

# Ground-based self-gravity tests for LISA Pathfinder and LISA

**C Trenkel, C Warren and D Wealthy**

Astrium Ltd, Gunnels Wood Road, Stevenage SG1 2AS, UK

E-mail: christian.trenkel@astrium.eads.net

**Abstract.** Gravitational coupling between the free-falling test masses and the surrounding spacecraft is one of the dominant noise sources for both LISA Pathfinder and LISA. At present, there are no plans to verify any of the self-gravity requirements by test, on the ground. Here, we explore the possibilities of conducting such tests, using a customised torsion balance. We discuss the main sources of systematic and statistical uncertainty present in such a set-up. Our preliminary assessment indicates that the sensitivity is sufficient to carry out meaningful self-gravity tests.

## 1. Introduction

Self-gravitational effects contribute to limit the free-fall quality of the suspended test masses inside drag-free spacecraft such as LISA Pathfinder (LPF) and LISA. The dominant gravitational interactions between spacecraft and free-floating test masses are:

- DC gravitational field – due to spacecraft imbalance
- Thermoelastic effects – modulation of DC gravitational field
- Spacecraft residual jitter – modulation of DC gravitational field
- Gravitational stiffness due to spacecraft

The first three are direct forces acting on the test mass, while the last one represents a parasitic stiffness, which can couple to the test mass via the position sensor noise and/or residual spacecraft motion.

As a result, in order to meet the free-fall quality requirements, requirements on the total DC gravitational field, and gravitational stiffness, have been derived [1], [2]. These requirements are shown in Table 1:

Quantity	LISA	LPF	Units
DC Gravitational Field	$5 \times 10^{-10} - 1 \times 10^{-9}$	$1 \times 10^{-9}$	$\text{m/s}^2$
Gravitational Stiffness	$3 \times 10^{-8} - 1 \times 10^{-7}$	$-5 \times 10^{-7}$ $+7 \times 10^{-7}$	$1/\text{s}^2$

Table 1 LISA and LPF requirements on total DC gravitational field and stiffness

For LPF, which is in the advanced implementation phase, there has been a detailed apportioning of the contributions due to the Inertial Sensor (IS), the remainder of the LISA Technology Package (LTP), and the Spacecraft (SC) [2]:

Quantity	IS	LTP	SC	Units
DC Gravitational Field	$3.5 \times 10^{-10}$	$4 \times 10^{-10}$	$3.5 \times 10^{-10}$	$\text{m/s}^2$
Gravitational Stiffness	$-1 \times 10^{-7}$ $+2 \times 10^{-7}$	$-2 \times 10^{-7}$ $+3 \times 10^{-7}$	$-2 \times 10^{-7}$ $+3 \times 10^{-7}$	$1/\text{s}^2$

Table 2 Apportioning of total DC gravitational field and stiffness requirements for LPF

It should be pointed out that gravitational effects make a significant contribution to the overall error budget, and that at present no experimental verification of the above requirements is envisaged. For a meaningful verification of these requirements, target sensitivity levels of  $10^{-10} \text{ms}^{-2}$  and of  $10^{-8} \text{s}^{-2}$  can be set for the DC gravitational field and gravitational stiffness, respectively.

The purpose of this paper is to explore the potential of verifying the above requirements to as large an extent as possible, using an experimental method based on a customised torsion balance.

## 2. Gravitational Requirement Verification

### 2.1. Experimental Concept

The basic experimental concept is schematically illustrated in Figure 1. The spacecraft (LISA or LPF) is placed on a turntable which also incorporates a translation stage, such that the spacecraft can be both rotated and translated.

A torsion balance of design very similar to the original Eötvös torsion balance is proposed as force sensor. It has a lower test mass, which is used as “near” or sensing mass, and a balancing or “far” test mass. The sensing test mass needs to be located on the rotation axis of the turntable, and the torsion balance as a whole has to be structurally decoupled from the spacecraft / turntable assembly.

