Appendix H

LISA Pathfinder thermal stability analysis

Denis Fertin
(ESA/ESTEC, The Netherlands)


esa
SCIENCE
LISA Pathfinder
LISA Pathfinder
thermal stability
analysis
D. Fertin
European Workshop Thermal
& ECLS Software
ESA-ESTEC, Noordwijk,
30-31 2t October 2007


LISA Pathfinder
esa
SCIENCE
Lpf thermal stability analysis

LISA Pathfinder

Table of contents

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,
  - FEEPs: microNewton force is difficult to measured.

LISA Pathfinder

Mission objective

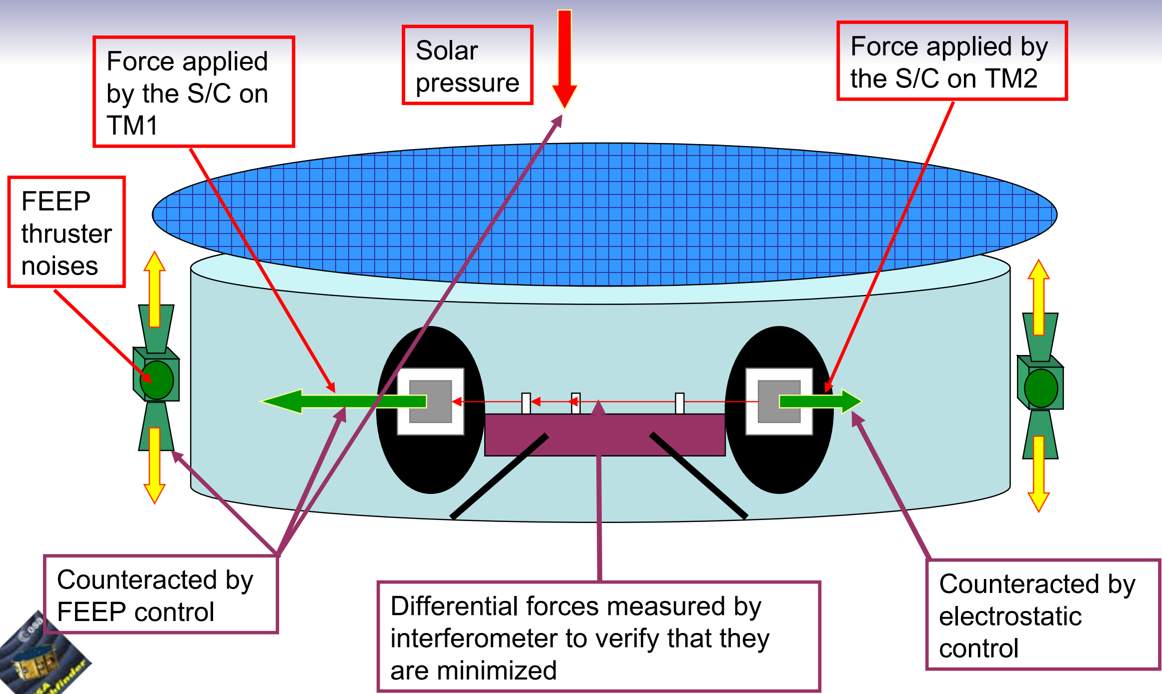
- Mission objective: verify that a test-mass can be put in pure gravitational free-fall within 3×10^{-14} m/s²/√Hz between 1 mHz and 30 mHz

