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Design of the Tx Attenuating Photoreceiver for the LISA Stray Light Assessment Instrumentation

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ABSTRACT

This paper describes the design of a unit called Tx Attenuating Photoreceiver (TAP), dedicated to the measuring and dumping of a 2 W beam with 300 mm diameter. This unit is a part of an instrumentation called Stray Light Optical Ground Segment Equipment for the test of the Interferometric Measurement System (IMS) of the LISA mission. The geometry of the instrument is studied to reduce the size of the beam, focus it on a photodiode, dump its power and minimize scattering and reflections back to the IMS. An off-axis parabolic absorber with anti-reflection coating will stop the beam, reflecting only 0.2 % towards a pinhole and a photodiode. Most of the materials and components are commercially available, but the design and size of the parabola are specific.

Keywords: LISA, Beam Dumping, Scattering, Stray Light

1. INTRODUCTION

The capability of gravitational waves detection, already proven by several observations made using LIGO and Virgo interferometers over the last 7 years,[1] has opened a wide range of opportunities for the study of black holes and neutron stars, with applications in cosmology, astrophysics and fundamental physics.

The mission LISA (Laser Interferometer Space Antenna), promoted by ESA in collaboration with NASA, will overcome the size limitation of terrestrial interferometers, measuring gravitational waves with interferometric arms of 2.5 millions kilometers. This will allow observation of gravitational waves at lower frequencies (from 0.1 mHz to 1 Hz), corresponding to gravitational wave sources that differ from those observable by LIGO and Virgo. With LISA it will be possible to observe supermassive black hole mergers, extreme mass ratio inspirals (i.e. objects of stellar mass spiralling towards a massive black hole), intermediate mass black hole binaries and to monitor compact binaries in the initial stages of their merger, foreseeing, weeks in advance, time and position of the event and allowing for full real-time observation of the electromagnetic or neutrino counterparts (multimessenger astronomy). Also black holes physics and evolution, expansion of the universe and gravitational wave background will be studied.

The mission, which is now in phase B and is scheduled for launch in 2035, will put three spacecraft in orbit around the Sun on a triangular constellation. On each spacecraft two laser beams will be generated and directed towards the other two, providing, by interference with the local beams, information on the deformations of the 2.5 million km distance caused by the passage of a gravitational wave.[2]

One of the main concerns for this mission is the amount of stray light present in the LISA interferometric measurement system, since the noise objective in the LISA arm length measurement ($10\ pm/\sqrt{Hz}$) implies that the allocations for stray light-related noise are kept well below $1\ pm/\sqrt{Hz}$ for most of the many possible contributions to stray light. To test the absence of such low levels of stray light after integration, an instrumentation must be built, the SL-OGSE (Stray Light Optical Ground Segment Equipment) with the purpose of measuring the stray light optical amplitude, for each possible stray light path length leading to one given LISA's photoreceiver.

To do so, the instrument will inject, using one of LISA's optical bench injectors, a laser beam with an optical frequency that is ramped linearly with time, and record the signals from several photoreceivers:

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- LISA's quadrant and single element photoreceivers
- Additional, dedicated photoreceivers, such as the photodiode in the "Tx attenuating photoreceiver" (TAP) described below.

The Fourier transform of the recorded signals will reveal the presence of interference fringes caused by stray light interfering with nominal light. From the frequency of a given fringe, and the knowledge of the laser's optical frequency ramp, one can infer the stray-to-nominal light path length difference, and thus identify the faulty component, in addition to providing the corresponding optical amplitude.[3]

The SL-OGSE will produce a 2 W laser beam and inject it in LISA's interferometric optical bench (OB) through the Tx fibered injector. A fraction will be picked-up for referencing the OB's interferometers, but most of this power will be transmitted through the 30 cm diameter telescope, designed to send the beam to the distant spacecraft. During the SLOGSE tests, this powerful and large beam must be dumped, yet keeping to a minimum the optical return (back-reflection and scattering) to LISA's telescope and interferometers. But the variations of the emitted beam power must also be measured, to assess the fraction of stray light present in the beam emitted to the distant spacecraft.

The TAP (Tx attenuating photoreceiver) is the part of the SLOGSE instrument that is dedicated to these tasks, and given the peculiar nature and characteristics of the beam involved, it requires a custom design and a careful study of its performance in terms of geometry and optical return.

This document will describe the foreseen design, choice of optical elements, materials and performance of the TAP.

2. SETUP DESCRIPTION

The schematic of Fig. 1 shows the ensemble of the instrument within its vacuum chamber and with associated equipment and electronics.

- The MOSA (Movable Optical Sub-Assembly), is the assembly of LISA's optical bench, telescope and gravitational reference sensor which needs to be tested; it is highlighted in yellow.
- The frequency-swept laser beam is injected through the Tx injector.
- The command/control unit acquires the signals from the MOSA photoreceivers, which are devoted to measuring the heterodyne interferometer signals during the LISA mission, and from additional photoreceivers, such as the TAP photoreceiver, dedicated to the SL-OGSE tests.
- The CAS (Constellation Acquisition Sensor) is an imaging camera that is devoted to finding the distant spacecraft and assisting in finding the orientation of the MOSA for which the received (Rx) beam interferes with the local beams.

