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The Engineering of LISA Pathfinder – the quietest Laboratory ever flown in Space

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The Engineering of LISA Pathfinder – the quietest Laboratory ever flown in Space

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Abstract. We review the engineering approach adopted to ensure the required gravitational, magnetic, thermal and residual acceleration stability on-board LISA Pathfinder, and present the in-flight results that have been achieved. Arguably, this stability makes LISA Pathfinder the quietest laboratory ever flown in space. The implications for LISA are also discussed.

1. Introduction

The mission objective for LISA Pathfinder is to demonstrate the technology required for LISA, as far as the following two performance aspects are concerned:

- (1) The suppression of residual forces acting on the freely-floating test masses on-board the spacecraft
- (2) The local test mass metrology, ie the relative spacecraft-to-test mass metrology entering the overall LISA metrology chain

In this paper, we focus and review the engineering approach adopted to ensure the success of (1), ie how LISA Pathfinder as a laboratory is made stable enough to guarantee sufficiently low residual force noise acting on the test masses.

In particular, the following sources of disturbance will be discussed:

- (1) Gravitational forces
- (2) Residual accelerations
- (3) Test Mass residual charge
- (4) Thermal effects
- (5) Magnetic forces

In each case, the engineering approach will be presented, the predicted performance will be compared to the observed in-flight performance, and implications for LISA will be discussed.



In order to avoid duplication with many other papers even in this volume, only a brief description of the main couplings will be provided. Detailed description of the physical effect, or a derivation of the requirements placed on individual parameters, can be found elsewhere.

The overall LPF performance observed during the first few weeks of nominal science operations has been described in [1].

2. Control of Force Noise Disturbances acting on Test Masses

2.1. Gravitational environment

Many parameters characterising the gravitational environment of the Test Masses needed to be controlled, such as

- DC absolute linear accelerations
- DC differential linear accelerations
- DC angular accelerations
- Gravitational stiffness (linear acceleration gradient)
- Differential linear acceleration fluctuations (at low frequency)

2.1.1. Engineering Approach Unfortunately, a direct verification by test of the gravitational environment was not feasible. Instead, the engineering approach was based on the following elements:

- (1) Spacecraft design – eg no moving components, material choice in order to minimise thermoelastic distortions, etc
- (2) Verification by analysis – modelling of the entire spacecraft hardware in order to predict the gravitational field, field gradient etc at the test mass location. This relied, heavily, on measured inputs such as location and mass of all items on-board the spacecraft. Just as one example of many, the mass model of one of the Low Gain Antennas (LGA) is shown below:

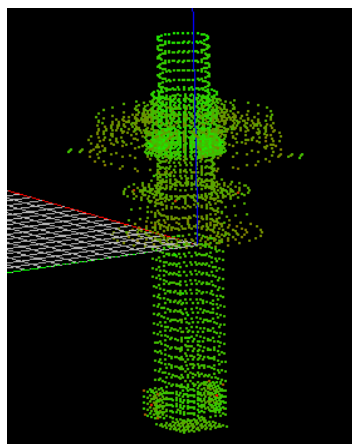


Figure 1 LGA gravitational model

- (3) Strict gravitational control during manufacture, assembly and integration, throughout the project – both at payload and spacecraft level. For example at Airbus D&S UK, of order 10^4 individual mass measurements were carried out over an AIT phase that lasted around seven years.

ASTRUM LISA Pathfinder SC AV Mass Tracking Log 3.6

Line Item	Date	Time	ACIS Address	Description of Item Added/Removed (in column 4)	Description of Location	Net Mass (g)	Net Mass (kg)	Flight Hardware	Non-Flight Hardware	Comments
3671	15/11/14	15:52	ACIS 572	3x10 Battery supply on AIT	3x10 AIT Unit	16.8		+	✓	
3672	17/11/14	15:45	ACIS 573	1000 mass up with cap 10 up	1000 gms	11.8		+	✓	
3673	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3674	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3675	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3676	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3677	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3678	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3679	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3680	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3681	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3682	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3683	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3684	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3685	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3686	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3687	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3688	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3689	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3690	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3691	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3692	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3693	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3694	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3695	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3696	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3697	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3698	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	
3699	18/11/14	16:05	ACIS 573	1000 mass down	1000 gms	11.8		-	✓	
3700	18/11/14	16:05	ACIS 573	1000 mass up	1000 gms	11.8		+	✓	

Figure 2 Representative Mass Log sheet used at Airbus D&S for gravitational model during AIT

(4) Final mass balancing of residual imbalance upon AIT completion

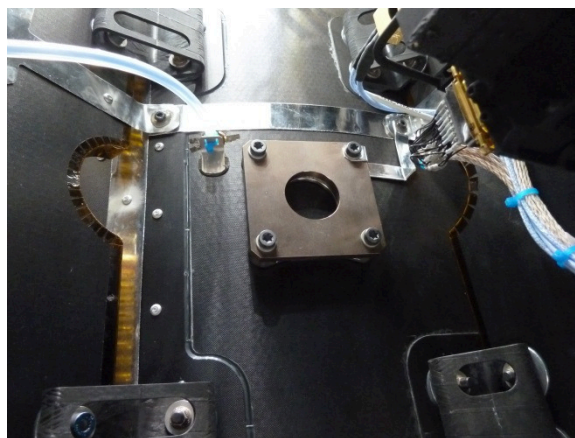


Figure 3 Mass balances installed to compensate residual imbalance following AIT

2.1.2. Comparison of predicted vs in-flight performance Where possible, a comparison of the predicted and measured parameters has been carried out. Not all of the gravitational parameters lend themselves to this comparison. The following table summarises the comparison that was done in time for the in-orbit commissioning review, ie approximately one week into science operations:

Parameter	Pre-flight Estimate	In-flight Measurement	Requirement	Requirement Met
Ax	-1.7e-10 -1.8e-10	(1.4±5.0)e-10 (TM1) (-3.9±2.2)e-10 (TM2)	<1.0e-8	Yes
Ay	-1.5e-9 -1.5e-9	(-1.0±0.2)e-9 (TM1) (-1.9±0.2)e-9 (TM2)	<1.0e-8	Yes
dAx	<5.5e-10	<1.0e-10	<6.5e-10	Yes
dAy	<3.9e-10	5.0e-10	<1.1e-9	Yes
dAz	<2.8e-10	0.1e-10	<1.85e-9	Yes
θ	-0.4e-9 +0.4e-9	-0.6e-9 (TM1) -0.1e-9 (TM2)	<13.5e-9	Yes
η	+3.1e-9 -1.2e-9	+2.9e-9 (TM1) -1.3e-9 (TM2)	<11.5e-9	Yes
φ	+0.8e-9 -0.2e-9	+1.0e-9 (TM1) -0.1e-9 (TM2)	<8.0e-9	Yes

Table 1 Comparison of predicted and in-flight observed gravitational parameters

As can be seen, all requirements have been met with margin. Along the y direction, the differential acceleration requirement is met with a margin of more than 100%, but this is still highlighted here as it is, in fact, the “worst” performance, relatively speaking. Unfortunately it has not been possible to verify the absolute linear acceleration along z with any useful accuracy, due to the degeneracy with the Solar Radiation Pressure (SRP).

