Thermal effects on-board LISA Pathfinder

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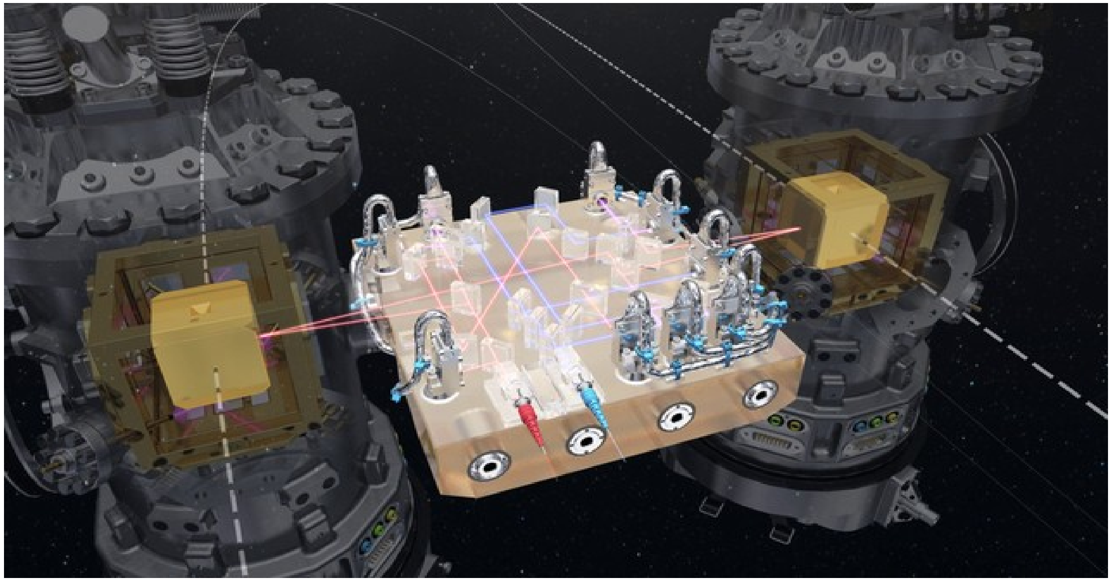
1.Introduction

- The launch of LISA Pathfinder was December 3, 2015.
- The scientific operations took place from March to June, 2016.
- We are in the phase of extension of scientific operations that ends at the end of June.

1.Introduction

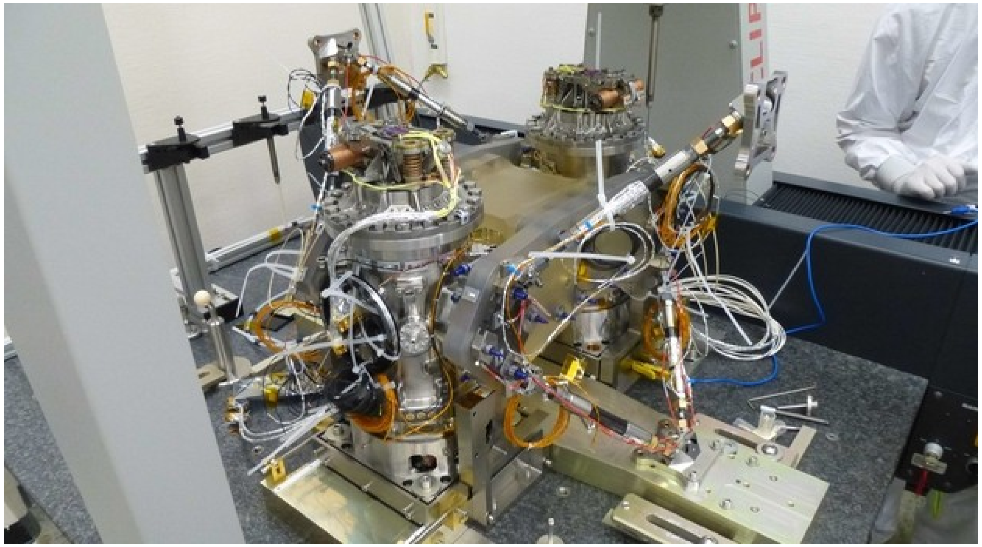
- LISA Pathfinder has tested critical parts of the Laser Interferometer Space Antenna (LISA), the first space-borne gravitational wave observatory.

- The spacecraft has two test masses in nominally perfect geodesic motion (free fall) and a laser metrology system that detects residual deviations of the test massses from the ideal free fall, to a given level of accuracy.



1.Introduction

- The science module of LISA Pathfinder is the LTP (Lisa Technology Package).
- The analysis of the different experiments are realized with pipelines built with LTPDA (LISA Technology Package Data Analysis) toolbox, that is a MATLAB toolbox.



1.Introduction

- The precision of the measurement done with LISA Pathfinder is required to be:

$$S_{\Delta a}^{1/2}(\omega) \leq 3 \cdot 10^{-14} \quad \mathrm{m\,s^{-2}\,Hz^{-1/2}} \qquad 1mHz < f < 30mHz$$

- The total contribution of temperature fluctuation noise to the total acceleration noise is estimated in:

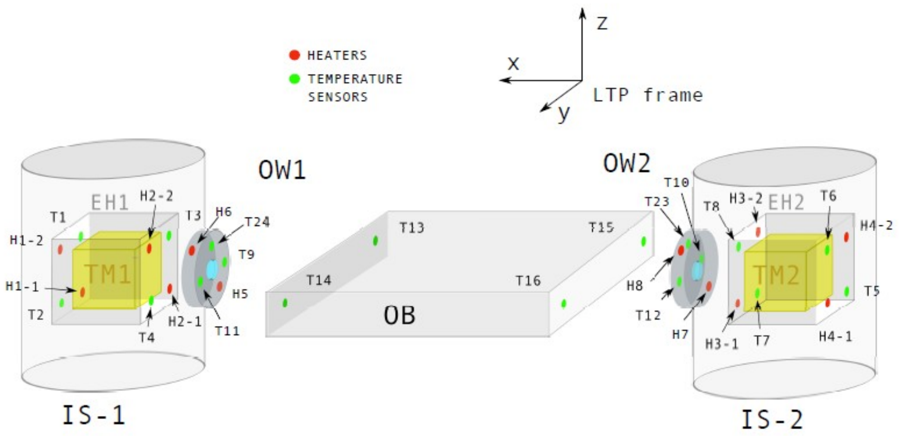
$$S_{a,T}^{1/2}(\omega) \leq 3 \times 10^{-15} \quad \mathrm{m\,s^{-2}\,Hz^{-1/2}} \qquad 1mHz < f < 30mHz$$

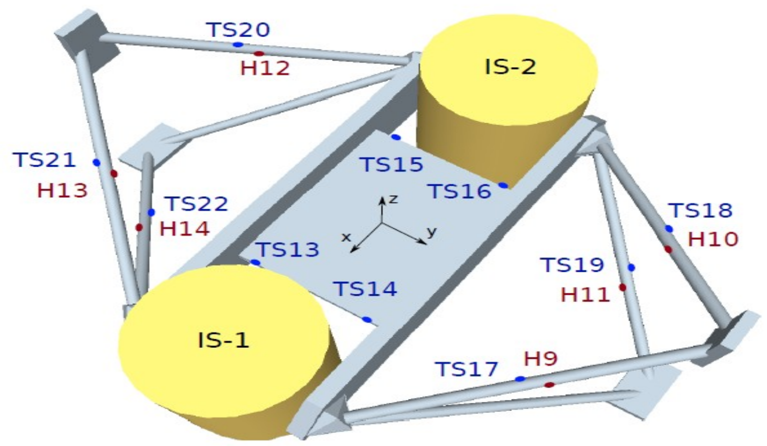
- Then, we can hope this stability requirement for the temperature fluctuation:

$$S_T^{1/2}(\omega) \leq 10^{-4}\,\mathrm{K}/\sqrt{\mathrm{Hz}} \qquad 1mHz < f < 30mHz$$

1.Introduction

- We have heaters to inject a power in different parts and thermal sensors to measure thermal fluctuations.





