Appendix C

LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain

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Abstract

LISA Pathfinder is the precursor of the ESA/NASA mission LISA (Laser Interferometer Space Antenna); it aims at demonstrating the feasibility of all the challenging key technologies needed by the operational mission.
CGS is responsible of the Thermal Design and Analysis of LISA Pathfinder ISH (Inertial Sensor Head). The main goal of the ISH TCS, as a part of the overall instrument TCS, is to damp the thermal disturbances coming from outside (i.e. external environment, rest of the satellite); the system performance requirements are expressed in terms of frequency-dependent allowable noise, inside the detector bandwidth (1 mHz - 30 mHz); for this reason most of the thermal analysis are not performed in the usual time domain, but in the frequency domain.
Main assumption of this approach shall be presented and the results compared with the standard time domain results and with test results, used to validate the thermal model. Finally the advantages of this method in terms of computational time and post-process capability shall also be presented.

Paolo Ruzza, 14 October 2014,
ESTEC

SPACE SYSTEMS

LISA pathfinder Inertial Sensor Head thermal analysis in frequency domain

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SPACE SYSTEMS

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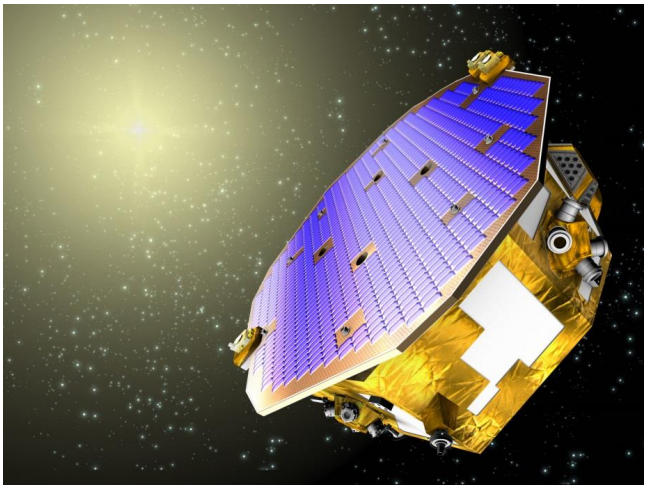
Introduction

Introduction to LISA Pathfinder (1)

LISA Pathfinder will test in flight the concept of low-frequency gravitational wave detection and all the technologies for future mission LISA (ESA/NASA)

Shall be orbiting in Earth-Sun L2

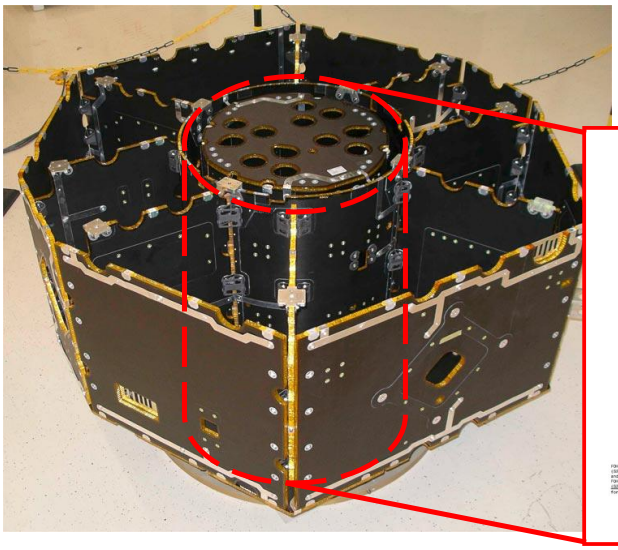
Launch foreseen in 2015



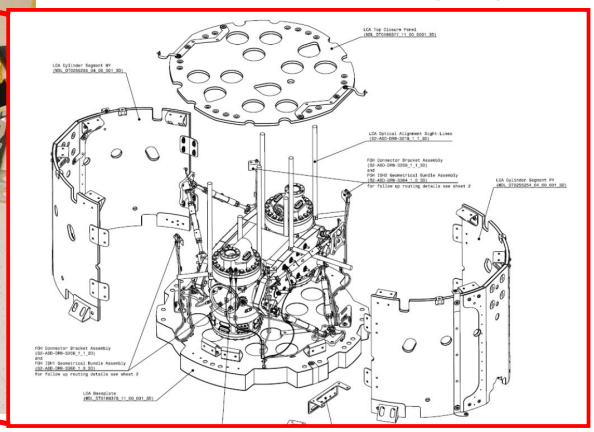
Introduction

Introduction to LISA Pathfinder (2)