The effect of the continuous cold gas depletion on the differential acceleration between the test masses had been predicted before the mission, and was found to be acceptable. It is interesting to note how the predicted change in differential gravitational acceleration as a result of changing the feed branch from which cold gas is used, agrees to within better than 10% with the one that was observed:

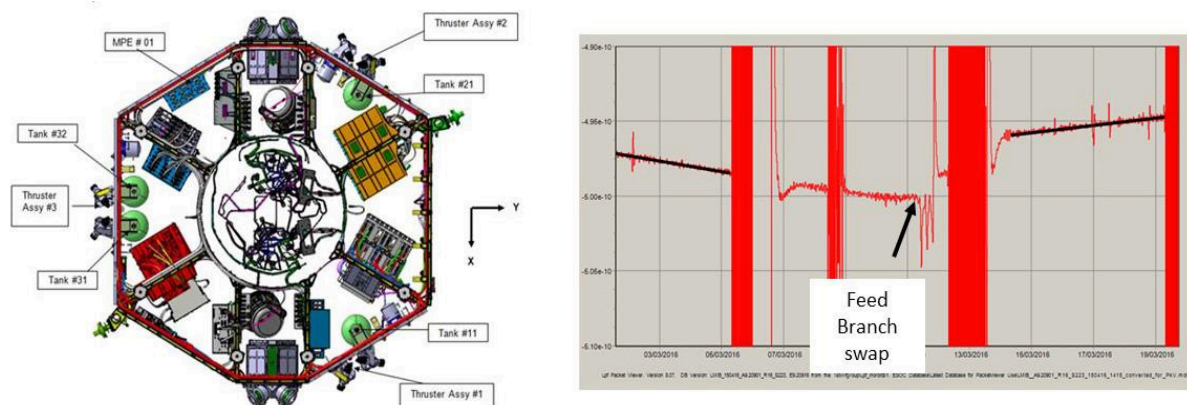


Figure 4 Change in in-flight differential acceleration drift rate during cold gas feed branch swap

The predicted change in slope was approx. $6.6 \times 10^{-13} \text{ ms}^{-2}/\text{day}$, and the observed one was approx. $6.2 \times 10^{-13} \text{ ms}^{-2}/\text{day}$.

Finally, it is worth noting that the worst-case pre-flight noise estimate related to electrostatic actuation fluctuations coupling to DC differential linear test mass acceleration, along X, was not realised in flight:

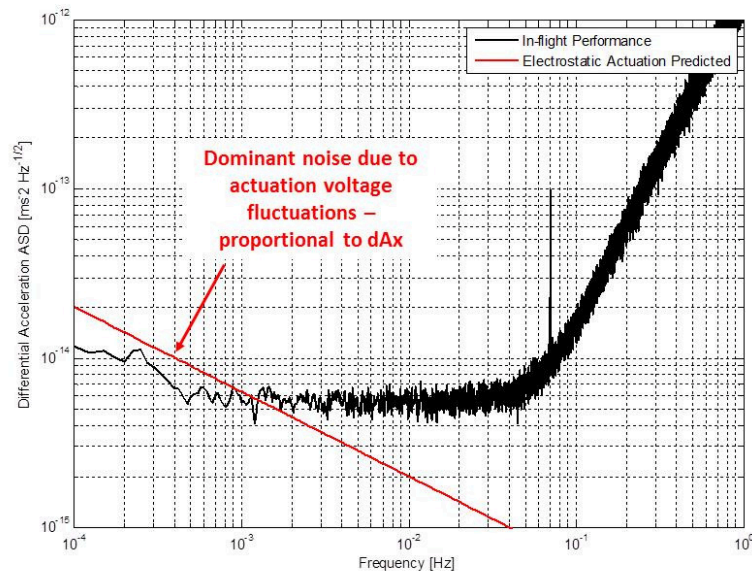


Figure 5 Pre-flight worst-case estimate of actuation voltage fluctuations coupling to differential gravitational acceleration, together with in-flight noise performance

2.1.3. Implications for LISA As far as LISA is concerned, the following can be concluded regarding gravitational control:

- (1) No improvements to the approach adopted for LPF is necessary (in fact LISA is not as susceptible as LPF to differential gravitational accelerations)
- (2) The effect of the depletion of large amounts of cold gas propellant is well understood and manageable – a micropropulsion system based on cold gas is certainly an option for LISA

Even so, the following considerations apply:

- (1) Moving parts (eg periodic repointing of HGA) need careful assessment for LISA
- (2) Partial verification of gravitational requirements by test could result in time & cost savings, and reduce risks.

2.2. Residual Accelerations

The LPF shields the test masses on-board from external disturbances, primarily SRP. This shielding does not come completely for free, and now many residual spacecraft Test Mass couplings need to be considered.

No matter what the detailed coupling mechanism is (electrostatic, magnetic or gravitational), the relative spacecraft – test mass motion (acceleration) needs to be kept to a minimum.

2.2.1. Engineering Approach A relatively complex and sophisticated Drag-Free Attitude Control System (DFACS), comprising a set of algorithms that control one spacecraft and two free-flying test masses simultaneously along 15DOFs, is used to minimise the relative motion between LPF spacecraft and test masses.

DFACS relies on a number of low noise sensors (optical and electrostatic test mass sensing, star tracker sensing of spacecraft attitude) and actuators (electrostatic test mass actuation, micropropulsion system acting on spacecraft) to achieve its goal, namely the robust control from the initial test mass release through to the nominal science operation modes.

