Construction of the LTP Optical Bench Interferometer

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Abstract. The LISA Technology Package is an experiment that will fly onboard the LISA demonstrator mission, LISA Pathfinder. Integral to the LISA Technology Package and to LISA are ultra-stable optical benches capable of measuring inertial test mass positions to below $10\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ over 1000 second timescales. Aspects of the current design and construction of the LISA Technology Package optical bench interferometer are described.

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LTP OPTICAL BENCH OVERVIEW

The joint ESA/NASA mission LISA will combine many technologies to detect gravitational waves using a spaceborne detector [1]. A key technology is the use of 'drag free' test masses as the points between which long baseline measurements are made. The intertial purity of the test mass motion in LISA is technically very demanding and cannot be adequately demonstrated in the 1g earth environment. To address this a smaller scale space mission (LISA Pathfinder) is planned as a technology demonstrator.

The LISA Technology Package (LTP) onboard LISA Pathfinder [2] comprises two intertial test masses and an interferometric readout system to monitor the fluctuations in relative separation of the test masses. One surface of each test mass acts a mirror in the interferometer. An optical bench is situated between the test masses and beamsplitters and mirrors mounted to it form the paths for the heterodyne interferometry that is used for the measurements. The noise level in the principal length measurements will be maintained to less than $10\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ within the frequency range 3 mHz to 30 mHz.

The dimensional stability of the optical bench must meet this demanding requirement whilst being sufficiently rugged to survive launch and the radiation exposure that it will experience *en route* to its operating orbit at the Lagrange point L1. The design and construction of such an optical bench is now well underway and some aspects of this process are described here.

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HISTORICAL PROGRESSION OF OPTICAL BENCHES

The approach to stable interferometry in the context of LTP has been to develop essentially a monolithic bench with all critical components rigidly attached. Light is conducted to the optical bench by a pair of single mode optical fibres carrying 1064 nm laser light with a small frequency offset of typically $\sim$2 kHz. The output fibre collimators are rigidly mounted to the optical bench.

The method of attaching the optical bench components to the baseplate surface has to meet a number of requirements. The bonds must be strong and the position and alignment of the optical components must be maintained throughout the mission. At the same time, however, the attachment method has to allow precision alignment during the assembly phase.

A proven technique that meets these needs is that of hydroxy-catalysis bonding [3]. This is a process whereby certain materials whose surface topologies match very closely can be attached to form an essentially monolithic piece. This process was developed at Stanford University for the Gravity Probe B mission [4] and has subsequently been extended for use in gravitational wave detectors [5].

Prototype optical benches of the style required for LTP have been built at the University of Glasgow and have successfully demonstrated the required interferometry performance [6]. Following this earlier work the LTP engineering model was constructed at the Rutherford Appleton Laboratory, Oxford with assistance from staff at the University of Glasgow and the Albert Einstein Institute, Hannover. The engineering model programme showed that an optical bench of the complexity required for LTP could be successfully constructed using hydroxy-catalysis bonding [7].

FROM ENGINEERING MODEL TO FLIGHT MODEL

Optical Layout

The current optical layout of the LTP optical bench interferometer (OBI) is shown in Figure 1. This layout has some relatively minor changes from the engineering model design, primarily to improve the mounting of the photodiodes and to optimise beam clearances. The optical layout shows:

- the input beams (labeled 'BEAM1' and 'BEAM2') entering *via* the two fibre injector optical subassemblies. The beam height is 12.5 mm above the baseplate surface,
- the beam paths through the interferometers being reflected and transmitted off the various mirrors (labeled with prefix 'M') and beamsplitters (labeled 'BS'),
- the two test masses and the beam reflection points thereon,
- the quadrant photodiodes (labeled with the prefix 'PD') and
- the limits of the Zerodur® baseplate (indicated by a thin line forming a square of $\sim 200 \times 212$ mm). Zerodur® is an ultra-low expansion glass ceramic [8].

