Highlights in thermal engineering at CGS:

1) Thermal Stability in the frequency domain

2) THERMAL DESKTOP® translation tools

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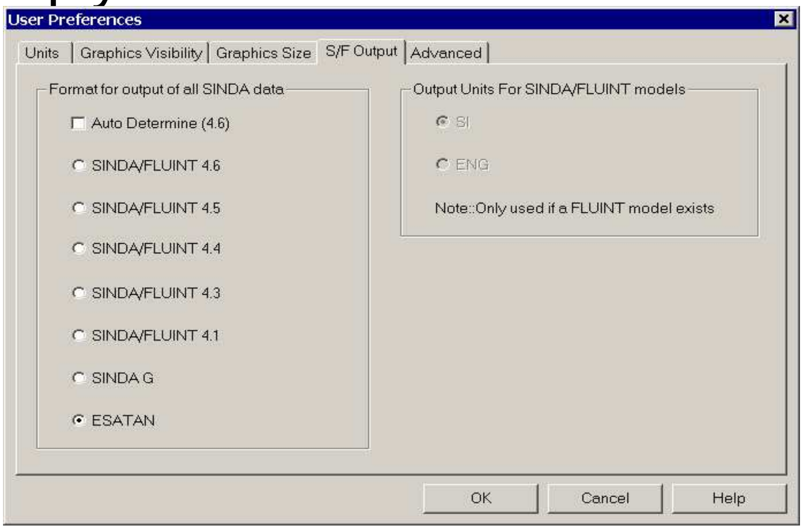
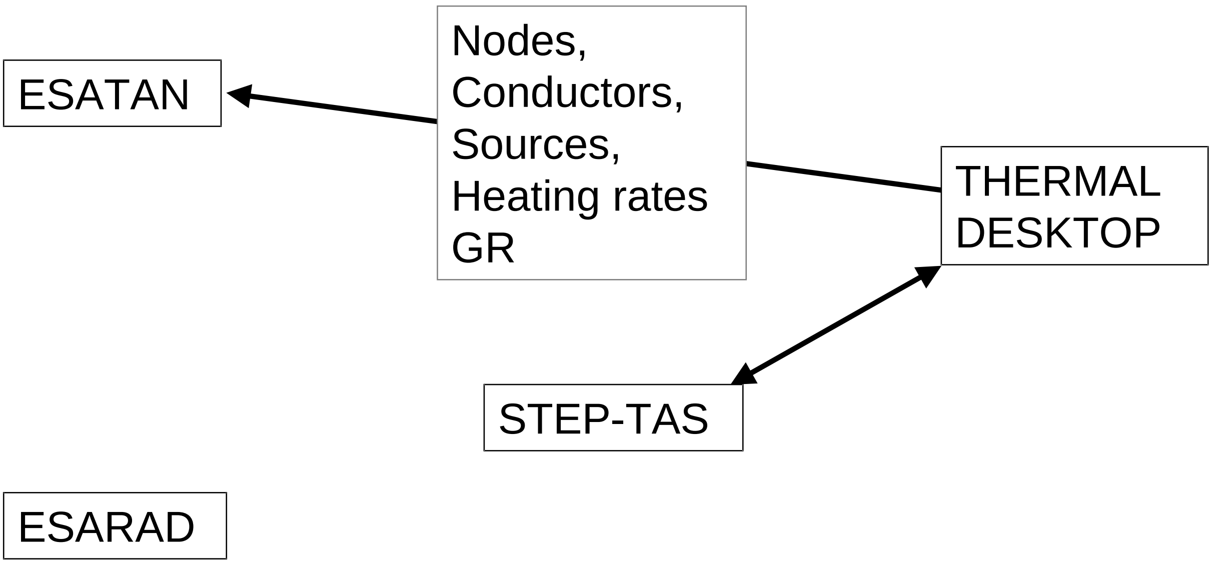
2) ESARAD (via STEP-TAS)/ESATAN translation from Thermal Desktop® 4.6

Enabling ESATAN Output

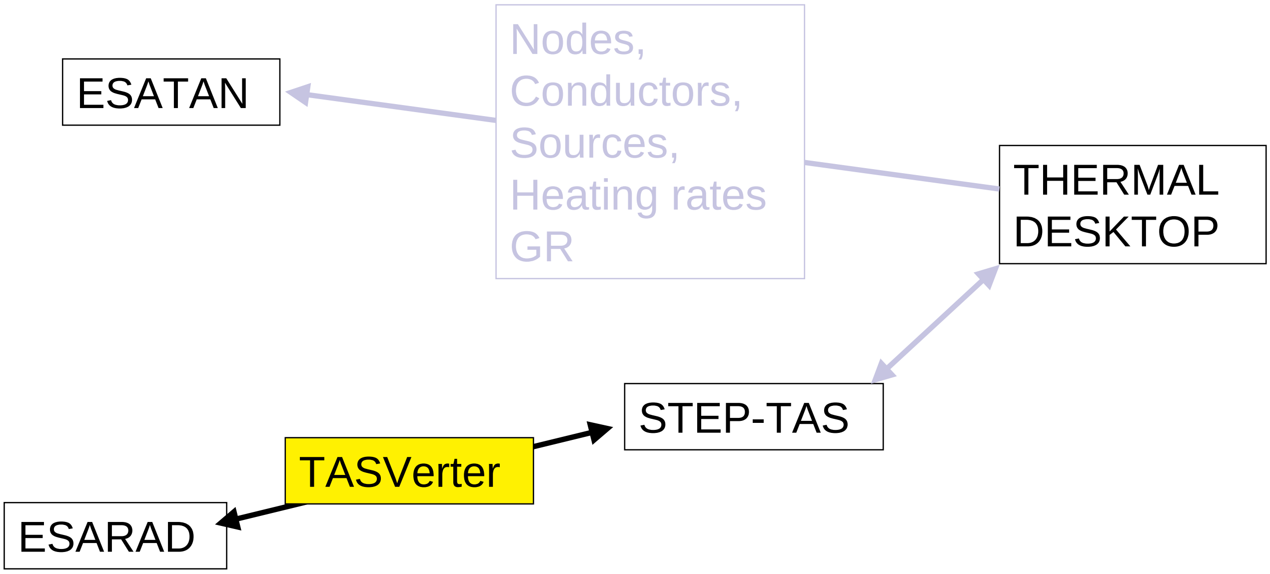
- Simply turn on the ESATAN button



Thermal Desktop® 4.6 features



How to fill the gap



Thermal Desktop ® Radiation Calculations

- Geometries built in Thermal Desktop are exported in STEP-TAS format
  - Current limitations
    - all geometry must be placed in a single submodel
- STEP-TAS can be imported into Thermal Desktop
- RADK and Heating Rate calculations are output in ESATAN format