LISA SATELLITE

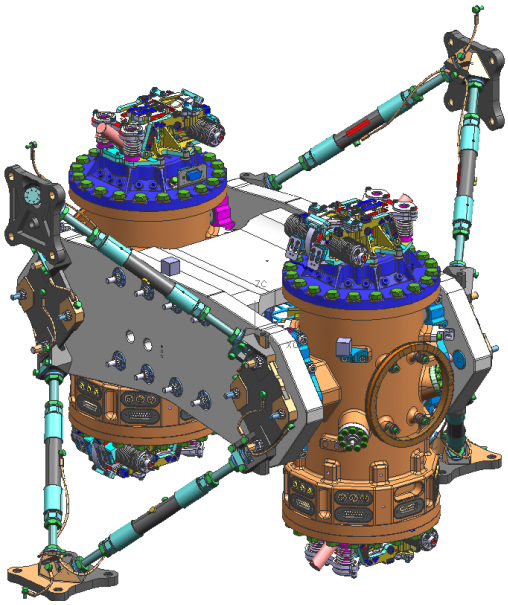


LISA CORE ASSEMBLY (LCA)



Introduction

Introduction to LISA Pathfinder (3)



The LCA is composed by two Inertial Sensor Heads (ISH) separated by an optical bench. The whole assembly is connected to the LCA cage by means of 8 low conductance CFRP struts

The two ISH contain two test masses in a near-perfect gravitational free-fall, whose motion is controlled and measured with unprecedented accuracy

ISHs have been designed, manufactured integrated and tested at CGS

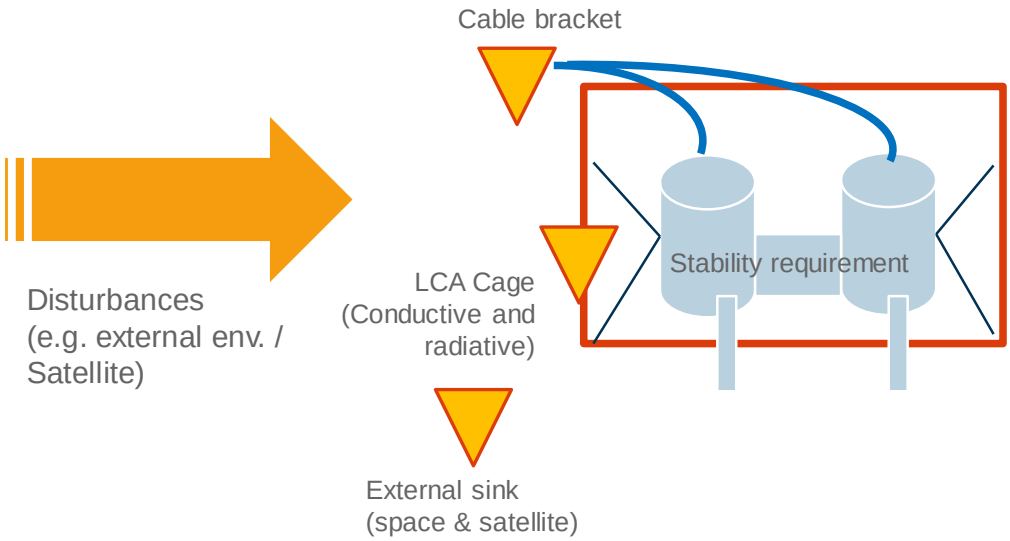
Analysis Approach

LCA analysis (and testing) philosophy

- The LCA is a completely passive device;
- Thermal analyses have been performed at LCA level to predict the system damping capability with reference to external temperature oscillation;
- Performance requirements are expressed in terms of frequency-dependent allowable temperature noise, inside the bandwidth [1 mHz – 30 mHz];
- For this reason all analyses are performed in frequency domain (via transfer function);
- This approach also lead to design and perform a dedicated test for thermal model correlation

