LISA Pathfinder Inertial Sensor Head Thermal Correlation in Frequency Domain

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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.

During the qualification thermal test campaign, some dedicated tests have been performed with the aim of correlating the existing ISH thermal model, in order to improve its prediction capability. Following the analysis approach, also the test and the correlation have been conducted in the frequency domain.

During the correlation test, two different sets of heaters have been individually operated with a 1mHz frequency profile (i.e. 500s ON 500s OFF) and the thermal response of different points on the hardware has been measured and compared with test prediction.

In the paper a brief description of the test setup and the test results is given: since the measured oscillations were in some cases extremely small (less than 1 mK, only slighter larger than the measurement noise,) a series of post-processing techniques (e.g. filtering, detrending) have been adopted to clean up the available data.

The test results show a very good agreement with the performed test prediction, and – where the deviations were larger - the model has been tuned following the outcomes of the test.

The frequency-domain thermal testing has turned out to be an interesting feature, capable of allowing very accurate testing, and allowing the measurement of very small perturbations. This approach has strong potential, especially for the testing of highly insulated elements, characterized by extremely high time transients.

Nomenclature

A = amplitude of oscillation
dt = time step
f = frequency

I. Introduction

LISA Pathfinder is the precursor of the ESA/NASA mission LISA and will test in flight – with a satellite orbiting in Earth-Sun L2 Lagragian point – the concept of low-frequency gravitational wave detection: it will put two

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test masses in a near-perfect gravitational free-fall, and it will control and measure their motion with high accuracy. The two masses are enclosed inside two Inertial Sensor Heads (ISH) that have been built and integrated at CGS. A laser beam is bounced in between the two test masses, separated by an optical bench, allowing an ultra-precise relative position measurement.

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 [2,3].

This paper describes the thermal vacuum (TVAC) tests performed on the ISH qualification model, in the frame of its qualification campaign. During the TVAC, several different input excitations at a known frequency have been injected in the system; The analysis in the frequency domain of the temperature acquisitions all along the ISH allowed a thermal model correlation. The feasibility of a non-standard approach, suitable in the case of a highly-insulated element with slow time transients, has been demonstrated.

II. Hardware description

The ISH is shown in the pictures below: the ISH is composed by a titanium enclosure (VE) that contains the mechanisms that allow the caging of the mass during launch (CVM) and its repositioning during on orbit operations (GPRM). At ISH center a support structure (IIS Internal Interface Structure) holds the Electrode Housing (EH that allows the measurement of the mass position) and a 46mm gold-platinum cube (Test Mass). The VE is equipped with flanges for cabling connection and one Optical Window (OW) that faces directly to the Test Mass.

