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The Breadboard Model of the LISA Telescope Assembly

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***Abstract*— The primary goal of the LISA mission is the detection of gravitational waves from astronomical sources in a frequency range of 10-4 to 1 Hz. This requires operational stabilities in the picometer range as well as highly predictable mechanical distortions upon cooling down, outgassing in space, and gravity release.**

In March 2011 ESA announced a new way forward for the L-class candidate missions, including LISA. ESA and the scientific community are now studying options for European-only missions that offer a significant reduction of the costs, while maintaining their core science objectives. In this context LISA has become the New Gravitational wave Observatory (NGO).

Despite this reformulation, the need for dimensional stability in the picometer range remains valid, and ESA have continued the corresponding LISA Technology Development Activities (TDA's) also in view of NGO. In such frame Astrium GmbH and xperion (Friedrichshafen, Germany) have designed and manufactured an ultra-stable CFRP breadboard of the LISA telescope in order to experimentally demonstrate that the structure and the M1 & M2 mirror mounts are fulfilling the LISA requirements in the mission operational thermal environment. Suitable techniques to mount the telescope mirrors and to support the M1 & M2 mirrors have been developed, with the aim of measuring a system CTE of less than 10^{-7} K^{-1} during cooling down to -80 °C. Additionally to the stringent mass and stiffness specifications, the required offset design makes the control of relative tilts and lateral displacements between the M1 and M2 mirrors particularly demanding.

The thermo-elastic performance of the telescope assembly is going to be experimentally verified by TNO (Delft, The Netherlands) starting from the second half of 2012.

This paper addresses challenges faced in the design phase, shows the resulting hardware and present first outcomes of the test campaign performed at TNO.

***Index Terms*— LISA, NGO, Stable Telescopes.**

I. SCOPE OF THE OPTICAL STABILITY CHARACTERIZATION FOR LISA

The key objective of Technology Development Activity "Optical Stability Characterisation" is to develop and build a Breadboard (BB) of the structure of the LISA Telescope Assembly (LISA TA) based on CFRP technology and demonstrate experimentally:

1. that the structure and the M1 and M2 mirror mounts are dimensionally stable to the pm level in the LISA operational thermal environment.
2. that the structure exhibits a highly predictable mechanical distortion upon cooling down, outgassing in space, and going from 1g environment to 0g.

In order to achieve this key objective the following activities have been required:

- design of an ultra-stable CFRP based structure to support the M1-M2 telescope mirrors, to achieve an overall CTE lower than 10^{-7} K^{-1}.
- design of a suitable technique to mount the telescope mirrors on the structure
- design and manufacture of an M1-M2 Telescope Assembly Breadboard.

Astrium GmbH and xperion have been awarded the above tasks, assuming the roles of design authority and manufacturer respectively.

TNO, as Prime Contractor for the TDA, are in charge of defining and procuring the measurement set-up, as well of verifying by test the BB performance. This includes the metrology required to monitor dimensional changes of the telescope upon cool-down, performing path-length stability measurements in representative operational conditions [2].

II. Main Requirements, Constraints and Boundary Conditions

The main driving requirements for the design of the Telescope BB are:

- A (passive) system-CTE for the distance between M1 and M2 of 10^{-7} K^{-1}.
- Lateral displacements of the M2 relative to the M1 of less than 2 µm (goal), even for the cool down from room temperature to -80 °C (i.e. a $\Delta T = -100$ K) and an axial temperature gradient of up to 18 K.
- The same order of magnitude for the distortions induced by the in-orbit moisture desorption (from saturation at 50% RH to completely dry status).
- A first natural frequency > 80 Hz
- A mass lower than 5.5 kg, without mirrors.
- No ferromagnetic materials can be used, except at the M2 position.

Additionally, and even if no specific requirement has been formulated with this regard, ASD have pursued to achieve a small CTE and CME also for the distance between M1 and telescope interface. In fact, distortions of this distance are less critical than the distance M1-M2, but not negligible.