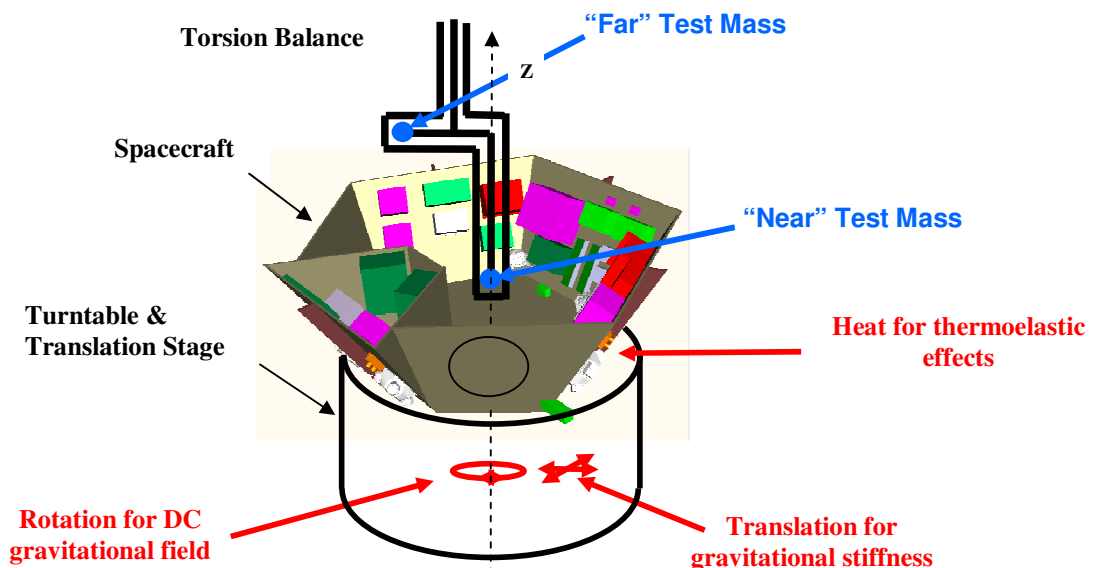


Figure 1 Schematic principle of experimental verification of gravitational requirements using a torsion balance

The positioning of the spacecraft on the turntable / translation stage will be such that the near test mass is at the point of interest, ie where gravitational requirements have to be verified.

In this setup, continuous rotation of the spacecraft will result in a modulated force projected onto the sensitive torsion balance direction, and can be used to measure the residual DC gravitational field. Linear oscillations of the spacecraft using the translation stage can in turn be used to determine the gravitational stiffness. Ideally these measurements would be carried out as late as possible during the AIT phase, such that as much hardware as possible participated.

As indicated in Figure 1, in principle one could even look at thermoelastic effects, by deliberately applying heat to the spacecraft. This possibility is not further explored here.

## 2.2. Possible Verifications

The schematic illustration above already shows that not all of the gravitational requirements will be directly verifiable using this method. It will be difficult to verify some requirements at the location of the test mass itself, in the presence of all the hardware. Neither the LPF nor the LISA spacecraft have been designed to allow access for a torsion balance.

The requirements on the spacecraft could be verified by removing the payload. For LPF, it may be possible to remove an individual IS, in order to verify the LTP contribution.

In order to include as much flight hardware as late as possible in the AIT phase as possible, one could also measure the gravitational field and stiffness at one or more locations *outside* the IS. This would then allow to verify the effect of the entire mass distribution. The gravitational models could be used to predict fields and stiffness at these other locations, and an experimental confirmation of the predictions could then be taken as verification of the actual mass distribution on board the spacecraft.