1.Introduction

★ We have three thermal experiments to see the thermal contribution to the total noise:

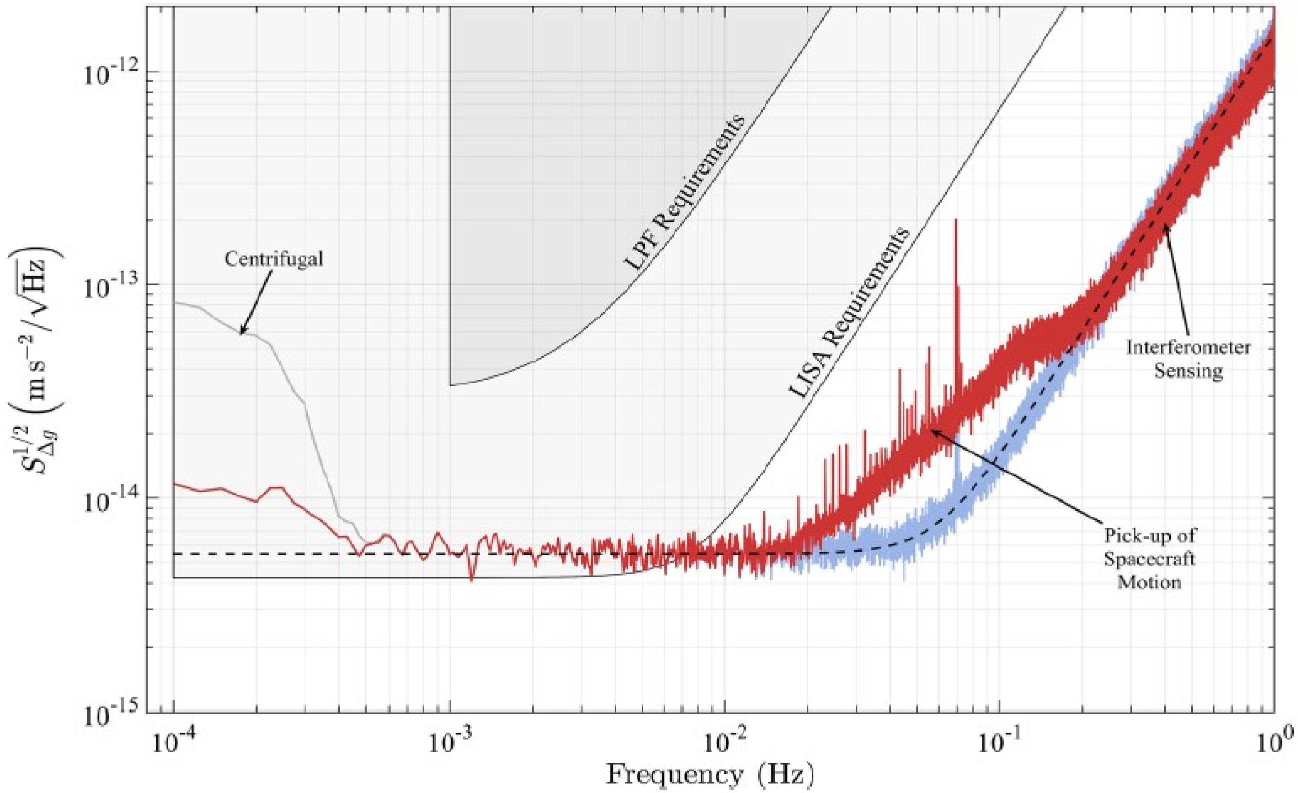
Electrode Housing thermal experiment.

Struts thermal experiment.

Optical Window thermal experiment.

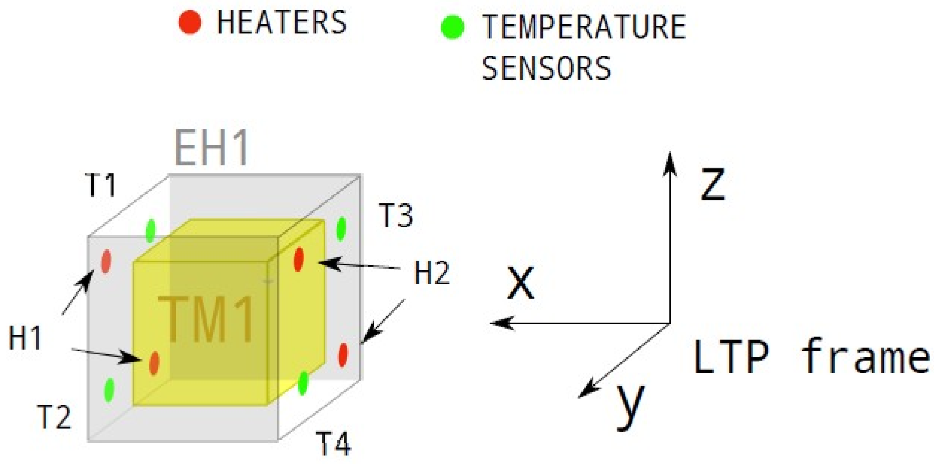
1.Introduction

- LISA Pathfinder first results:



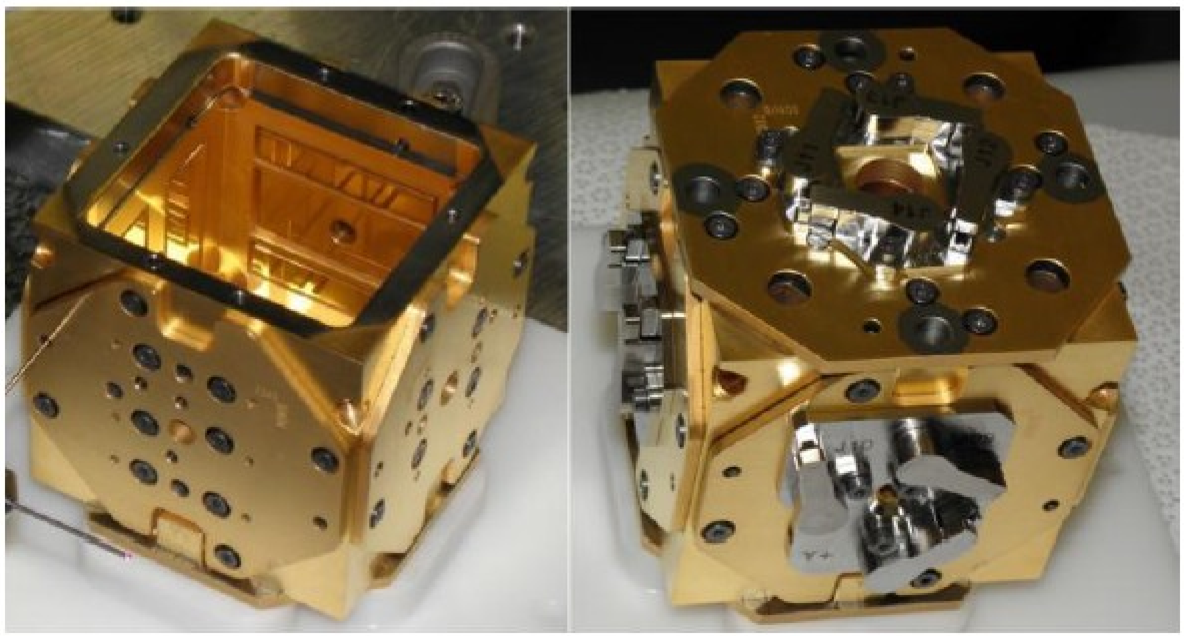
M. Armano et al., Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results , Physical Review Letters 116, 231101 (2016).