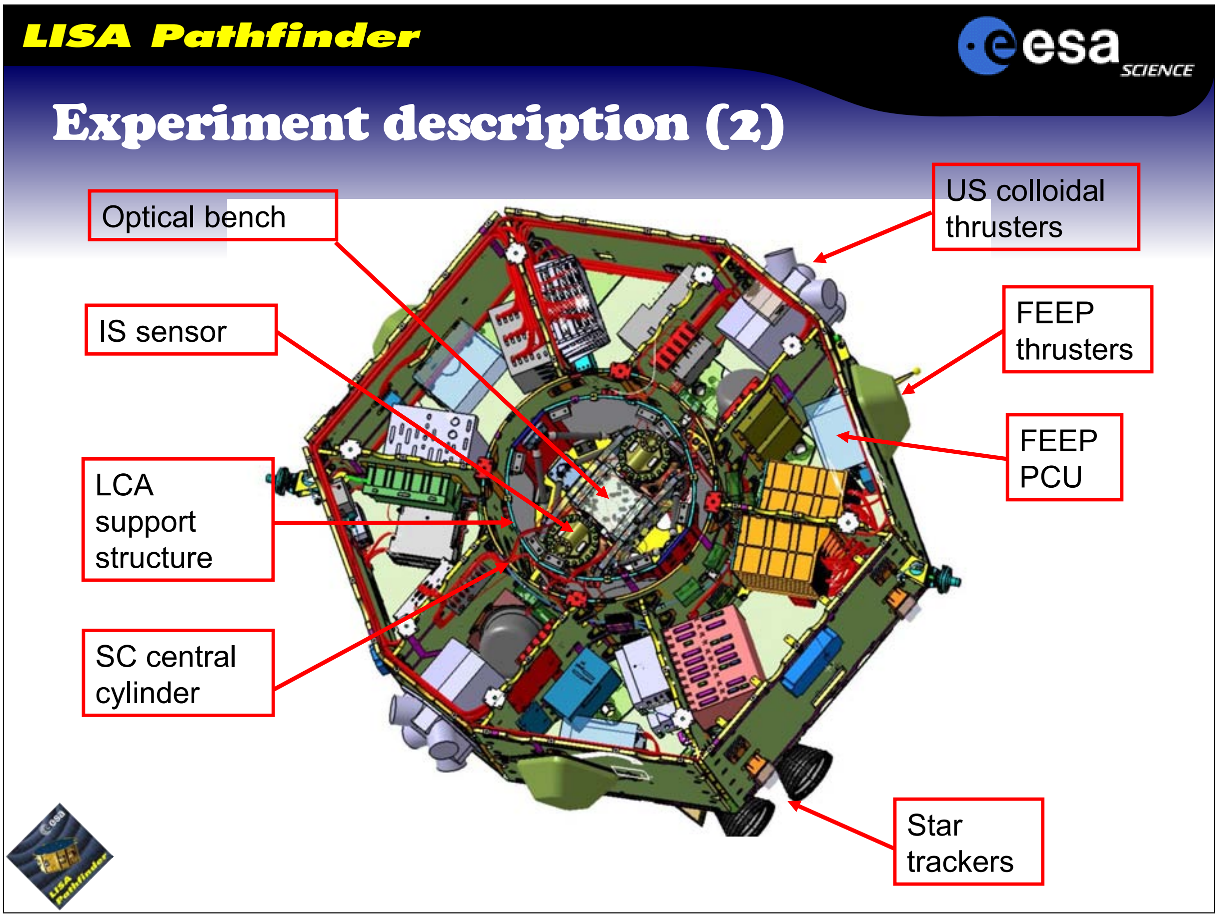
$$S_a^{1/2}(f) \le 3\times10^{-14}\left[1+\left(\frac{f}{3mHz}\right)^2\right] ms^{-2}/\sqrt{Hz}$$