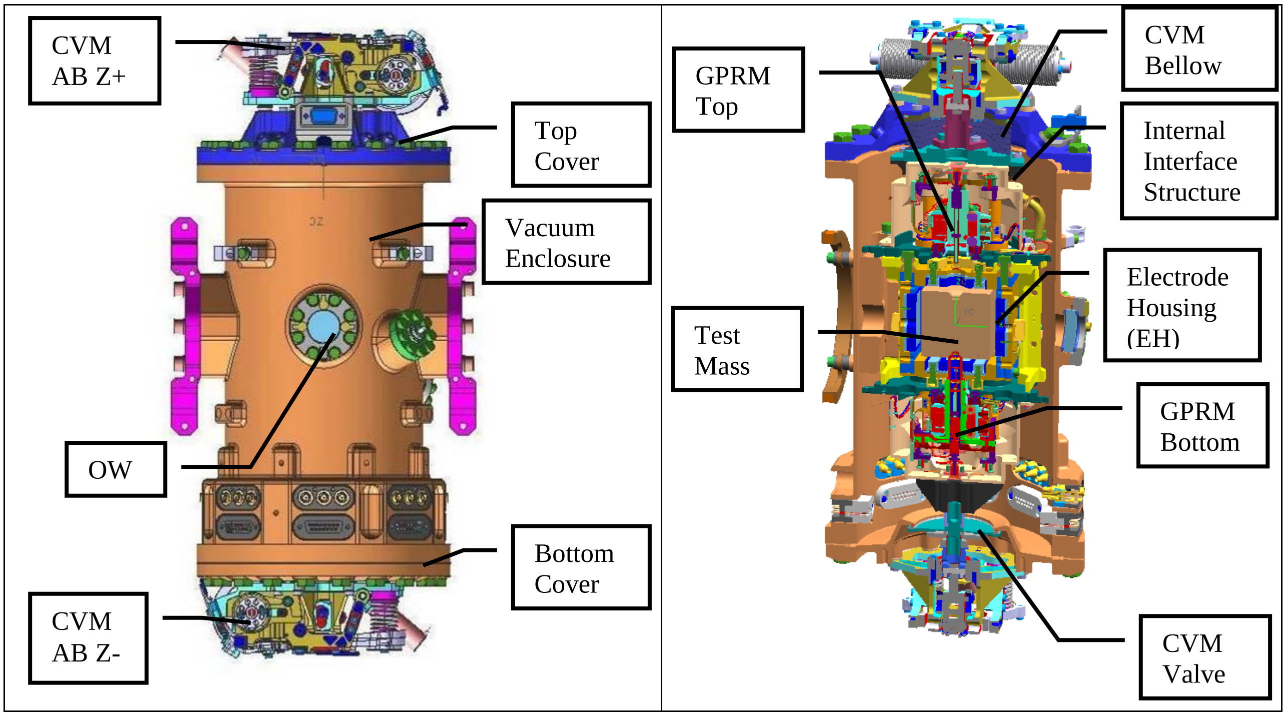

Figure 1. LISA Inertial Sensor Head: *assembly (left) and section (right) – in the tested QM the Electrode Housing EH was a dummy only partially representative of the flight configuration*

III. Test setup and test description

The tests have been performed in a VGSE (Vacuum Ground Support Equipment) thermal vacuum chamber. The Qualification Model (QM) of the ISH has been installed inside VGSE Test Chamber. It is thermally insulated with ceramic washers and hard mounted using fixation points on the bottom side. The test was made of two main sessions: firstly a standard qualification thermal cycling profile has been followed between minimum and maximum qualification temperatures; afterwards, a session devoted to the test correlation in the frequency domain has been performed.

A total of 15 thermal sensors have been installed on the unit:

- 2 sensors on the EH dummy (flight sensors)
- 2 sensors installed on the GPRM flanges (1 top and 1 bottom) (test sensors)
- 2 sensors installed on the GPRM dust cover (1 top and 1 bottom) (test sensors)
- 6 sensors on the external of the VE (test sensors)
    - 1 on the bottom cover and 1 on the bottom side of the VE (to characterize the I/F between the bottom cover and the VE body)
    - 1 on the top cover and 1 on the top side of the VE (to characterize the I/F between the bottom cover and the VE body)
    - 1 additional on the bottom cover on +X side
    - 1 on the VE body
- 3 sensors on the Optical Window (OW) (flight sensors)

NTC Thermal sensors were installed on the OW and EH and have been read with a dedicated electronic designed to assure a low noise read between +7 and +32 °C: these sensors shall be read also during the in space operative life and for this reason have a separate and dedicated acquisition system. All other installed thermal sensors were a combination of PT100 and PT1000 sensors read by a standard data acquisition system.

Additionally 2 sets of test heaters have been installed on the QM:

- On the OW (2 heaters for a total of 2W)
- On the top and bottom cover (4 heaters for a total of 8W)