The following schematic shows most of the main hardware elements used by the DFACS control loops:

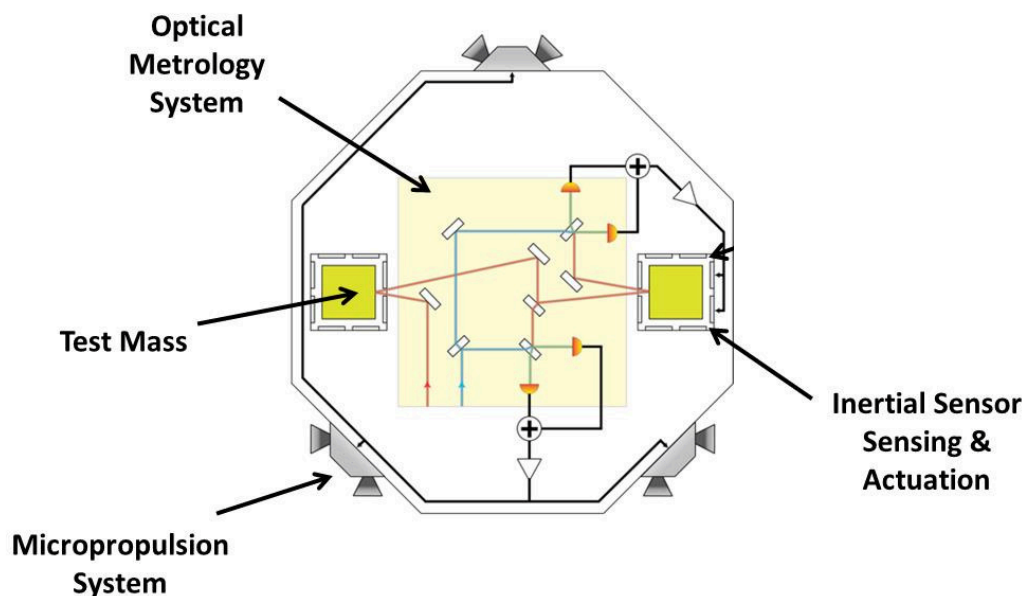


Figure 6 Sensors and actuators used by DFACS to control spacecraft and two test masses

2.2.2. Comparison of predicted vs in-flight performance As far as the DFACS in-flight performance is concerned, compared to the pre-flight predictions, three main conclusions can be drawn:

- (1) Test Mass initial release conditions in orbit were much worse than expected
 - a. Initial offsets and velocities exceeded by factors of up to 60 and 8, respectively
 - b. Nevertheless DFACS managed to capture TMs eventually
- (2) DFACS handled all transitions to science mode very reliably and with excellent repeatability – the figure below shows several transitions from ACC3 mode to SCI1_2 mode:

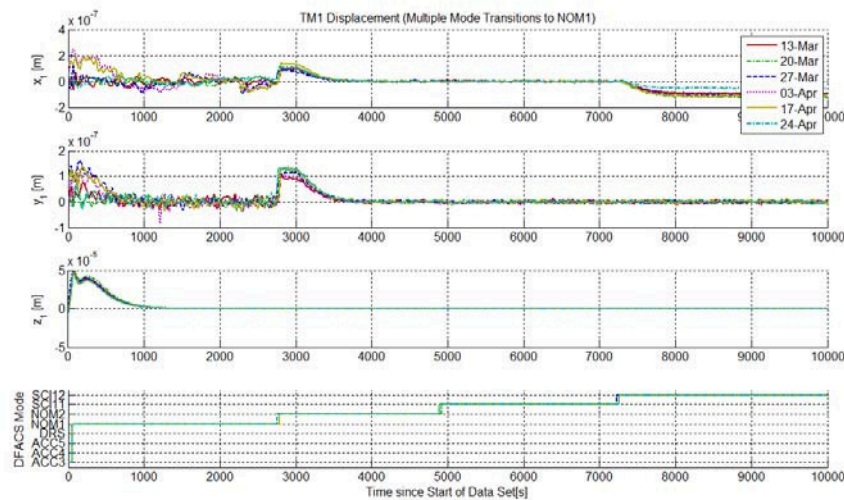


Figure 7 Multiple DFACS transitions from Acc3 to SCI1_2 mode

- (3) The actual science mode performance was better than predicted, as shown by data taken during commissioning
- Sensor and actuator noise models were conservative
 - Offsets and misalignments were conservative

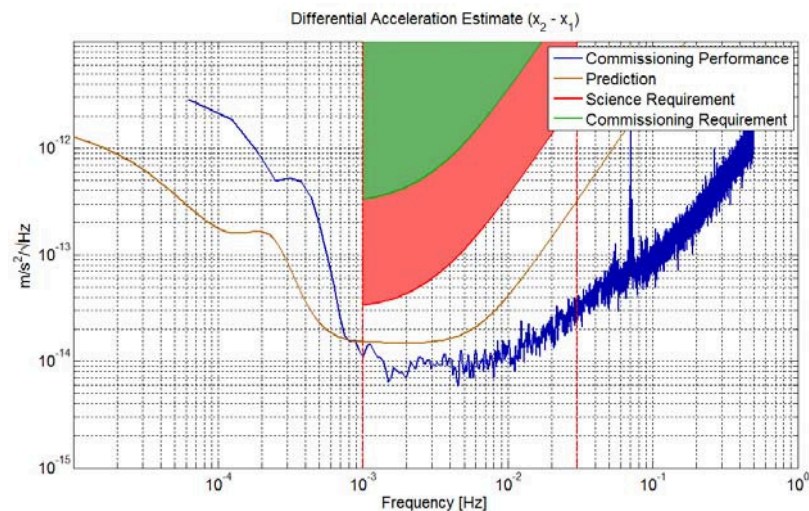


Figure 8 SCI1_2 mode Performance during Commissioning

Finally, the relative spacecraft – test mass motion can be taken as proxy for residual spacecraft accelerations, assuming that the test masses provide a perfect free-fall reference frame. The plot below shown this relative motion as a function of frequency, together with typical seismic vibrations experienced on ground:

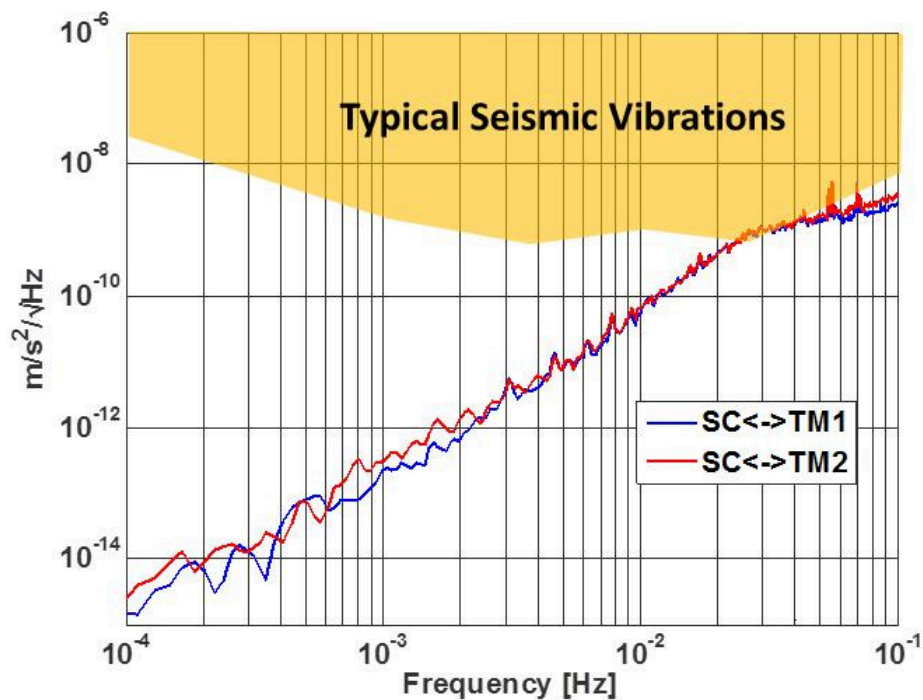


Figure 9 Relative spacecraft – TM acceleration spectrum, compared to typical seismic noise on ground

The above plot is effectively a perfect “vindication” of the approach to use space as the only environment where low frequency gravitational waves become observable. Seismic vibrations at low frequencies simply cannot be attenuated sufficiently. Arguably, this plot also justifies calling LPF “the quietest laboratory ever flown in space”.

2.2.3. Implications for LISA As far as LISA is concerned, the following can be concluded regarding the required attitude control system:

- (1) LPF DFACS science mode performance goes a long way towards LISA requirements
- (2) The DFACS performance model has been verified in-flight, and can be extended for LISA
- (3) The robustness of mode transitions could be improved further:
 - a. Uni-directional thruster configuration is efficient, but limits control authority during critical phases. Additional thrusters would enhance margins.
 - b. Margins for electrostatic suspension actuation should be increased – this would account for disturbance uncertainties

2.3. Test Mass Charge control to minimise electrostatic couplings

The freely floating test masses on-board LPF can become electrostatically charged, primarily from radiation and cosmic rays continuously bombarding the spacecraft. Any such net charge will couple electrostatically to the electrode housing surrounding the test masses, resulting in unwanted interactions. The test mass charge level therefore needs to be actively controlled.

2.3.1. Engineering Approach A dedicated, active charge management system (CMS) has been developed for LPF. Based on the photoelectric effect, it uses UV light to release electrons either from the test mass or from the surrounding electrodes, depending on the polarity of the test mass charge that needs to be reduced.

The schematic discharge principle is illustrated below:

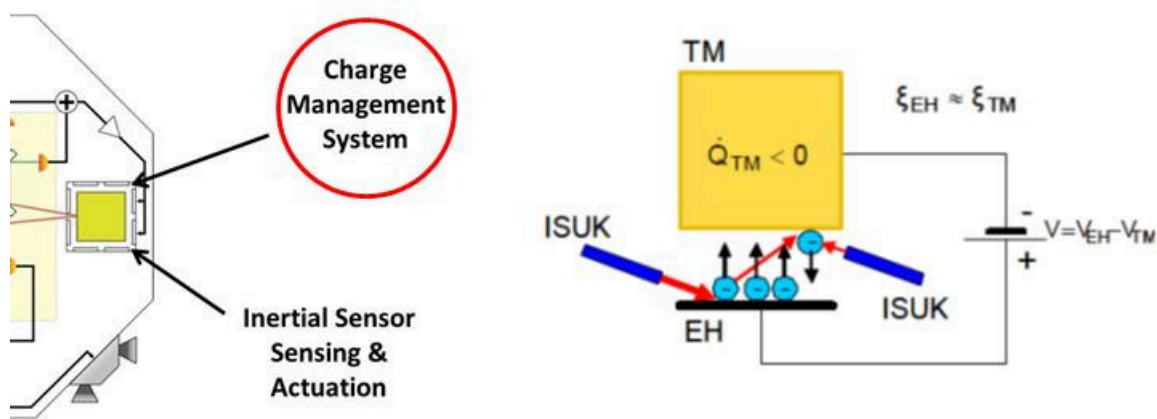


Figure 10 Schematic showing Charge Management System elements. EH: Electrode Housing, ISUK: Inertial Sensor UV Kit (UV feedthroughs)

The CMS provides a robust way to reduce unwanted charges on the test masses, and comprises automatic on-board algorithms to achieve regular semi-autonomous test mass discharge.

2.3.2. Comparison of predicted vs in-flight performance The in-flight performance of the CMS on-board LPF can be summarised as follows:

- (1) The on-board charge estimation performance is in line with pre-launch predictions
- (2) The closed loop discharge performance is also in line with predictions
- (3) On-board closed loop fast discharge is used regularly for LTP and DRS operations