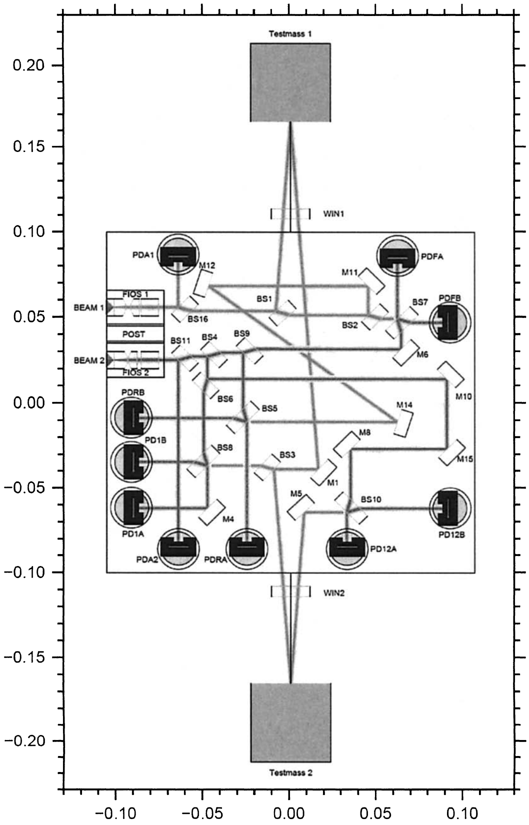

FIGURE 1. The current LTP OBI optical layout, calculated and plotted using the optical propagation program OptoCAD (written by Roland Schilling). Dimensions are in metres.

A CAD model showing the baseplate, optical components and photodiodes is shown in Figure 2.

Tighter reflection point requirements

In the construction of the engineering model a tolerance of 2 mm in the positioning of the reflection points on the test masses was allowed as precision alignment was not necessary to achieve the noise performance, since fixed mirrors took the place of the test masses. In the flight model the relative alignment noise between the test masses and the interferometer leads to a vastly tighter tolerance in the positioning of this reflection point of ±25 μm. This is a challenging target and advanced metrology and alignment capabilities are required to achieve it. These will be discussed further in a later section.

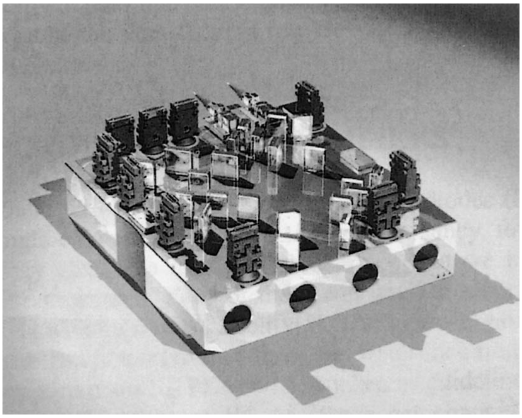

FIGURE 2. A CAD model of the LTP optical bench interferometer.

Fibre injector developments

The fibre injectors used for the engineering model were custom off-the-shelf components. These were used as an expedient solution during the time constrained engineering model programme, but it was recognised that further development was required for the flight model. Whilst the engineering model injectors passed environmental tests it was clear that alterations would have had to be made to the materials for the flight model and more crucially an improved alignment strategy would have been required to reach the tighter flight model beam positioning tolerances. Against this background it was decided that the development of an essentially all fused silica fibre injector should be undertaken.

A novel fibre injector optical subassembly

Since hydroxy-catalysis bonding was already demonstrated to meet the stability requirements for attaching the optical components to the baseplate, it was a natural extension to consider using the same bonding technology to construct and to mount a new type of fibre injector. In the new fibre injectors the beam will travel from the fibre to the exit of a first collimating lens without leaving fused silica, and so without experiencing a refractive index change. The philosophy adopted is to make fibre injector subassemblies (FIOS) and bond them independently to a post that is itself hydroxy-catalysis bonded to the baseplate.

Figure 3 shows one FIOS viewed parallel to the plane of the baseplate surface. The fibre strain relief can be seen on the right hand side of the Figure and is glued onto the cylindrical glass disk into which the stripped fibre is glued. This disk is bonded to a precision length spacer (which is to allow the beam to expand a controlled amount), onto which is bonded a spherical lens. This assembly is bonded to a small baseplate and an aspherical lens bonded a precise distance from the first lens (this lens is for collimation

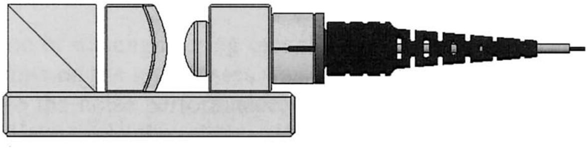

FIGURE 3. CAD model of one fibre injector optical subassembly. The beam travels from right to left from the fibre through a spacer, two lenses and a polariser.