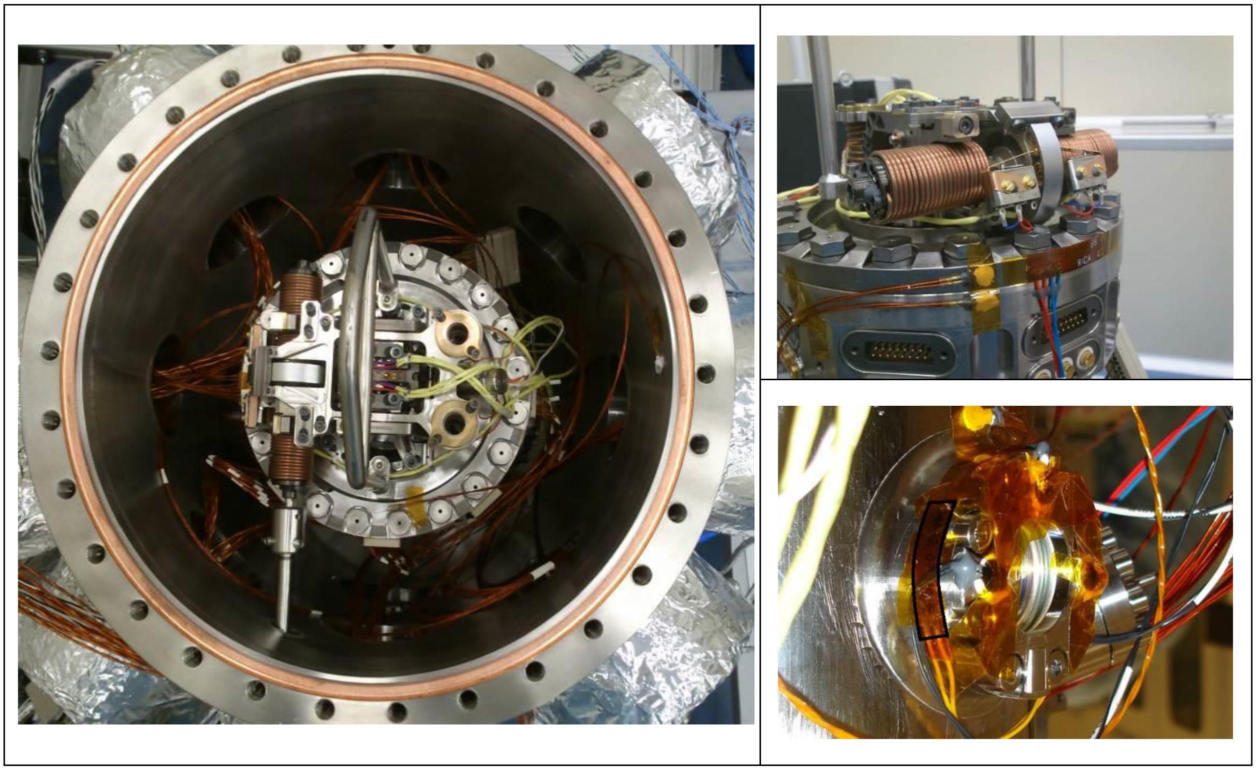

Figure 2. ISH Test Setup. *On the left the ISH installed into the test chamber (VGSE); on the right the installed heaters on the ISH bottom (top) and OW (kapton has been removed before the test)*

For the correlation test, the two sets of heaters have been individually activated with a 1mHz profile (500s ON / 500s OFF):

- TEST #1 - The heaters on the OW have been activated with 1mHz profile for a time period of about 6 hours.
- TEST #2 - The heaters on the top and bottom cover have been activated with 1mHz profile for a time period of about 5 hours.

IV. Test Data

The collected data, especially from the standard CGS acquisition system used for all sensors but OW and EH, either shows a significant noise that in some is comparable to the signal expected to be measured, or present still large transients effects, which completely mask the signal underneath.

For this reason the collected data has been post processed in order to have a cleaner signal to be compared with the model data. In fact, one of the strongest key points of the thermal correlation in the frequency domain is constituted by the fact that it is not necessary to wait for completely stabilized data: a proper data processing allows to extract the signal at the appropriate frequencies, also during the long-term transients.

The software Octave has been used to manipulate both test and model data.

A. Data detrending

Data has been detrended in order to highlight the oscillation, removing the rising trend of the recorded signal with a 3rd grade polynomial.

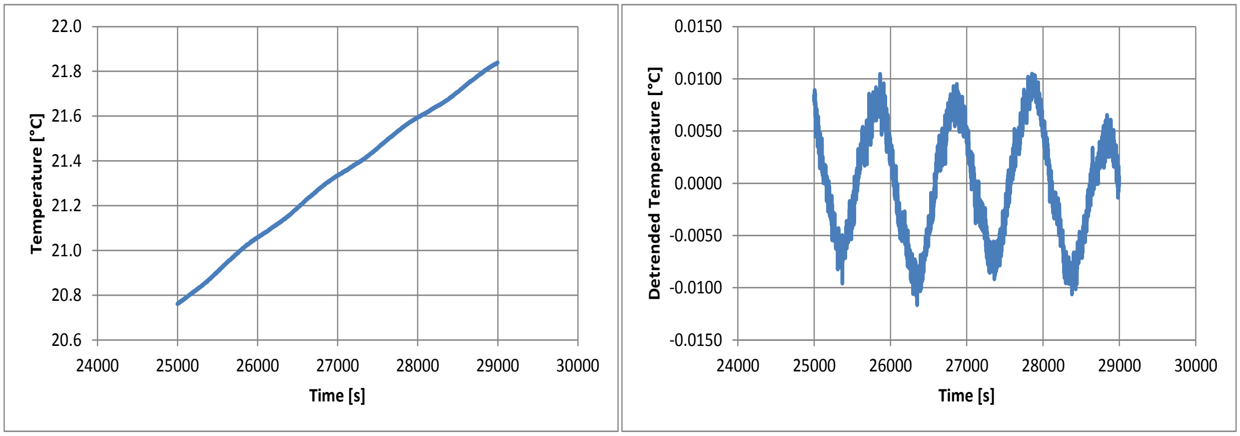

Figure 3. Signal detrending example *with third grade polynomial*

B. Data filtering

Detrended data has been then filtered to remove measurement noise. a low pass Butterworth filter with a 2mHz (twice the characteristic frequency of the system) cut off frequency has been used