Analysis Approach

Set of boundary nodes



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Theory

Frequency domain analysis* – brief theory (1)

$$\begin{cases} C_1\dot{T}_1 = -\sum_{i=1}^{N} GL_{1-i}\left(T_1 - T_i\right) - \sum_{i=1}^{N} GR_{1-i}\left(T_1^{\,4} - T_i^{\,4}\right) + Q_1 \\ C_2\dot{T}_2 = -\sum_{i=1}^{N} GL_{2-i}\left(T_2 - T_i\right) - \sum_{i=1}^{N} GR_{2-i}\left(T_2^{\,4} - T_i^{\,4}\right) + Q_2 \\ \vdots \\ C_j\dot{T}_j = -\sum_{i=1}^{N} GL_{j-i}\left(T_j - T_i\right) - \sum_{i=1}^{N} GR_{j-i}\left(T_j^{\,4} - T_i^{\,4}\right) + Q_j \\ \vdots \\ C_N\dot{T}_N = -\sum_{i=1}^{N} GL_{N-i}\left(T_N - T_i\right) - \sum_{i=1}^{N} GR_{N-i}\left(T_N^{\,4} - T_i^{\,4}\right) + Q_N \end{cases}$$

Linearization of radiative term

$$C_i\delta\dot{T}_i = -\sum_{i=1}^{N} GL_{i-j}\left(\delta T_i - \delta T_j\right) + -\sum_{i=1}^{N} GR_{i-j}\left(\delta T_i \cdot 4T_i^{\,3} - \delta T_j \cdot 4T_j^{\,3}\right) + \delta Q_i$$

* see [1],[2]

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Theory

Frequency domain analysis – brief theory (2)

$$\{\delta\dot{T}\} = C^{-1}(K\{\delta T\}) + C^{-1}\{\delta Q\} \equiv A\{\delta T\} + B\{\delta Q\}$$

$$\begin{Bmatrix} \delta\dot{T}_V \\ \delta\dot{T}_B \end{Bmatrix} = \begin{bmatrix} A_{VV} & A_{VB} \\ A_{BV} & A_{BB} \end{bmatrix} \begin{Bmatrix} \delta T_V \\ \delta T_B \end{Bmatrix} \Rightarrow \quad \delta\dot{T}_V = A_{VV}\,\delta T_V + A_{VB}\,\delta T_B$$

$$\frac{T_V(s)}{T_B(s)} \equiv F(s) = (sI - A_{VV})^{-1} A_{VB}$$

With s = *i*ω the frequency of interest

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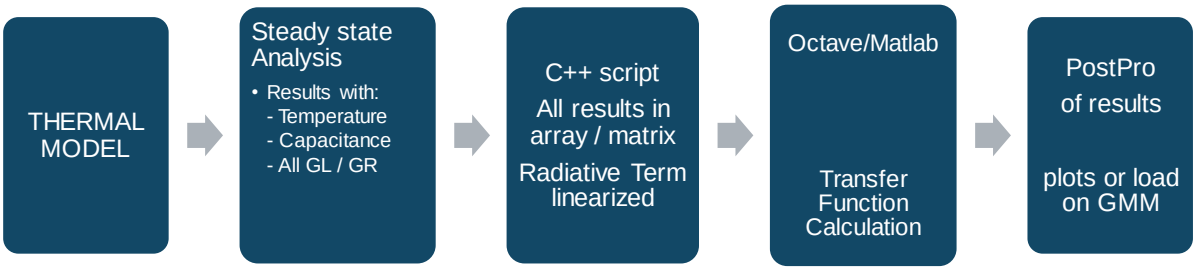
Practice