Sample Output (RADKS)

```
C    SINDA/FLUINT data created with Thermal Desktop 4.6
C    Generated on Fri Oct 17 08:41:04 2003
C    Generated from database BASE-RcOptics.rck
C    Bij Cutoff factor:      0.0010000
C    Conductor units are: m^2
C
C   radk format:
C   node_1     node_2     Area*e*Bij $  Bij   Bji
C
        GR(      1,     999)=       0.50000;  $      1.0000
        GR(      2,     999)=       0.50000;  $      1.0000
        GR(      3,     999)=       0.50000;  $      1.0000
        GR(      4,     999)=       0.50000;  $      1.0000
C
C Summary data for nodes with Bij sums < 1.0000 or > 1.0000
C BijSum always contains Bij Self
C
C         node         area           rays    emiss      Bij     Bij     Bij   Weighted
C                                                        sum    self   inact   % Error
C         MAIN.1    0.50000     5000    1.0000   1.0000                     0.0
C         MAIN.2    0.50000     5000    1.0000   1.0000                     0.0
C         MAIN.3    0.50000     5000    1.0000   1.0000                     0.0
C         MAIN.4    0.50000     5000    1.0000   1.0000                     0.0
```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Sample Output (Heating Rates)

```
#
    GENMOR
#
    IF(NSOL.GT.1.0)THEN
       QS:1=INTCYC(TIMEM,ARTIME,ARSAMAIN1,1,5676.98D0,0.0D0)
       QS:2=INTCYC(TIMEM,ARTIME,ARSAMAIN2,1,5676.98D0,0.0D0)
       QS:3=INTCYC(TIMEM,ARTIME,ARSAMAIN3,1,5676.98D0,0.0D0)
       QS:4=INTCYC(TIMEM,ARTIME,ARSAMAIN4,1,5676.98D0,0.0D0)
    ELSE
       QS:1=193.242
       QS:2=192.891
       QS:3=191.811
       QS:4=192.912
    ENDIF
```

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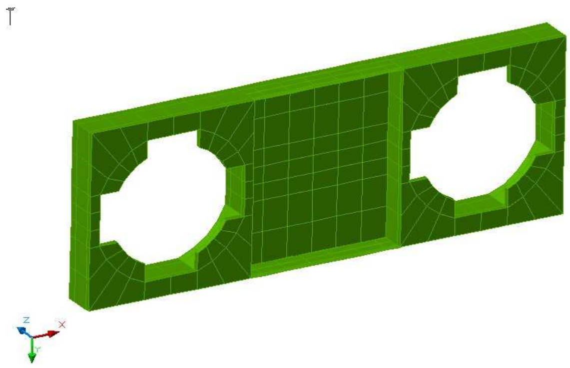
Sample Output (Heating Rates)

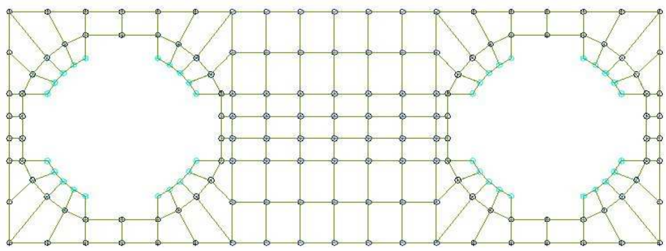
```
# Time Array
 ARTIME(17)=        0.0,4.730820e+002,9.461640e+002,1.419250e+003
          1.764227e+003,1.767633e+003,1.892330e+003,2.365410e+003
          2.838490e+003,3.311570e+003,3.784650e+003,3.909347e+003
          3.912753e+003,4.257740e+003,4.730820e+003,5.203900e+003
          5.676980e+003;
#
# solar albedo planetshine - MAIN.1 Area = 0.500000 Avg = 112.887535 31.783997 48.570499
 ARSAMAIN1(17)=4.880749e+002,4.282346e+002,2.696814e+002,5.125848e+001
            1.733135e+002,4.857050e+001,4.857050e+001,4.857050e+001
            4.857050e+001,4.857050e+001,4.857050e+001,4.857050e+001
            1.734149e+002,5.122900e+001,2.669101e+002,4.294877e+002
            4.880749e+002;
#
# solar albedo planetshine - MAIN.2 Area = 0.500000 Avg = 113.716866 31.922405 47.252102
 ARSAMAIN2(17)=4.929644e+002,4.238430e+002,2.660976e+002,4.994052e+001
            1.747323e+002,4.725210e+001,4.725210e+001,4.725210e+001
            4.725210e+001,4.725210e+001,4.725210e+001,4.725210e+001
            1.762022e+002,5.012827e+001,2.717307e+002,4.300657e+002
            4.929644e+002;

…. More Arrays…
```


ESATAN

- Node, Conductor, and Heatloads are output in ESATAN format





ESATAN Sample Output (from Thermal Desktop® 4.6)

```
#   SINDA Data generated with Thermal Desktop 4.6
#   Generated on Fri Oct 17 08:35:37 2003
#   TDUNITS,  Energy  =   J
#   TDUNITS,  Time    =   sec
#   TDUNITS,  Temp    =   K
#   TDUNITS,  Mass    =   kg
#   TDUNITS,  Length  =   m
#   TDUNITS,  Orbit   =   km
#   TDUNITS,  Pressure =  Pa
$NODES
 D1='MAIN #1', T=293.15, C=INTRP1(T1,AR2,1)*0.00025;
 D2='MAIN #2', T=293.15, C=INTRP1(T2,AR2,1)*0.00025;
 D3='MAIN #3', T=293.15, C=INTRP1(T3,AR2,1)*0.00025;
 D4='MAIN #4', T=293.15, C=INTRP1(T4,AR2,1)*0.00025;
 B999='MAIN #999', T=0.;
```

```
$ARRAYS
# DEFAULT.k
 AR1(10)=
   0., 1.
   100., 5.
   200., 7.
   300., 10.
   1000., 11.
# DEFAULT.rhocp
 AR2(8)=    0., 100.

   100., 105.
   200., 150.
   500., 175.
$CONDUCTORS
 GL(1,2)=INTRP1( (T1+T2)*.5, AR1,1)*0.001;
 GL(1,3)=INTRP1( (T1+T3)*.5, AR1,1)*0.001;
 GL(2,4)=INTRP1( (T2+T4)*.5, AR1,1)*0.001;
 GL(3,4)=INTRP1( (T3+T4)*.5, AR1,1)*0.001;
$VARIABLES1
```


Conclusions

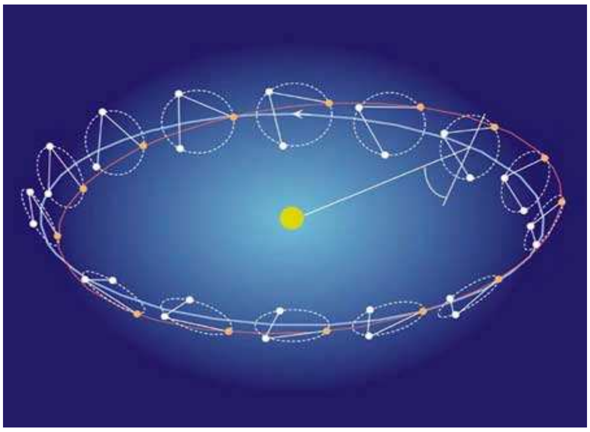
- Thermal Desktop 4.6 translates model+sources+heating rates into ESATAN
- Translation to STEP-TAS under testing
- Open point
  - How to ‘certify’ the compatibility with STEP-TAS?
- Important applications
  - ISS (NASA standard required)
  - Large Space Simulator (@ESTEC): GMM and TMM models now only available in ESATAN/ESARAD.