An implicit design requirement is derived form the required system CTE/CME. The thermo-elastic performance is so demanding that it is definitely difficult to be met on the first attempt, because of a few unavoidable manufacturing tolerances. The design of the Telescope Assembly shall therefore include a number of features to compensate for deviations between the measured and predicted thermo-elastic stability.

The MAIT flow of the Telescope Assembly has been therefore structured as follows:

- Manufacturing of the nominal design, as resulting from the optimisation work performed up to the CDR;
- Verification by test of the thermo-elastic performance
- Compensation of the difference between predictions and measurement using of counteracting features foreseen in the design (calibration of the system CTE)
- Final verification by test.

III. Trade-Offs and Preliminary Investigations

A number of trade-offs and investigations have been performed to enable a sound choice of the most appropriate solutions for the detailed design and MAIT phases.

A. Adhesive bond performance during cool down

The capability of the chosen adhesive bonds to survive to the cool down form room temperature to -80 °C has been demonstrated by sample tests using internal TNO and Astrium funding. All samples survived a cool down of -118 °C without damage.

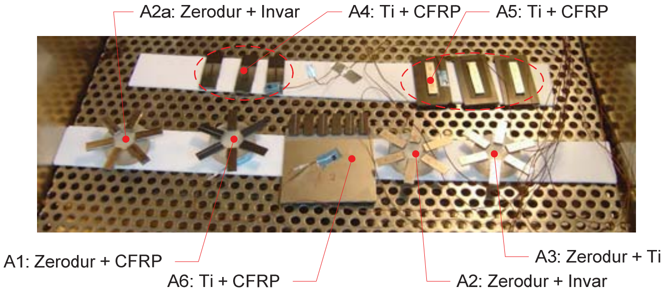

Fig. 1. Overview of the samples used for testing of the adhesive bonding

B. Materials trade-offs

Although the Customer was requesting a CFRP telescope structure, potential alternative materials have been reviewed too.

1) Silicon Carbide SiC 100

Due to the high Young Modulus, the low specific density, the good thermal conductivity and the excellent homogeneity this material is very interesting and used already for telescope structures and reflectors like the HERSCHEL 3.5 m telescope.

However, the CTE of about $2 \cdot 10^{-6}$ K^{-1} at room temperature or about $1 \cdot 10^{-6}$ K^{-1} at -90°C (lower end of operational temperature) makes the design sensitive to temperature gradients. Because for the LISA TA an axial temperature gradient of about 15 K is calculated due to the open aperture and the deep space looking, the deformations do not occur in a so-called "athermal" way, i.e. the change of the focal length of the mirrors is not compensated by the length change of the connecting structure. By this, the optical design and performance is degraded. Furthermore, temperature gradients may disturb the mirror surface accuracy itself due to the CTE different from Zero. Therefore, a passive dimensionally stable design using SiC seems not to be feasible for this application.

2) CSiC or CeSiC

The 3-phase ceramic material shows in tendency similar properties as SiC, but it is less stiff, less homogeneous and the CTE is even larger than for SiC, i.e. about $2.3 \cdot 10^{-6}$ K^{-1} at room temperature and about $1.6 \cdot 10^{-6}$ K^{-1} at -90°C. Hence CSiC and CeSiC are considered even less suited for this application than SiC.

3) ZERODUR

The glass ceramic material provides a low CTE, which is about $-0.5 \cdot 10^{-7}$ K^{-1} at room temperature and about $-1.7 \cdot 10^{-7}$ K^{-1} at -90°C. So, this would fit more or less to this application.

However, ZERODUR has a low stiffness (E = 90 GPa), a higher density (2.57 g/cm³) than CFRP (1.6 to 1.8 g/cm³) and the strength is limited. Compared to a CFRP design lower eigenfrequencies, a higher mass and problems with local stress concentrations can be expected. Therefore, it has not been selected for this application.