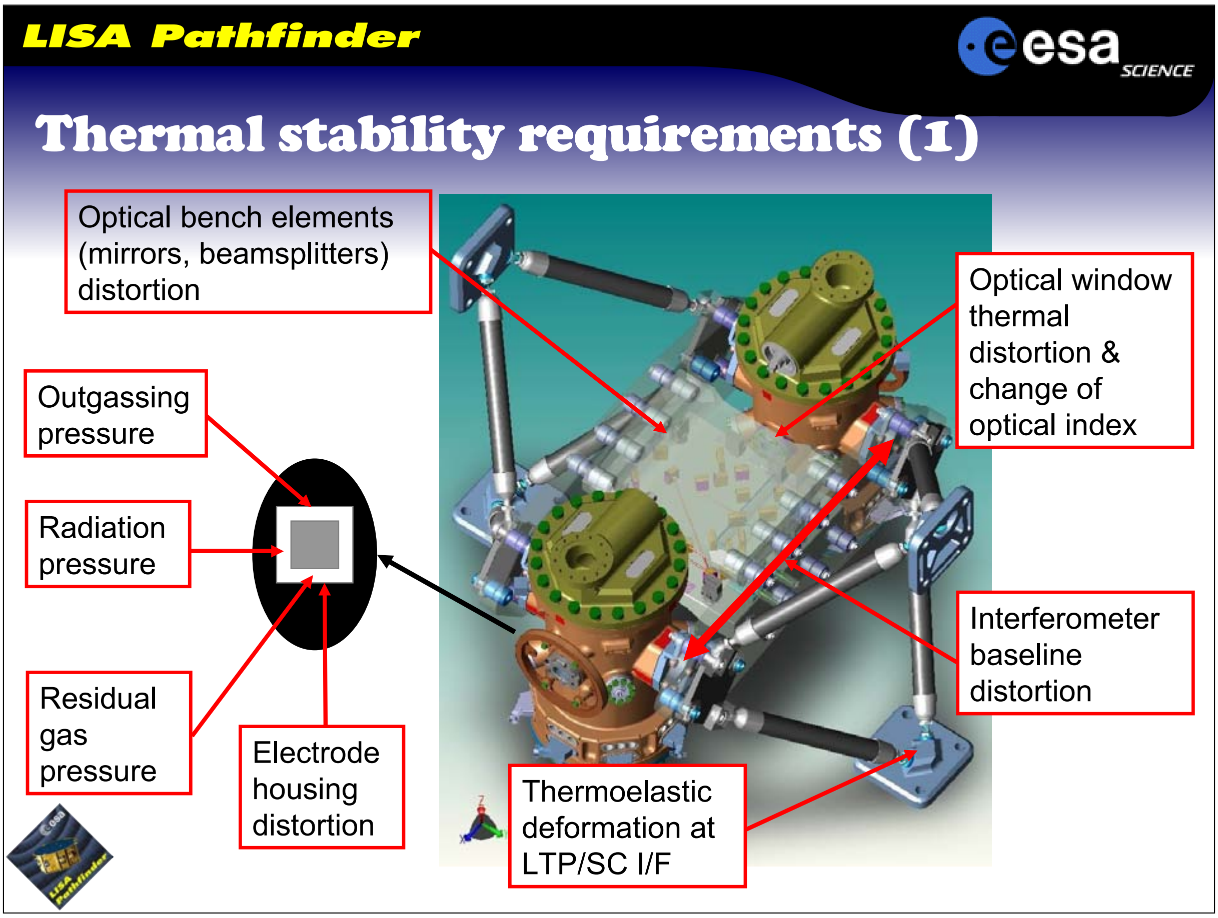
- Sources of force noise must be minimized:
  - ⇨No pressure force or mechanical contact force: “drag-free” mission.
  - ⇨No electromagnetic forces.
  - ⇨No self-gravity forces from SC and instrument itself.
- Differential acceleration measurement must be one order of magnitude better:
  - ⇨ Measurement by interferometry with accuracy better than 9 [pm/√Hz].

LISA Pathfinder

Experiment description (1)




LISA Pathfinder
esa SCIENCE
Experiment description (2)
Optical bench
IS sensor
LCA support structure
SC central cylinder
US colloidal thrusters
FEEP thrusters
FEEP PCU
Star trackers


LISA Pathfinder
esa SCIENCE
Thermal stability requirements (1)
Optical bench elements (mirrors, beamsplitters) distortion
Outgassing pressure
Radiation pressure
Residual gas pressure
Electrode housing distortion
Thermoelastic deformation at LTP/SC I/F
Optical window thermal distortion & change of optical index
Interferometer baseline distortion

LISA Pathfinder

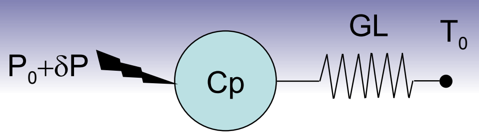
Thermal stability requirements (2)

- 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.

LISA Pathfinder

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: $\left[\frac{dT_1}{dt}\right] = 0 \text{ and } \delta P = 0 \Rightarrow T_1 = T_0 + \frac{P_0}{GL}$

- Transient: $C_p\left[\frac{\delta T_1}{dt}\right] + GL \times \delta T_1 = \delta P$

ω=0

- Sinusoidal power variation:

$$\delta P_1(t) = P_{10} \times e^{j\omega t}$$
$$\delta T_1(t) = T_{10} \times e^{j\omega t}$$
$$(C_p j\omega + GL) T_{10} \times e^{j\omega t} = P_{10} \times e^{j\omega t}$$

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

LISA Pathfinder

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.