1) Thermal Stability in the frequency domain

Marco Molina, Federico Pamio,
Alberto Franzoso, Christian Vettore

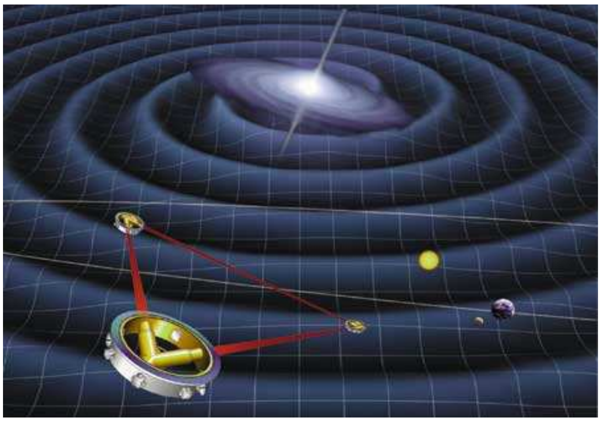
INTRODUCTION

- LISA (Light Interferometer Space Antenna)
- Constellation of 3 S/C, Heliocentric orbit, average distance $5*10^6$ km
- Scientific purpose: Gravitational Wave Detector
  - 3 couples of free-floating test masses to detect differential displacements (of the order of 10^{-12} m, 1/10 the atomic size!)
  - Laser beams bouncing between test masses, to build up a 2-3 arms interferometer



SCIENTIFIC GOAL

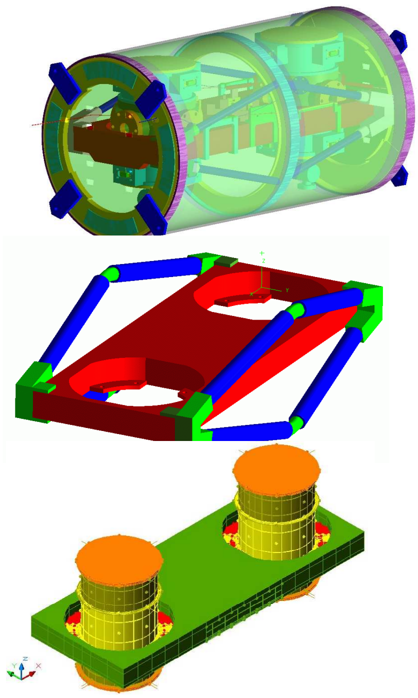
- LISA detects Gravitational Waves, Space-time distortions due to:
- Black Holes
- Supernovae
- Binary massive systems (e.g. Neutron Stars)



- A chance to test General Relativity predictions on the most energetic events in Universe

Detector Description (1)

- The scientific core of each satellite is contained in a Thermal Shield (TS), to lower the thermal noise
- Inside the TS an Optical Bench (OB) is located, hosting Laser beam optics
- A couple of Inertial Sensors (IS) lies on the OB. Each IS is a ultra-vacuum enclosure for the Test Mass, the Caging Mechanism (CM) and the Electrode Housing (EH), located around the TM.



Detector Description (2)

- Inside the Inertial Sensor:
- The Caging Mechanism
  - To block the Test mass during non-scientific phases
- The Electrode housing
  - To allow re-positioning
- The Test Mass
  - Free floating, the “mirror” at the interferometer arm ends

Thermal Analysis requirements

- Thermally driven changes of the distances on the OB will degrade the measurement accuracy if they differentially affect the two arms of the laser interferometer

- LISA detects GW within a defined frequency range => **temperature requirements given in the FREQUENCY domain**

Physical quantities DEFINITION

- TSD = Temperature Spectral Density = [K^2/Hz]

$$TSD \equiv \lim_{\Delta f \to 0} \frac{T^2}{\Delta f}$$

- TPSD = (Thermal) Power Spectral Density = [W^2/Hz]

$$TPSD \equiv \lim_{\Delta f \to 0} \frac{Q^2}{\Delta f}$$

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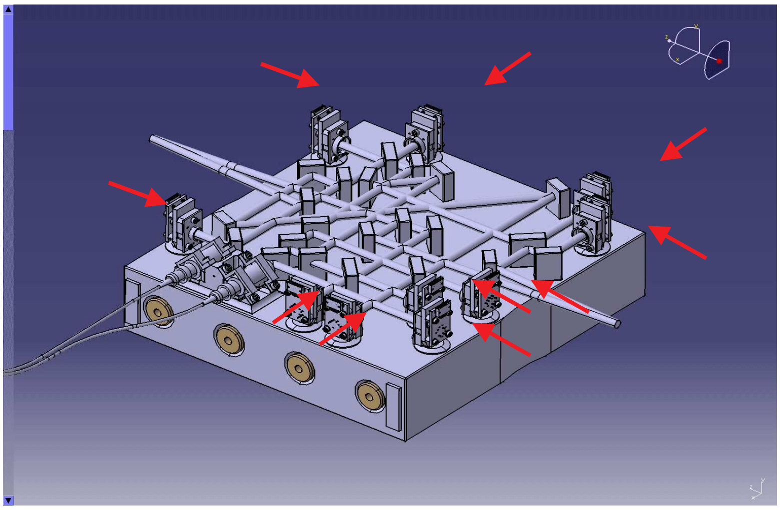
TPSD = (Thermal) Power Spectral Density Example

- Single Photo-diode (located on OB) av. dissipation : 1mW
- Overall av. dissipation power of 10mW throughout the OB



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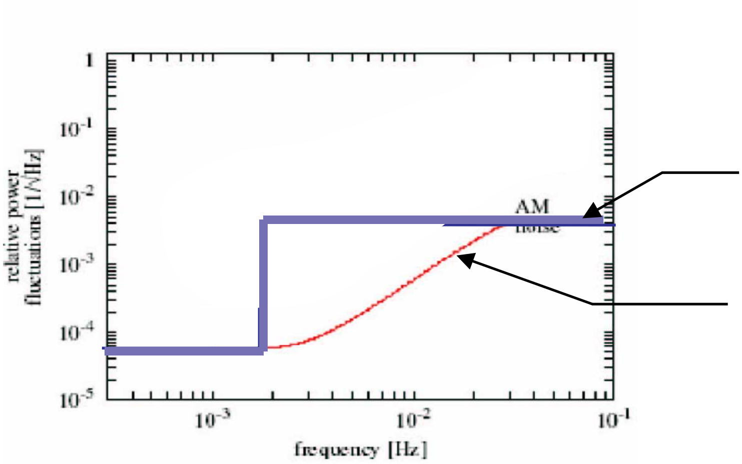
- Photo-diodes power fluctuation: two levels
  - DP/P = $4*10^{-3}$ [ ]/√Hz for frequencies ≥$1.8*10^{-3}$ Hz
  - DP/P = $6*10^{-5}$ [ ]/√Hz for frequencies <$1.8*10^{-3}$ Hz



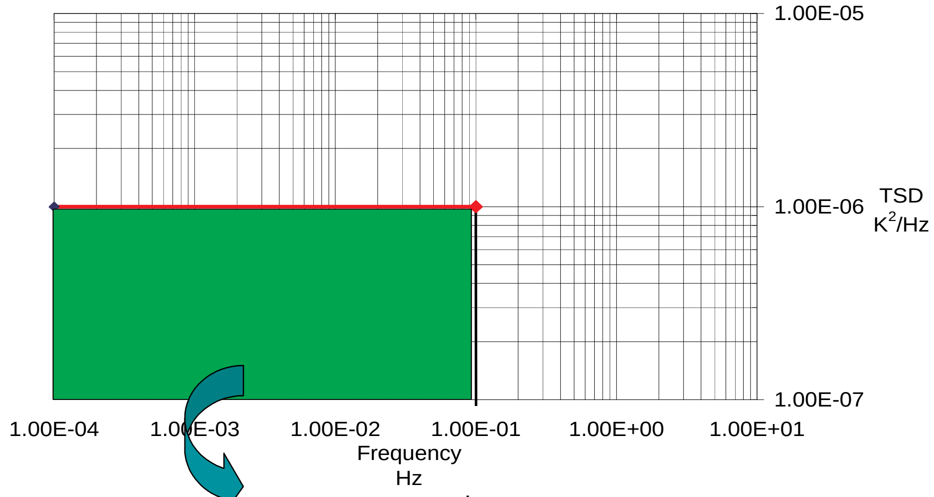
Once multiplied by the Power (W) and squared
this is really a (Thermal) “POWER” Spectral Density