4) CFRP

In general, CFRP provides high stiffness, low density and the possibility of tailoring the properties depending on the used fibres, resin and laminate lay-up. A CTE and CME near to Zero can be achieved in one direction.

Despite its manufacturing and the resulting laminate properties may be affected by a larger scattering compared to isotropic materials, CFRP appears to be the best choice. In particular, the chosen carbon fibre / resins system has been successfully used and characterised at Astrium for more than 20 years. Dedicated sample test programmes on the unidirectional data have been determined and permanently updated comparing the measured distortions of several telescope structures (SEVIRI, CARTOSAT 2, KOMPSAT 3…) with the predicted values. The excellent agreement of test to prediction on KOMPSAT 3 confirms that the used data as well as the used analysis approach are correct within a small range of uncertainty. Regarding the resin, the decisive criteria for a proper choice are well defined, predictable properties in the CFRP parts and a very good reproducibility, which requires low variations in the fibre/resin content and a high precision of the fibre directions in the laminate. This can be achieved only by a tight controlled wetting process in combination with an automatic lay-up process. Astrium and xperion have optimised and successfully applied such processes in combination with epoxy resins, achieving scattering in the fibre volume content less than 1% and deviations in fibre direction of less than 0.5°, even on curved parts.

C. Trade-offs on potential design concepts

Within the frame of the preliminary design two potential design concepts have been identified as candidates

- A design with a CFRP cylinder as bridging structure between M1 and M2.
- A design with a CFRP truss structure holding the M2 mirror.

Both telescope designs connect to the mechanical interface via isostatic mounts, shaped as two-legged supports.

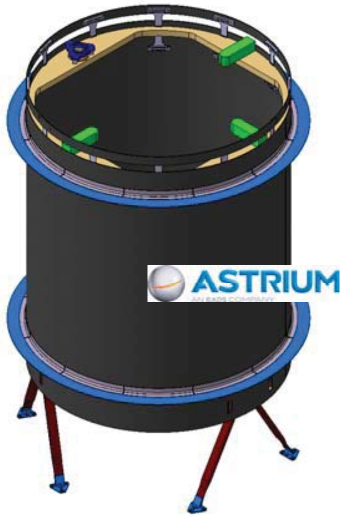

Fig. 2. Cylinder design concept of the LISA Telescope Assembly Breadboard

The design principle of the cylinder design concept is to provide as far as possible a radial symmetric behaviour from the interface to the MOSA up to the upper end of the cylinder, where the M2 is located.

Because a CFRP cylinder that has a very small CTE/CME in length direction will have in any case a CTE and CME quite different from Zero in the circumferential direction, a symmetrically supported Zerodur ring acts as stabiliser in radial direction for the M2.

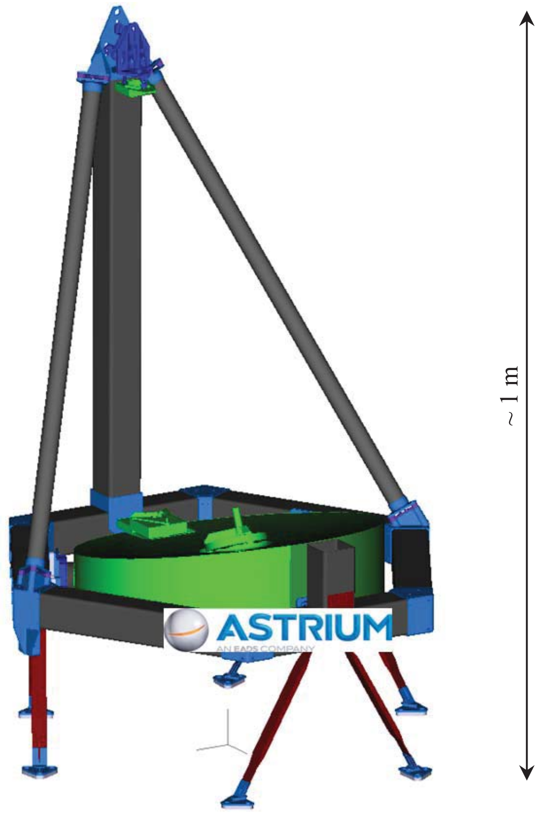

Fig. 3. Truss design concept of the LISA Telescope Assembly Breadboard.