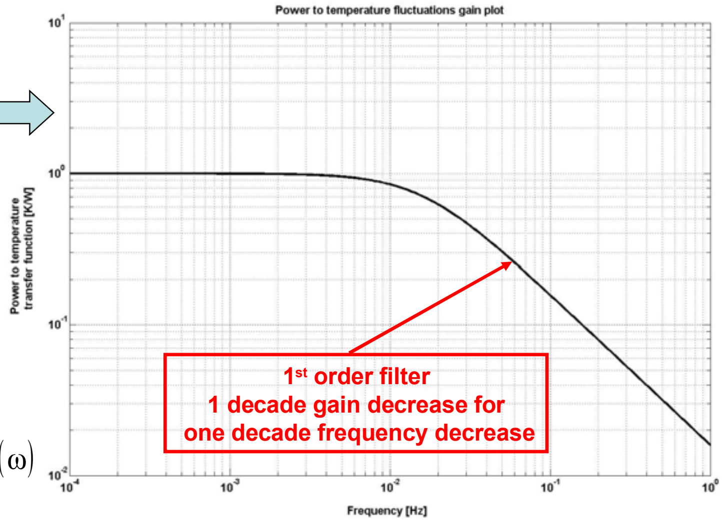
- For example for the previous system with Cp=10 and GL =1.

- Power spectrum density is related to transfer function:

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

$$\Rightarrow$$

$$PSD_{\delta T}(\omega) = |H(j\omega)|^2 \times PSD_{\delta P}(\omega)$$



LISA Pathfinder

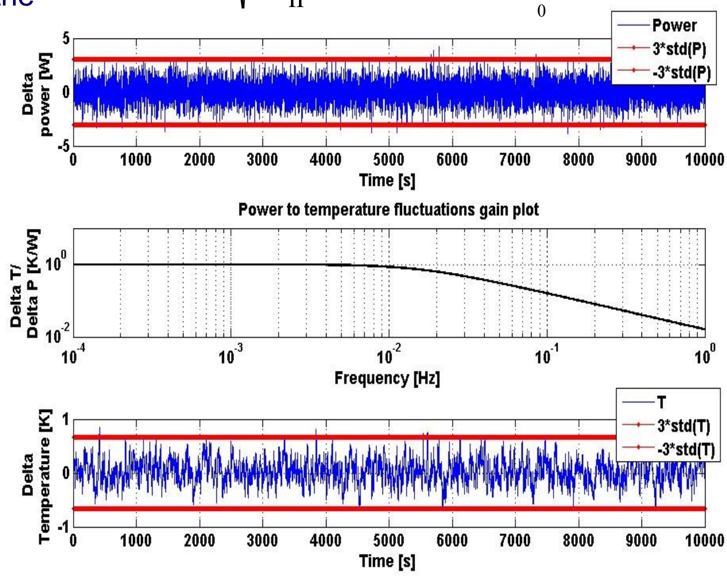
Time and Frequency domain analysis

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

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

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

$$\delta T_{RMS} = \sqrt{PSD_{\delta T}} \times f_{MAX}$$



LISA Pathfinder

Proposed ESATAN add-on

- ESATAN includes the non-linear thermal model:

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

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: $C\times\left[\frac{d\delta T}{dt}\right]=\left(K+F\times 4\times T_e^3\right)\times\delta T+B\times\delta P$

- Derive the thermal filter transfer function:

Add-On 2: Computation of gain & phase plots

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

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).

LISA Pathfinder esa SCIENCE

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 FEEP 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.

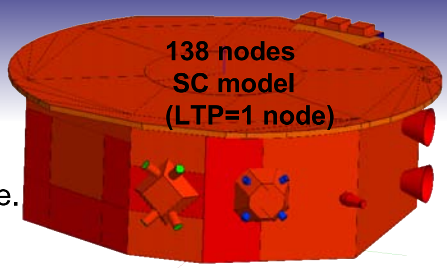
- Problems:
  - ➢ Simulations needs to be very long without step transient in input power,
  - ➢ Numerical estimate of power spectrum density is intrinsically limited,
  - ➢ Results are difficult to interpret.