2.Electrode Housing Thermal Experiment



The Electrode Housing experiment aims to estimate the thermal couplings between temperature gradients in the Electrode Housing and direct forces on the Test Masses.

2.Electrode Housing Thermal Experiment



Flight model Electrode Housing.

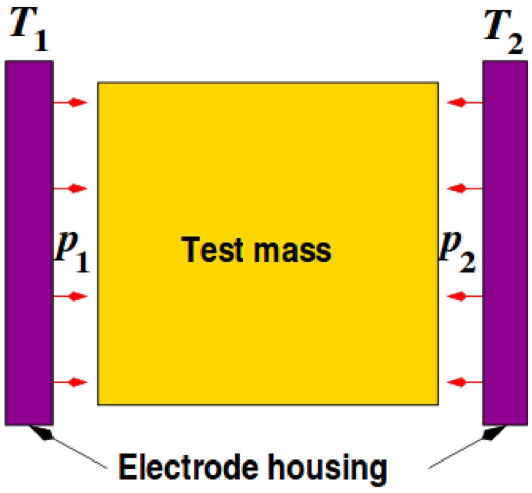
2.Electrode Housing Thermal Experiment

Mechanisms produced by thermal fluctuations

Three different mechanisms produced by thermal fluctuations change the LTP (LISA Technoloy Package) readout:

Radiation pressure

A body at any absolute temperature T emits thermal radiation that exerts pressure on any surface that the radiation hits.



$$F_{\rm RP} = \frac{8}{3}\frac{\sigma}{c} k_{\rm RP} A_{\rm TM} T_0^3 \Delta T$$

$$\alpha_{\rm RP} = \frac{8}{3}\frac{\sigma}{c} k_{\rm RP} A_{\rm TM} T_0^3$$

$A_{\rm TM}$	Area of one face of the Test Mass
σ	Stefan-Boltzmann constant
$k_{\rm RP}$	Geometrical and optical factor

2.Electrode Housing Thermal Experiment

Mechanisms produced by thermal fluctuations

Radiometer effect

This is an effect which happens in rarefied gas atmospheres.

In low pressure atmospheres, where the gas particles have a mean free path well in excess of the dimesions of the containing vessel, equilibrium conditions do not happen when pressure is uniform, but rather:

$$\frac{p_1}{\sqrt{T_1}} = \frac{p_2}{\sqrt{T_2}}$$

$$F_{\mathrm{RM}} = \frac{1}{4}\frac{P}{T_0}\Delta T \quad \Rightarrow \quad \alpha_{\mathrm{RM}} = k_{\mathrm{RM}}\frac{1}{4}\frac{P}{T_0} \quad \Rightarrow \quad S_a^{1/2} = 1.3\cdot 10^{-15}\left(\frac{P}{10^{-6}\,\mathrm{Pa}}\right)^{1/2}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$$

Brownian noise contribution

k_{RM} Geometrical factor

2.Electrode Housing Thermal Experiment

Mechanisms produced by thermal fluctuations

Asymmetric Outgassing

Any surface exposed to an atmosphere at a given pressure presents an interchange of particles with the environment which is highly dependent on the temperature and the kind of particles.

At low pressures, the flux is dominated by outgoing particles defining the so called outgassing rate Q.

$$F_{OG} = A_{TM} \frac{Q_{rate}(T_0)}{C_{eff}} \frac{\Theta_{OG}}{T_0^2} \Delta T \quad \Rightarrow \quad \alpha_{OG} = A_{TM} \frac{Q_0 e^{-\frac{\Theta_{OG}}{T_0}}}{C_{eff}} \frac{\Theta_{OG}}{T_0^2}$$

$$Q_{rate}(T) = Q_0 \exp\left(-\frac{\Theta_{OG}}{T}\right)$$

Q_0	Outgassing prefactor
C_{eff}	Equivalent conductance
Θ_{OG}	Activation temperature

2.Electrode Housing Thermal Experiment

Mechanisms produced by thermal fluctuations

$$F = \left(\alpha_{\mathrm{OG}} + \alpha_{\mathrm{RP}} + \alpha_{\mathrm{RM}} \right) \Delta T$$

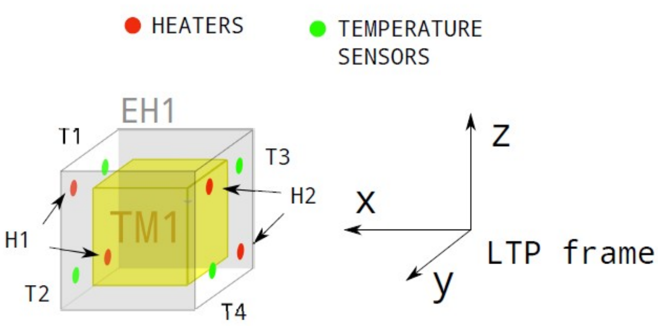
- We want to mesaure the global coupling.
- We want to disentangle the contributions of the different thermal effects from the global coupling.
- We will estimate the EH noise contribution to the total noise.

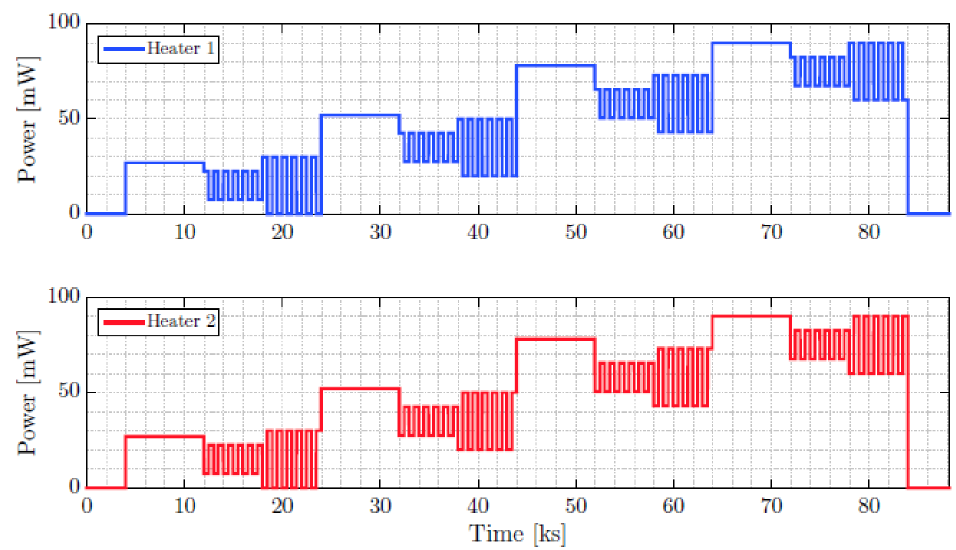
FERRAN GIBERT GUTIÉRREZ, THERMAL DIAGNOSTICS EXPERIMENTS FOR LISA PATHFINDER, PhD THESIS, 2016

