

Appendix H

LISA Pathfinder thermal stability analysis

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LISA Pathfinder

esa SCIENCE

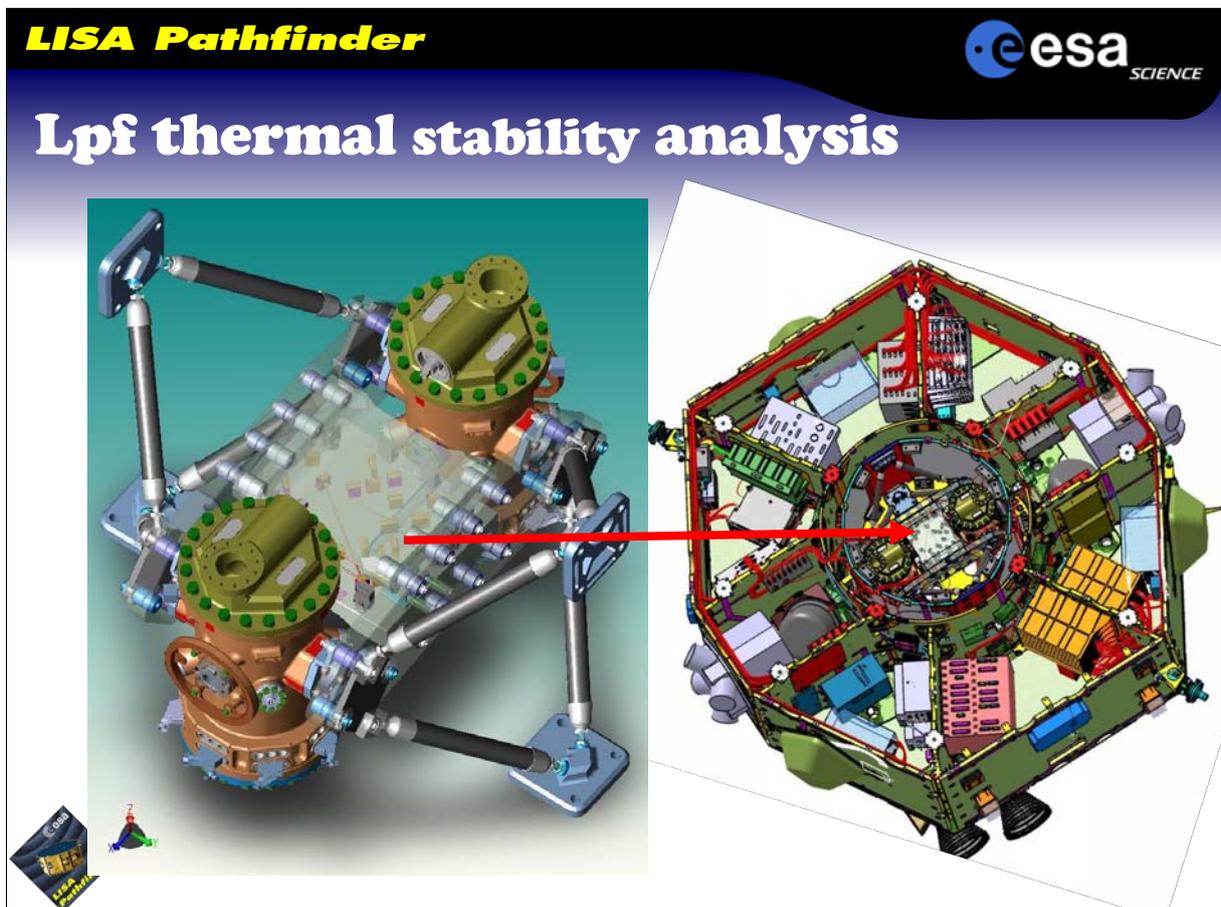
LISA Pathfinder thermal stability analysis

D. Fertin

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This slide features a dark blue background with a 3D rendering of the LISA Pathfinder satellite. The satellite is shown from a perspective view, highlighting its gold-colored thermal blankets and large blue solar panels. In the top left corner, there is a diamond-shaped logo with the text 'LISA Pathfinder' and the ESA logo. In the top right corner, the 'esa SCIENCE' logo is displayed. The main title 'LISA Pathfinder thermal stability analysis' is centered in large white font. Below the title, the author's name 'D. Fertin' and the event details are listed in white text. A small image of the Earth and Moon is visible in the bottom right corner.