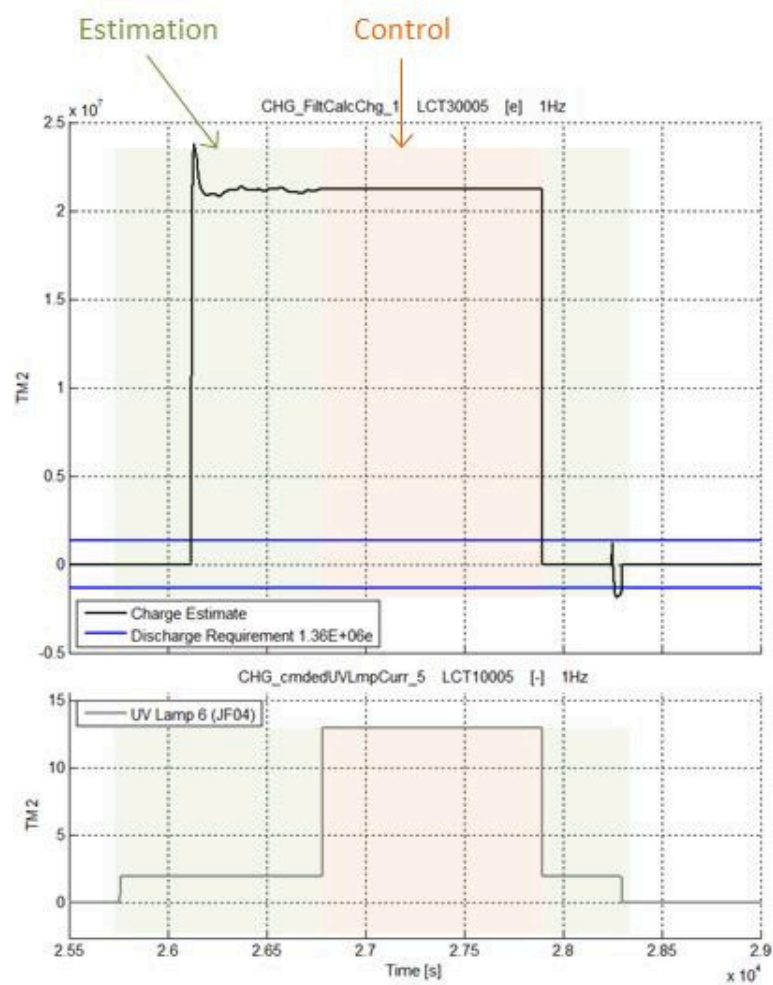


Figure 11 TM2 Closed Loop Discharge performance

The above plot shows just one example of successful in-flight charge control on test mass 2.

2.3.3. Implications for LISA As far as LISA is concerned, the following can be concluded regarding the charge management system:

- (1) On-board charge estimation has been verified
 - a. Highly flexible and can be adjusted for the use of different DOFs
 - b. DOFs with optical readout are preferred
- (2) Closed loop discharge control has been verified
- (3) The robustness of charge control could potentially be improved:
 - a. Optimization of light injection would avoid the need for DC biasing

2.4. Thermal Environment

An ultra-stable thermal environment, at low frequencies, is essential to achieve the required LPF performance – numerous physical effects couple to temperature, and fluctuations in temperature can then result in fluctuating forces acting on the test masses.

2.4.1. Engineering Approach The nominal LPF orbit around L1, together with the constant sun-pointing attitude of the spacecraft, already provides a highly stable external environment.

Nevertheless, a careful thermal spacecraft design is still essential to reach the required levels of stability. The schematic diagram below illustrates the main thermal features of the nested design that has been implemented for LPF:

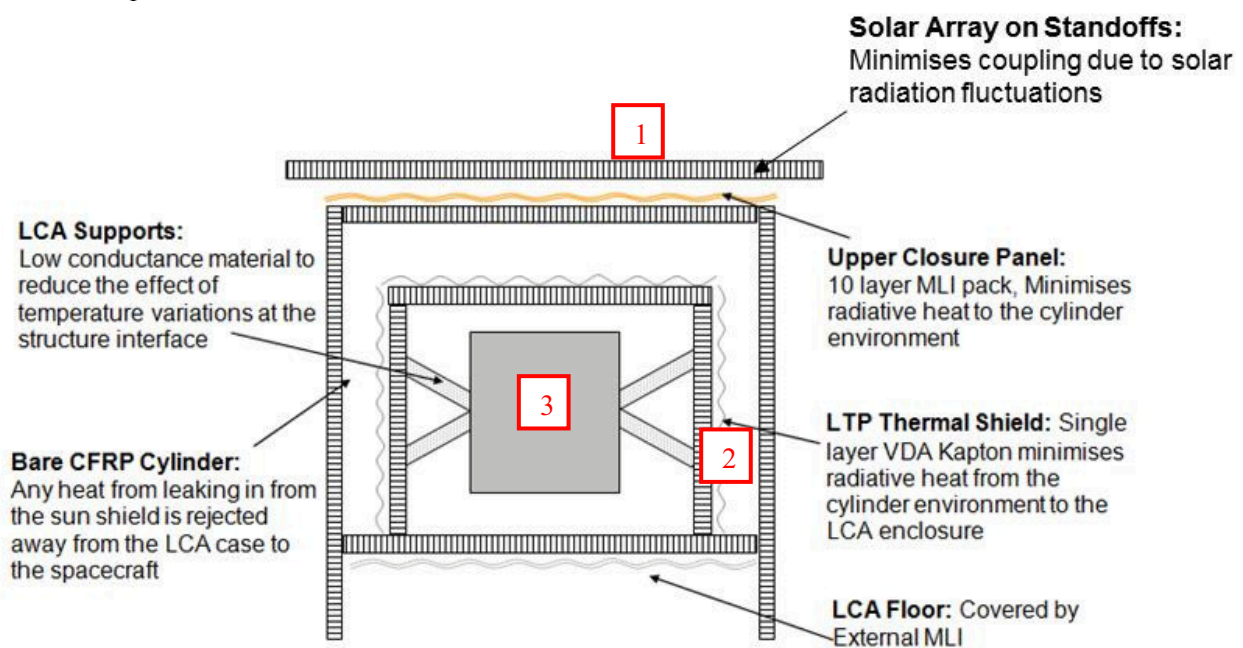


Figure 12 Nested LPF spacecraft design with thermal features necessary to reach required thermal stability. Numbers correspond to locations where thermal stability has been measured below.

In addition, the thermal design was based on the principle that no unit or heater switching was allowed during nominal operations, so as not to disturb the stable environment. One of the consequences of this was a purely passive thermal control – all the heaters are either permanently ON or OFF.

Finally, extensive thermal test campaigns were carried out to verify as many requirements by test as was possible, thus strongly reducing the risk of in-flight surprises.

2.4.2. Comparison of predicted vs in-flight performance The thermal stability achieved in flight is shown below for the following locations indicated in the figure above:

- (1) Solar array temperatures – a very slow drift of approx. -0.4K over 6 days is apparent due to the increasing Sun distance at the time of the measurement.