Physical quantities DEFINITION

- T_{RMS} = Square root of the Area under the TSD vs. frequency curve
  - It is the root mean squared 1-sigma temperature fluctuation
    - For 68.3 % of the time, the temperature time history would have peaks no exceeding the 1-sigma temperature
    - For 99.7% of the time, the temperature time history would have peaks no exceeding the 3-sigma temperature

INPUT

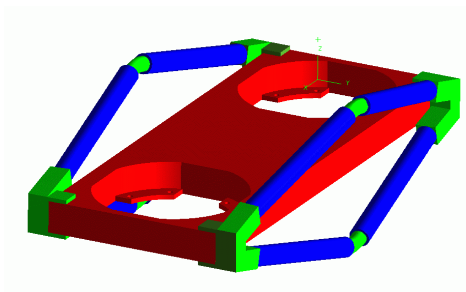
Temperature Spectral Density



$$T_{RMS}=\sqrt{A}=3.2\ E\text{-}5\ [K]$$

Optical Bench requirements

REQUIREMENTS	*REQ. VALUE*
OB temperature	20 ± 10°C
OB temperature stability	10^{-4} K/$\sqrt{\mathrm{Hz}}$
OB temperature gradient stability	10^{-4} K/$\sqrt{\mathrm{Hz}}$



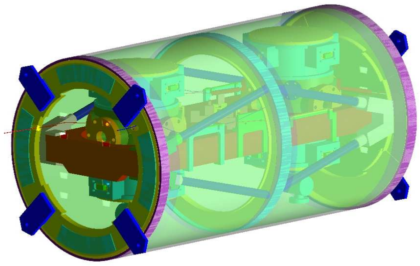
FREQUENCY RANGE:

$10^{-1} \div 10^{-4}$ Hz

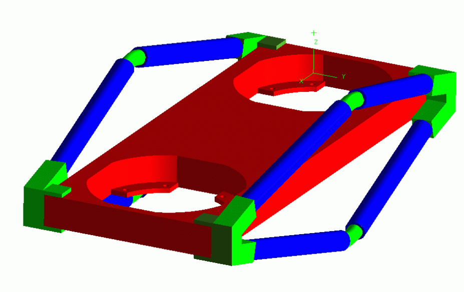
Boundary conditions for LTPA

(LISA Technology Package Architecture)

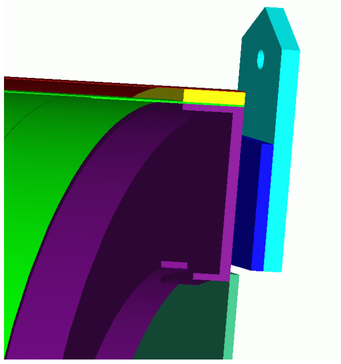
- As an input for the OB stability requirement study, temperature stability over the S/C interfaces of 10^{-3} K/√Hz was considered.
- First step: An aluminum thermal shield, made up of a cylinder with the internal and external surfaces goldized to damp the external temperature changes, was designed.



OB thermal insulation mechanical design



- The Optical bench assembly is mechanically fixed to the thermal shield by means of a system composed by pyroceram rods and titanium brackets
- An insulating washer has been foreseen under each titanium brackets attachment point; brackets are fixed to a C-shaped ring, and low emissivity coating was foreseen

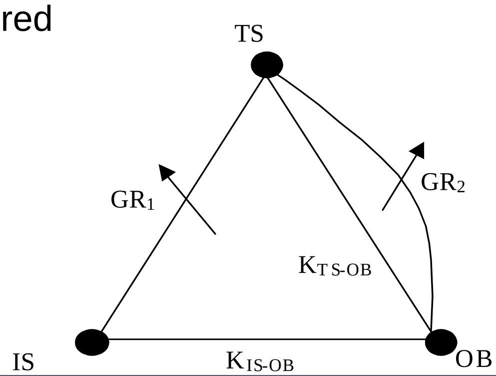


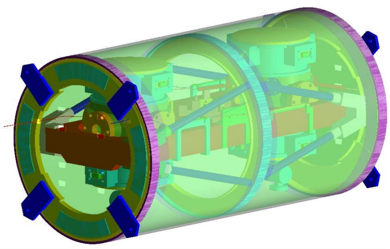
Thermal modelling steps

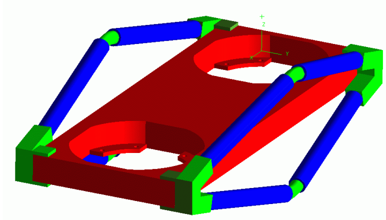
- PHASE 1: Simplified 3-nodes mathematical model
  - Test bed to get comfortable with frequency domain
  - Develop general metodology
- PHASE 2: Linearization of the 3-nodes system
  - Transfer function
  - Fast tuning
- PHASE 3: Detailed model
  - Refine and confirm preliminary results
  - Response to random boundary condition in the whole frequency range

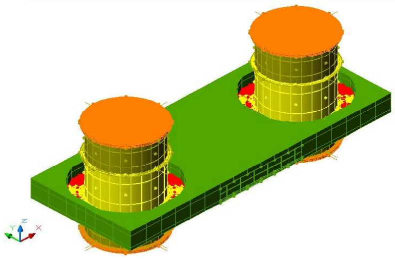
LTPA – Phase 1

- 3-nodes model: TS, IS, OB
- identify allowed conductive values provided by the OB structural supports, to satisfy the LTP thermal requirements
- provide a guideline to the structural design
- oscillating temperature was applied to the TS, no direct power introduction has been considered





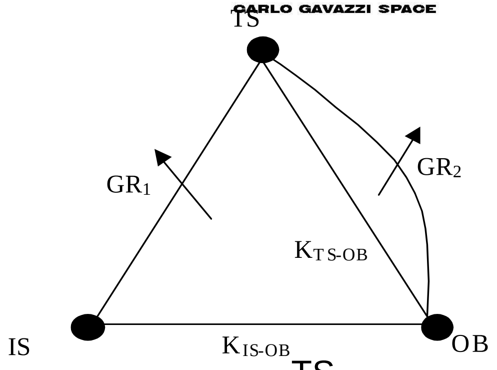




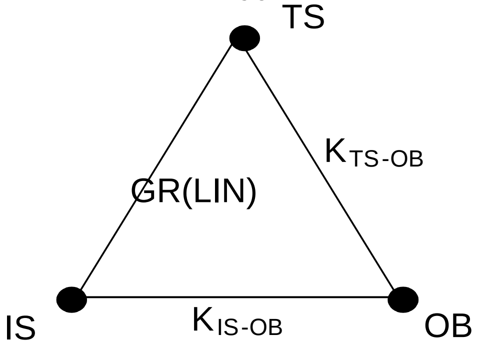
LTPA – Phase 2

Linearization of 3-nodes model

- Linearization => to use the analytic expression of the transfer function
- Linearized system:



$$\begin{cases} -k_{IS-OB}(\delta T_{OB}-\delta T_{IS}) - k_{TS-OB}(\delta T_{OB}-\delta T_{S}) = \\ \qquad = C_{OB}\,\partial \dfrac{\delta T_{OB}}{\partial t} \\ -k_{IS-OB}(\delta T_{IS}-\delta T_{OB}) - \sigma A \varepsilon \left(4T_{IS\,eq}^{3}\,\delta T_{IS} - 4T_{S\,eq}^{3}\,\delta T_{S}\right) = \\ \qquad = C_{IS}\,\partial \dfrac{\delta T_{IS}}{\partial t} \end{cases}$$



