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LISA TELESCOPE ASSEMBLY OPTICAL STABILITY CHARACTERIZATION FOR ESA

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I. INTRODUCTION

The LISA Optical Stability Characterization project is part of the LISA CTP activities to achieve the required TRL level for all of the LISA technologies used. In 2012 the LISA mission was reformulated and transferred to the New Gravitational Observatory (NGO), which has similar performance requirements. This activity targets the demonstration of the Telescope Assembly (TA), with a structure based on CFRP technology, to show that total deformations corresponding to a system CTE of 10^{-7} K^{-1} can be passively achieved, i.e., without a dedicated thermal control. In addition it is required to prove that the structure exhibits highly predictable mechanical distortion characteristics when cooling down to -90°C, during outgassing in space and when going from 1g environment to 0g.

A dedicated test setup is designed and realized to allow monitoring dimensional variations of the TA-structure using three interferometers, while varying the temperature in a thermal vacuum chamber. Critical parameters of the verification setup are the length metrology accuracy in thermal vacuum and the stability. For practical application also a high degree of flexibility and ease of operation are required. The test programme includes CTE measurements and thermal gradient characterization of the Telescope Assembly.

This paper describes the current development status of the telescope structure. Previously the test facilities as well as the first test results were presented [1]. In this paper the results of these thermal vacuum experiments are described. These results then are analyzed using FEM analysis and compared to the predicted performance. From this comparison modifications are derived to finely trim the thermo-elastic behavior of the telescope assembly. A second thermal vacuum experiment is performed to validate the improved thermo-elastic performance of this off-axis telescope. A third experiment has been performed, which confirms the findings of the second test.

The primary goal of the Laser Interferometer Space Antenna (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 the context of this reformulation exercise LISA has become the New Gravitational wave Observatory (NGO) [2].

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 an elegant breadboard of the LISA Telescope Assembly (TA) structure is designed and tested in a newly developed test facility. Airbus DS and xperion aerospace (Immenstaad/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 -90 °C. Additionally to the stringent mass and stiffness specifications, the required off-axis design makes the control of relative tilts and lateral displacements between the M1 and M2 mirrors particularly demanding.

The thermo-mechanical performance of the telescope assembly is experimentally verified by TNO (Delft, The Netherlands) in three experiments from 2012 to 2014. For the purpose of these experiments a comprehensive verification setup is designed and realized, which consists of a dedicated Thermal Vacuum Chamber (TVC) equipped with three displacement interferometers. These interferometers monitor length changes directly between the TA-structure mirrors, providing mirror relative displacement and tilt information, while the TA-structure is exposed to a thermal cycle. The test programme includes Telescope Assembly CTE measurements and thermal gradient characterization.

This paper addresses challenges faced in the TA-structure experiments. First the realized test facility design and operation are explained. Next the most important test results are shown, followed by a detailed analysis. The paper is concluded by the first outcomes of the test program.

II. TELESCOPE ASSEMBLY STRUCTURE

The TA-structure is designed by Airbus DS, based on components delivered by project partners. Carbon Fibre Reinforced Plastic (CFRP) and metal parts are manufactured by xperion aerospace, while the Zerodur mirror blanks are provided by Schott. TNO has grinded and polished the test mirrors to their final shape and provided them with the required coatings to be thermo-mechanically representative. The shapes of these test mirrors are (locally) modified allowing interferometric distance measurements. To simulate the interface to the LISA Optical bench a high stability Invar structure is used. In Fig. 1 the TA-structure and the test mirrors are shown during the integration at Airbus DS.