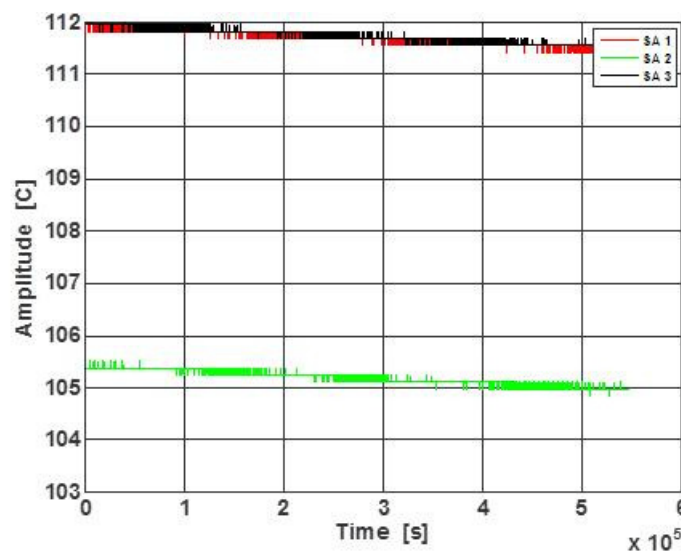


Figure 13 Solar Array temperature measurement

(2) LTP Composite Assembly Cylinder – a stability of $\approx 10^{-3} \text{K}/\sqrt{\text{Hz}}$ is achieved down to 1mHz:

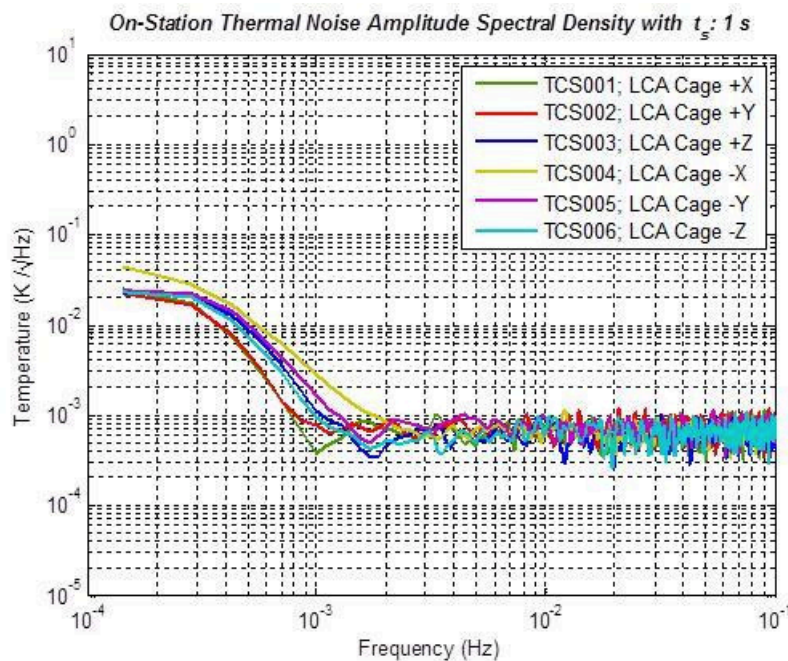


Figure 14 LCA temperature stability

(3) Optical Bench – a stability of $< 3 \times 10^{-5} \text{K}/\sqrt{\text{Hz}}$ is achieved down to 0.1mHz:

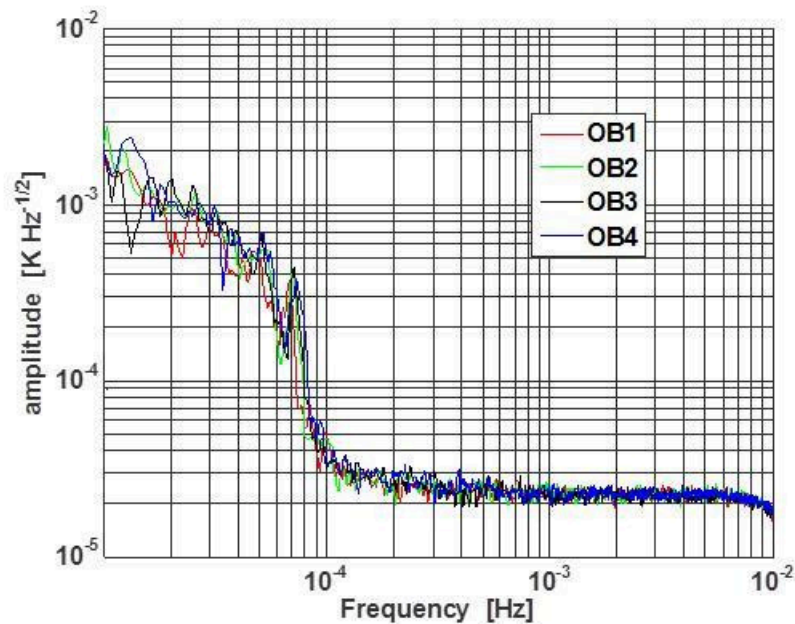


Figure 15 Optical Bench temperature stability

2.4.3. *Implications for LISA* LPF has shown that the stringent temperature stability requirements at low frequencies can be met through careful spacecraft design. Specifically, the following conclusions can be drawn:

- (1) A stable thermal external environment certainly helps – LISA will also benefit from this
- (2) The Solar Array shadowing of the spacecraft body is essential for thermal stability
- (3) The following considerations, lessons learnt and potential improvements apply:
 - a. The nested LPF spacecraft design helps, but will not be directly transferable to LISA – LISA will have large telescope apertures
 - b. Thermal control using only fixed (trim) heaters is not as flexible as would be desirable – quiet PID control should be possible

Equipment like a PCDU should not be placed near thermally sensitive equipment

2.5. Magnetic Environment

Non-zero magnetic test mass properties will couple to the local magnetic environment, generating force noise as a result. A significant number of magnetic environmental parameters need to be controlled, such as:

- DC magnetic field and magnetic field gradients
- Fluctuating magnetic fields and field gradients

Unlike most magnetically sensitive missions, these parameters do not have to be controlled on a long instrument boom, at a large distance from the spacecraft, but right in the centre of the LPF spacecraft.

2.5.1. Engineering Approach The approach adopted to ensure that magnetic requirements were met was based on a combination of:

- (1) Mitigation by design – avoid magnetic parts and establish clear EMC design guideline
- (2) Little heritage information due to unusually low frequency range – extensive test campaigns were conducted at unit and spacecraft level.