LTPA – Phase 2

- Linearization at equilibrium:
- TRANSFER FUNCTION

$$G_R = \frac{\Delta T_{IS}}{\Delta T_{TS}} = \frac{A_{IS} A_{TS} \varepsilon_{IS} \varepsilon_{TS} F_{IS-S}}{(1-\varepsilon_{IS}) A_{TS} \varepsilon_{TS} F_{IS-S} + \varepsilon_{IS} \varepsilon_{TS} A_{TS} + (1-\varepsilon_{TS}) A_{IS} \varepsilon_{IS} F_{IS-S}}$$

- Where: A_{IS}=IS external area
- A_{TS}=TS internal area
- ε_{IS}=IS emissivity
- ε_{TS}=TS emissivity
- F_{IS-TS}=IS-TS view factor

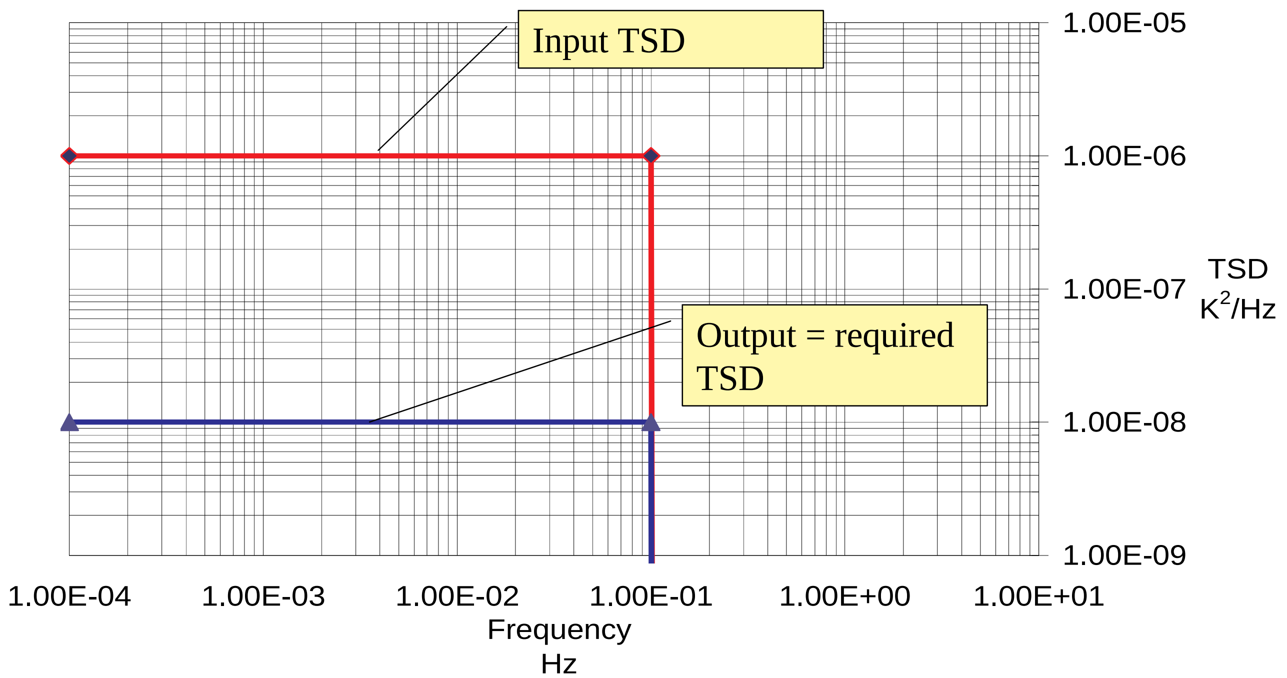
LTPA – Phase 2

- Requirement: attenuation of input temperature T_{TS} ($10^{-6}\ K^2/Hz$) on the output temperature T_{IS} ($10^{-8}\ K^2/Hz$), which is equivalent to require a transfer function of

$$G_{\max} = \frac{\Delta T_{IS}}{\Delta T_{TS}} = \frac{\sqrt{T_{RMS\ \ IS}}}{\sqrt{T_{RMS\ \ S}}} = \frac{10^{-4}\ K/\sqrt{Hz}}{10^{-3}\ K/\sqrt{Hz}} = 0.1$$

- Geometrical/optical/physical parameters can be adjusted accordingly

Temperature Spectral Density



LTPA – Phase 2 results

- 3-nodes model: Applied boundary + transfer function

$$T_S = T_{S\,eq} + \Delta T sin(\omega_{TS} t) = 293 + 0.293\sin(2\pi 10^{-4} t)$$

- Frequency of the sinusoid: 10^{-4} Hz (it is sufficient to verify the thermal requirement at the lower extreme of the relevant frequency band)

ATTENUATION FACTOR G		
	Radiative+linear	***Radiative only***
Optical bench	0,105398	0,09077
Inertial sensor top	0,105405	0,09091

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LTPA – Phase 2

- The frequency of the external perturbation was chosen to be the LOWEST in the frequency domain of interest
- The thermal models are LOW PASS FILTERS
- Once the requirements are met at the minimum frequency, then we are confident they will be respected at higher frequencies
- The three-nodes model system equation linearization led to an analytical transfer function explicitly dependent on the thermal parameters, allowing their quick tuning.

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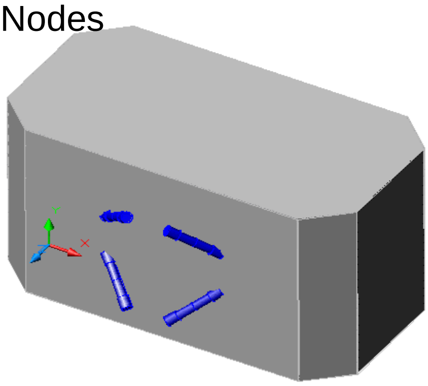
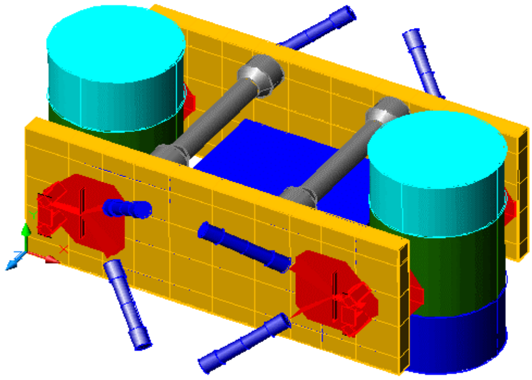
LTPA – Phase 3 Geometric model

MODEL FINAL DIMENSIONS:

- 51 Submodels
- 2300 Nodes





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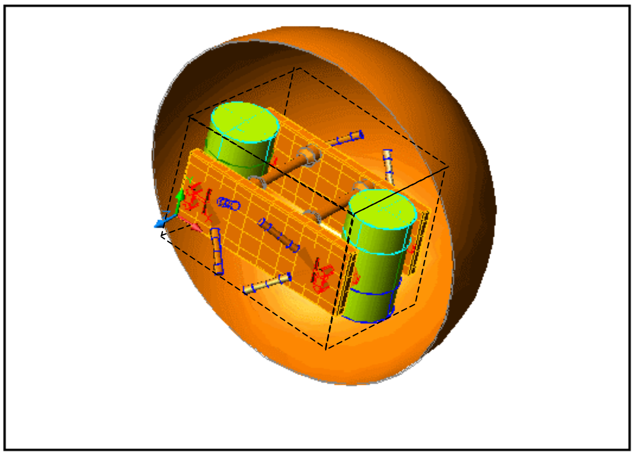
Interfaces definition (1/3)