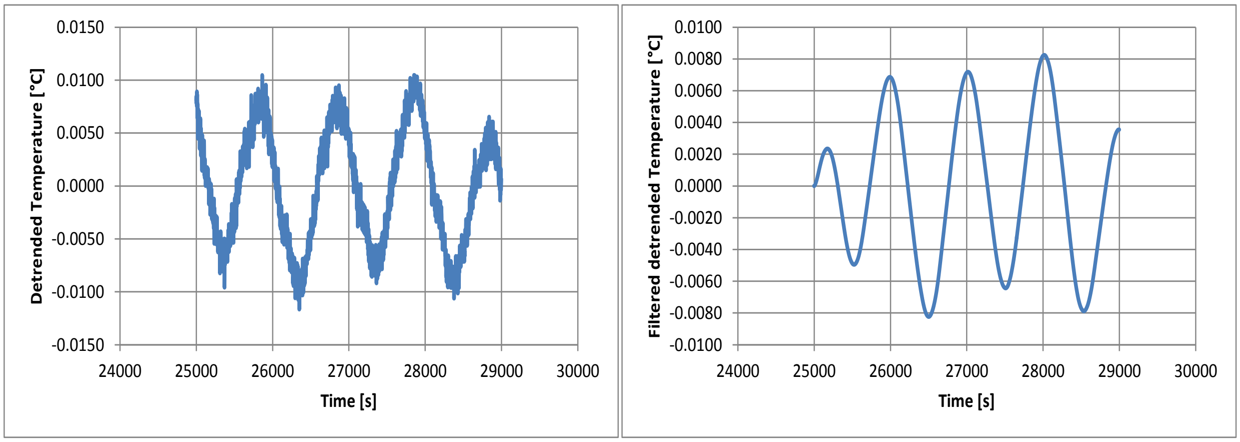

Figure 4. Signal filtering example *with a low pass Butterworth filter with a 2mHz (twice the characteristic frequency of the system) cut off frequency*

V. Correlation results

A. Correlation success criteria

Such kind of correlation does not represent a standard approach and therefore there is not a clearly defined success criterion. Moreover, the typical amplitude of the oscillations ranges from few Kelvin to few tenths of millikelvin, spanning four orders of magnitude.

Considering the different level of measured response, different success criteria have been established: first of all, the success criteria shall be applied to the *ratio* of the oscillation amplitudes, and not to the absolute values differences. The ratio between the measured amplitude and the predicted amplitude is defined in eq. (1):

$$R_{T/M} = \frac{A_{test}^{p2p}}{A_{\text{model}}^{p2p}} \qquad (1)$$

$R_{T/M}$ target value has been selected in order to allow a larger error when very small oscillation have been observed:

Peak to peak (p2p) variation Test	**Allowable $R_{T/M}$**	**Equivalent % error**
p2p >1K	$0.8 < R_{T/M} < 1.2$	<20%
1K < p2p < 0.01K	$0.5 < R_{T/M} < 2$	<100%
p2p <0.01K	$0.25 < R_{T/M} < 4$	<400%

Figure 5. Test/Model correlation success criteria

B. Correlation results

A subset of the model results (before and after the correlation process) are shown in figure 5 (test #1) and figure 6 (test #2): It is shown how the model predicted results are very well aligned with the test measurement. A large deviation has been found for test #1 on the sensors installed on the GPRM flange top, but the deviation has been largely improved with the correlation activity. In order to improve the correlation, some modifications have been introduced in the model:

- GPRM flanges have been conductively coupled with internal interface structure (IIS) since this coupling was not modelled in the original model
- Dust covers have been conductively coupled with GPRM flanges (this coupling was not modelled in the original model)