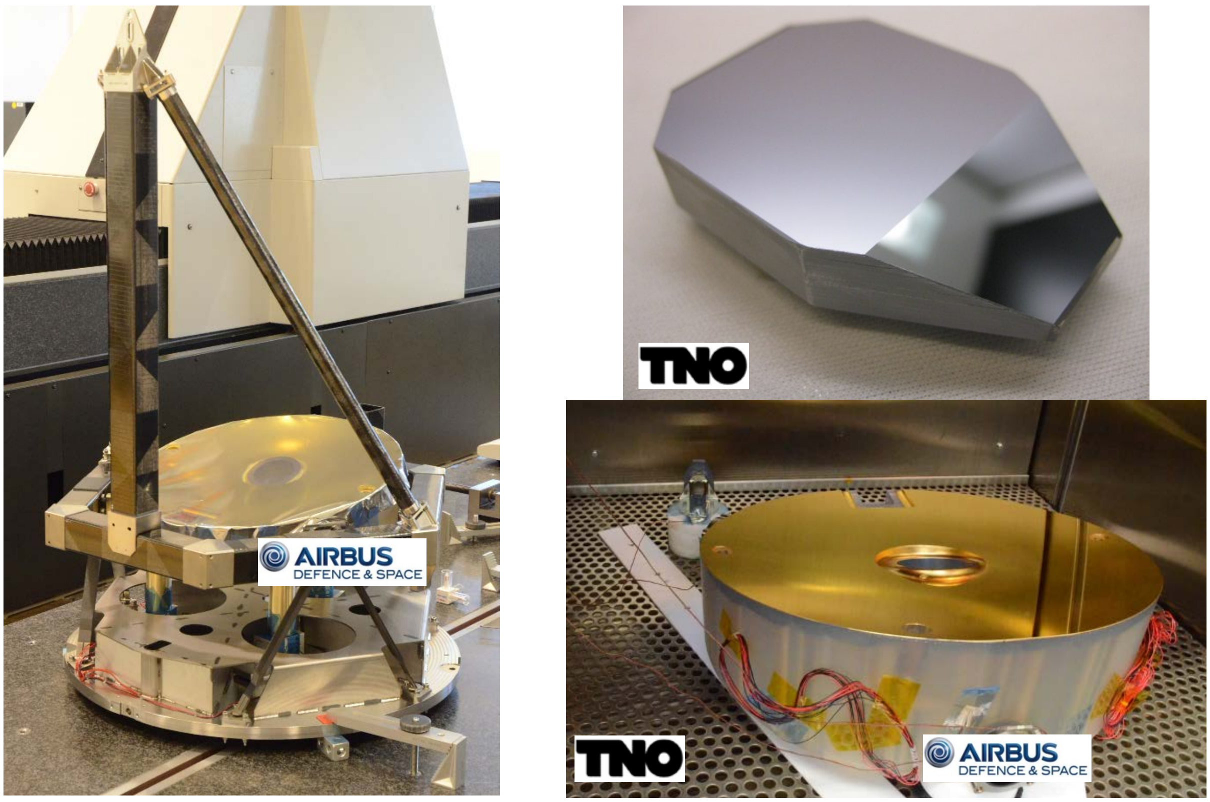

Fig. 1. Left: Telescope Assembly structure at Airbus DS under the coordinate measurement machine. Right top: Facetted secondary test mirror enabling interferometric measurements. Right bottom: Primary test mirror after gluing of inserts and temperature sensors

Core element of the TA-structure is the CFRP, which provides the required stiffness and the ability to be trimmed to the required CTE. By carefully analyzing all predicted load cases, the structure is designed to nominally yield a very small ($<10^{-7}$ K^{-1}) CTE up to operational temperatures (-45ºC to -90ºC) and low deformation during the cool-down. Design choices are supported by material experiments, extensive FEM analyses [3][4] and in-house heritage from similar projects.

III. THERMAL VACUUM CHAMBER

Core of the studies is the characterization and demonstration of the TA-structure thermal behavior. A newly developed Thermal Vacuum Chamber is constructed to offer a combination of high thermal stability (<0.1K/hr) and uniformity (<1K) as well as fast thermal adjustment. In the TVC design more stringent thermal stabilities are anticipated to allow future use for direct demonstration of pm-stabilities. In Fig. 2 the realized TVC setup is shown.