Practical application of the method



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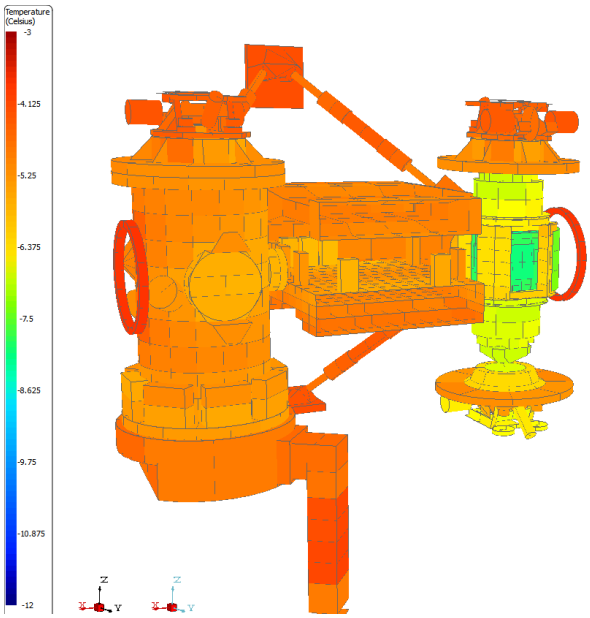
Post-processing

Post Processing of data (1)

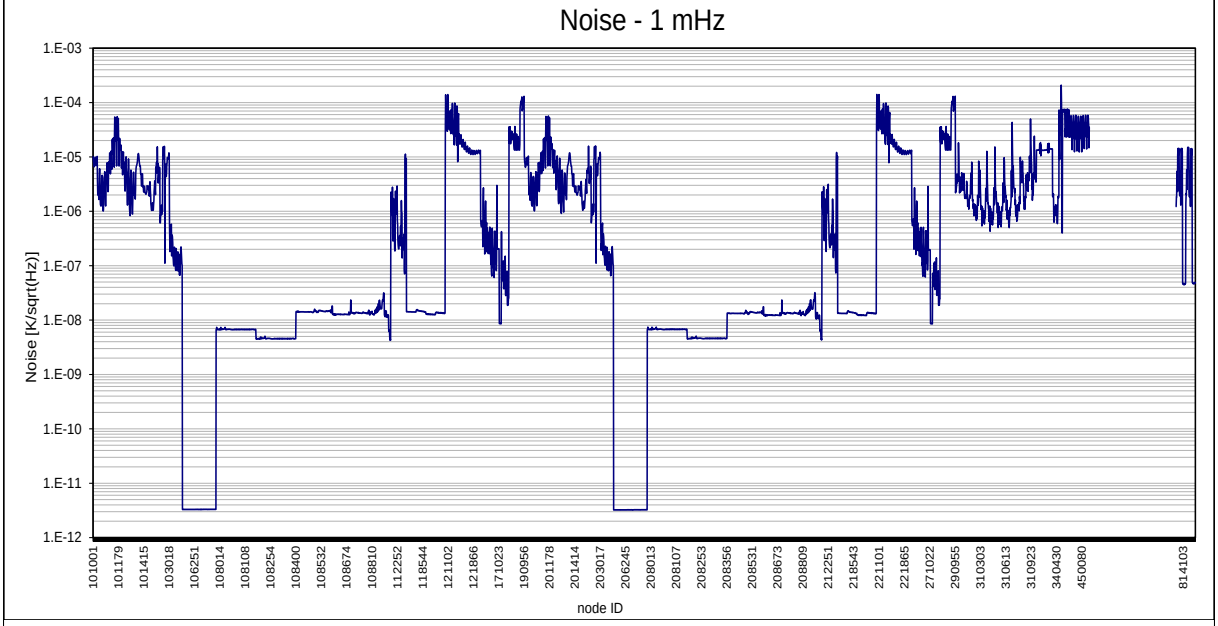


The temperature gain due to the boundary temperature oscillation (1mHz frequency) is calculated and plotted (in logarithmic scale) on the Geometrical Mathematical Model.