2.Electrode Housing Thermal Experiment

Simulated experiment

Power with heaters → **Temperature gradient** → **Force**



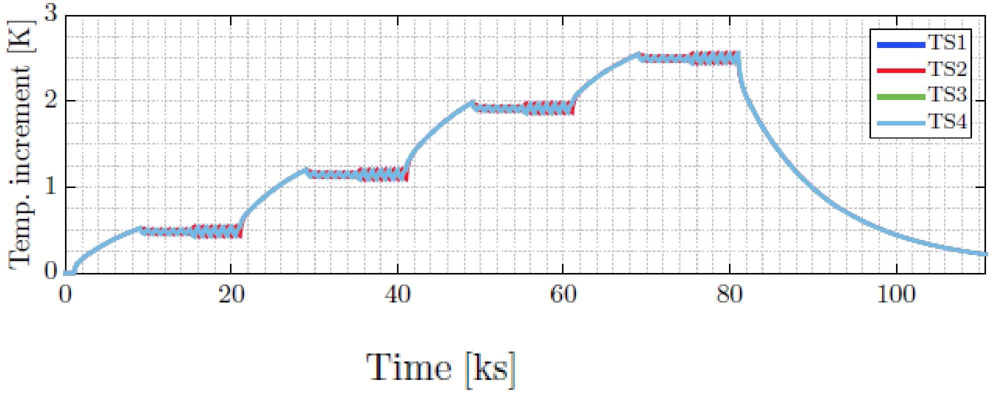


Signal proposed for heaters H1 and H2. As observed, the same modulation pattern is repeated with different DC levels and pre-heating steps.

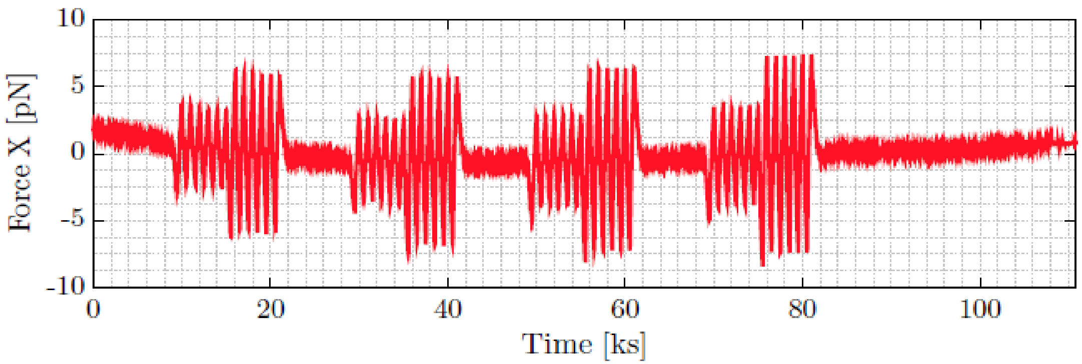
FERRAN GIBERT GUTIÉRREZ, THERMAL DIAGNOSTICS EXPERIMENTS FOR LISA PATHFINDER, PhD THESIS, 2016

2.Electrode Housing Thermal Experiment

Simulated experiment



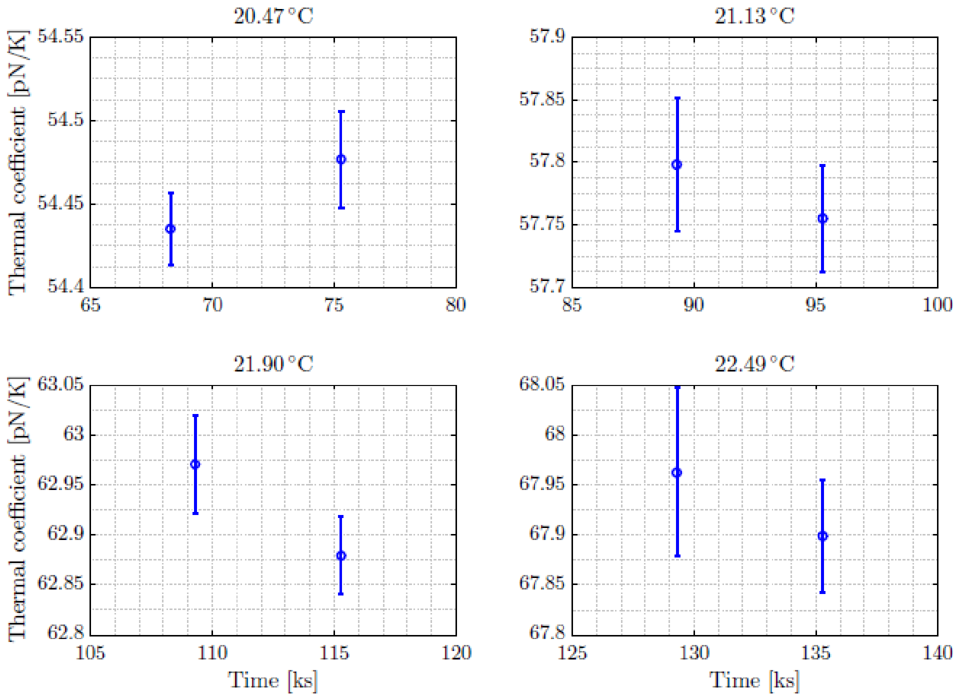
Electrode Housing temperature sensors readouts.



Force x induced on the Test Mass.

2.Electrode Housing Thermal Experiment

Simulated experiment



Average thermal coefficients, classified in temperature levels.

2.Electrode Housing Thermal Experiment

Simulated experiment

Temperature [K]	$\alpha_{x,A1}$ [pN K^{-1}]	**Error** $\alpha_{x,A1}$ [%]	$\alpha_{x,A2}$ [pN K^{-1}]	**Error** $\alpha_{x,A2}$ [%]
293.62	54.43	0.02	54.48	0.03
294.28	57.80	0.05	57.75	0.04
295.05	62.97	0.05	62.88	0.04
295.64	67.96	0.08	67.90	0.06

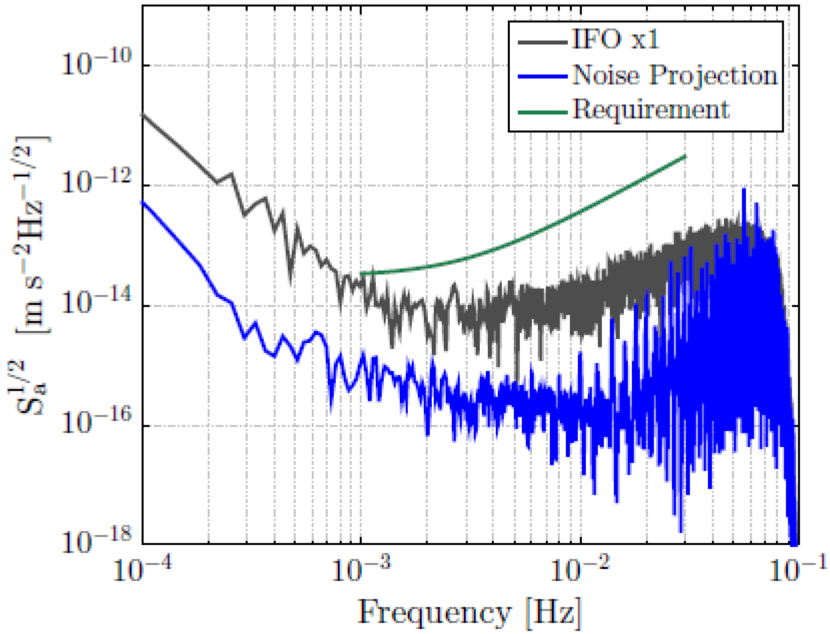
Thermal coefficients estimated for the different temperature modulations. A1 and A2 correspond to the small and largemodulation amplitudes respectively.