LISA Pathfinder

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Lpf thermal stability analysis

This slide contains two 3D CAD models of the LISA Pathfinder satellite. On the left is an external view of the satellite, showing its complex structure with various instruments and sensors. On the right is a cutaway view of the satellite, revealing the internal components, including the payload bay and the central instrument bay. A red arrow points from the cutaway view towards the external view, indicating a specific area of interest. The background is a gradient from blue to white. The 'LISA Pathfinder' logo is in the top left, and the 'esa SCIENCE' logo is in the top right.

LISA Pathfinder 

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LISA Pathfinder 

LISA Pathfinder

-  First fundamental physics science mission.
-  To prepare for the Lisa mission by testing the concept of gravitational wave detection:
 - Demonstrating that the required force noise floor can be achieved (appropriate S/N ratio will be reached for LISA).
-  To validate in flight technologies not fully testable on ground:
 - Inertial sensor: test mass cannot be free floating on the ground,
 - FEFPs: microNewton force is difficult to measured.



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Mission objective

 Mission objective: verify that a test-mass can be put in pure gravitational free-fall within $3 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}$ between 1 mHz and 30 mHz

$$S_a^{1/2}(f) \leq 3 \times 10^{-14} \left[1 + \left(\frac{f}{3 \text{ mHz}} \right)^2 \right] \text{ m s}^{-2} / \sqrt{\text{Hz}}$$

 Sources of force noise must be minimized:

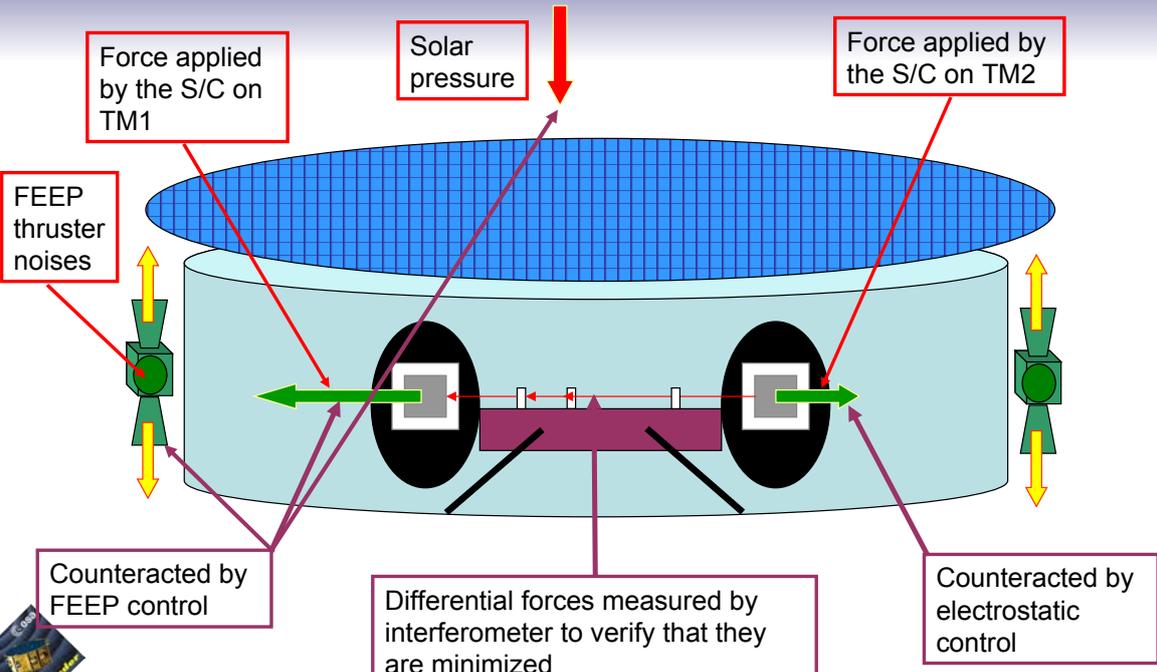
- ⇒ No pressure force or mechanical contact force: “drag-free” mission.
- ⇒ No electromagnetic forces.
- ⇒ No self-gravity forces from SC and instrument itself.