Two separate thermal zones are created inside the TVC; a warm vacuum and the thermal vacuum. The warm vacuum contains the support frame and the interferometer breadboard and is maintained at a temperature slightly above ambient. In this way the metrology performance and stability can be best guaranteed. By thermally insulating the interferometer (IFM) breadboard from the surrounding support frame using MLI-blankets, predicted temperate variations at this location are significantly smaller than 0.1K.

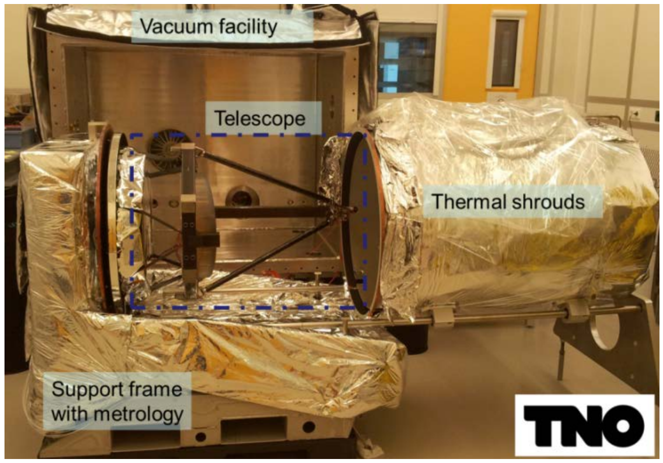

Fig. 2. Realized Thermal Vacuum Chamber setup with TA-structure during the test campaign at TNO.

The thermal vacuum is realized using a combination of two shrouds. An outer shroud, filled with liquid Nitrogen, provides a stable cold environment. Inside this shroud an electrically heated shroud is adjusted to the desired temperature. Commissioning experiments [1] demonstrate over the operational temperature range of -90°C to -45°C that a shroud homogeneity of <1.2K and stability of 12mK/hr can be obtained.

IV. LENGTH METROLOGY SYSTEM

The length metrology system consists of three displacement interferometers to measure the deformations of the breadboard telescope throughout the thermal vacuum experiments. Using these three relative displacement interferometers the displacement between the test mirrors M1 and M2 are monitored optical directly, see Fig. 3.

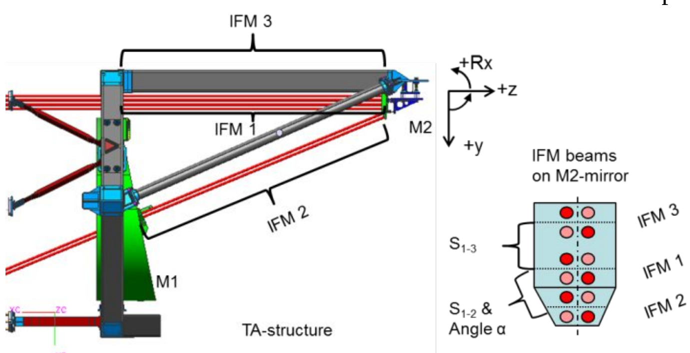

Fig. 3. Schematic overview interferometer monitored paths, TA-coordinate system and measurement positions on M2.

From the obtained length changes *dIFM1*, *dIFM2* and *dIFM3*, the telescope deformation *dRx*, *dy* and *dz* can be determined following the relation below.

$$\begin{pmatrix} dIFM1 \\ dIFM2 \\ dIFM3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ \cos\alpha & -sin\alpha & S_{12} \\ 1 & 0 & -S_{13} \end{pmatrix} \begin{pmatrix} dz \\ dy \\ dRx \end{pmatrix}$$

where *dy* and *dz* are the lateral and longitudinal length changes between the two test mirrors and *dRx* is the change in relative rotation. S_{12} and S_{13} refer to the distances between the interferometer measurement positions on the M2 mirror, whereas α is the angle under which the inclined interferometer (IFM2) obtains its data.

