations includes 8 thermistors (4 as temperature sensors and 4 as heaters) surrounding each of the

1 BetaTherm thermistors.
TM’s. Thermistors are manufactured mixing and synthesising oxides doped with ferromagnetic materials [4] which make them potentially dangerous as they are placed close\(^2\) to the TM’s —see figure 1— since magnetic field and magnetic field gradient in the TM translate into a force due to its non-zero susceptibility and remanent magnetic moment —see section 2.

Figure 1. Situation of the thermistors surrounding the TM. Units in mm.

The LTP noise acceleration budget assigned to magnetic effects in the TM is [5]

\[ S_{\delta a, \text{magn}}^\frac{1}{2}(\omega) \leq 12 \text{ fm s}^{-2} \text{ Hz}^{-1/2} \]  \hspace{1cm} (2)

in the measurement bandwidth (MBW). For this reason magnetic field, magnetic field gradient and their fluctuations must be well kept under a certain limits. The presence of the NTC’s might add noticeable noise to the differential acceleration. This paper describes the steps performed in order to quantify this effect. It is organised as follows: in section 2 the expression of the acceleration noise as a function of the magnetic field and magnetic field gradient is given together with the nominal properties of the TM and background magnetic conditions. Section 3 shows the measured hysteresis curve of the thermistors. Section 4 describes the numerical calculations performed to obtain the magnetic field and magnetic field gradient in the TM considering the 8 NTC’s surrounding it. Section 5 shows the measurement of the first magnetisation curve (FMC) of the thermistors. Section 6 details the excess acceleration noise caused by the presence of the NTC’s surrounding the TM. Finally, in section 6 the conclusions are given.

2. Force fluctuations in the TM due to magnetic issues

The force fluctuation due to magnetic effects is [6]:

\[ S_{\delta F_x}(\omega) = V^2(|\langle M \rangle|^2) S_{\nabla B_x}(\omega) + \left( \frac{\chi V}{\mu_0} \right)^2 |\langle \nabla B_x \rangle|^2 S_B(\omega) + \]

\[ + \left( \frac{\chi V}{\mu_0} \right)^2 |(\langle B \rangle)|^2 S_{\nabla B_x}(\omega) \]  \hspace{1cm} (3)

where \( V \) is the TM volume, \( M \) is the remanent magnetisation of the TM, \( \chi \) is the magnetic susceptibility of the TM, \( \langle B \rangle \) is the magnetic field average over the TM volume and \( \langle \nabla B_x \rangle \) the same for the magnetic field gradient. \( S_B \) and \( S_{\nabla B_x} \) are the magnetic field and magnetic field gradient fluctuations over the TM\(^3\). The nominal values for these parameters are [1]:

\(^2\) The distance from the sensors to the closer face of the TM is 13 mm.

\(^3\) Assuming the fluctuations are homogeneous in all the TM volume.
• TM magnetic properties: $|\chi| = 10^{-5}$ and $M = 10^{-4}$ A m$^{-1}$,
• Background dc values: $|B_{bg}| \leq 10$ $\mu$T and $|\nabla B_{bg,x}| \leq 5\sqrt{3} \mu$T m$^{-1}$,
• Magnetic fluctuation values: $S_{B_{bg}}^{1/2}(\omega) \leq 650$ nT Hz$^{-1/2}$ and $S_{\nabla B_{bg,x}}^{1/2}(\omega) \leq 250\sqrt{3}$ nT m$^{-1}$ Hz$^{-1/2}$ in the frequency band from 1 mHz to 30 mHz

By using these values and equation (3) the noise acceleration due to the magnetic effects in the absence of thermistors is calculated and shown in table 1.

**Table 1.** Foreseen differential acceleration noise in the LTP due to magnetic effects in the TM (in the absence of thermistors).

| Term | $S_{\Delta a_{x}}$ [fm s$^{-2}$ Hz$^{-1/2}$] |
|------|------------------------------------------|
| $V|\langle M\rangle|S_{\nabla B_{x}}^{1/2}(\omega)$ | 2.15 |
| $(\chi V/\mu_0)|\langle \nabla B_{x}\rangle|S_{B_{bg}}^{1/2}(\omega)$ | 2.22 |
| $(\chi V/\mu_0)|\langle B\rangle|S_{\nabla B_{bg,x}}^{1/2}(\omega)$ | 1.70 |
| $S_{\text{total mag}}^{1/2}(\omega)$ | 4.46 |

The presence of the thermistors implies that

$$B = B_{\text{background}} + B_{NTC}$$

and, thus, the effect of $B_{NTC}$ (and its associated gradient) in the TM acceleration needs to be quantified.

**3. NTC’s magnetic characterisation: the hysteresis curve**

The hysteresis curve for a set of thermistors is shown in figure 2. The measurement was performed by using a SQUID (Quantum Design MPMS XL SQUID) at the Serveis Científico-Tècnics of the Universitat de Barcelona [7, 8].

![Hysteresis curve at 300 K](image)

**Figure 2.** Hysteresis curve at 300 K for the set (four samples) of 10 kΩ NTC thermistors of BetaTherm.

The relevant information that can be extracted from figure 2 is shown in table 2.