You can obtain a total average coefficient.

2.Electrode Housing Thermal Experiment

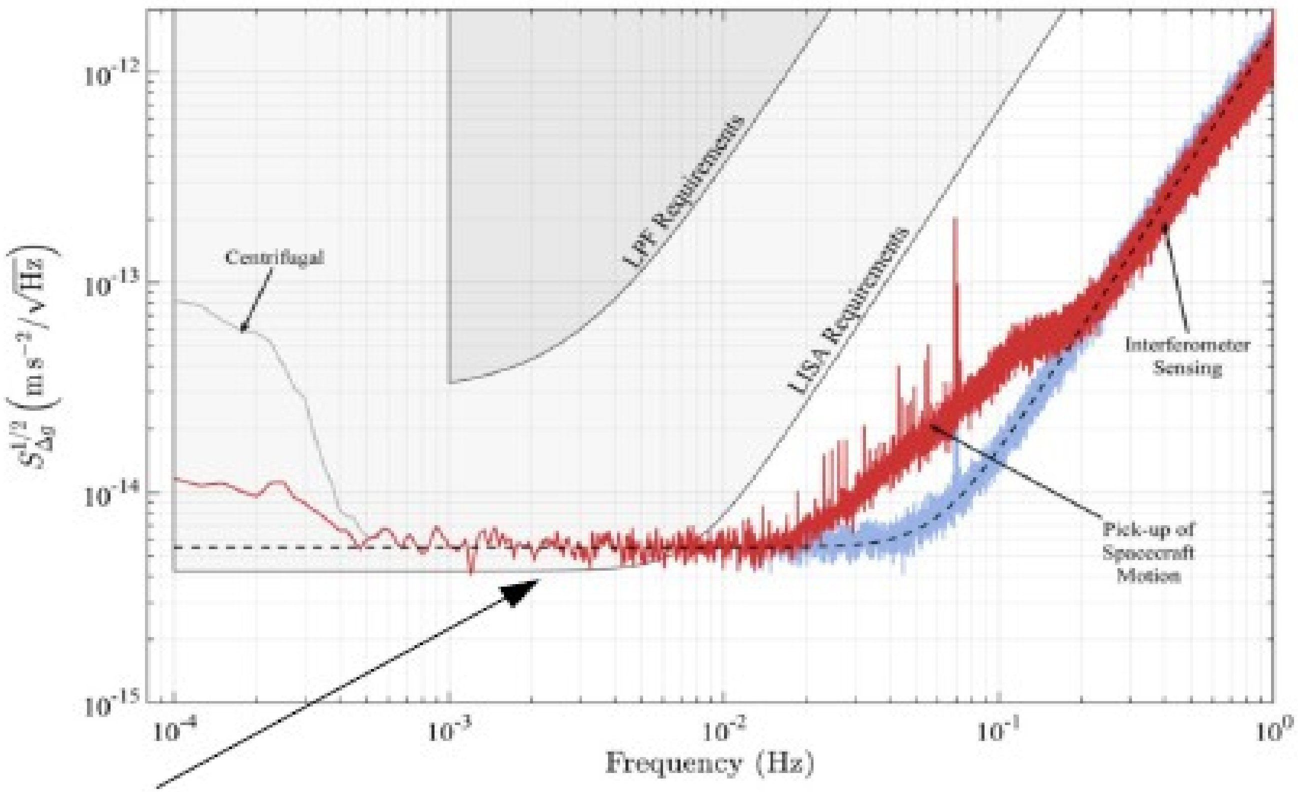
Simulated experiment

The thermal noise contribution of this effect will be:



2.Electrode Housing Thermal Experiment

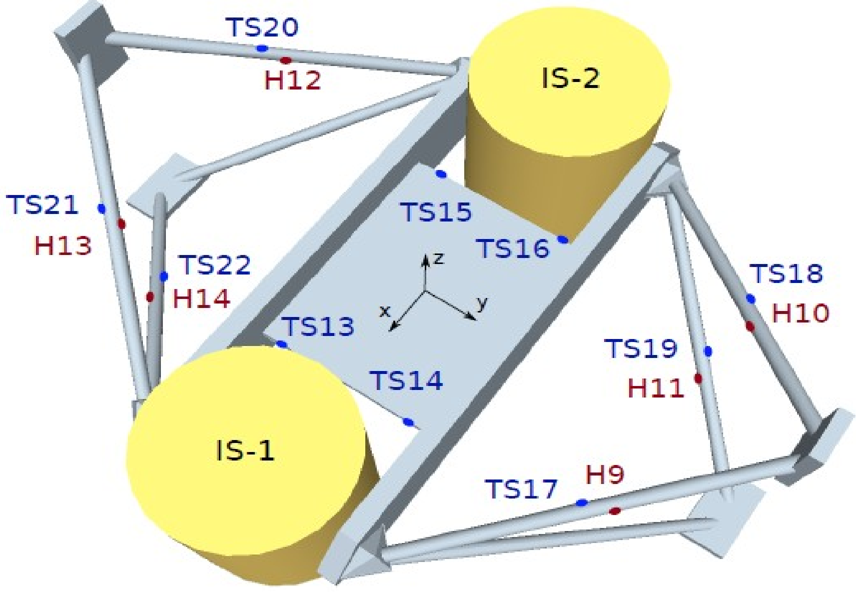
Real data



Brownian noise contribution

3.Struts Thermal Experiment

The Struts heating experiment is a LPF experiment aimed to characterise the thermoelastic distortion when we have temperature fluctuations in the Struts.



F Gibert, M Nofrarias, N Karnesis, L Gesa, V Martín, I Mateos, A Lobo, R Flatscher, D Gerardi, J Burkhardt, R Gerndt, D I Robertson, H Ward, P W McNamara, F Guzmán, M Hewitson, I Diepholz, J Reiche, G Heinzel and K Danzmann, Thermo-elastic induced phase noise in the LISA Pathfinder spacecraft, January 2015, Classical and Quantum Gravity.

