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Abstract—**LISA (Laser Interferometer Space Antenna) is a proposed space-based instrument for astrophysical observations via the measurement of gravitational waves at mHz frequencies. The triangular constellation of the three LISA satellites will allow interferometric measurement of the changes in distance along the arms. On board each LISA satellite there will be two optical benches, one for each testmass, that measure the distance to the local test mass and to the remote optical bench on the distant satellite. For technology development, an Optical Bench Elegant Bread Board (OB EBB) is currently under construction. To verify the performance of the EBB, another optical bench - the so-called telescope simulator bench - will be constructed to simulate the beam coming from the far spacecraft. The optical beam from the telescope simulator will be superimposed with the light on the LISA OB, in order to simulate the link between two LISA satellites. Similarly in reverse, the optical beam from the LISA OB will be picked up and measured on the telescope simulator bench. Furthermore, the telescope simulator houses a test mass simulator. A gold coated mirror which can be manipulated by an actuator simulates the test mass movements. This paper presents the layout and design of the bench for the telescope simulator and test mass simulator.**

Fig. 1. Illustration of the LISA mission constellation. The sketch leaves out the test mass interferometers for clarity. [1]

I. INTRODUCTION

LISA will consist of three spacecraft forming an equilateral triangle with five million kilometer side length trailing the Earth in its heliocentric orbit. The triangular plane rotates over a year, while its normal remains tilted at 30° to the plane of the ecliptic and pointed towards the sun. In LISA laser heterodyne interferometry will be used to measure the relative displacement of test masses shielded inside the spacecraft. Each spacecraft houses two optical benches, each including a test mass, as illustrated in Fig. 1. On the optical bench heterodyne interferometry will take place. The interferometric metrology system to measure the test mass displacement should achieve a noise level of $1.42 \, \mathrm{pm}/\sqrt{\mathrm{Hz}}$. The interferometric metrology system of each arm is split into three parts as shown in Fig. 2. At the end of each interferometric link there is an optical bench, which measures the distance to the other optical bench (science interferometer) and its test mass (test mass interferometer).
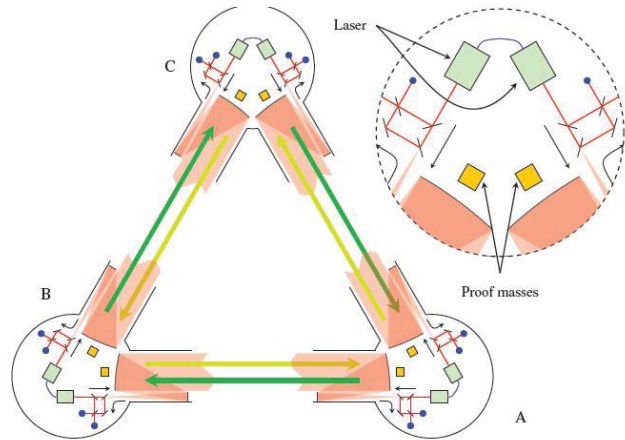
Within the framework of the ESA LISA technology development, a LISA Optical Bench (LISA OB) is under construction [2][3] . For verification of the LISA OB, the beam of the far spacecraft is provided by a telescope simulator. Part of the simulator bench will be also a test mass simulator which consists of an actuator mounted gold mirror.
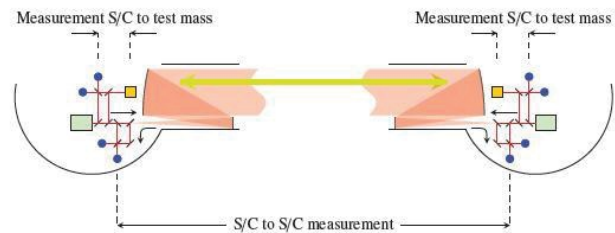

Fig. 2. Partitioning of the pathlength measurement in a single LISA arm. Each measurement between two test masses is broken up into three measurements: two between the respective test mass and the spacecraft and one between the two spacecraft. The blue dots indicate where the interferometric measurements are taken. [1]