The CTE of the structure between the center points of the M1 and M2 mirrors can be determined from

$$CTE_{dT} = \frac{1}{L_0 dT}\left[dL_{IFM2} - \frac{S_{12}}{S_{13}}(dL_{IFM1} - dL_{IFM3})\right]$$

where L_0 is the nominal separation between these center points and *dT* the temperature step over which the CTE is determined.

The actual IFM light source, the laser, as well as the detectors are located outside the TVC. In this way commercial devices can be used and the main (un-controlled) heat sources are removed from the TVC. In order to allow a correction of the beam pointing, two tip-tilt mirrors are included in the optical path in combination with two PSD's, that monitor the beam position at two locations. The laser beam is pointed towards the IFM breadboard through a vacuum window in the TVC.

V. TEST FACILITY CHARACTERIZATION

The performance of the complete metrology system inside the thermal vacuum is validated experimentally by running a full thermal test cycle on a perfect (zero length) telescope. The thermal vacuum test cycle comprises a bake-out at 50°C, homogeneous temperature measurements at -90°C, -60°C and -40°C, and a thermal gradient load case. In the latter case, one side of the thermal shroud is cooled to -90°C, whilst stabilizing all other sides at -50°C. Resulting length changes on the interferometers remain under 5nm in all these cases, well sufficient for all measurements.

VI. MEASURMENT CAMPAIGN

Overall three thermal vacuum tests have been performed. The baseline test program consists of a bake-out at +55ºC, a number of stabilization steps at low temperatures down to -90ºC and a thermal gradient test, see Fig. 4. From a single test a number of parameters can be assessed, comprising air-to vacuum effects, deformation, CTE, hysteresis and sensitivity to thermal gradients. Variations are made to the test program for the individual tests, following the points of attention.

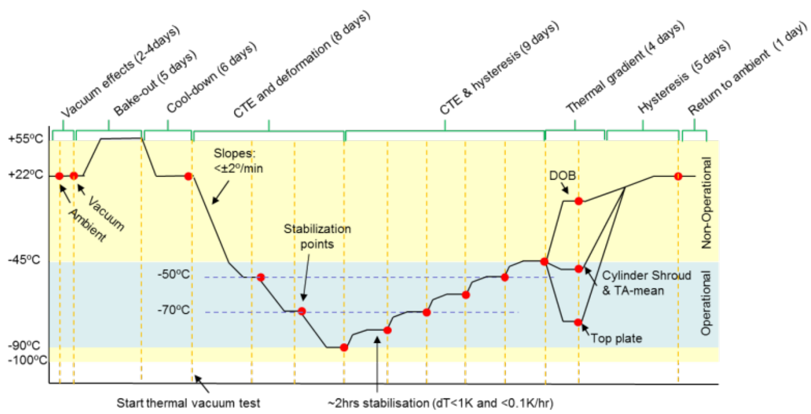

Fig. 4. Schematic overview of thermal vacuum test.

In the first experiment the thermal behavior of the TA-structure in terms of deformation and CTE are assessed. According to plan, the aim of such first test is to assess the behavior of the structure and allow a fine trimming of the thermo-elastic behavior. This has been particularly relevant to the rotation *Rx*, while the demanding total CTE requirement could be remarkably achieved with no need of further adjustments.

In the second thermal vacuum test the applied fine trimming of TA-structure is assessed, while the third and last thermal vacuum test proves the measurements repeatability. The second and third tests are performed without breaking the vacuum in between; the third test is a limited re-run of the second test, with differences between the two limited to a reduced bake-out time, less stabilization points and omission of the thermal gradient verification.

