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Construction of an optical test-bed for eLISA

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Abstract. In the planned eLISA mission a key part of the system is the optical bench that holds the interferometers for reading out the inter-spacecraft distance and the test mass position. We report on ongoing technology development for the eLISA optical system like the back-link between the optical benches and the science interferometer where the local beam is interfered with the received beam from the distant spacecraft. The focus will be on a setup to investigate the tilt-to-pathlength coupling in the science interferometer. To test the science interferometer in the lab a second bench providing a laser beam and a reference interferometer is needed. We present a setup with two ultra-stable low expansion glass benches and bonded optics. To suppress the tilt-to-pathlength coupling to the required level (few $\mu\text{m}/\text{rad}$) imaging optics are placed in front of the interferometer photo diodes.

1. eLISA optical system technology development

'The Gravitational Universe' [1] was selected as the science theme for the L3 mission by the European Space Agency (ESA). The launch is currently planned for 2034. The Laser Interferometer Space Antenna (LISA), a laser interferometer measuring gravitational waves, addresses this science theme. At the Albert Einstein Institute in Hannover we are developing technologies for the optical system for eLISA (evolving LISA, standing for the constantly evolving LISA mission scheme). The experiments are addressing different aspects of the optical system that have been identified by the LISA community to need further experimental investigation.

2. eLISA interferometry test-bed

Together with the University of Glasgow and Airbus Defense and Space we developed and built a representative setup to test the interferometry for eLISA. The minimal optical bench operates with a reduced set of optical components to what the optical bench for an eLISA spacecraft would require. The optical bench is located between the test mass and the telescope for sending and receiving a laser beam from the distant spacecraft. It incorporates several interferometers for reading out the distance to the remote spacecraft and the test mass. The



individual measurements are then combined to form the laser link between two test masses in distant spacecrafts.

The minimal version has only one measurement interferometer but is built with space qualified techniques and the experience from the University of Glasgow who built the optical bench for LISA Pathfinder [2]. The interferometer is the science interferometer that is reading out the inter spacecraft distance and this is the most challenging one because of spacecraft jitter and the long distance of millions of kilometers. The spacecraft jitter is inducing a tilt-to-pathlength coupling that is, after shot noise, the second largest noise source for eLISA. For reducing this coupling imaging optics are placed in front of the interferometer photo diodes. They are imaging the entrance pupil of the telescope to the photo diode to reduce the beam walk due to the tilt of the beam. There have been extensive theoretical studies on this topic [3] but no representative experiments have been conducted so far. Because of its significance a good understanding of the tilt-to-pathlength coupling and a verification of the simulations are important.

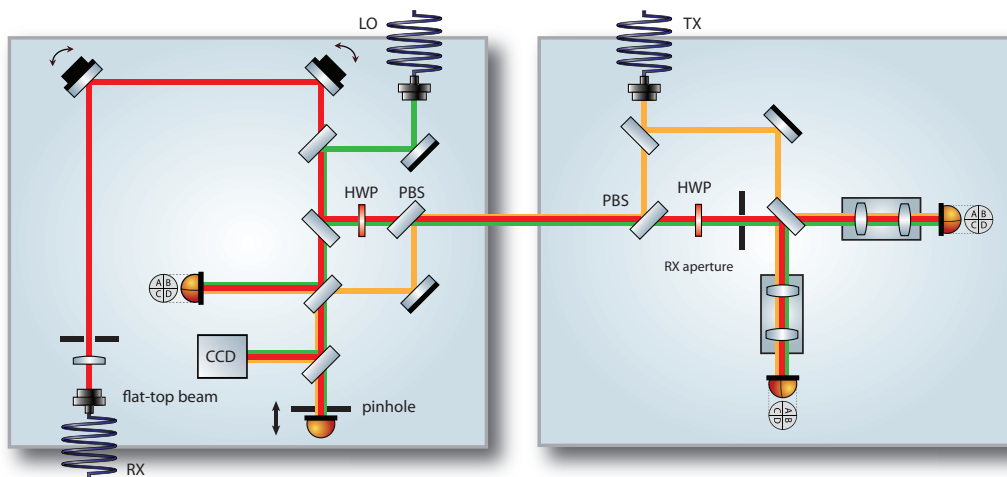


Figure 1. Schematic of the layout of the minimal Optical Bench (right) and the Telescope Simulator (left).