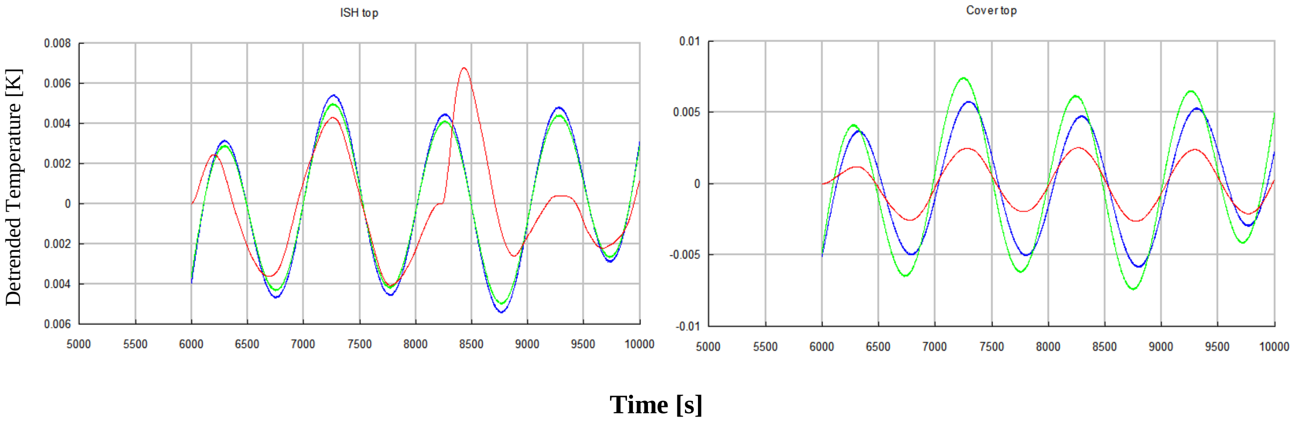

Figure 6. TEST#1 results external sensors: *red line represents test data, green and blue lines represent respectively the model data before and after the correlation activity*