II. LISA OPTICAL BENCH

The design of the LISA OB is presented in Fig. 3a. The optical bench forms several interferometers and also has an acquisition sensir anda backfiber link. Figure 3 illustrates all the interferometers: the test mass interferometer (Fig. 3b), reference interferometer (Fig. 3c), science interferometer (Fig. 3d), the backlinkfiber to the other optical bench (Fig. 3e) and the light to the telescope (Fig. 3f).
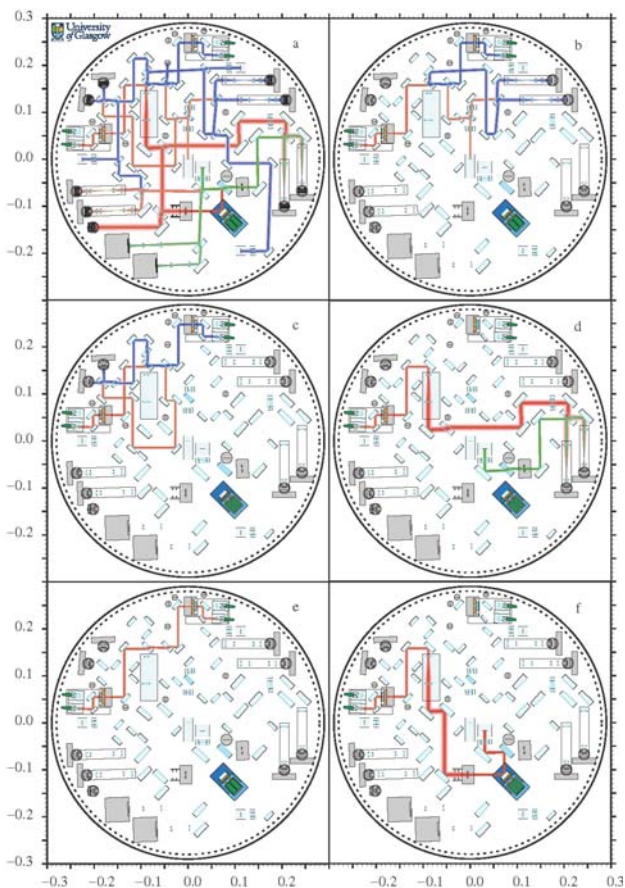

Fig. 3. The optical bench design with all the light beams drawn (panel a); the test mass interferometer with the local oscillator (blue) and the light sampling the position of the test mass passing through the OB (orange) (panel b); only the reference interferometer with the light from the two different lasers (panel c); only the science interferometer with the local oscillator (red) and the beam received from the other spacecraft (green, panel d); passing the light from one laser to the other optical bench through the backfiber link (panel e); and the light transmitted to the other spacecraft via the telescope, passing through the beam expander and through the OB (panel f). [1]

III. TELESCOPE SIMULATOR

The outgoing beam from the LISA OB to the other space-craft is steered by the so-called PAAM actuator [7]. The initial misalignment of the telescope simulator and the outgoing beam pointing have to be corrected on the telescope simulator bench. Two mirrors (M101 and M102) are mounted on piezo driven actuators on the telescope simulator to correct for the PAAM movement. IfoCAD [4] was used to design the layout

shown in Fig. 4. IfoCAD is a raytracing program, which simulates the path of a Gaussian beam passing through programmed components with consideration of their properties. The local fibre injector is located on the top right side. S-polarised light is injected onto the bench. To purify the polarisation the light gets reflected by a polarisation beamsplitter (p-pol light is transmitted and dumped with a beam dump) before the beam splits into two parts. The first part splits again into the commissioning and into a beam which will be guided to the LISA OB. The second part of the beam stays on the telescope simulator bench and is the local beam for the interferometer with the light coming from the LISA OB. Good alignment at BS103 between the local beam and the received beam from the LISA OB is achieved by actuator mounted mirrors M101 and M102 in the local beam path. The lens system, consisting of two lenses on the telescope simulator, transforms the 5 mm collimated outgoing beam of the LISA OB into a 2 mm collimated beam and vice versa. Polarisation optics are used to separate the counter-propagating beams. The outgoing beam of the LISA OB continues through the lens system in p-polarisation before being transmitted through the polarisation beamsplitter PBS102. Its polarisation is changed into s-polarisation via a half waveplate before the superposition with the s-polarised local beam at BS103. The s-polarised local beam reflects at PBS102 and injected into the LISA OB.
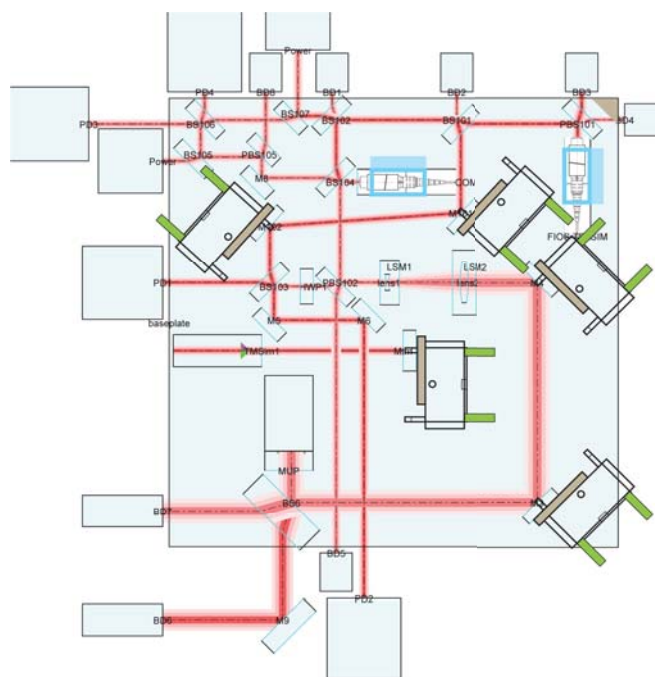