The pictures below show a selection of magnetic tests carried out at various stages of the LPF project:

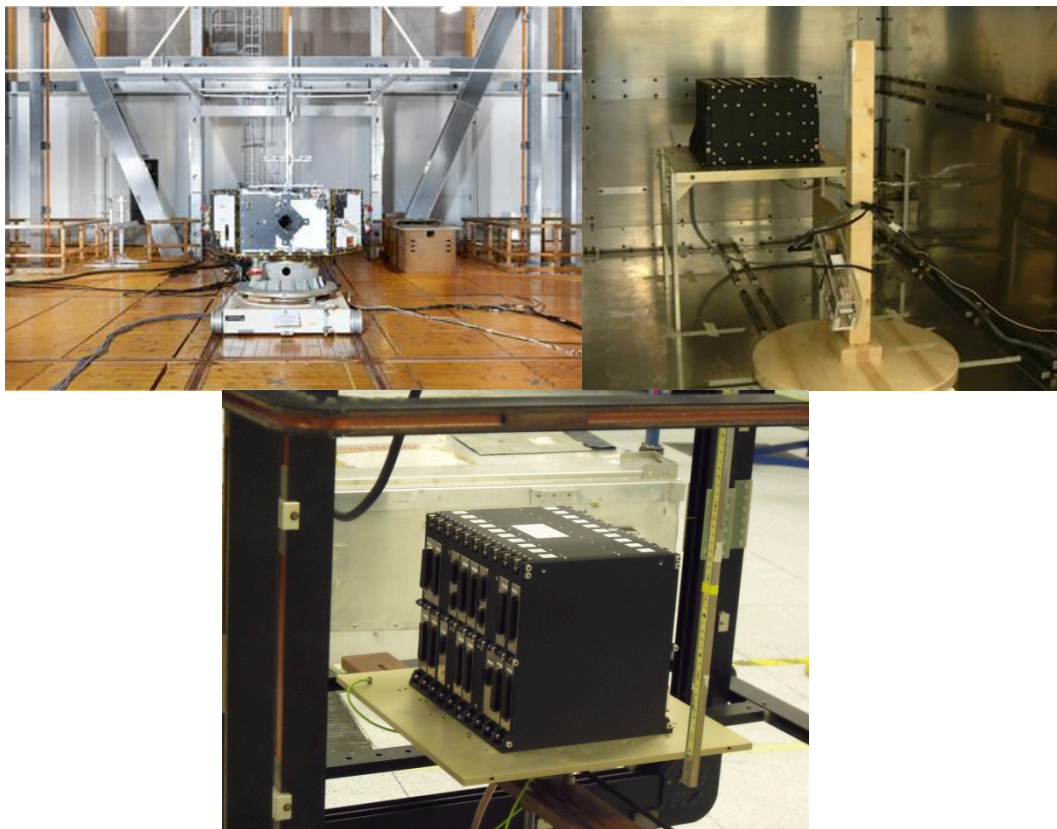


Figure 16 Selection of LPF magnetic tests. Top left: Spacecraft test at IABG, top right: IS FEE test at Airbus DS, bottom centre: OBC test at Airbus DS

2.5.2. Comparison of predicted vs in-flight performance Local absolute DC magnetic fields have been found to be of order $1\mu\text{T}$, as predicted and shown below.

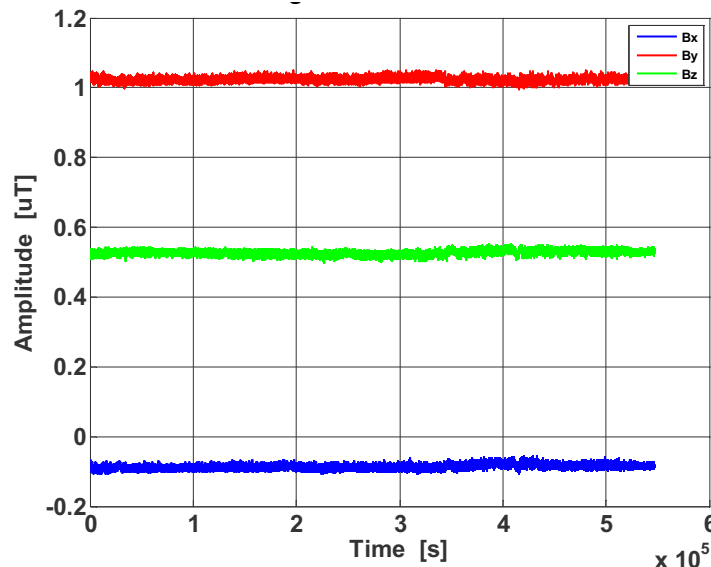


Figure 17 Magnetic field recorded by magnetometer on-board LPF

Low frequency magnetic field fluctuations of order $30\text{nT}/\sqrt{\text{Hz}}$ were measured at 1mHz :

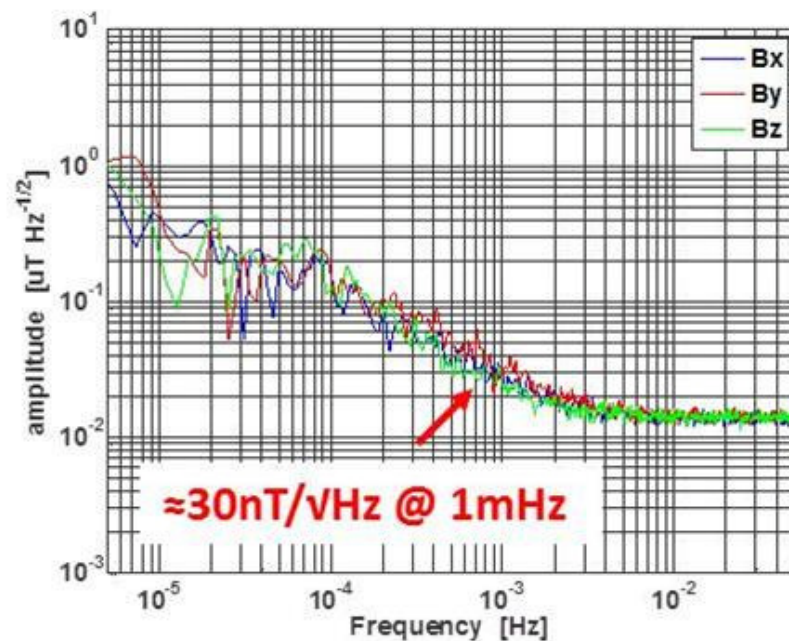


Figure 18 Low frequency magnetic field fluctuations on-board LPF

Above about 4mHz , the noise becomes white at a level of about $13\text{nT}/\sqrt{\text{Hz}}$, and is not thought to correspond to real magnetic field fluctuations, but instead is due to intrinsic DAQ noise.