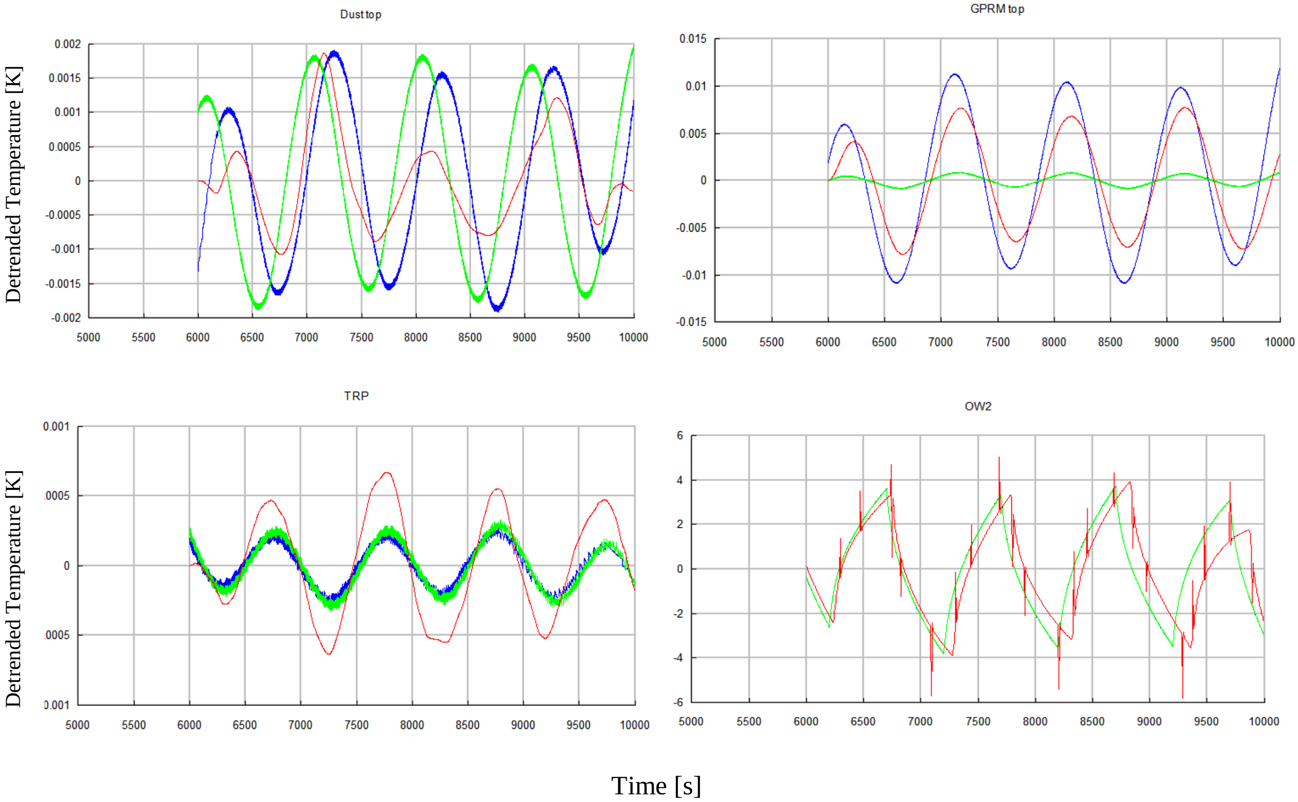

Figure 7. TEST#1 results internal sensors: *red line represents test data, green and blue lines represent respectively the model data before and after the correlation activity*

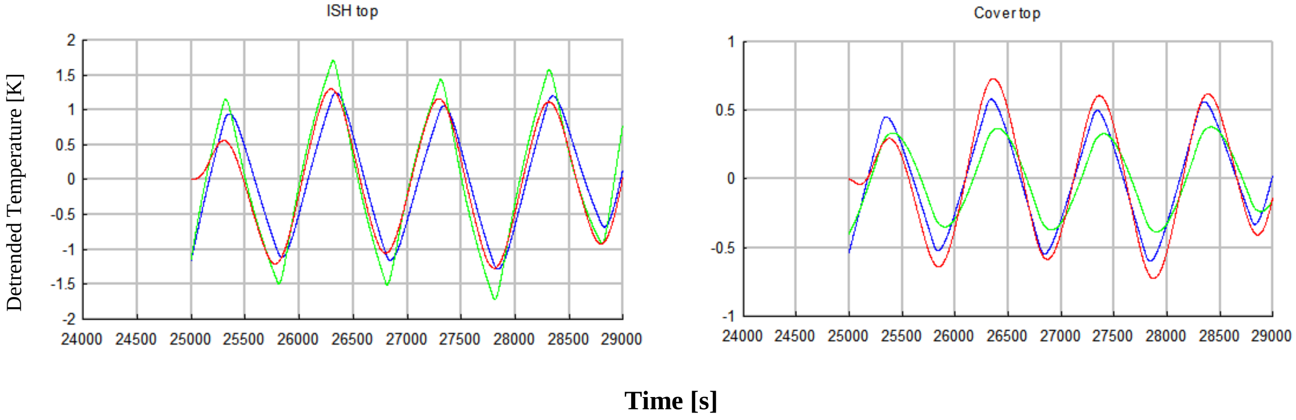

Figure 8. TEST#2 results external sensors: *red line represents test data, green and blue lines represent respectively the model data before and after the correlation activity*