VII. TEST RESULTS

To arrive at the TA-structure deformation data the raw measurement data is processed in a number of steps. As an example the first thermal vacuum test is taken. Here Fig. 5 shows the raw interferometer data as acquired without any processing. When plotting this data as a function of temperature, see Fig. 6, a more instructive figure results. Here the thermo-elastic behavior is shown more directly. Still the data is hard to read due to the transient behavior between stable temperatures (at the indicated temperatures in the figure). After conversion of IFM readings to TA-structure deformation Fig. 7 results. For the interpretation of this data, only the lengths and deformation found under thermally stable and homogeneous conditions should be regarded. Further aspects of the structure can be understood from the transient data; these are however not addressed here. In Fig. 8, Fig. 9, and Fig. 10 the resulting IFM data is shown as a function of temperature for the 3 thermal vacuum cycles.

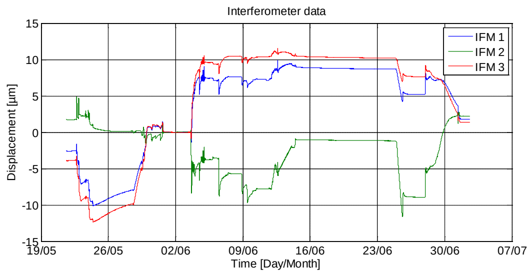

Fig. 5. Raw IFM readings during complete 1st thermal vacuum experiment

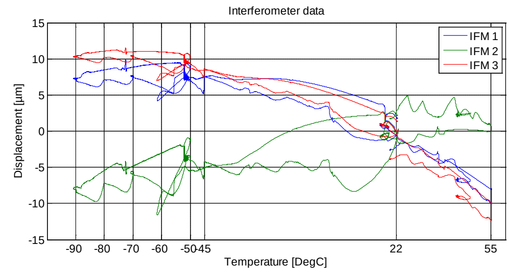

Fig. 6. Raw IFM readings as a function of temperature during complete 1st thermal vacuum experiment

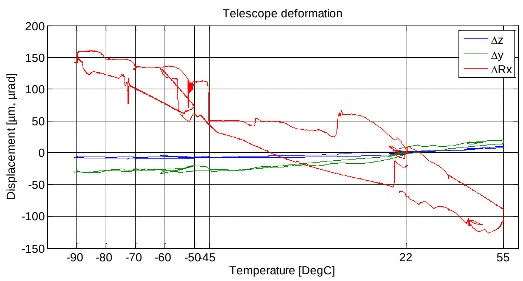

Fig. 7. TA-structure deformation as a function of temperature during complete 1st thermal vacuum experiment

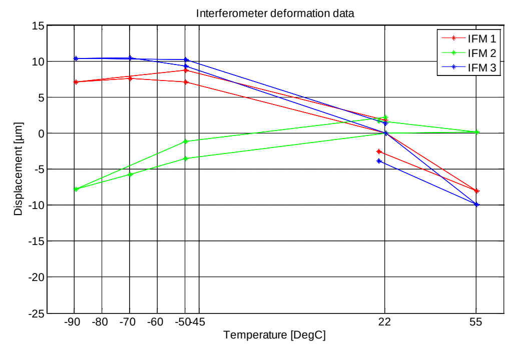

Fig. 8. Thermal deformation at stabilization points of the TA-structure results of the 1st thermal vacuum test.

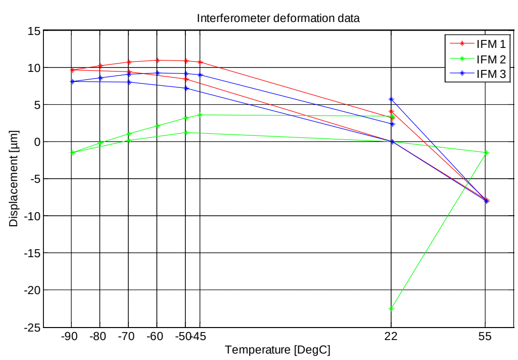

Fig. 9. Thermal deformation of the TA-structure results of the 2nd thermal vacuum test.