Fig. 4. IfoCAD layout of the telescope simulator. In total five actuator are placed on the optical bench, one of them is part of the test mass simulator. The green part of the actuator is simulating the cables. Photodiodes and beam dumps are positioned beside the optical bench above side slabs, which will be attached to the optical bench.

Independent tests of the stability of the actuator mounted mirror have been carried out. These tests provided infor-

mation on the stability of a single actuator and its thermal compensating mount. The stability of a single actuator stays below the requirement of $2.84\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$. In the case of the test mass simulator these tests are representative since only one actuator is in use. The telescope simulator is operated using a total of four actuators, two in each optical path - therefore a more realistic test scenario of the actuator stability shall be carried out directly related to their later use in the interferometer set-up. For this reason, an additional second fiber injector is providing the so-called commissioning beam for independent commissioning measurement of the telescope simulator without the light from the LISA OB. The commissioning interferometer measures the stability of the telescope simulator bench without having any actuators in its optical path and acts as a reference interferometer. At BS103 the stability of the superimposed beams travelling over the actuators will be measured. A mirror and a quarter-wave plate is located in the optical path between the actuator mirror M3 and BS6 (shown in Fig. 5) to close the optical path. The s-polarised beam is reflected back and transformed into a p-polarised beam by passing twice through the quarter-wave plate and such passes through PBS102, before it gets combined with the local beam at BS103. Also the local beam between BS102 and BS104 has to be blocked for commissioning. The difference of both interferometer measurements provides the stability of the complete telescope simulator including all four actuators.
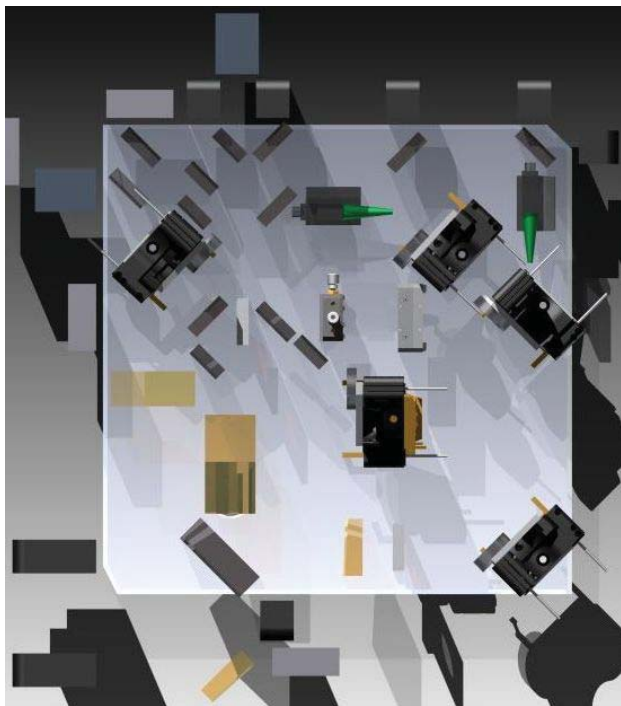

Fig. 5. CAD drawing of the telescope simulator with a mirror and a quarter-wave plate for the commissioning of the telescope simulator.