 Differential acceleration measurement must be one order of magnitude better:

- ⇒ Measurement by interferometry with accuracy better than 9 [pm/√Hz].

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Experiment description (1)



The diagram illustrates the forces and controls acting on the test masses (TM1 and TM2) inside the spacecraft. A central purple test mass is shown between two black circular test mass holders. A red arrow labeled 'Solar pressure' points down from the top. Two red arrows labeled 'Force applied by the S/C on TM1' and 'Force applied by the S/C on TM2' point towards the test masses from the left and right respectively. Two green arrows labeled 'Counteracted by FEED control' point away from the test masses towards the left and right. Two green arrows labeled 'Counteracted by electrostatic control' point away from the test masses towards the left and right. A green arrow labeled 'Differential forces measured by interferometer to verify that they are minimized' points from the test mass towards the center. Two yellow arrows labeled 'FEED thruster noises' point up and down from the test mass holders. A central green arrow points from the test mass towards the center.

Force applied by the S/C on TM1

Solar pressure

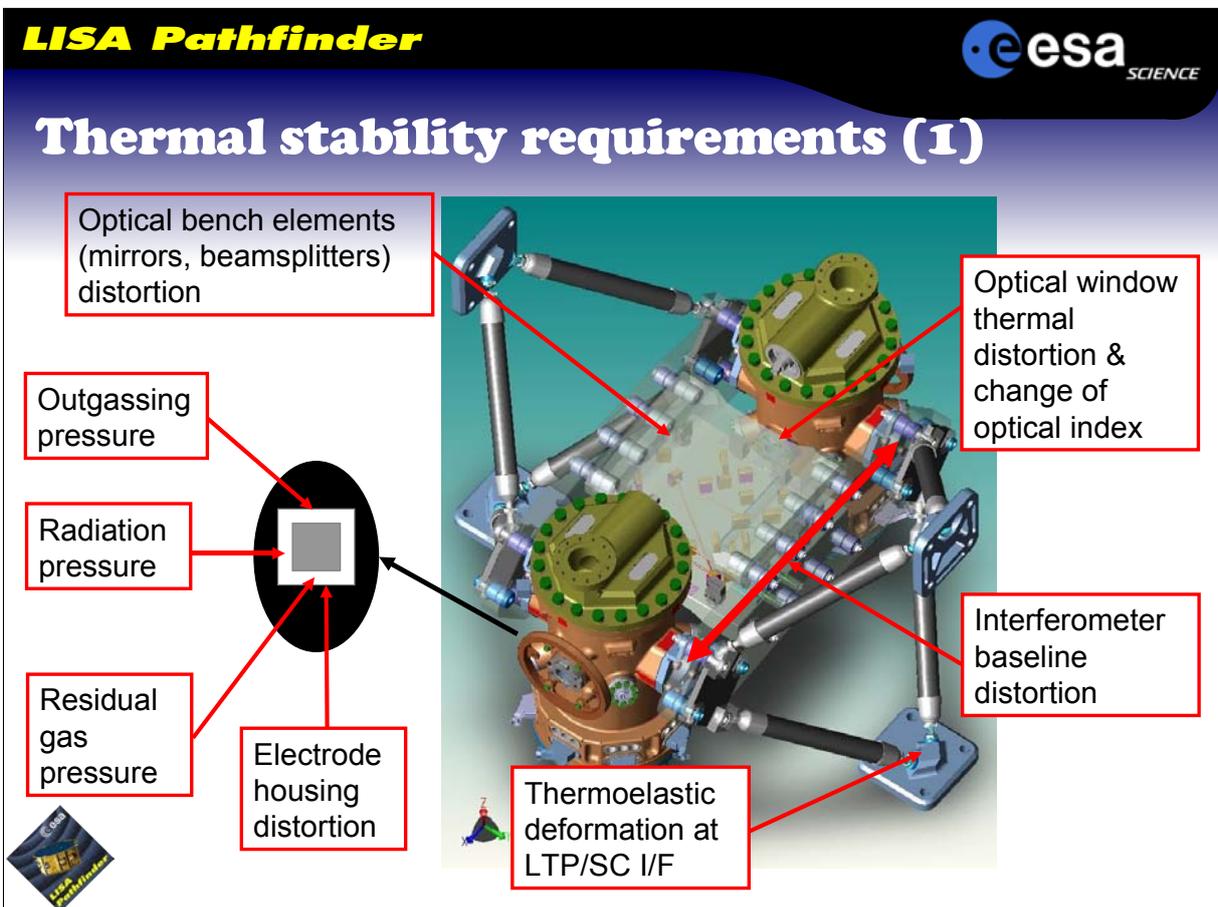
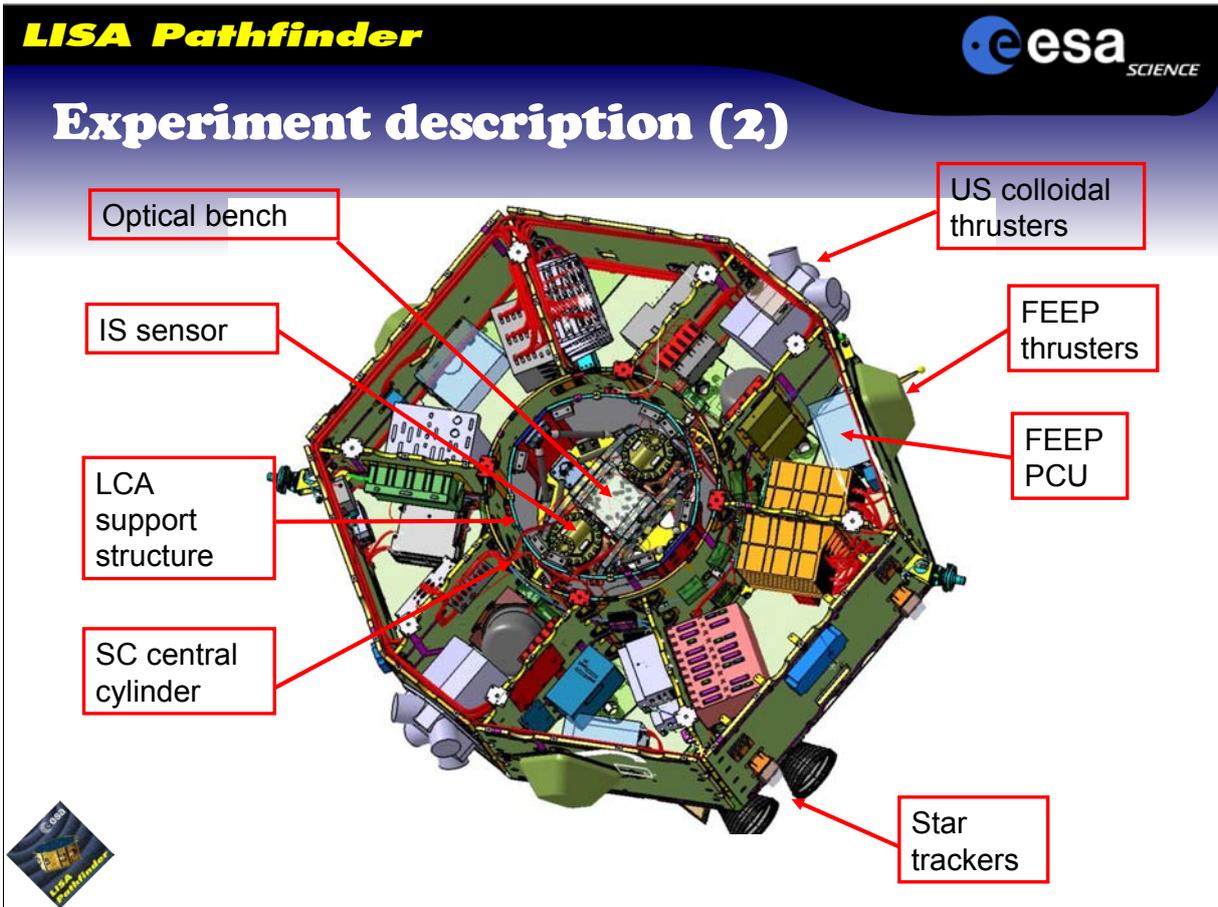
Force applied by the S/C on TM2