3.Struts Thermal Experiment

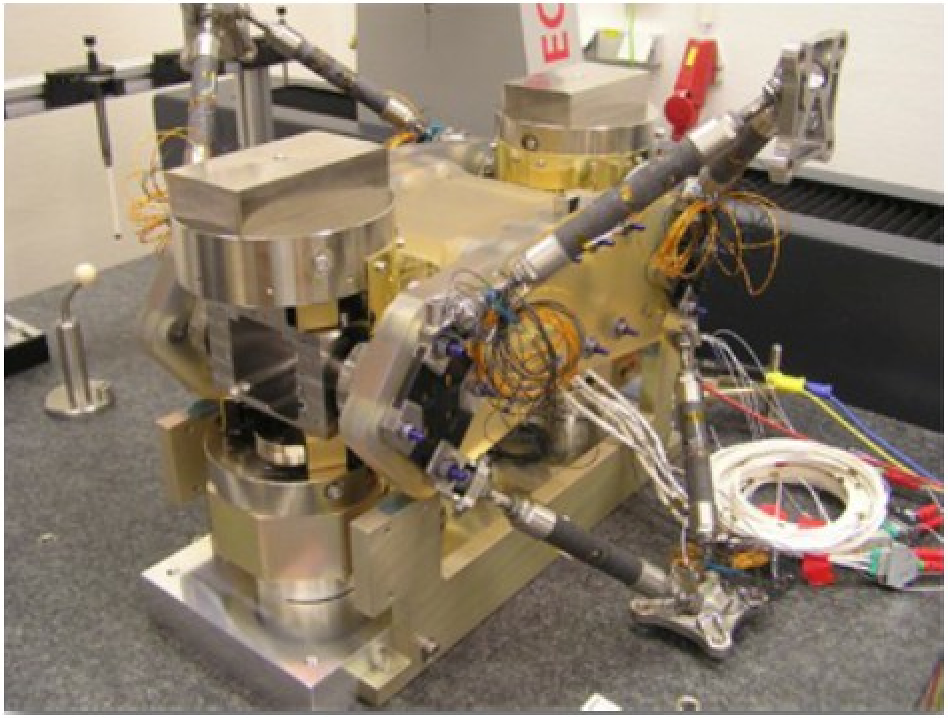
OSTT's data

During the On-Station Thermal Test (OSTT) of the LISA Pathfinder the Diagnostics Subsystem was tested in nearly space conditions for the first time after integration in the satellite.

Space vacuum chamber with the satellite during the OSTT campaign. Credits: Airbus Defence and Space UK.

3.Struts Thermal Experiment

OSTT's data

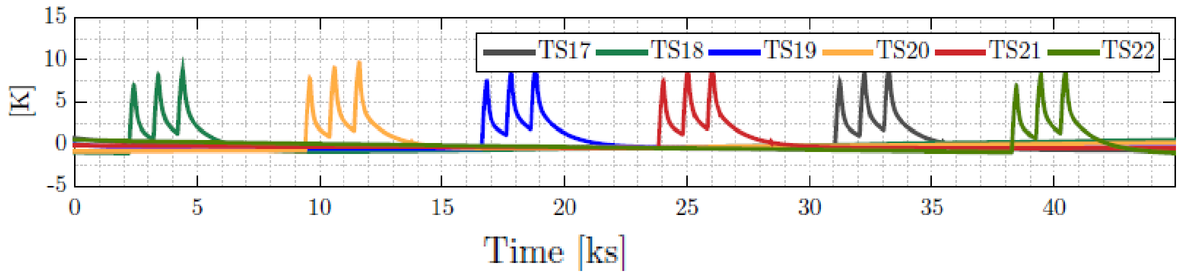


LTP Core Assembly (LCA) as during the OSTT campaigns.

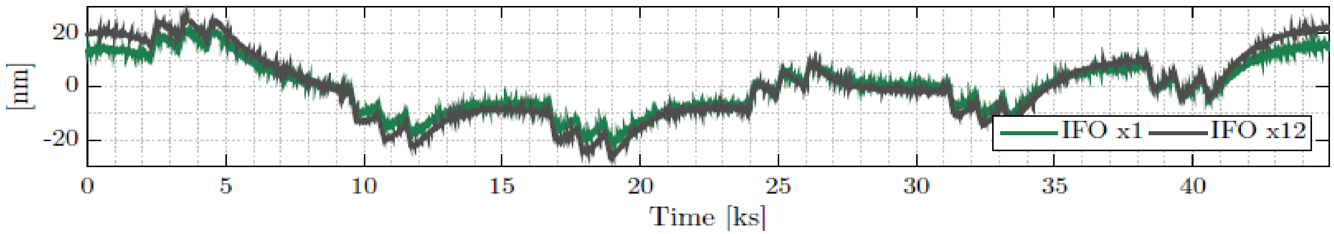
3.Struts Thermal Experiment

OSTT's data

Power with heaters → **Temperature gradient** → **Displacements measured by the interferometer**



Temperature measurements at the different Struts.

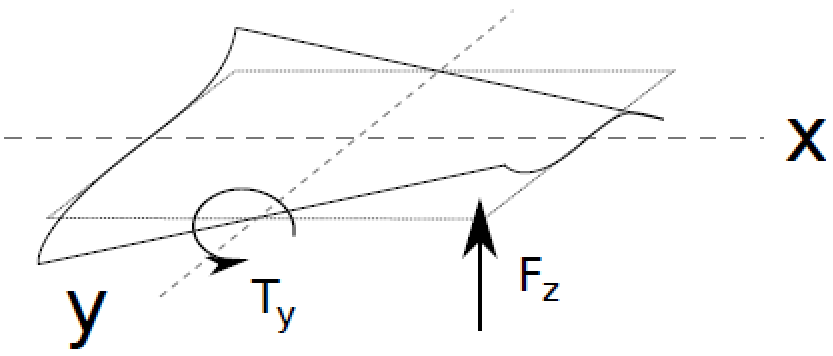


Displacements measured by the interferometer.

3.Struts Thermal Experiment

OSTT's data

The thermal gradient produces distorisons in the struts.



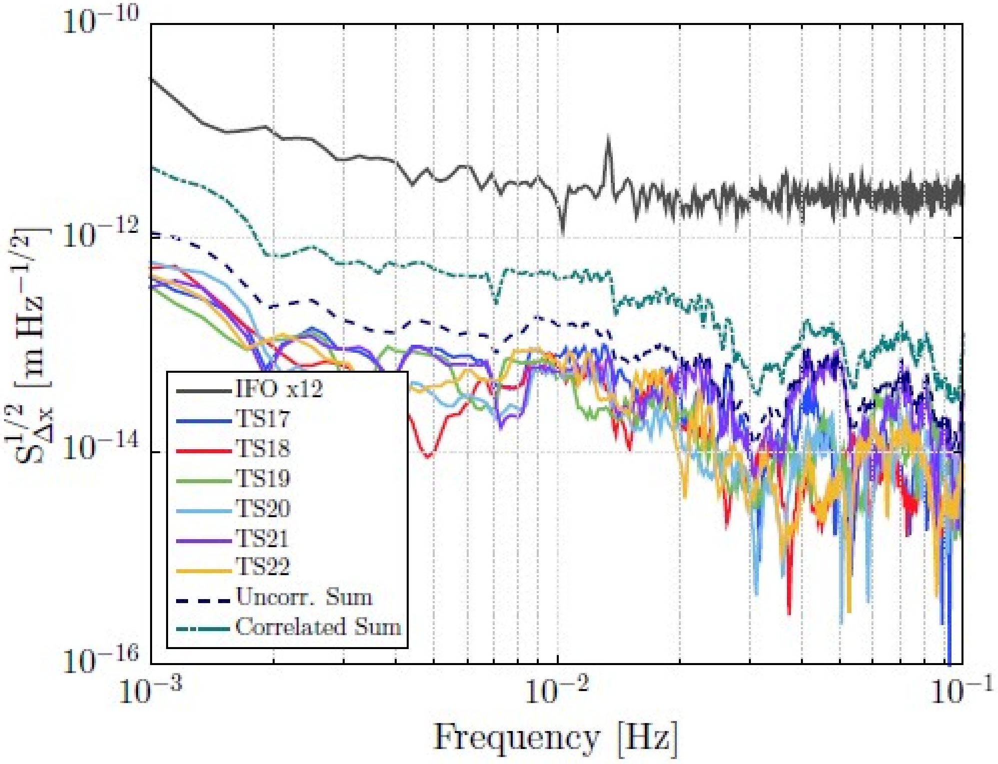
Schematic of the torsion mechanism on y produced by the vertical component of the force exerted by a heated strut. The case of the image would correspond to a lower strut heater activation such H11 or H14.