The truss design concept provides a stiff hexagonal frame consisting of CFRP tubes with slightly negative CTE, a nominal zero CME in length direction (corresponding to the circumferential direction of the hexagon frame) and Titanium fittings. All elements have been dimensioned so that the support points to the M1 and to the struts towards the M2 remain stable at their position under temperature and moisture load.

The same design principle has been applied to the three beams holding the M2, i.e. the slightly negative CTE of the CFRP compensates the positive CTE of the metal fittings.

The cylinder design concept provides a rotational symmetric build-up and it is stable in the lower part (M1 support), but for the required lateral stability of the off-set positioned M2 mirror a Zerodur ring has to be applied in the upper part. The support of this ring is rather complex, because the CTE of the cylinder in circumferential direction is quite different to the CTE of the Zerodur. This support is sensitive with regard to differences in CTE, CME and stiffness between the cylinder and cylinder ring. In fact, these lead to a warping of the Zerodur ring and, as a consequence, to displacements and tilts of the M2 mirror. This sensitivity could require very tight manufacturing tolerances.

On the other hand, the truss design relies on relatively simple CFRP parts/tubes connected by Titanium brackets. Due to the offset main strut holding the M2 mirror the main hexagonal frame holding the M1 mirror is not fully rotational symmetric, but by adaption of the properties of the CFRP tubes and the consideration of the expansion of the Titanium brackets the overall stability is better than for the cylinder design. Furthermore, the mass of the truss structure is significantly smaller and the first eigenfrequencies are higher. Concerning the capability of later tuning of the system-CTE of the structure the truss design offers much more possibilities.

Hence, while the cylinder design could have been still feasible, and serve as fall-back option in case of unexpected difficulties, the truss design has been chosen as baseline due to its clear advantages.

IV. EFFECT OF UNCERTAINTIES IN THE LAMINATE PROPERTIES

Astrium have heritage in the field of such sensitivity analyses also due to dedicated internal R&D activities started in the last years and aimed at achieving robust design solutions.

In order to establish the amount of the needed compensation range for thermal and moisture variations, a Montecarlo simulation has been used to verify the effect of material data uncertainties and manufacturing tolerances on the M1/M2 displacement for the two main load cases (ΔT= -100°C and moisture desorption). To this end, the main sensitivities to uncertainties have been calculated

$$\frac{\partial CTE}{\partial x_i} \quad \text{and} \quad \frac{\partial \varepsilon_{mm}}{\partial x_i} \qquad (1)$$

where x_i represents thermo-elastic properties of the resin and fibre (E, ν, CTE, CME) or manufacturing parameters (volume fibre content, laminate thickness, ply angles).

The sensitivities, combined with the expected variation of the parameters (determined through material tests, knowledge of the manufacturing process, and heritage from previous projects), have been used to conduct a Montecarlo simulation to quantify the expected scatter (mean value and standard deviation) of the CTE and moisture strain of all laminates used in the telescope. The following results have been obtained:

1) *M1-M2 distance change due to a ΔT= -100 °C:*
- Average: -0.4 µm
- Expected scatter (3σ): ±1.1 µm

2) *M1-M2 distance change due to moisture desorption*
- Average: 0.03 µm
- Expected scatter (3σ): ±0.1 µm