FEED thruster noises

Counteracted by FEED control

Differential forces measured by interferometer to verify that they are minimized

Counteracted by electrostatic control



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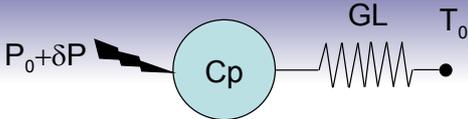
Thermal stability requirements (2)

- Mission performance requirements expressed as power spectrum density:
 - all thermal requirements are also expressed as power spectrum density.
- What is power spectral density function?
 - Power spectral density function (PSD) shows the strength of the variations (energy) as a function of frequency. In other words, it shows at which frequencies variations are strong and at which frequencies variations are weak.



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A simple thermal filter (1)



$$C_p \left[\frac{dT_1}{dt} \right] = GL \times (T_0 - T_1) + (P_0 + \delta P)$$

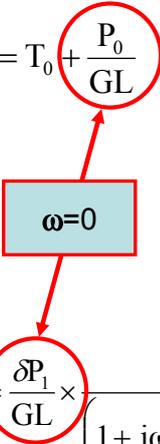
- Steady-state:** $\left[\frac{dT_1}{dt} \right] = 0$ and $\delta P = 0 \Rightarrow T_1 = T_0 + \frac{P_0}{GL}$
- Transient:** $C_p \left[\frac{\delta T_1}{dt} \right] + GL \times \delta T_1 = \delta P$
- Sinusoidal power variation:**

$$\delta P_1(t) = P_{10} \times e^{j\omega t}$$

$$\delta T_1(t) = T_{10} \times e^{j\omega t}$$

$$(C_p j\omega + GL) T_{10} \times e^{j\omega t} = P_{10} \times e^{j\omega t}$$

$$\Rightarrow \delta T_1(j\omega) = \frac{\delta P_1}{GL} \times \frac{1}{\left(1 + j\omega \times \frac{C_p}{GL} \right)}$$





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A simple thermal filter (2)

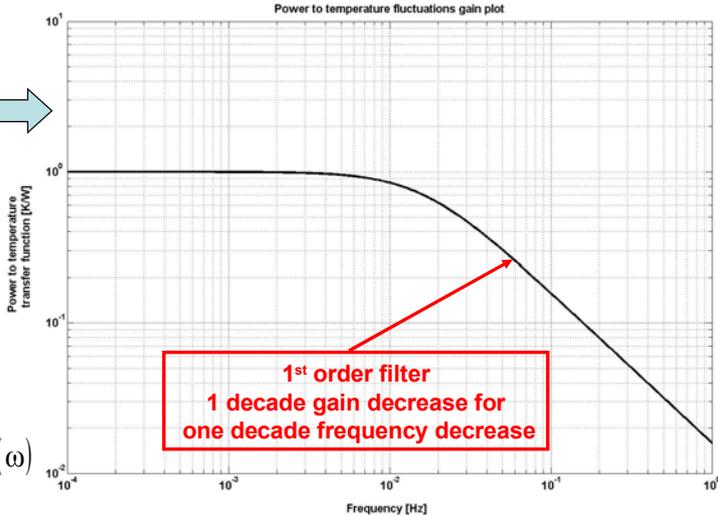
From the linearized thermal model, the thermal filter gain and phase plot can be derived. They express how a power or temperature boundary fluctuation is attenuated at another node by the thermal network.