3.Struts Thermal Experiment

OSTT's data

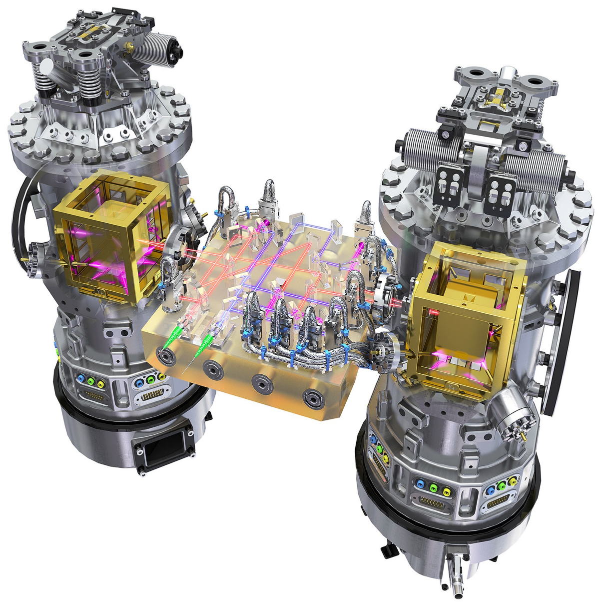
The thermal noise contribution of this effect will be:

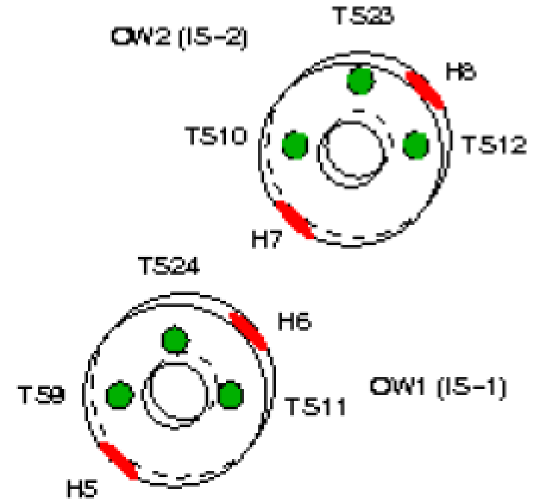
$$S^{1/2}_{\Phi,T_{\mathrm{m}}}(\omega) = k_{\mathrm{m}}(\omega) S^{1/2}_{T_{\mathrm{m}}}(\omega)$$



Noise projection of thermo-elastic induced phase noise on the x_{12}. The contribution from each suspension strut is shown together with the uncorrelated sum of all.

4.Optical Window Thermal Experiment





- The Optical Window is the interface between the Optical Bench and the test mass.

- The glass of the OW is clamped in a titanium ring.

- There are three temperature sensors in this titanium ring and there are two heaters in the lateral face.

4.Optical Window Thermal Experiment

Two diferent kinds of thermal effects have been identified as sources of changes in the optical path-length of a light beam traversing a plane-parallel piece of glass:

1) Temperature dependent changes of the refraction index:

$$\left.\frac{d\phi}{dT}\right|_{\text{free}} = 2\pi\frac{L}{\lambda}\left[\frac{dn}{dT} + (n-1)\,\alpha_E\right]$$

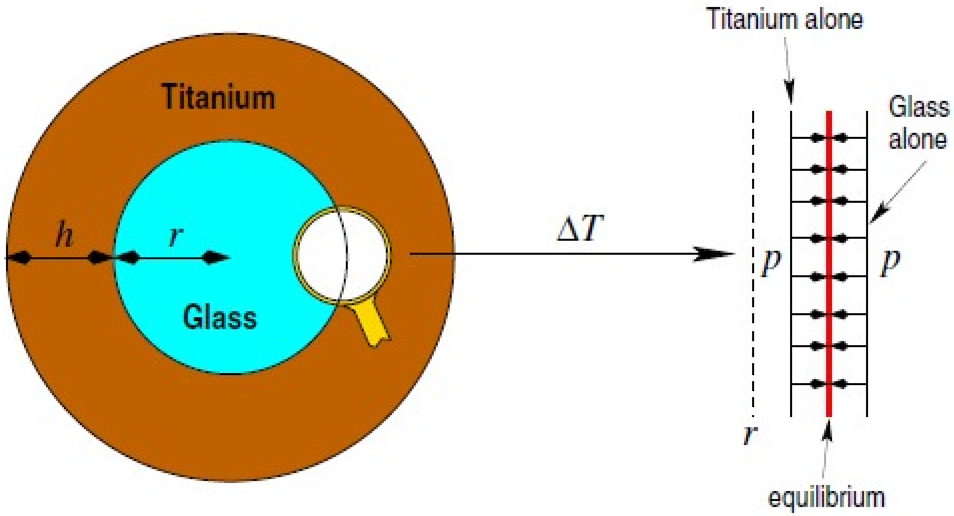
Linear thermal expansion factor of the glass: $\alpha_E = L^{-1}\,dL/dT$

This effect is more prominent at very low frequencies.

4.Optical Window Thermal Experiment

2) Mechanical stress produces changes of the refraction index:

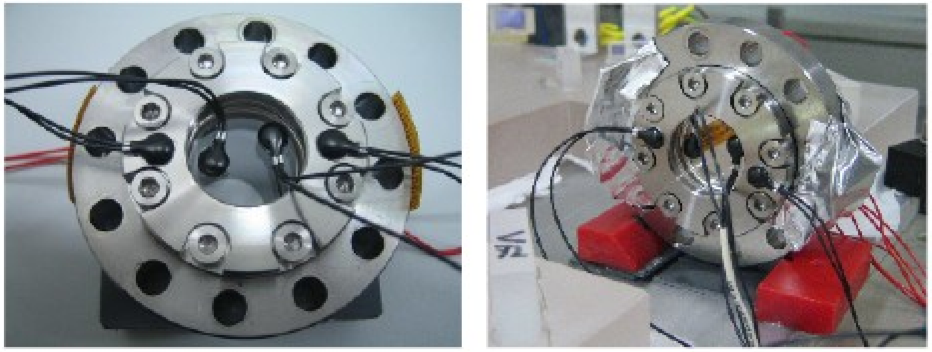
The stress on the glass is due to diferential thermal dilatation of the Titanium flange and the OW glass itself.



This effect is more prominent at higher frequency band.