For operating the science interferometer a second bench, the so called Telescope Simulator, was built. The Telescope Simulator is providing a laser beam representing the beam from the distant spacecraft (RX beam). This beam is tilted for simulating spacecraft jitter and has a flat top beam profile. A schematic of the combined setup is shown in Fig. 1. For aligning and calibrating the setup a stable reference beam (LO beam) was included as well as a calibrated quadrant photo diode pair (CQP) [4] on the optical bench. The Telescope Simulator has also a phase camera for beam diagnostics and an additional Gaussian beam for comparison and a back-up for the flat-top beam. The Telescope Simulator base plate has a Zerodur[®] tip-tilt mount for alignment so that the whole setup has an ultra low thermal expansion coefficient. Pictures of the setup are shown in Fig. 2 and Fig. 3. All optics are bonded using hydroxide catalysis bonding [5] and precision alignment techniques similar to those developed for the LISA Pathfinder optical bench interferometer [6].

Two different designs of imaging systems will be tested and compared. One is a classic four lens imaging optic, the second one has only two lenses (see Fig. 3). The tilt-to-pathlength

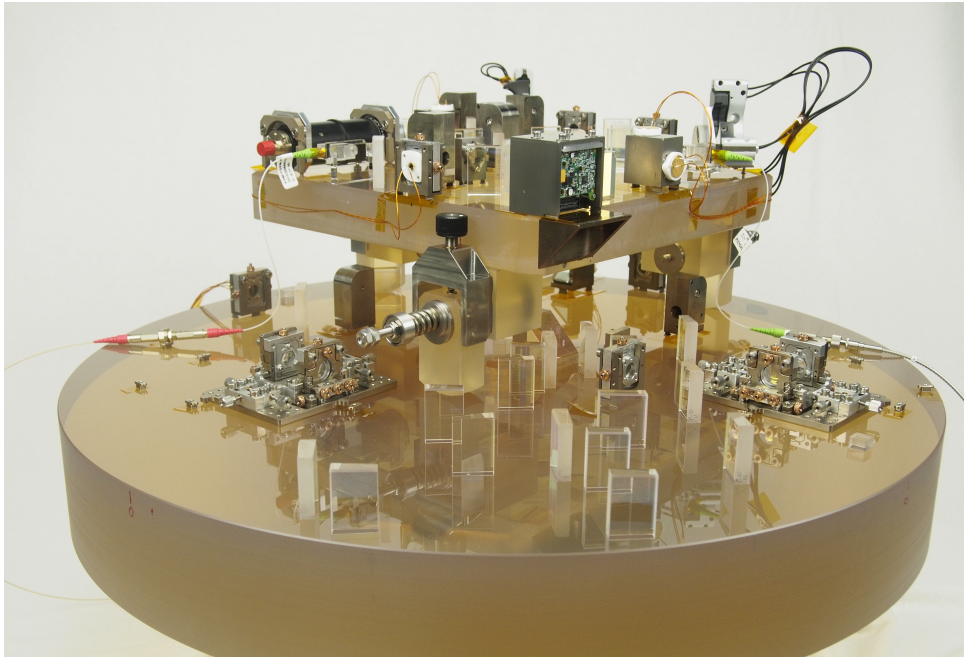


Figure 2. Photograph of the Optical Bench with the Telescope Simulator on top. The beams are going through a hole in the Telescope Simulator base plate to the Optical Bench via periscope optics. The baseplate of the Optical Bench is 58 cm in diameter.

coupling is measured by tilting the RX beam via two piezo driven mirror mounts and measure coupling factors in the science interferometer. The requirement is to reduce the coupling to a few $\mu\text{m}/\text{rad}$. In addition the experiment will investigate alignment tolerances of the lenses and compare the results to the optical simulations. This is important to be able to adapt the imaging systems to the exact mission parameters.