For example for the previous system with $C_p=10$ and $GL = 1$.

Power spectrum density is related to transfer function:

$$\delta T(j\omega) = H(j\omega) \times \delta P(j\omega)$$

$$\Rightarrow \text{PSD}_{\delta T}(\omega) = |H(j\omega)|^2 \times \text{PSD}_{\delta P}(\omega)$$



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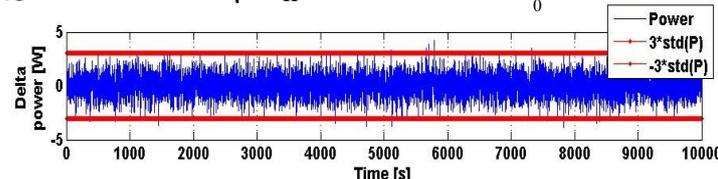
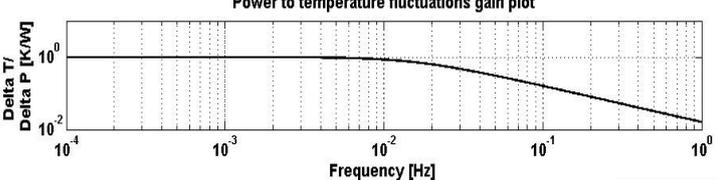
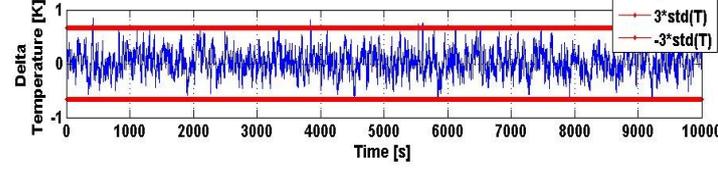

Time and Frequency domain analysis

Root Mean Square (and standard deviation) of input or output signal is related to the integral of the power spectrum density:

$$\delta T_{\text{RMS}} = \sqrt{\frac{\sum_{k=1}^n \delta T_k^2}{n}} \quad \text{and} \quad \delta T_{\text{RMS}}^2 = \int_0^{f_{\text{MAX}}} \text{PSD}_{\delta T}(\omega) d\omega$$

If power spectrum density is constant, standard deviation is directly related to the square root of the psd:

$$\delta T_{\text{RMS}} = \sqrt{\text{PSD}_{\delta T}} \times f_{\text{MAX}}$$

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Proposed ESATAN add-on

📖 ESATAN includes the non-linear thermal model:

$$C_{N \times N} \left[\frac{dT}{dt} \right]_{N \times 1} = K_{N \times N} \times [T]_{N \times 1} + F_{N \times N} \times [T^4]_{N \times 1} + B_{N \times q} \times P_{q \times 1}$$

Add-On 1:
Extraction of matrices

- ❑ C (size N×N) matrix of thermal capacitances of the nodes (diagonal).
- ❑ K (size N×N) matrix of thermal conductances between the nodes.
- ❑ F (size N×N) matrix of radiative couplings between the nodes.
- ❑ P (size N×q) matrix of input power dissipation (and external fluxes).