## 3. Sensitivity Analysis

### 3.1. Acceleration sensitivity requirement

As discussed above, an acceleration sensitivity of  $10^{-10} \text{ms}^{-2}$  is adequate for verifying DC fields, and if the spacecraft carries out linear oscillations of amplitude 1cm, then the stiffness sensitivity requirement of  $10^{-8} \text{s}^{-2}$  is also equivalent to an acceleration sensitivity of  $10^{-10} \text{ms}^{-2}$ . This, then, will be the acceleration sensitivity required from the torsion balance, for all experiments. If we assume that a single measurement should not take more than  $10^4 \text{s}$ , we can derive a spectral density acceleration noise requirement of  $\delta a \approx 10^{-8} \text{ms}^{-2} / \sqrt{\text{Hz}}$  for the torsion balance.

State-of-the-art torsion balances are performing close to their thermal noise limit ([3], [4]). Their acceleration sensitivity is approximately  $\delta a \approx (3 - 10) \times 10^{-13} \text{ms}^{-2} / \sqrt{\text{Hz}}$ . This is about 4 orders of magnitude better than what is required here. Nevertheless, these are compact, highly optimized torsion balances, and the design proposed above is very different.

The remainder of this paper assesses, qualitatively, the main sources of systematic and random uncertainty, in order to get some preliminary idea as to the feasibility of the proposed verification.

### 3.2. Random Noise Sources

The following random noise sources will in general be present:

- Thermal Noise (via dissipation processes)
- Magnetic Noise (coupling of torsion balance to random magnetic field fluctuations)
- Sensor Noise
- Seismic Vibration (excitation of torsion balance due to ground vibrations)
- Gravitational Noise (coupling of torsion balance to random gravitational field fluctuations)

A qualitative assessment shows that the last two may be significantly larger for the torsion balance proposed here than for the torsion balances referred to earlier ([3] and [4]), mainly because of its much larger size and also shape.

This qualitative assessment is summarized in Table 3:

Noise Source	Predicted noise levels compared to [3] and [4]	Comment
Thermal Noise	Same or slightly higher	Sources include intrinsic fibre material losses, residual gas damping and others. Intrinsic fibre losses could be higher if fibre diameter larger
Magnetic Noise	Same	Determined by torsion balance material properties, magnetic shielding and magnetic environment
Sensor Noise	Same	Same type of sensor (optical or capacitive) could be used, no reason to expect increased noise levels
Seismic Vibrations	Higher	Depends on seismic environment, torsion balance modes and damping, and torsion balance geometry. Large quadrupole will increase noise levels
Gravitational Noise	Higher	Depends on gravitational environment and torsion balance geometry. Large quadrupole will increase coupling

Table 3 Qualitative assessment of random noise sources

A quantitative analysis of the likely noise levels has not been carried out. However, given a margin of 4 orders of magnitude in random noise levels, we are confident that the sensitivity requirements could easily be met.

### 3.3. Systematic Noise Sources

During the experiments, the following systematic noise sources will in general be present:

- Mechanical – coupling between spacecraft motion and torsion balance suspension
- Magnetic – direct magnetic coupling between spacecraft, and/or turntable, and torsion balance
- Thermal – torsion balance may be sensitive to thermal fluctuations correlated with spacecraft motion
- Gravitational I – Turntable and / or translation stage may generate a gravitational field or stiffness
- Gravitational II – direct coupling to “far” torsion balance test mass which is not infinitely far

The first four effects are standard effects, and well-known procedures exist for dealing with them. However, the last effect turns out to be highly relevant in our case, and is investigated further in the next section. The problem is that the far mass will also couple gravitationally to the spacecraft, and the net torque on the torsion balance will not be just due to the quantities of interest.

### 3.4. Gravitational Coupling to “far” mass

The most obvious approach to deal with this problem is to place the far test mass as far away from the spacecraft as possible, but it is important to note that the LPF and LISA spacecraft have typical diameters between 2.5m and 3m. It can therefore be anticipated that dimensions of the torsion balance will also have to be of this order.

In order to make quantitative predictions, we have modeled the distribution of all discrete electronic units on the latest LISA spacecraft design [5].