This approach gives a direct and immediate view of the coupling strength at a given frequency inside the model for all the nodes in the model

Post-processing

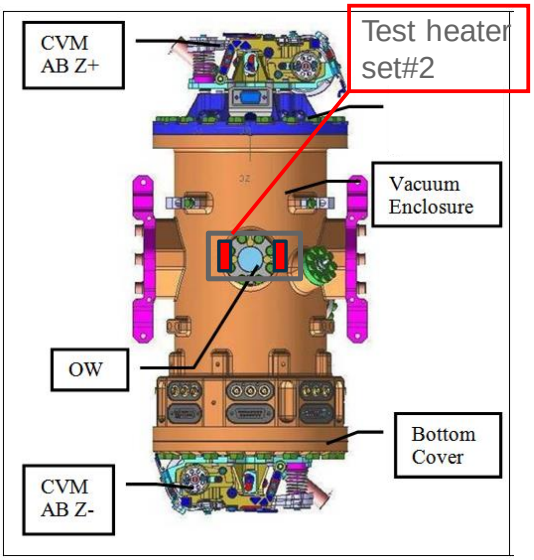
Post Processing of data (2)

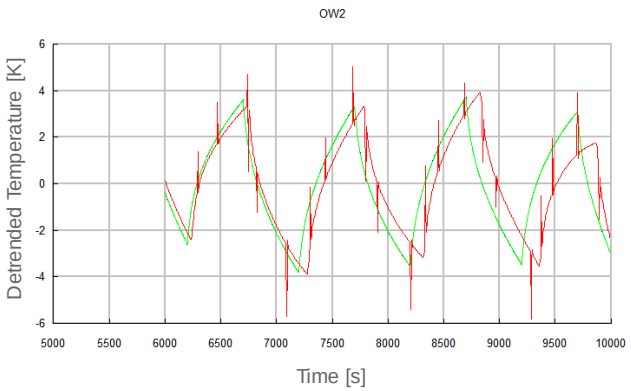


Thermal model correlation (on ISH)

- A dedicated test during qualification campaign has been designed and performed to correlate the thermal model in the frequency domain
- A standard balance test was not feasible since a too long stabilization time was needed (mass, high decoupling)
- A pulse input has been given to the system and the resulting oscillations have been considered for correlation:
  - ADVANTAGE: not needed to wait temperature stabilization, but the oscillation to be relatively stable
  - Two sets of heaters have been independently actuated with 1mHz profile (i.e. 500s ON / 500s OFF) to have two different correlation case