📖 Linearize the thermal model: $C \times \left[\frac{d\delta T}{dt} \right] = (K + F \times 4 \times T_c^3) \times \delta T + B \times \delta P$

📖 Derive the thermal filter transfer function:

$$\delta T(j\omega) = \{Cj\omega - (K + F \times 4 \times T_c^3)\}^{-1} B \times \delta P(j\omega)$$

Add-On 2:
Computation of gain & phase plots



LISA Pathfinder


Thermal disturbances

📖 During science phase:

- The spacecraft is constantly facing the sun at L1,
- No equipments are switched on or off.

➡ Major sources of thermal disturbances:

- FEEP power control units (3 PCU),
- On-board computer (1 OBC),
- Power Control and Distribution Unit (PCDU),
- Solar flux variation.

📖 FEEP PCU is the leading source of disturbances in the Lisapathfinder measurement bandwidth:

- The applied thermal disturbances can be derived of the control system commands (thrust is going up and down therefore PCU power dissipation goes up and down).



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Numerical performance assessment

- ❏ Alternative way to determine the thermal stability is to estimate numerically the power spectrum density:
 1. Define time series of inputs for FEOP PCU, OBC, PCDU and solar flux fluctuations.
 2. Perform a transient simulation with ESATAN detailed thermal model.
 3. Estimate numerically the power spectrum density of the outputs using fast-Fourier transform techniques.

- ❏ **Problems:**
 - Simulations needs to be very long without step transient in input power,
 - Numerical estimate of power spectrum density is intrinsically limited,
 - **Results are difficult to interpret.**



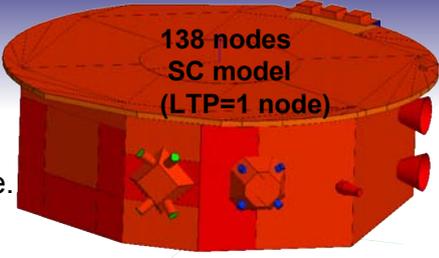
Both analytical and numerical performance needs to be done and compared to provide confidence in the results and enable interpretation.



LISA Pathfinder

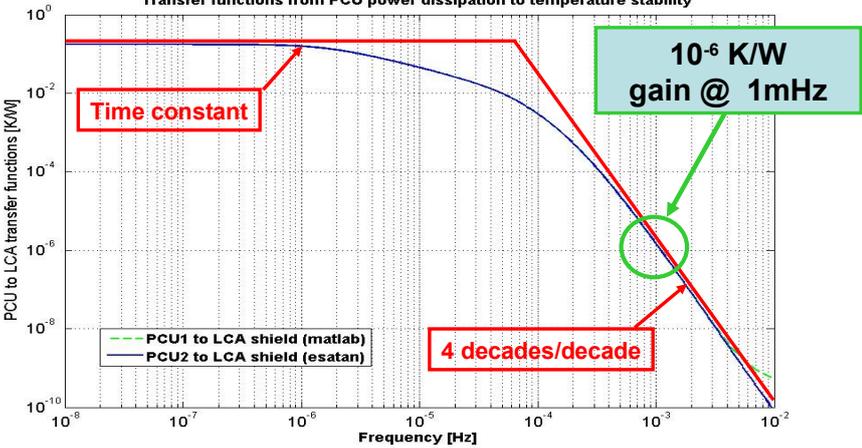

Results (1): analytical

- ❏ Performed with PDR reduced S/C model (CLA model without convection):
 1. Extracting matrices from ESATAN model,
 2. Using beta version of ESATAN new release.
 - Enable only assessment of SC/LCA I/F structure thermal stability.