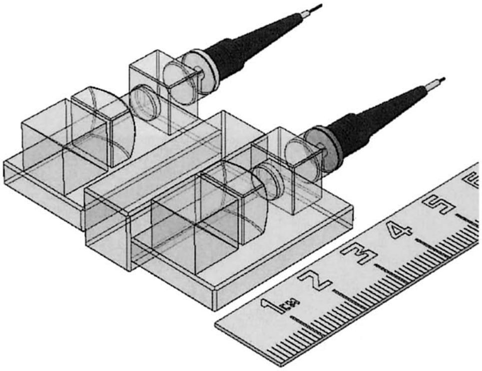

FIGURE 4. A CAD model of the FIOS pair bonded to the post, with ruler for scale.

of the beam and correction of spherical abberation). Finally, a polariser is glued to the baseplate to ensure the correct polarisation is present in the interferometers. A CAD model of the FIOS pair is shown in Figure 4.

To optimise the interference signals in the interferometry the two FIOS must produce beams with slightly different parameters. This is achieved during assembly of the FIOS by precise adjustment of the interlens spacing and by choice of the length of the spacer prior to the first collimating lens.

Photodiodes

The quadrant photodiode (QPD) assemblies used in the engineering model were successful but some changes were considered beneficial.

- The active area of the QPD is very sensitive and can be easily destroyed by physical contact, *e.g.* during further assembly of the OBI with the other subsystems. For this reason it was decided to make the QPDs replaceable using a ‘top-loading cartridge’ design.
- Fused silica windows will be used for the flight model QPDs (there were no windows on the engineering model QPDs).
- The QPDs are attached to the Zerodur® baseplate after the optical components are mounted. Unlike the engineering model, the flight model photodiodes must be centered on the optical beams to $\sim 30\,\mu$m.

The photodiode redesign and manufacture are being undertaken by the University of Birmingham.

ALIGNMENT PLAN

The tight tolerances needed have necessitated the development of a new alignment approach.

- The use of a coordinate measurement machine allows surface positions to be determined at the ∼micron level. This is essential for steps such as aligning the FIOS to the baseplate and also for hitting the ‘virtual’ test mass reflection points (which are just coordinates in space during the OBI assembly).
- In order to position the mirrors and beamsplitters (which have reflecting surface dimensions of $\sim 20 \times 15$ mm and are 7 mm deep) micro-positioner actuators are used. These are two part actuators, one DC stepper stage (with micron resolution) and a PZT stage (with 10 nm resolution). The actuators with contacting styli are shown in Figure 5.
- To be able to measure the beam centre with respect to the baseplate, calibrated quadrant photodiodes will be used. These are quadrant photodiodes in a casing whose location with respect to the photodiode centre is known. By positioning a pair of these photodiodes at known distances along the beam path, the direction of the beam can be determined. These photodiodes will also function as precision targets by mounting them at the desired location and steering the beam onto them.

SUMMARY

Ultra-stable optical benches are now a proven means of assembling the interferometry subsystems for missions like LISA and LISA Pathfinder. The flight model optical bench interferometer for the LISA technology Package onboard LISA Pathfinder is a challeng-

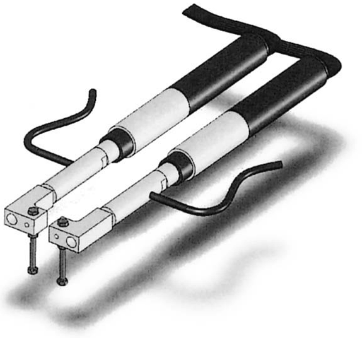

FIGURE 5. CAD model of the micro-positioner actuators to be used for component manipulation.

ing demonstration of precision technology, and is currently being built at the University of Glasgow.

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