Test description

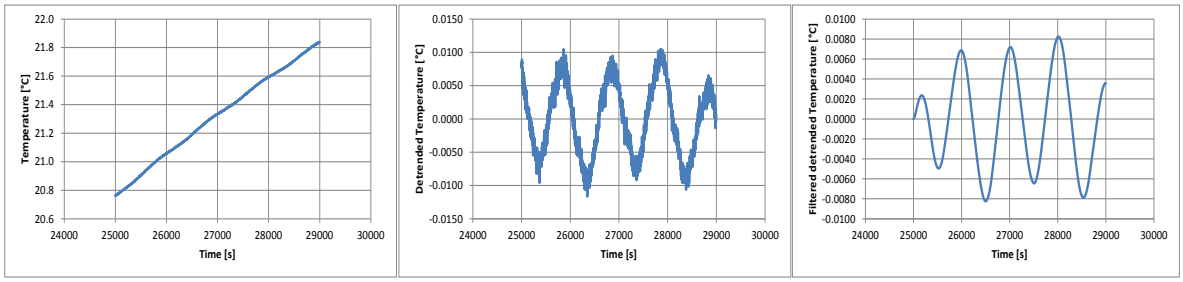




Heater applied on Optical window
Red – test data / green model data

Thermal model correlation

Test data post-processing



Raw data → **Detrended data** → **Filtered data**

Detrending with 3rd grade polynome

Low pass Butterworth filter with a 2mHz cut off frequency

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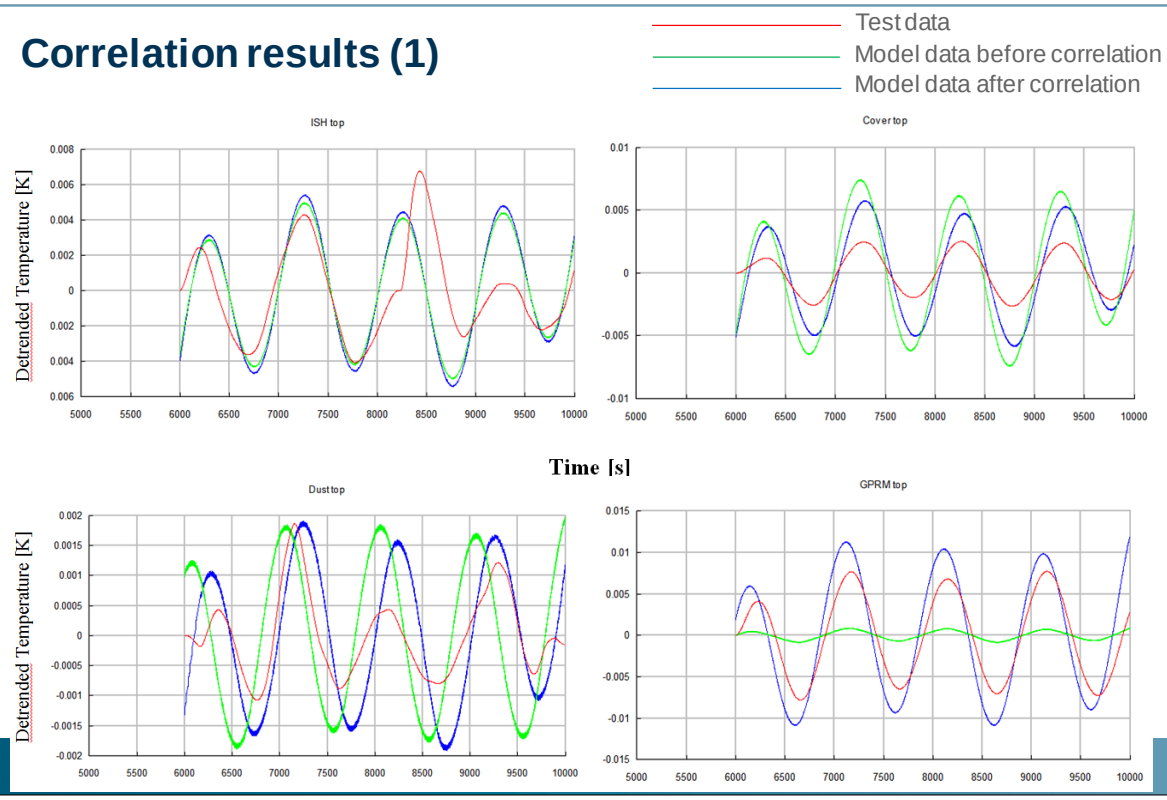
Thermal model correlation

Correlation results (1)



Thermal model correlation

Correlation results (2)

Analyses in time domain are very time-consuming (several hours each analysis)

Frequency domain approach permits fast Steady State analysis (few minutes each). This approach has been used for all the intermediate analyses (with correlation parameters variation)

The two approaches show very similar results, especially with small oscillation.

Thermal model correlation

Correlation results (3)

The time domain analysis (i.e. standard transient analysis with oscillating input) and the frequency domain analysis are showing comparable results

Peak to peak amplitude with given input power (1mHz)

	TEST [°C]	MODEL wt Time Domain Approach [°C]	MODEL wt Frequency domain Approach [°C]
ISH TOP	0.008	0.01	0.0103
COVER TOP	0.005	0.01	0.0106
DUST TOP	0.002	0.0036	0.0035
GPRM FLNG TOP	0.014	0.02	0.0215
TRP	0.0011	0.00052	0.0005
OW2	8	8	6.9

Conclusions

The presented approach has been extensively used in LISA TCS analyses:

- Calculation of transfer function between a set of boundary nodes (which are assumed the source of the perturbations) and all the other nodes in the model
- The approach is valid for small oscillation / superimposition of effects (need to linearize the radiative coupling)
- The method has been validated with analytical and experimental results
- The strength of this alternative approach is that, with a unique analysis run in the frequency domain, one is able to calculate the response of the system to a set of oscillatory sources (Temperature or power sources)
- Great advantages for computational time (one steady state analysis only is needed)

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