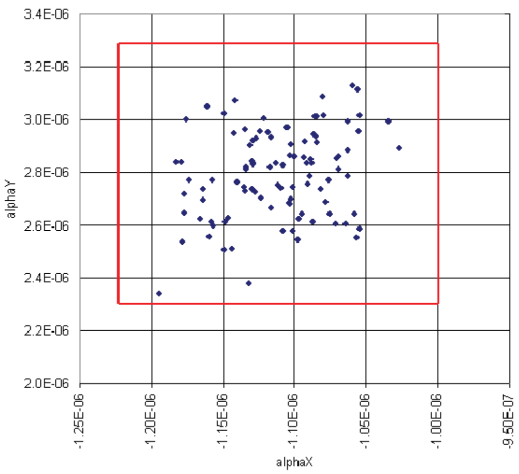

Fig. 4. Typical example for the variation of the in-plane CTE of the laminate of the rectangular tube (100 calculations). The red lines mark the 3σ-limits used for the M1-M2 distance change analysis.

The results show a very limited sensitivity of the distance M1-M2 to variation in the CFRP properties. However, additional scattering must be expected due to limitations of the FEM model, which will be correlated after the first performance test.

V. SUMMARY OF MAIN ANALYSIS RESULTS

The table below summarises the main results obtained from the finite element predictions at the end of the detailed design phase of the truss design concept:

Specification	**Requirement**	**Predicted results**
Mass, w/o mirrors	< 5.5 kg	4.79 kg
First eigenfrequency	> 80 Hz	82.2 Hz
Gravity		
M1 surface distorsion	< 10 nm_{rms}	5.7 nm_{rms}
ΔT=100K		
Distance M1-M2	< 6 µm	2.1 µm
Rel. lat. displ. M2-M1	< 2 µm	0.7 µm
Rel. tilt M2-M1	< 20 µrad	8.2 µrad
18K axial T-gradient		
Distance M1-M2	< 6 µm	0.4 µm
Rel. lat. displ. M2-M1	< 2 µm	0.6 µm
Rel. tilt M2-M1	< 20 µrad	1.5 µrad
Moisture desorption		
Distance M1-M2	< 6 µm	0.1 µm
Rel. lat. displ. M2-M1	< 2 µm	~ 0 µm
Rel. tilt M2-M1	< 20 µrad	4.7 µrad

All requirements, including the goal of max 2µm relative displacement between M1 and M2, are predicted to be met.

VI. PRESENT HARDWARE STATUS AND FIRST TEST RESULTS

After a successful Manufacturing Readiness Review in August 2011, xperion have started the manufacturing of the Breadboard of the Telescope Structure based on Astrium drawings. The final integration of the primary and secondary mirrors has been performed by Astrium, who have handed over the Telescope Assembly to TNO in May 2012.

In June 2012 TNO have performed a frequency signature test on the Telescope Assembly. This test, consisting of the measurement of the response spectrum of the Telescope Assembly after application of a small mechanical impulse, has confirmed the fulfillment of the requirement asking for a first eigenfrequency higher than 80Hz.

Currently the Thermal Vacuum Chamber and the Length Metrology system, specifically developed by TNO for the LISA TA measurement, are being integrated and tested together using a dummy telescope [3]. This dummy telescope will undergo a similar thermal trajectory as the breadboard model demonstrating the performance and limitations of the setup. These qualification experiments are planned to be finalized before the Test Readiness Review (TRR) in October 2012. In the period following the TRR the LISA TA will be tested extensively. Core of the test program comprises of a combined experiment in the Thermal Vacuum Chamber. In this experiment the CTE, integrated deformation and thermal gradient experiment are combined.

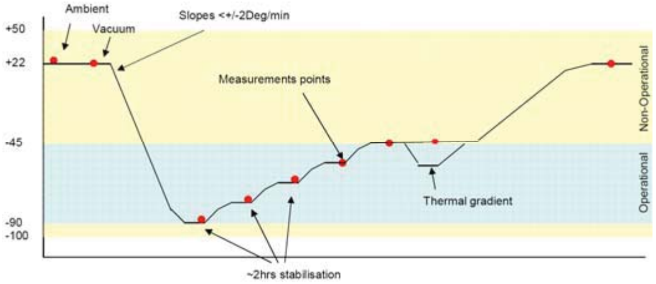

Fig. 5. Combined thermal vacuum experiment, showing thermal trajectory and measurement points

During the integration phase of the project the functionality of the thermal vacuum has been demonstrated. All sensors and control loops are operational and tested. In addition the liquid nitrogen system and the electrical heater shroud are operational. The interferometer bench at the hearth of the Length Metrology system has been tested separately in the lab to show stabilities of few tens of nm over a weekend.