For operation the setup is placed in a vacuum chamber and operated with 1064nm laser light prepared on a three-arm modulation bench, providing three different laser frequencies with kHz heterodyne frequencies.

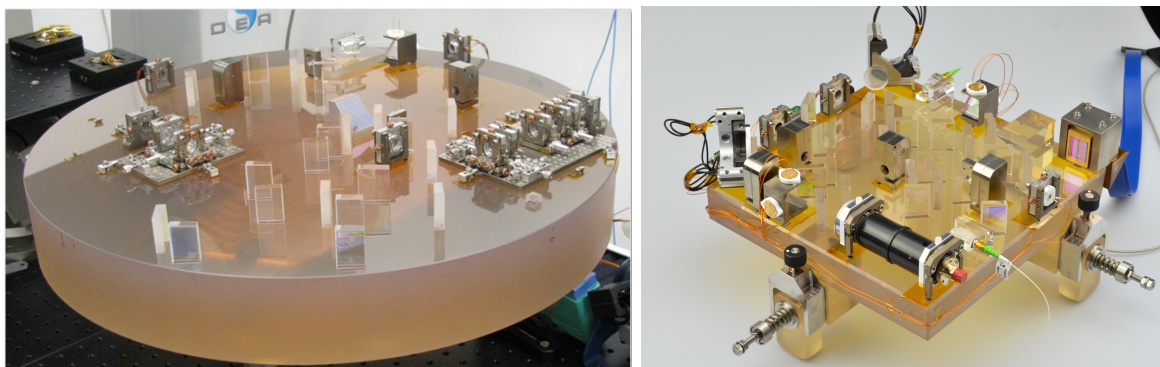


Figure 3. Optical bench with the two different imaging systems to test (left, photography courtesy University of Glasgow) and Telescope Simulator (right)

The construction and integration of the experiment is finished and the investigation of the tilt-to-pathlength coupling has started. The setup is a great test bed to test a lot of aspects of

the eLISA interferometry. Most components have been developed for an elegant breadboard design for LISA and therefore to be space qualified. The all-Zerodur design should make the setup stable to the picometer level as required for eLISA. All components except for the ultra stable optics are replaceable for flexibility. This setup will allow experiments to test picometer interferometry, MHz heterodyne frequencies, improved imaging optics, extreme low power measurements (Picowatts) and untested new ideas like an active aperture.

3. Three back-link experiment

eLISA has two test masses and optical benches in the middle spacecraft of the triangular constellation, one for each link. This is necessary because the constellation is breathing and the angle between the links is changing. To form a Michelson-like interferometer in post processing the phase relations between the individual links are needed. An optical back-link between the optical benches is used that has to be reciprocal in both directions to single picometers. This is possible with a fiber-based link with sufficient straylight suppression [7]. To investigate alternative solutions with less straylight issues a setup with three different back-links is currently planned and built. It includes two optical benches that can be rotated with regard to each other. The tested solutions are a free beam back-link with actuated mirror mounts and a fiber based link that includes an additional laser frequency to separate the stray light by frequency.

4. Amplifier phase fidelity measurements

A possible laser source for eLISA is the laser used for LISA Pathfinder amplified by a fiber amplifier. A candidate for the amplifier is a Ytterbium doped fiber amplifier developed for inter-spacecraft communication. To test this amplifier a portable test setup is developed to measure the phase fidelity which is unknown for this amplifier. For eLISA GHz sidebands will be modulated on the laser to transmit clock information. This is necessary because the clocks of the spacecraft are not stable enough and a clock noise correction is needed. The clock noise information is imprinted on the laser by an EOM in front of the amplifier and therefore the amplifier has to transmit the sideband phase with very low phase distortions [8].

Acknowledgments

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