4.Optical Window Thermal Experiment

Hannover's experiments

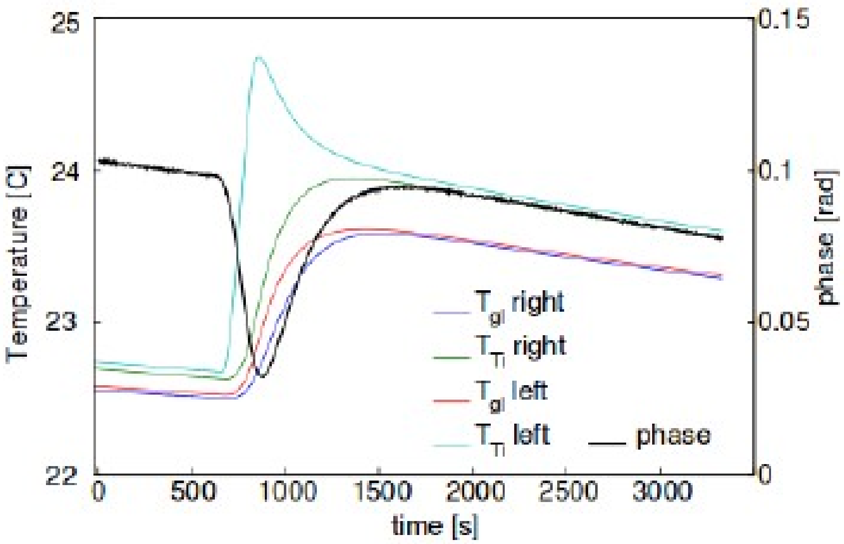


The OW (left), with the plane-parallel plate inside the Titanium flange, heaters on the lateral surface of the latter (pale brown foils) and two pairs of NTC temperature sensors (black beads with wires). On the right, mounting of the OW on rails for measurements. Note heaters are covered with aluminium foils: This is to prevent undesired heating of other components by heaters' emission of thermal radiation.

M Nofrarias, A F García Marín, A Lobo, G Heinzel, J Ramos-Castro, J Sanjuán and K Danzmann, Thermal diagnostics of the optical window on board LISA Pathfinder, October 2007, Classical and Quantum Gravity.

4.Optical Window Thermal Experiment

Hannover's experiments



Phase (black curve) and various temperature sensors' responses (coloured curves) to a 2 Watt heat pulse applied during 100 seconds.

4.Optical Window Thermal Experiment

Hannover's experiments

We have two models that show the relationship between the temperature fluctuations and the deviations of the interferometric signal.

Direct Linear Regression: $\phi(t) = p_1 T_{Ti}(t) + p_2 T_{Glass}(t)$

ARMA model: $\phi[n] = G(q,\theta) T_{Ti}[n]$ $\quad G(q,\alpha,\beta,\delta) = \alpha \frac{1-q^{-1}}{1+\beta q^{-1}} + \frac{\delta}{1+\beta q^{-1}}$

$$qx[n] = x[n+1],$$

$$q^{-1}x[n] = x[n-1]$$

3. Models

Direct Linear Regression: $\phi(t) = p_1 T_{Ti}(t) + p_2 T_{Glass}(t)$

ARMA model: $\phi[n] = G(q,\theta) T_{Ti}[n]$ $G(q,\alpha,\beta,\delta) = \alpha \frac{1-q^{-1}}{1+\beta q^{-1}} + \frac{\delta}{1+\beta q^{-1}}$

$$qx[n] = x[n+1],$$

$$q^{-1}x[n] = x[n-1]$$

Continuous time model: $\dot{\phi} - \tau^{-1}\phi(t) = A\dot{T}_{Ti}(t) + BT_{Ti}(t)$

$$\beta = -(1+\eta)$$

$$\eta < -10^{-2}$$

$$\tau \simeq -\Delta t/\eta$$

$$\beta = -(1 + \frac{\Delta t}{\tau})^{-1}$$

$$\alpha = A(1 + \frac{\Delta t}{\tau})^{-1}$$

$$\delta = B\Delta t(1 + \frac{\Delta t}{\tau})^{-1}$$

4.Optical Window Thermal Experiment

Hannover's experiments

With the ARMA model and the values of the parameters of this slide:

$$G(q,\alpha,\beta,\delta) = \alpha\frac{1-q^{-1}}{1+\beta q^{-1}} + \frac{\delta}{1+\beta q^{-1}}$$

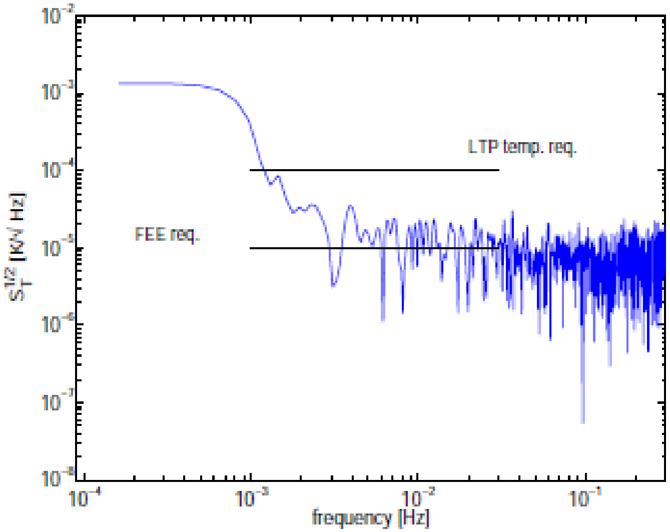
$$\alpha \equiv -\alpha_1, \quad \delta \equiv \alpha_0 + \alpha_1, \quad \beta \equiv \beta_1$$

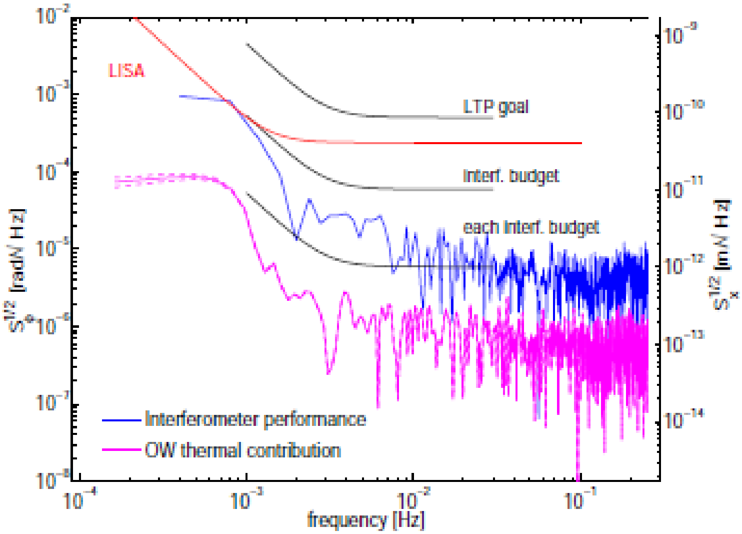
Parameters	Values
α_0	$(-39.6\pm3)\times10^{-3}\mathrm{rad}\cdot\mathrm{K}^{-1}$
α_1	$(39.5\pm3)\times10^{-3}\mathrm{rad}\cdot\mathrm{K}^{-1}$
β_1	-0.996 ± 0.001

4.Optical Window Thermal Experiment

Hannover's experiments

With the transfer function can be obtained the optical window thermal noise contribution in the total interferometric noise.





5.Conclusions

1) The contribution of the thermal fluctuations to the total noise is roughly 10%.

2) We have done three experiments:

EH thermal experiment

OW thermal experiment

Struts thermal experiment

3) We can conclude that :

- EH effect is more prominent at low frequencies.
- OW and Strut effect are more prominent at high frequencies.

4) We are going to do more experiments to obtain more in-flight data to complete our investigations.