Since the thermal stability of the lab is far worse than in the thermal vacuum chamber, the stability of the interferometer signals is more than sufficient. In addition the beam pointing sensor was maintained operational over this period.

At present the full integrated system is under test and the final control parameters are being determined. Measurements are performed using all included systems.

A more detailed description of the current and future test activities is available in [3].

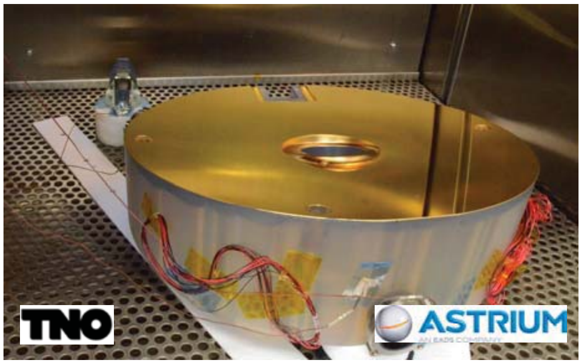

Fig. 6. The main and secondary test Zerodur mirrors after curing of the bracketry bonding at Astrium. Both test mirrors are provided by TNO, and used for the measurement of the optical stability.

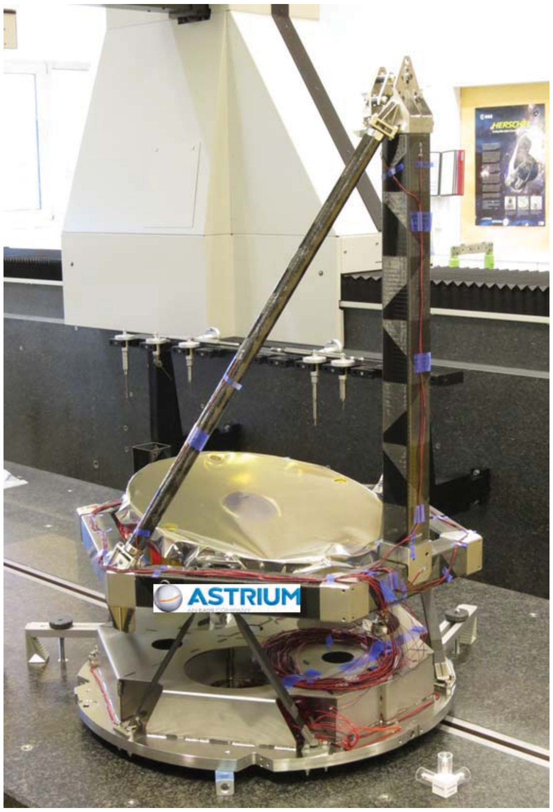

Fig. 7. The Breadboard of the Telescope Structure under a coordinate measurement machine during alignment of the primary test mirror.

VII. CONCLUSION AND OUTLOOK

The present paper has been focused on the telescope breadboard developed by Astrium GmbH and manufactured by xperion Aerospace for the optical stability characterisation of the LISA Telescopes. The test facility for the demanding verification of the telescope is presently being commissioned by TNO in Delft, and a beginning of the test campaign is planned to begin in October 2012.

Astrium and TNO are confident that the test campaign will confirm the outstanding thermo-elastic stability predicted during the detailed design phase, in line with the objectives of the LISA/NGO mission.

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The authors would like to thank the team at ESA for the support and cooperation that has characterised the work since the very beginning of the Technology Development Activity.

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