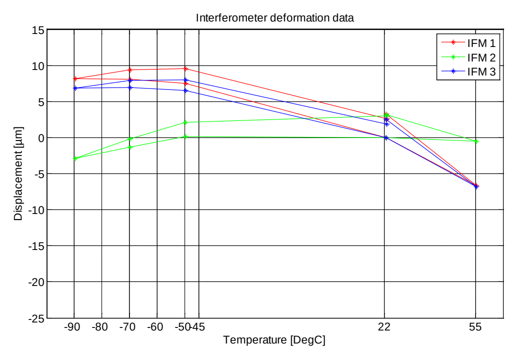

Fig. 10. Thermal deformation of the TA-structure results of the re-run of the 2nd thermal vacuum test.

VIII. TEST RESULTS DISCUSSION

In table 1 the TA-structure requirements are given together with the tested performances in the three thermal vacuum tests.

Table 1. Telescope Assembly Structure thermo-mechanical requirements and tested performances

Performance	Requirement	1st test	2nd test	2nd test re-run
CTE over 100K [1/K]	$<10^{-7}$	$9.8\ 10^{-8}$	$5.7\ 10^{-8}$	$6.9\ 10^{-8}$
M1-M2 Longitudinal displacement dz [µm]	<5	-7.6	-8.5	-7.4
M1-M2 Lateral displacement dy [µm]	<2 (goal)	-25.7	-26.3	-26.2
M1-M2 Rotation dRx [µrad]	<20	134.4	-57.3	-47.2

From the results presented in Table 1 a number of conclusions can be drawn. The main requirement regarding the CTE performance is met in all experiments, even in the very first test, without any specific calibrations of the thermo-elastic behavior. This is an excellent result, considering that it is achieved passively, i.e., without a dedicated thermal control, and a considerable step forward toward the development of high stability structures for LISA/NGO. Additionally, it is interesting to highlight that the applied fine trimming has not degraded the CTE performance, showing a good grade of decoupling between the compensation capabilities for each requirement.

On the other hand, the control of the rotation *Rx* between the test mirrors has proved hard to be achieved. In the first test a rotation between the M1 and M2 mirrors is found of 134.4µrad. Applied modifications to the structure to compensate this, result in a substantial reduction of this rotation to -57.3µrad, showing however some overshoot in the correction.

Although the lateral displacement goal of 2µm is not met in the first test, no effort was undertaken to alter this performance during the TA-structure modifications. (Compensation possibilities are present in the telescope design.) Therefore it is good to notice that this performance remains stable throughout the performed experiments.

IX. DESIGN IMPROVEMENT

A number of lessons learned could be gained during the design and MAIT activities. Focusing here on the measured thermo-elastic performance, while the achievement of a system CTE well within the stringent requirement of 10^{-7} K^{-1} is remarkable, there is some room for improvement with particular regard to the rotational stability *Rx* between the two mirrors. Indeed, the second and third test campaigns have shown that the introduced measures to trim the behavior have led to an unexpected overcompensation of the rotation measured during the first measurement.

Design improvements shall be therefore mainly aimed to a reduction of the sensitivity of the rotation *Rx* e.g. with regard to uncertainties linked to material data, mathematical (FEM) modelling and manufacturing tolerances, also in view of unavoidable tolerances on the actual future thermal environment during operation. Although detailed analyses are needed before implementing new design solutions (which could have negative drawbacks on other degrees of freedom), some indications are already available. Possibly, the most promising improvement concerns the increase of the distance between elements supporting the secondary mirror, which are the main features controlling *Rx* due to their differential expansion.

In the frame of a further development of the structure, i.e., for the definition of a flight configuration, it is also deemed helpful to enlarge the range of the feasible thermo-elastic trimming, which could enable an easier compatibility to tolerances on the operational environment as well as the achievement of specific goal values for additional degrees of freedom.

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