RADIATIVE INTERFACES : LTP has been wrapped by a sphere, simulating external environment

- LTP radiative environment (sphere) static T : 20°C +/- 10°C
- LTP radiative environment (sphere)
  TSD: 10^{-6} K^2/Hz
- Sphere has been considered black painted



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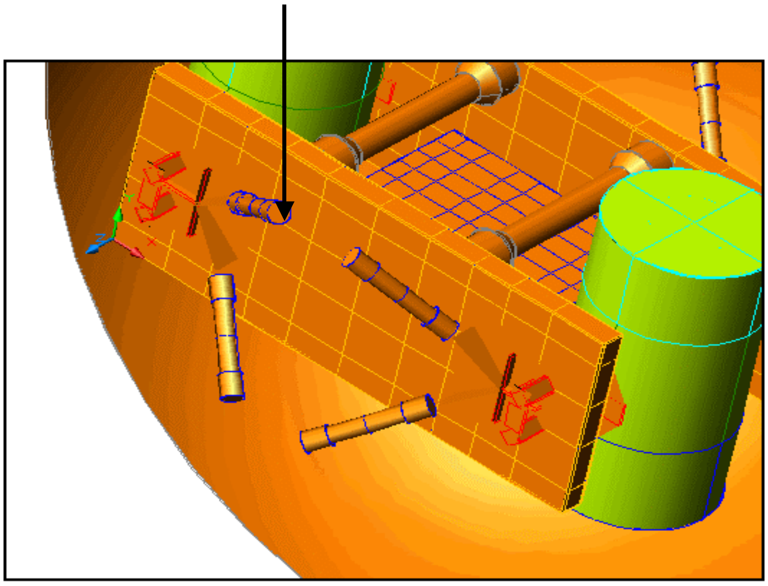
Interfaces definition (2/3)

CONDUCTIVE INTERFACES : Boundary temperatures have be assigned to the glass fiber struts end parts

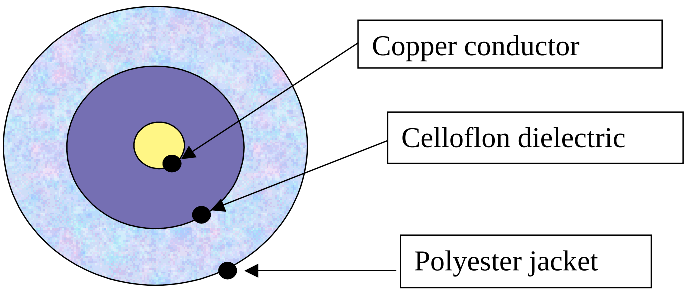


- LTP attachments points (struts ending) static T : 20°C +/- 10°C
- LTP attachments points (struts ending) T stability: TSD: 10^{-6} K^2/Hz

Interfaces definition (3/3)

CONDUCTIVE INTERFACES : Boundary temperature has been assigned also to the FEE and coupled to the Electrode Housing through coaxial cables as in IS analysis.

- FEE static T : 20°C +/- 10°C
- FEE T stability TSD: 10^{-6} K^2/Hz



No radiative coupling has been implemented
No other cables modelled

LET'S GENERATE a time history of a known TSD signal!

SINDA → Matlab interface

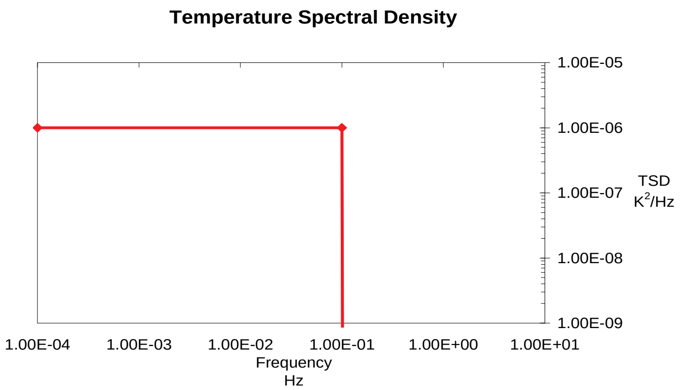
Spectral analysis

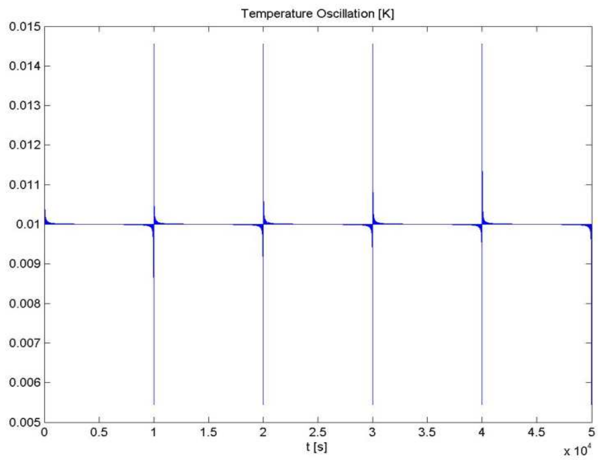
- Given a Temperature Spectral Density (TSD), the time dependent (periodic) signal is:

$$x(t) = \bar{x} + \frac{\sqrt{\mathrm{TSD}}}{\sqrt{\mathrm{P}/2}} \sum_{i=1}^{1000} \sin\left(2\pi \cdot i \cdot 10^{-4} t\right)$$

- where $\bar{x}$ is the mean value

Input signals (plots from MATLAB)

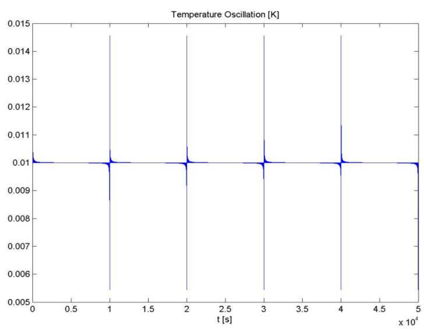




Is the plot below a RANDOM signal?

A real random signal cannot be plotted

– As soon as we plot it, it becomes deterministic!



Guidelines for the Analysis

- After the modelling phase, transient runs were made to study the temperature stability
- Sampling frequency : 1Hz (10 times higher than the higher extreme of the frequency band of interest, to avoid aliasing problems)
- Double precision calculations

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Analysis results

- The TSD of the output signals was calculated as follows:

$$X\left(f_m, P\right) = \Delta T \sum_{k=0}^{N-1} x(k) \cdot e^{-i 2\pi \frac{m}{N} k}$$