The target of the SL-OGSE instrument is to observe the different contributions to stray light in the photoreceivers and in the emitted beams, and measure the fractional optical amplitude of each contribution. One can show[3] that the fractional optical amplitude is equal to half the fractional fringe amplitude in the photoreceiver signal when the SL-OGSE laser's optical frequency is swept. The list of the fractional fringe amplitudes *vs* the corresponding fringe frequencies represent the stray light content to a given photoreceiver when shining a given fibered injector and allows identification of the faulty components.

At the 30 cm diameter telescope aperture a 2 W "Tx" (transmit) beam is emitted, and, during the stray light tests, such a powerful beam coud be a tremendous source of stray light if not appropriately dumped before it scatters on the walls of the vacuum chamber. The TAP is designed to avoid this occurrence.[3]

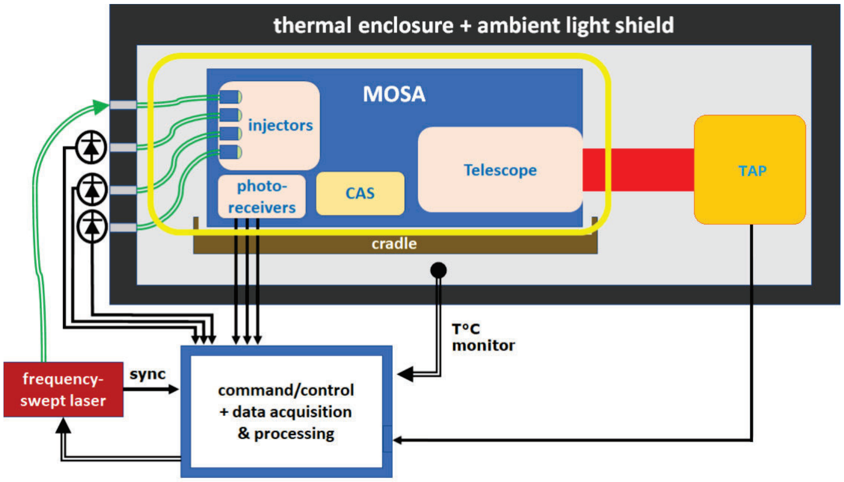


Figure 1: Schematic drawing of the SL-OGSE setup. Double green lines: polarisation maintaining fibers. Single black lines: photoreceiver signals. Double black lines: command/controls and sensors.

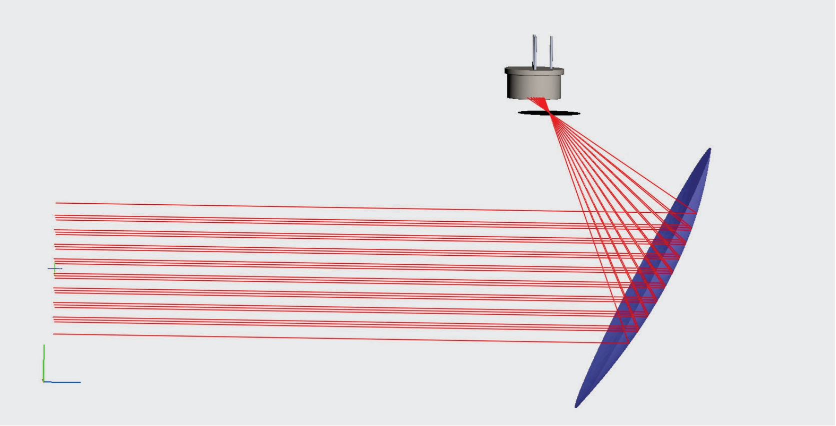


Figure 2: Schematic of the three elements of the TAP: parabolic mirror with 0.2 % reflection, pinhole and photodiode. Drawing is not to scale.

2.1 TAP design

The TAP will be composed by three optical elements: a parabolic absorbing mirror, a pinhole, a photodiode (PD), as shown in Fig. 2. The first element will focus the beam, reducing it to a manageable size, and its reflectivity will be chosen so as to decrease the beam power to a level (2 mW) that is appropriate for PD detection. The second element will block the reflection from the PD. The latter element will, during the frequency scans, record the Tx beam power, and hence, after Fourier transform, provide the required information about the stray light content in the Tx beam emitted towards the distant spacecraft.

The optimisation of the design has been carried on thanks to the optical analysis software FRED, see Fig. 3. In the optical setup the beam coming from the MOSA is simulated as a “Laser Diode Beam” source, which emulates the intensity profile and divergence of the Tx beam, and propagates the beam taking all coherence effects into account. The position of the source corresponds to the internal pupil of the telescope, where the beam has a waist radius of 1.1 mm and a power of 2 W. It is then reflected by the four mirrors of the LISA telescope and arrives first on the TAP’s parabolic mirror and then on the PD, passing through the pinhole.