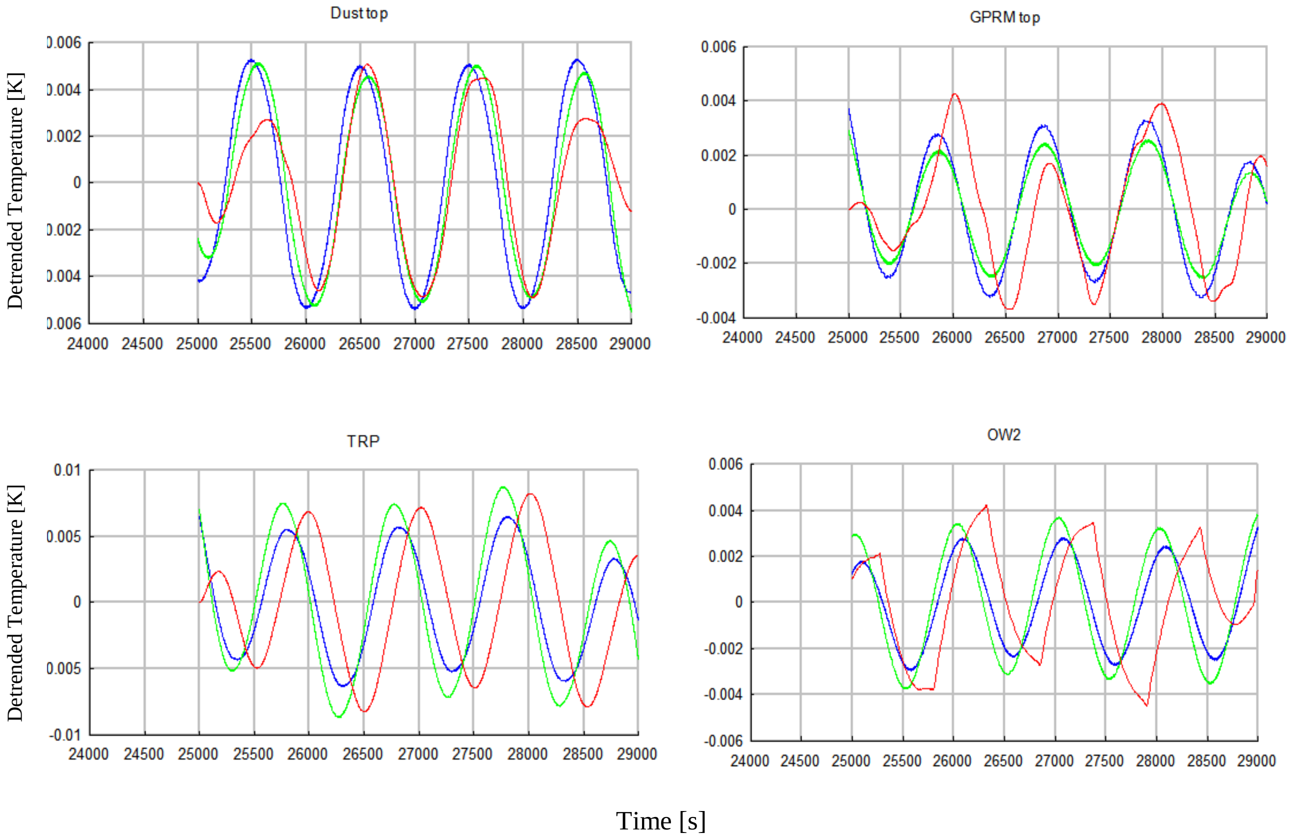

Figure 9. TEST#2 results internal sensors: *red line represents test data, green and blue lines represent respectively the model data before and after the correlation activity*

	TEST 1 Heater on OW				TEST 2 Test heaters on Covers			
	Oscillation Amplitudes		Amplitudes ratio		Oscillation Amplitudes		Amplitudes ratio	
	TEST [°C]	MODEL [°C]	$R_{T/M}$	*req* $R_{T/M}$	TEST [°C]	MODEL [°C]	$R_{T/M}$	*req* $R_{T/M}$
ISH TOP	0.008	0.01	0.8	*0.25<R<4*	2.4	2.4	1	*0.8<R<1.2*
COVER TOP	0.005	0.01	0.5	*0.25<R<4*	1.2	1	1.2	*0.8<R<1.2*
DUST TOP	0.002	0.0036	0.56	*0.25<R<4*	0.01	0.01	1	*0.5<R<2*
GPRM FLNG TOP	0.014	0.02	0.7	*0.5<R<2*	0.006	0.006	1	*0.25<R<4*
TRP	0.0011	0.00052	2.12	*0.25<R<4*	0.014	0.012	1.17	*0.5<R<2*
OW2	8	8	1	*0.8<R<1.2*	0.008	0.006	1.33	*0.25<R<4*

Figure 10. Correlated Model comparison results: *only one sensor/node couplet results slightly out of the defined success criteria*

VI. Transfer Function approach

The above described model results consider the frequency domain content of the calculated data but are coming from thermal analyses performed in transient. A different approach has been widely used for LISA pathfinder thermal analyses, that have been typically performed in frequency domain calculating the 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 transfer function represents a fast and effective way to calculate the propagation of perturbation inside a model.

There are two main assumptions beneath this approach: the first is the validity of the superposition principle and the second is the hypothesis of small oscillations: both are based on the linear system theory that required a linearization of the radiative coupling (further details of the method are discussed in Ref.3).

As example, this approach is shown in

Figure 11 (for reference applied to test 1). The temperature gain due to the heater power application on the Optical Window (at 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.