- Where Δt is the sampling time (1sec), m is the index of the discrete frequency values at which the Fourier Transform is calculated:

$$\mathrm{f_m} = \frac{\mathrm{m}}{\mathrm{N\Delta T}}$$

- The desired output signal TSD is given by:

$$TSD\left(f_m\right) = \frac{2}{P}\left|X\left(f_m, P\right)\right|^2$$

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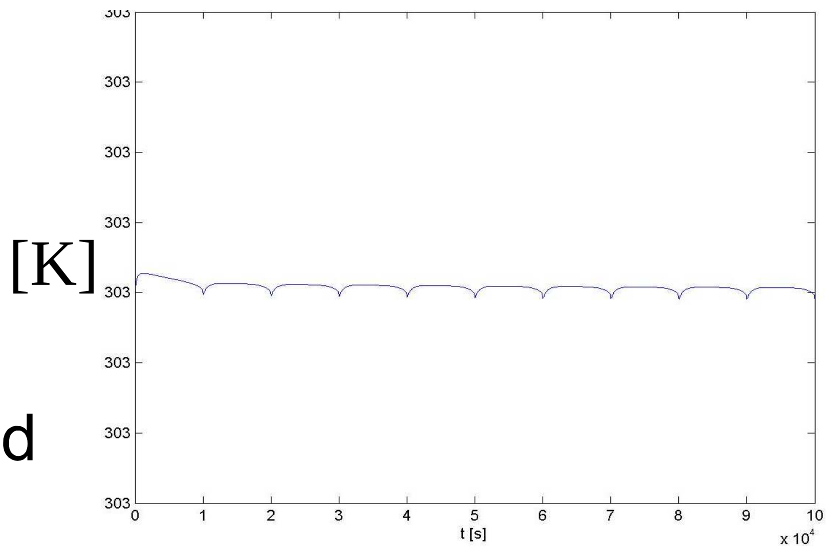
Example: Analysis results

Time transient
for a node on the
Electrode
Housing



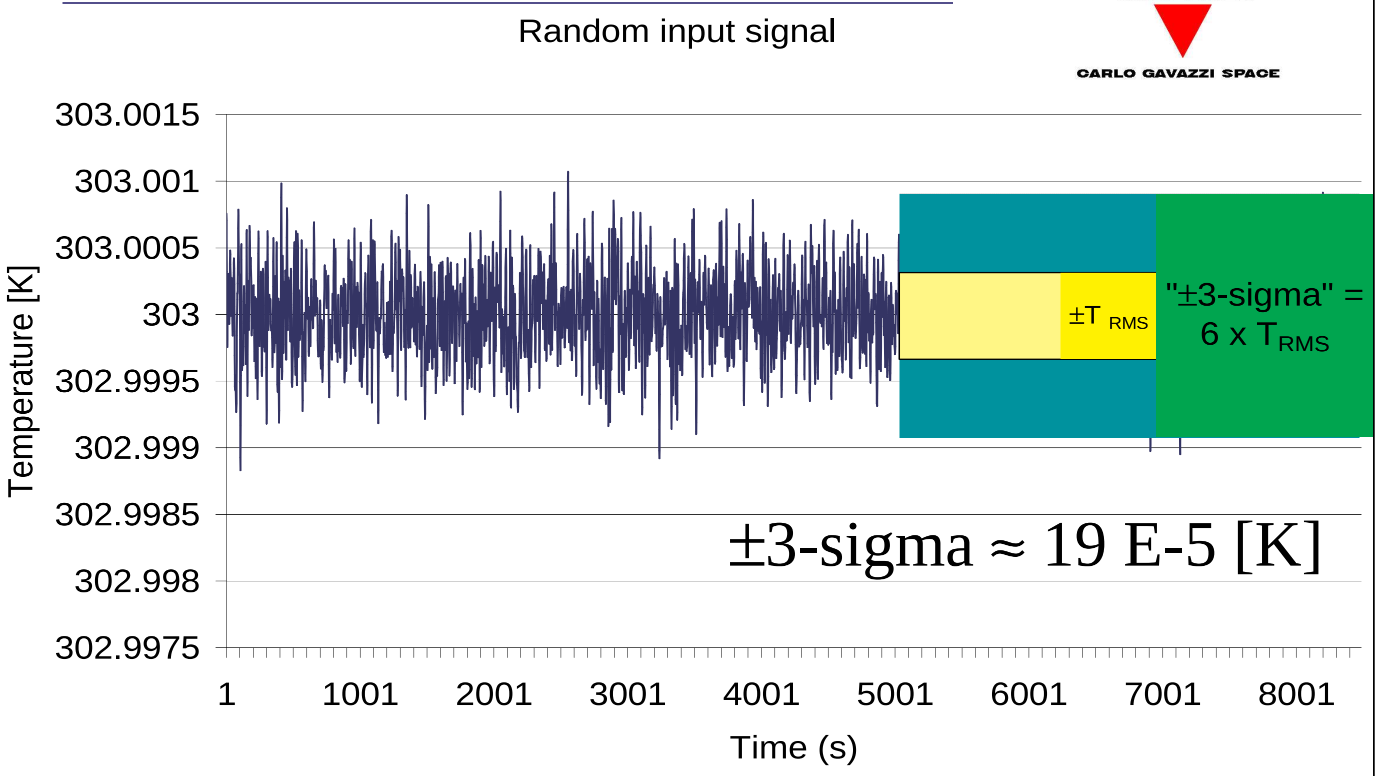
Thermal system damping effected

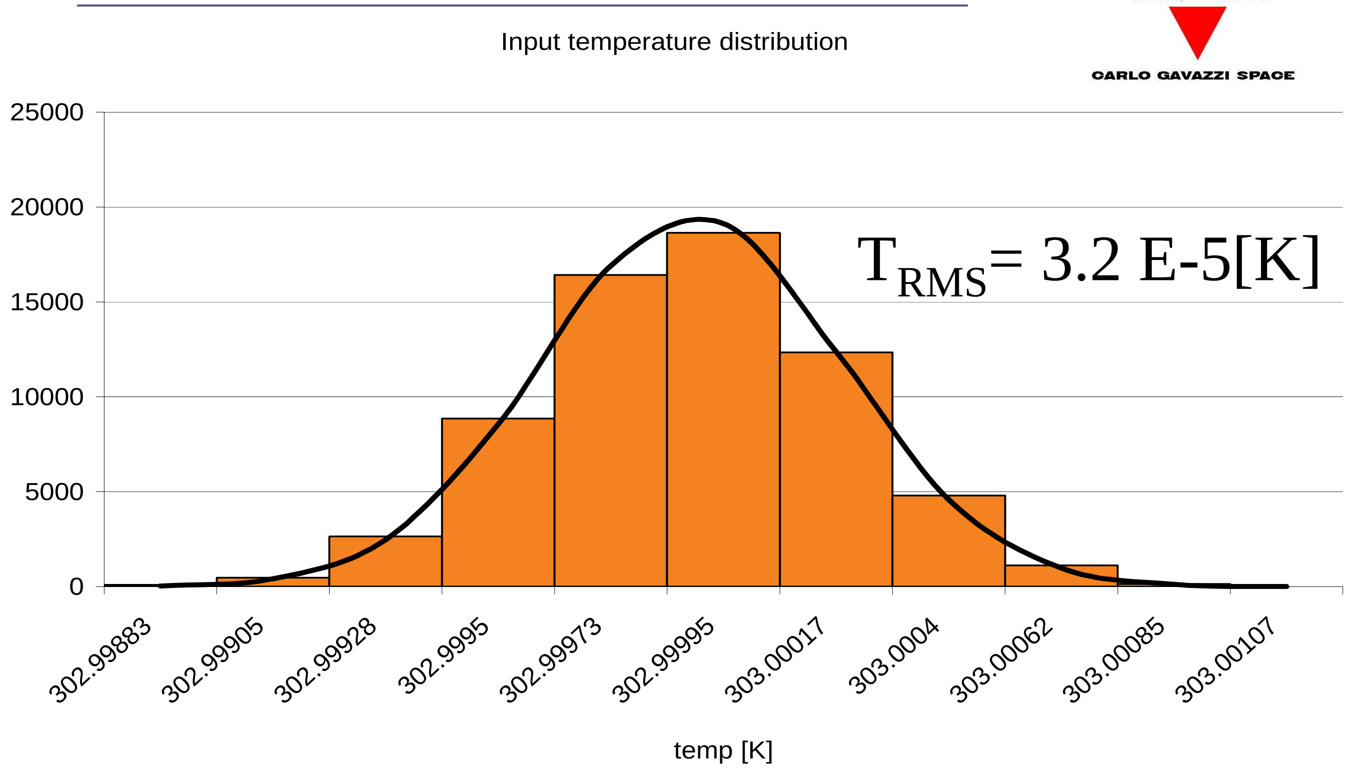
Let’s go random!