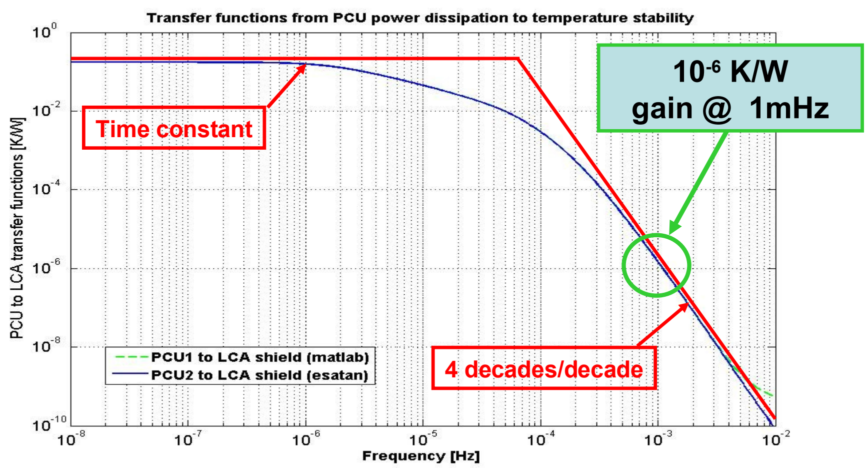
⇒ Both analytical and numerical performance needs to be done and compared to provide confidence in the results and enable interpretation.

LISA Pathfinder esa SCIENCE

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.

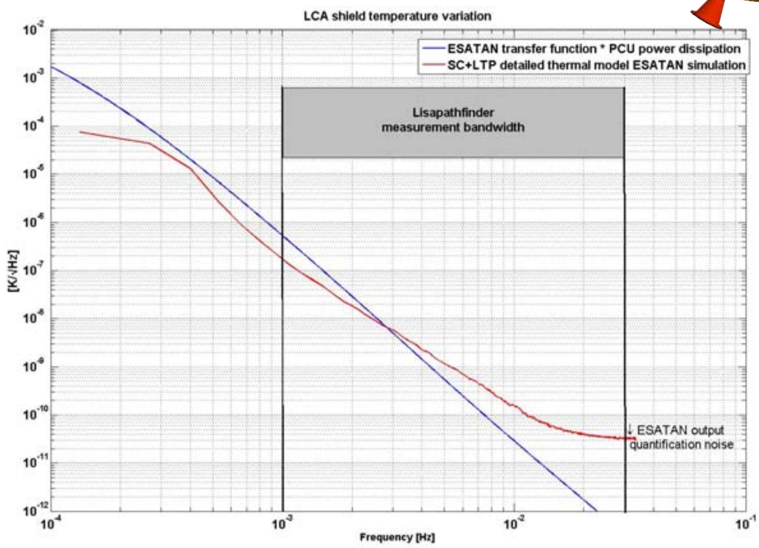


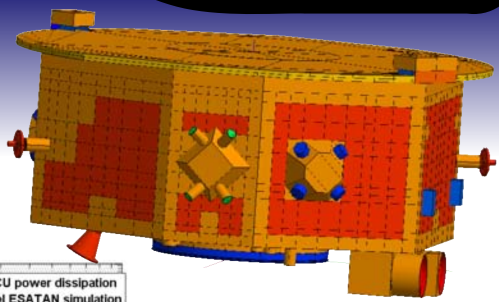


LISA Pathfinder

Results (2): numerical

- Performed with post PDR detailed S/C model.
  - Enable assessment of all thermal stability requirements.





SC + LTP model
detailed model
> 6000 nodes

LISA Pathfinder

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.

LISA Pathfinder

esa SCIENCE

References

- Use of Spectral Analysis in Thermal Stability Verification, ICES 2002 (2002-01-2373)

  G. Barbagallo and D. Stramaccioni, ESA-ESTEC
- LISA PathFinder Thermal Design and Micro-Disturbance Considerations

  S. Barraclough, A. Robson, K. Smith, Astrium UK, England.J.A. Romera Perez ESA ESTEC
- Thermal Analysis for Systems Perturbed in the Linear Domain Method development and Numerical Validation

  Marco Molina, Alberto Franzoso and Matteo Giacomazzo, Carlo Gavazzi Space SpA
- Probability, Random variables and Stochastic Processes

  Athanasios Papoulis, S. Unnikrishna Pillai, Mc Graw Hill