138 nodes
SC model
(LTP=1 node)

Transfer functions from PCU power dissipation to temperature stability



PCU to LCA transfer functions [K/W]

Frequency [Hz]

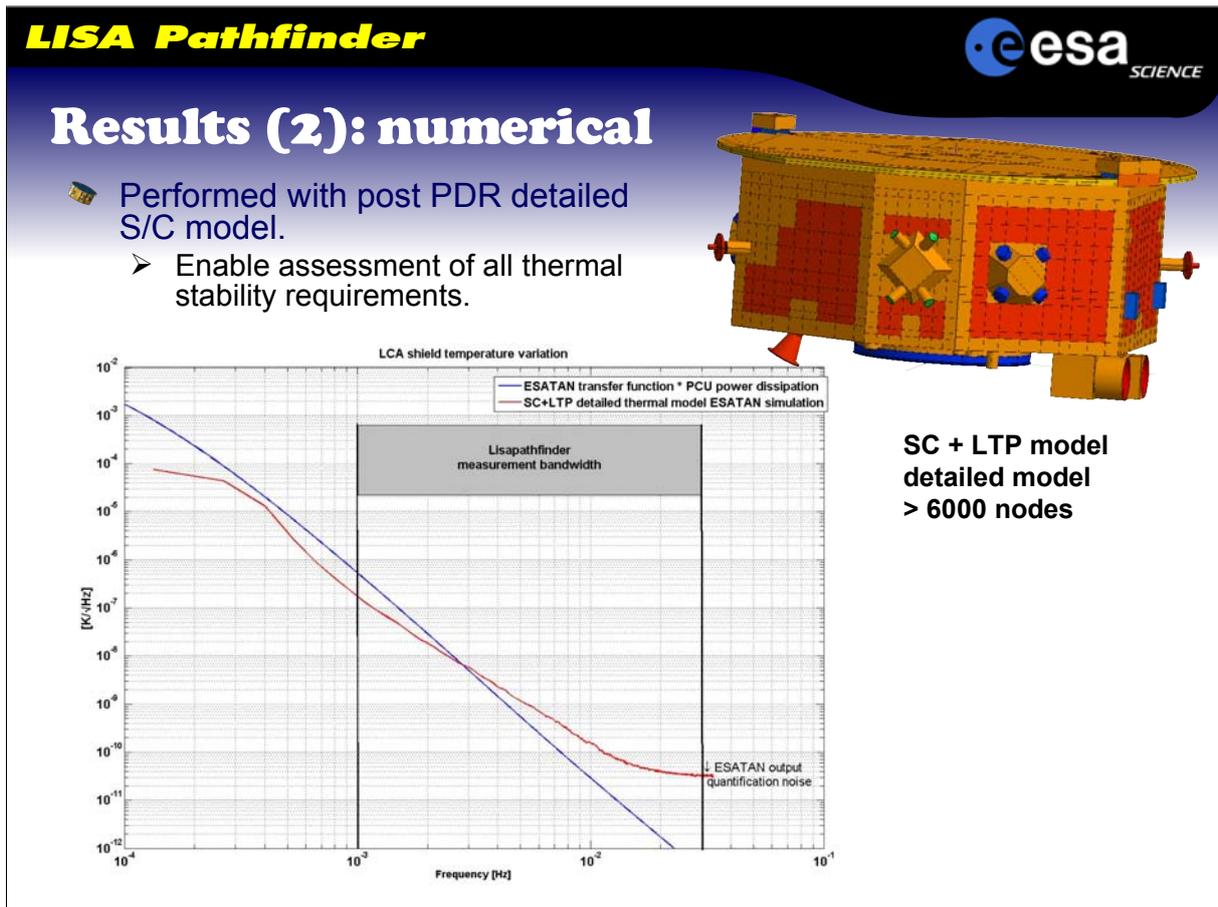
Time constant

10⁻⁶ K/W gain @ 1mHz

4 decades/decade

Legend:
--- PCU1 to LCA shield (matlab)
--- PCU2 to LCA shield (esatan)





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Follow-on

- Evaluate all thermal performance requirements with a reduced LTP+SC model with sufficient discretization for LTP.
- Extract the reduced (condensed) linear dynamic system of thermoelastic behaviour from Nastran and obtain analytically the transfer function between power dissipation and deformation.
- Insert thermoelastic model (and optical model?) into Lpf End To End performance simulator.



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