In order to generate a nonperiodic input signal (more similar to what we expect as ‘random’) the sinusoidal signals at different frequencies where summed with a RANDOM PHASE

$$\cancel{x(t) = \bar{x} + \frac{\sqrt{\mathrm{TSD}}}{\sqrt{\mathrm{P}/2}} \sum_{i=1}^{1000} \sin\left(2\pi \cdot i \cdot 10^{-4} t\right)}$$

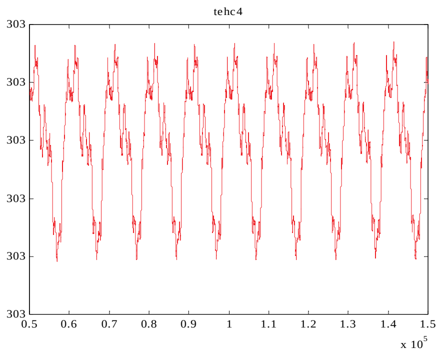
$$x(t) = \bar{x} + \frac{\sqrt{\mathrm{TSD}}}{\sqrt{\mathrm{P}/2}} \sum_{i=1}^{1000} \sin\left(2\pi \cdot i \cdot 10^{-4} t + \Delta\varphi_i\right)$$


Random input signal
303.0015
303.001
303.0005
303
302.9995
302.999
302.9985
302.998
302.9975
Temperature [K]
1
1001
2001
3001
4001
5001
6001
7001
8001
Time (s)
±T RMS
"±3-sigma" = 6 x T RMS
±3-sigma ≈ 19 E-5 [K]

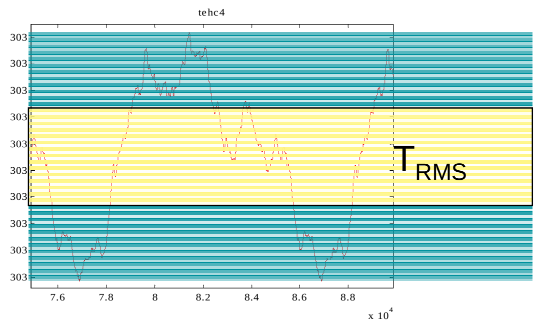

Input temperature distribution
25000
20000
15000
10000
5000
0
302.99883
302.99905
302.99928
302.9995
302.99973
302.99995
303.00017
303.0004
303.00062
303.00085
303.00107
temp [K]
TRMS= 3.2 E-5[K]

OUTPUT SIGNAL RESULTS

- Temperature profile of a internal node
- Damping effect of the thermal system



1.4E-5 [K]
(6 T_{RMS})



$$T_{RMS} = 2.3\ E\text{-}6\ [K]$$

RANDOM SIGNAL RESULTS

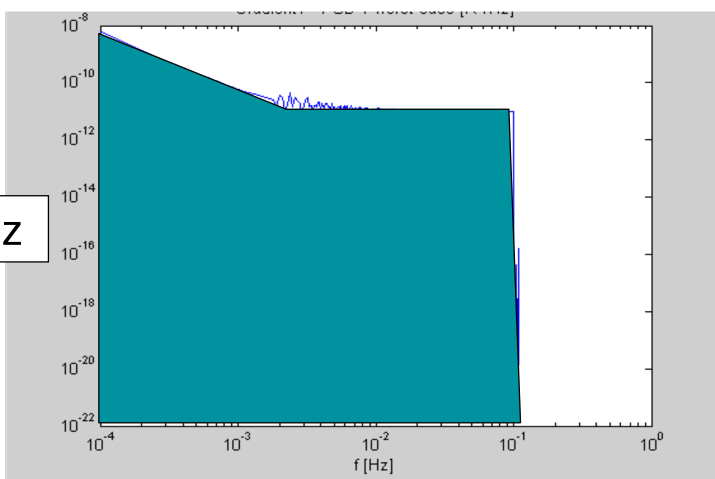
The TSD of the output signal has been computed:

TEMPERATURE STABILITY REQUIREMENT

TSD < $1*10^{-8} K^2/Hz$

•Maximum TSD : $6.6*10^{-9}$ [K^2/Hz]

K^2/Hz

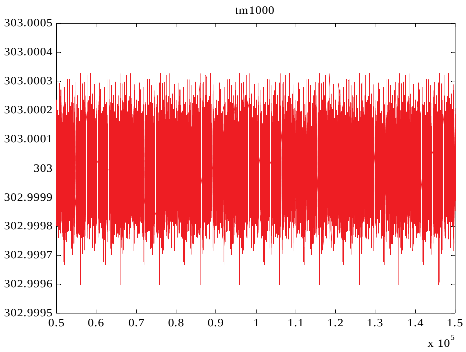


T_{RMS} = 2.3 E-6 [K]

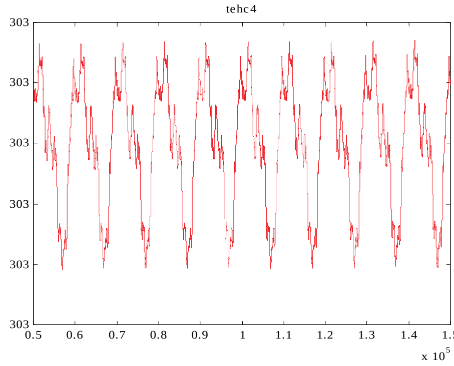
•Requirement met

COMMENTS

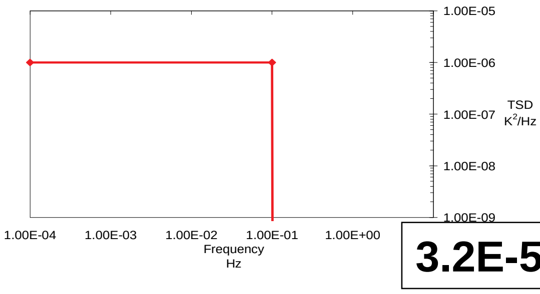
- The system act as a low-pass filter:



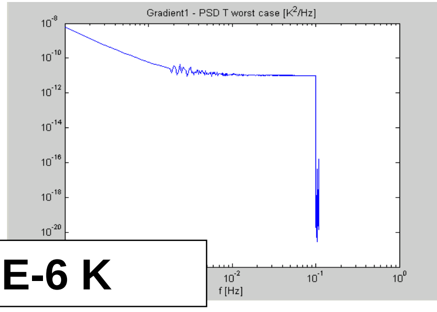
T(t)
[K]



IN → **OUT**



TSD
[K^2/Hz]



3.2E-5 K **T_{RMS}** **2.3 E-6 K**

Conclusions

- Disturbing signals were created as time dependent temperature series, starting from their TPSD or TSD
- The output signals TSD was calculated and compared with max temperature fluctuations, for a cross check
- Comparison with analytical results shows good correlation
- The system meets stability requirements in terms of thermal stability and thermal gradient stability
- TSD concept must be handled with care!