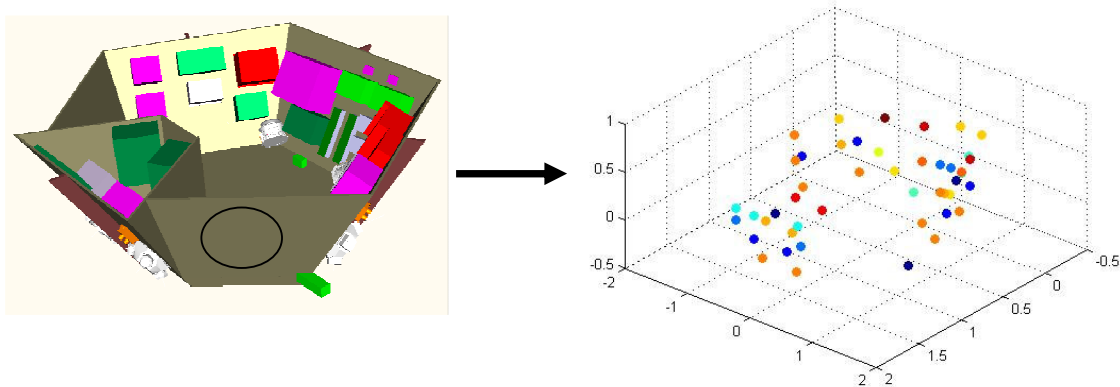


Figure 2 Simplified Gravitational Model of LISA Spacecraft – Electronic Units only

This model, shown in Figure 2, we have then used as “source” mass, and have calculated the total torque on a simple torsion balance of the design shown above. In order to see how far the far test mass had to be in order to reduce the systematic coupling to less than about  $10^{-10} \text{ms}^{-2}$ , we maintained a constant torsion balance beam length of 1m, and then varied the torsion balance height (effectively the vertical distance between the two test masses).

The systematic acceleration error, as a function of torsion balance height, is shown in Table 4:

Torsion Balance Height [m]	Acceleration error [ $\text{m/s}^2$ ]
2	$4 \times 10^{-10}$
3	$1.5 \times 10^{-10}$
4	$6 \times 10^{-11}$

Table 4 Acceleration measurement error due to coupling to “far” mass

As can be seen, a torsion balance height in excess of 3m would be required to reduce the unwanted coupling to less than  $1 \times 10^{-10} \text{ms}^{-2}$ . We have also investigated the impact on stiffness measurements, and found this to be negligible. Compared to a spacecraft oscillation amplitude of 1cm, a test mass at a height of 2m is already far enough.

In principle, there might be other options to minimise the effect of the far test mass:

- Optimise torsion balance design
  - Increase beam length
  - Alternative torsion balance design and gravitational multipoles
- Conduct differential experiments using torsion balances of different heights

For this preliminary work, these alternatives have not been further investigated.

#### 4. Conclusions and Future Work

We have shown that the self-gravity requirements existing for spacecraft such as LPF and LISA could be verified, to a large degree, in a ground based experiment using a customized torsion balance. These measurements could be used to verify the gravitational models and, crucially, also the hardware assembly and integration.

A qualitative assessment of the main random and systematic noise sources has been carried out, and the most critical sources have been identified. Although a detailed quantitative analysis has not been carried out, the sensitivity requirements on the torsion balance are very modest: even noise levels up to 4 orders of magnitude larger than those found in the best performing torsion balances would still be acceptable.

Therefore, even without this more rigorous analysis, our preliminary conclusion is that a meaningful experimental verification of self-gravity requirements for LPF and LISA on the ground is definitely possible. We have had preliminary contacts with Birmingham and Glasgow University, and would certainly be interested in taking this idea further. We also point out that a LPF Spacecraft mass dummy is available at Astrium UK, and could be used in any experimental demonstration of the method.

### **Acknowledgements**

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### **References**

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