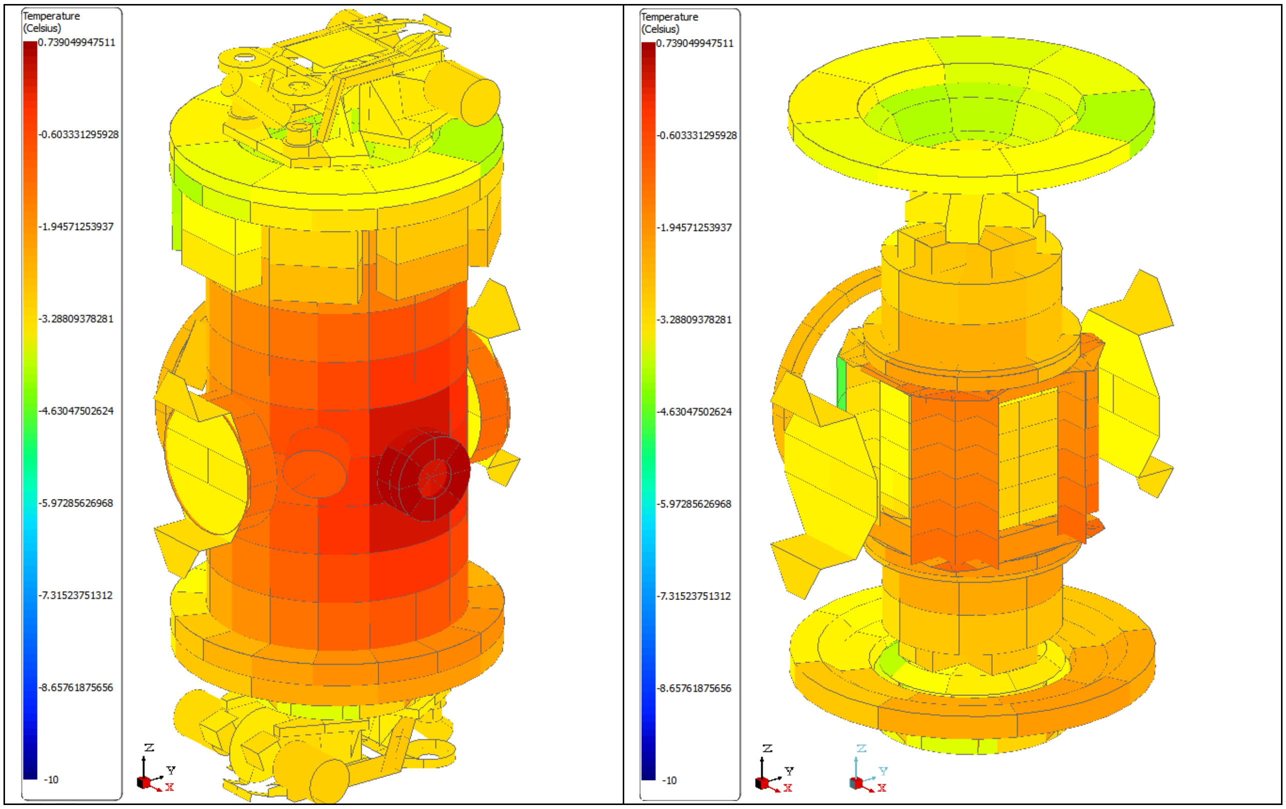

Figure 11. ISH External (left) and ISH internal (right) TEST#1 analysis results: *results are shown on the ISH GMM. Results are shown in Log10(K/W)*

The amplitude of the perturbation calculated with this approach is compared with the one calculated with the above presented time domain approach. As shown the results of the two methods are very similar.

	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

Figure 12. Time domain vs frequency domain approach: *the results show how the two methods are perfectly equivalent in terms of 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 power sources, in an extremely compressed time.

Moreover the output does not need further post-processing (e.g. detrending or filtering): in an extremely reduced time, one can calculate the propagation of several power sources to every node in the thermal model; in time domain this requires a much larger computational time (and proportional to the number of power sources), and a subsequent post-processing of data. From the point of view of the results the equivalence of the transfer function has been fully demonstrated.

VII. Conclusion

Due to the peculiar configuration of the system (completely passive with no dissipation) a non standard correlation approach was needed and has been developed and used to improve the confidence of the model. In particular, test heaters have been used to inject a frequency-driven disturbance in the system. Some post-processing has been performed on the data collected during the test in order to be able to identify temperature oscillations of mK order of magnitude.

The existing model shows very good behavior, predicting results in line with the data collected during the test. Minor model modification has been introduced and shall be considered for the final flight prediction.

The two LISA ISH FMs are approaching the final phases of integration and are foreseen to go under the acceptance campaign in late spring 2014. The launch is planned for 2015 with a VEGA launcher from Kourou space center.

Acknowledgments

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