IV. ACTUATOR

A thermal compensating mount has been constructed to minimise thermally driven displacements of the actuator mounted mirrors shown in Fig. 6. Three feet are glued to the baseplate and allow the thermal compensating mount to bend in one direction. The amount of bending will be compensated by the thickness increase of the adapter plate. The rotation point of the actuator (Newport AG-M100N-V6) is $7.4 \pm 0.05\,\mathrm{mm}$ from its outer edges. The center of the reflection point of the mirror has to be placed within this rotation point such that no coupling from tilt into the longitudinal pathlength is induced.
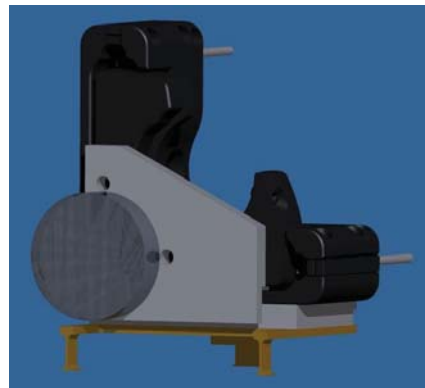

Fig. 6. CAD drawing of the thermal compensating actuator mount set-up

V. CONSTRUCTION

The requirements of the construction of the telescope simulator are similar to the LISA OB. The optical bench has to perform measurements within the picometer/$\sqrt{\mathrm{Hz}}$ stability range. For this reason the optical bench consists of Zerodur and the optical components are silicate bonded to the bench. Silicate bonding [5] is a technique which joins glass components such that they are forming a quasi-monolithic structure. The alignment of the components is critical as after bonding they cannot be removed without causing damage to the baseplate. For less position-critical components a template is used which defines the position of the components, shown in Fig. 7. In total the use of three templates is foreseen; a large main template for most components and two smaller ones. The reference points of the templates are the out-of-plane optics (TMSim and Mup in Fig. 4). The position of the out-of-plane optics is critical since they are steering the beam coming from the LISA OB through holes in the Zerodur baseplate and vice versa. Therefore the out-of-plane optics will be positioned for silicate bonding using a CMM (Coordinate Measurement Machine). The alignment of the reference interferometer on the telescope simulator can not be done fully using a template. Here the interferometer will be constructed by optimising the heterodyne signal in real-time during silicate bonding.
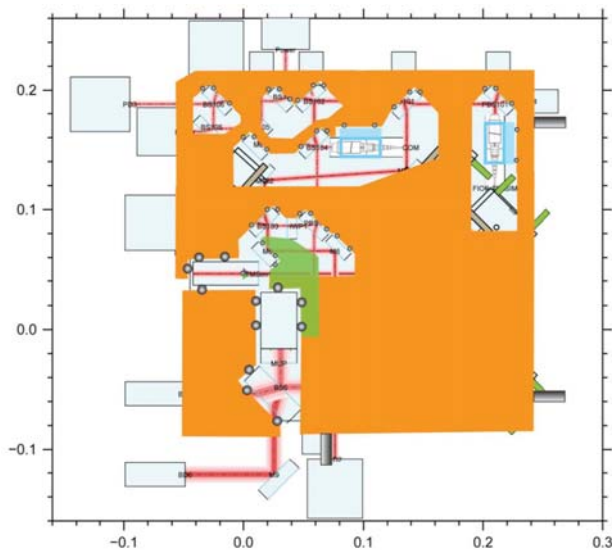
Fig. 7. Template alignment of optical components of the telescope simulator.

The actuator mounted mirrors, beam dumps, and photo-diodes will be positioned using the CMM on thermal compensating side slabs beside the Zerodur baseplate. The two photodiodes reading out the science interferometer have to be positioned on linear actuators since the combined beam positioning is variable due to the PAAM and actuator movements on the telescope simulator.

VI. Commissioning

For the commissioning of the telescope simulator a mirror and a quarter waveplate will be temporarily placed in the optical beam path. For stability the mirror will be optically contacted to the telescope baseplate and the quarter waveplate mount glued such that it can be removed afterwards. The commissioning of the telescope simulator will provide stability measurement of the actuators, also such an end-to-end performance measurement can be carried out using the LISA photodiodes [8] and the LISA phasemeter [9]. This will be an important performance measurement of the system.

VII. Conclusion

The LISA OB requires a simulator to test the test mass interferometer and the science interferometer.

Both of the simulators are placed on the same Zerodur baseplate and will be positioned above the LISA OB. A gold coated mirror mounted on an actuator simulates the test mass. The movement of the beam due to the PAAM on the LISA OB will be compensated using actuators in the telescope simulator. In addition both the layout and construction of the optical bench has been presented. A template will be used for positioning most optical components. Already several aspects of the technology development within the frame of the LISA OB development have been identified for further investigation. The end-to-end performance of the telescope simulator will be one of them.

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