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4 These values are superseded.
Table 2. Magnetic properties of the BetaTherm NTC thermistors. (i) $|\mathbf{m}_r|$ is the remanent magnetic moment after saturation and at zero magnetic field, (ii) $|\mathbf{m}_{\text{sat}}|$ is the magnetic moment at the saturating magnetic field and (iii) $\mu_0|H_{\text{coer}}|$ is the coercive field.

| $|\mathbf{m}_r|$ | $|\mathbf{m}_{\text{sat}}|$ | $\mu_0|H_{\text{coer}}|$ |
|---|---|---|
| $24\pm2\ \mu\text{A m}^2$ | $83\pm2.5\ \mu\text{A m}^2$ | $10\ \text{mT}$ |

4. Numerical calculations
Numerical calculations to obtain the average magnetic field, $\langle \mathbf{B} \rangle$, and the average magnetic field gradient, $\langle \nabla \mathbf{B}_x \rangle$, considering the 8 NTC’s surrounding the TM have been performed assuming: (i) NTC’s behave like magnetic dipoles and (ii) the remanent magnetic moment is the one measured after NTC magnetic saturation.

Calculations considering different orientations of the 8 magnetic moments of the NTC’s allow us to know the worst possible combinations. A simple scheme of the magnetic moment orientations (arrows in the figure) surrounding the TM and the numerical values obtained are given in figure 3 and table 3.

Figure 3. Configuration analysed for the magnetic field and magnetic field gradient calculations. This four configurations cover the worst cases involved in the problem. Intermediate configurations lead to smaller values of the magnetic field and magnetic field gradient in the TM. Arrows stand for the NTC’s magnetic moment orientation [6].

| Conf. | $|\langle \mathbf{B} \rangle|$ | $|\langle \nabla \mathbf{B}_x \rangle|$ |
|---|---|---|
| A | 0 | 15.5 |
| B | 0.25 | 0 |
| C | 0 | 11.3 |
| D | 0.18 | 0 |

Graphical representations of the magnetic field and magnetic field gradient in the TM volume are shown in figure 4.

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5 This is a very worst case scenario since exposing the thermistors to their saturating magnetic field ($\approx0.3\ \text{T}$) is unlikely.
5. NTC’s first magnetisation curve (FMC)

The numbers obtained in section 4 are very pessimistic since the magnetic field and magnetic field gradient have been calculated using the remanent magnetic moment, $|m_r|$, after saturating the NTC’s. To obtain more realistic estimations, the FMC was measured. The FMC consists in measuring the magnetic moment vs. applied field relationship after the de-magnetisation of the item [9]. The FMC is shown in figure 5 [7, 8].

![Figure 5](image-url)

**Figure 5.** Measured FMC for a set of BetaTherm thermistors.

The remanent magnetic moment measured after the de-magnetisation is:

$$|m_{demag}| = 1.4 \pm 0.2 \, [\mu A \, m^2]$$  \hspace{1cm} (5)

which is about one order of magnitude less than the one measured after saturating the thermistor.

The FMC for the NTC’s can be linearised near the de-magnetisation zone as —see figure 5:

$$|m_{FMC, BetaTherm}| \approx 1.45 \times 10^{-3} \mu_0 |H_{FMC}|$$  \hspace{1cm} (6)

This relationship will be useful for calculations of the maximum magnetic field the NTC’s can be exposed in order not to increase the acceleration noise —see section 6.
6. Excess TM noise calculations

The acceleration noise for three different scenarios will now be calculated and compared. The analysed scenarios are:

- absence of thermistors
- presence of thermistors with the maximum possible remanent magnetic moment, i.e., after saturation, \( |m_r| = 24 \, \mu A \, m^{-2} \),
- presence of thermistors after de-magnetisation, \( |m_{\text{demag}}| = 1.4 \, \mu A \, m^{-2} \).

The numbers obtained are summarised in Table 4.

### Table 4. Acceleration noise for three different scenarios. Units: fm s\(^{-2}\) Hz\(^{-1/2}\). \( \Delta \) stands for the increase of the noise with respect to the "NO NTC’s" noise numbers. The frequency band is between 1 mHz and 30 mHz.

| Term                                      | No NTC’s | \( |m_r| = 26 \, \mu A \, m^2 \) | \( |m_{\text{demag}}| = 1.4 \, \mu A \, m^2 \) |
|-------------------------------------------|----------|---------------------------------|-----------------------------------|
| \( V \rangle \langle M \rangle \nabla^{1/2} B_x (\omega) \) | 2.10     | 2.10                            | 2.10                              |
| \( (\chi V/\mu_0) \langle \nabla B_x \rangle S_{\text{B}}^{1/2} (\omega) \) | 2.22     | 6.12                            | 2.44                              |
| \( (\chi V/\mu_0) \langle B \rangle S_{\text{C} B_x}^{1/2} (\omega) \) | 1.70     | 1.70                            | 1.70                              |
| \( S_{\text{total mag}}^{1/2} (\omega) \) | 4.45     | 7.29                            | 4.54                              |
| \( \Delta \) | —        | 64%                             | 2%                                |

If a desired \( \Delta \) is chosen then the maximum magnetic field that the thermistors can tolerate can be calculated using equation 6. For instance, if \( \Delta < 10\% \) is required, the thermistors should be de-magnetised and not exposed to magnetic fields higher than 5 mT.

7. Conclusions

The investigations carried out with respect to the magnetic characteristics of the NTC’s and their impact on the performance of the LTP experiment are the following:

- NTC’s show ferromagnetic behaviour.
- The magnetic properties of the NTC’s can degrade the performance of the LTP, increasing the magnetic noise by \( \sim 65\% \) relative to the background in the very worst possible situation. However, even in such extreme conditions the budgeted magnetic noise (12 fm s\(^{-2}\) /\( \sqrt{\text{Hz}} \)) is not reached.
- de-magnetisation of the NTC’s produces very good results: the magnetic noise can be reduced by about an order of magnitude, which makes it mostly negligible.

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