This is corroborated by the spectrum of magnetic field gradient fluctuations, shown below:

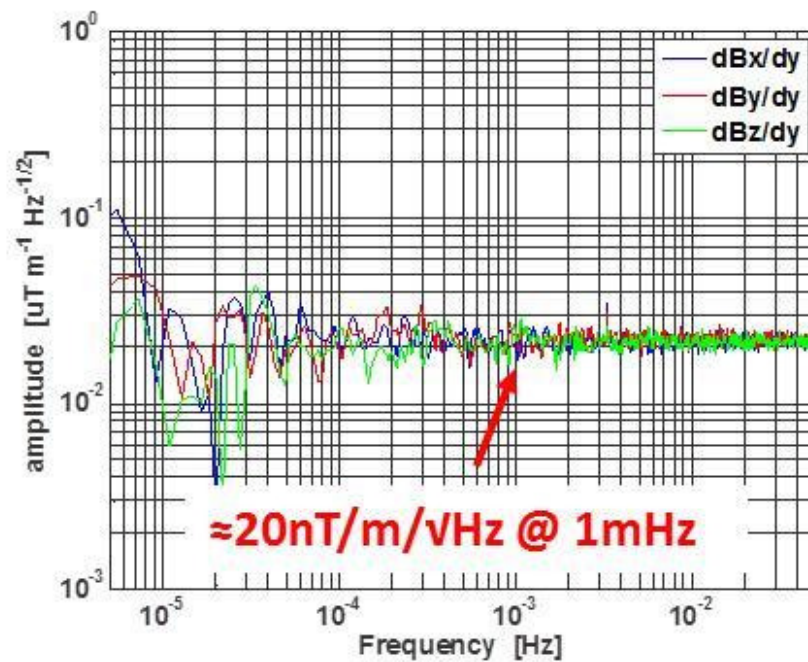


Figure 19 Low frequency magnetic field gradient fluctuations on-board LISA

The white noise level of just over $20\text{nT/m}/\sqrt{\text{Hz}}$ not only looks “unphysical”, indicating that it is not due to real magnetic field gradients, but the level also agrees very well with that expected from combining two uncorrelated magnetic field noise streams of $13\text{nT}/\sqrt{\text{Hz}}$, separated by a baseline of around 0.8m : $(13\text{nT}/\sqrt{\text{Hz}} \times \sqrt{2} / 0.8\text{m}) \approx 23\text{nT/m}/\sqrt{\text{Hz}}$.

The conclusion is that the magnetic field fluctuations observed above correspond, in fact, to fluctuations in a field that is uniform across the spacecraft – and this can only be the external, interplanetary magnetic field.

Finally, it is interesting to note that the worst-case pre-flight estimate of the magnetic noise has not been realised in flight:

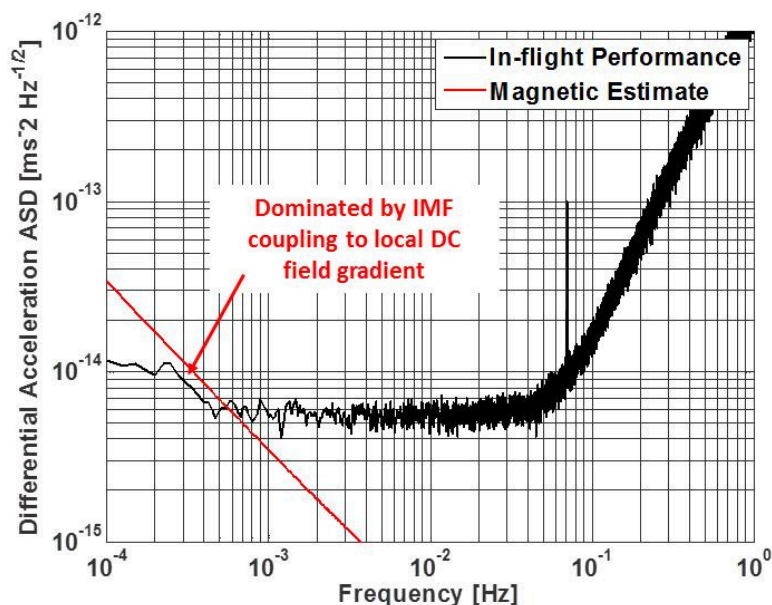


Figure 20 Worst-case pre-flight magnetic noise estimate, compared to overall LPF performance

The dominant contribution to the pre-flight estimate was the coupling of interplanetary field fluctuations of up to $55\text{nT}/\sqrt{\text{Hz}}$ at 1mHz , to local DC gradients of up to $18\mu\text{T/m}$, limited by the measurement accuracy of the magnetic testing.

2.5.3. Implications for LISA No showstoppers, or real problems, have been identified for LISA. Nevertheless, the following should be improved:

- (1) DC magnetic gradient testing (in particular for payload elements in close proximity)
- (2) The low frequency behaviour (eg amplitude modulation) of high frequency AC lines should be characterised by test
- (3) Needless to say, for LISA equipment without LPF heritage (eg TWTA), magnetic testing is still essential.

3. Summary and conclusions

In this article, we have presented the engineering approach, as well as compared in-flight performance with pre-flight estimates, of several aspects absolutely crucial to the success of LPF. The overall noise performance has been met with margin, and inevitably worst-case assumptions about offsets, noise levels etc have proved to be conservative.

LPF has shown itself to be an extremely stable platform to allow fantastically precise experiments to be carried out. In particular as far as residual low frequency accelerations are concerned, it can justifiably be called the quietest laboratory ever flown in space. The techniques and experience that have been developed in the process is sure to find applications in addition to the main target, LISA.

No real showstopper for LISA has been identified in any of the areas, and on the contrary, some concerns in certain areas have been laid to rest.

4. Acknowledgements

We would like to thank the LPF collaboration as a whole, from ESA through academia to industrial partners, as well as to all the national funding agencies, for the opportunity to work as a team on a mission as exciting and challenging as LPF. We should collectively be very proud of what we have achieved, and we look forward to working on the future observation of gravitational waves from space!

References

- [1] Armano, M. et al. (2016) Sub-femto-g free fall for space-based gravitational wave observatories: LISA Pathfinder results. *Physical Review Letters*, 116(23), 231101