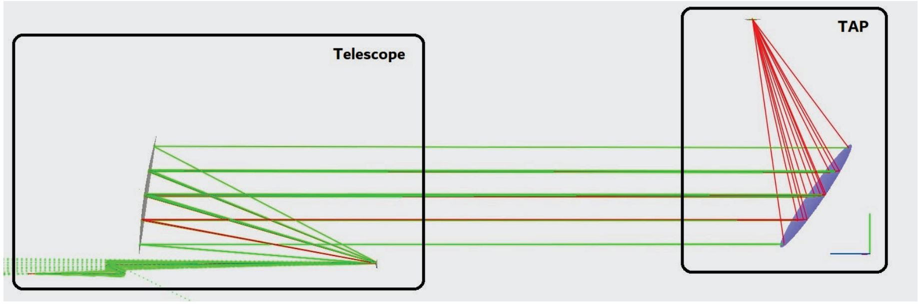


Figure 3: Optical design used for the optimisation of the setup (and later to calculate scattering from parabolic mirror, see 3.1). Nominal beam is in red and travels from the telescope (left) to the PD surface (top), back-scattered rays are in green.

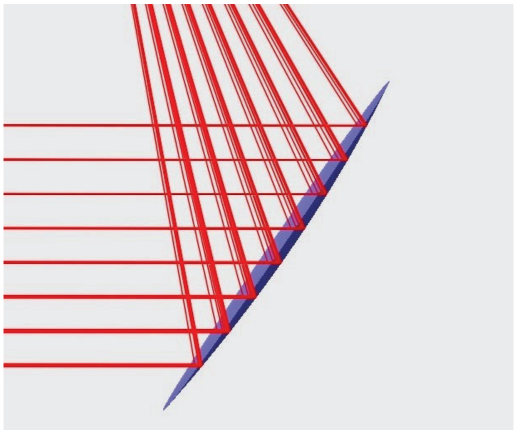


Figure 4: Parabolic mirror focusing rays coming from the telescope.

Details on the telescope design used for these simulations are shown in Ref. 4.

2.1.1 Parabolic reflector

The first optical element is designed to focus the beam towards the PD, at a reasonable distance and with a spot dimension that fits in the PD's active surface, while maintaining dimensions and shape that can be manufactured and handled without problems. The resulting object is an off axis parabolic surface, whose characteristics are listed in Tab. 1

The main constraints in the choice of the mirror geometry are the divergence of the reflected beam, which has to be kept low enough to allow for an easier positioning of the PD behind the focal plane, and the overall dimensions of mirror and TAP that must not exceed spatial and manufacturing limitations. An effective way to reduce divergence and mirror dimensions is to increase the decentering of the mirror in the y direction. When the distance between focal point and center of the mirror in the y direction is increased from 200 mm to 548 mm, in fact, the divergence of the beam is reduced from 20° to 15°. This position has been chosen as a good compromise between decentering and PD-mirror distance.

Several curvature radii have been tested, ranging from 200 mm to 1000 mm. A curvature radius of 800 mm has been chosen because it provides a small mirror surface and it directs the beam in a direction that is practical for PD positioning.

To absorb most of the power, the mirror will be made of KG3 Schott glass,[5] which has a typical transmission of about $3 * 10^{-4}$ (specified < 0.001) at 1060nm, for a thickness of 2 mm. The glass pane will be put on a metal

Table 1: Geometrical specifications for the first optical element of the system.

Characteristic	Value
Shape	Parabolic
Curvature radius	800 mm
Decentering	548 mm
Optical aperture radius	160 mm
Physical diameter of the disc	388 mm

substrate, to block residual transmission and dissipate the heat of the absorbed beam. An anti-reflection coating (ARC) will be applied, to bring the intensity of the reflected light to a few milliwatt and reach an ideal power range for measurements with the PD (see 2.1.3).

According to the simulations made with the optical analysis software FRED, the beam will be focused 554 mm away from the center of the mirror and it will have a waist of a few micrometers. It will then reach the PD with a slightly deformed gaussian profile of approximately 1.5 mm in diameter. Fig. 5 shows the expected intensity profile of the beam in the two positions.

Heating due to the 2 W absorption is not studied here.

2.1.2 Pinhole

In the focal plane a pinhole will be inserted. It will block both the stray reflection from the PD, which could be a significant source of bias in the SL-OGSE recorded signals, and the scattered light coming from other optical elements in the system.

Since at the spot the beam waist will be of just a few micrometers, the hole of this pinhole will be of 10 μm. This is a standard optical element, available commercially (e.g. Thorlabs[6]). The surface of the pinhole will be coated on both sides with a black polymer for better performance.

2.1.3 Photo-Diode

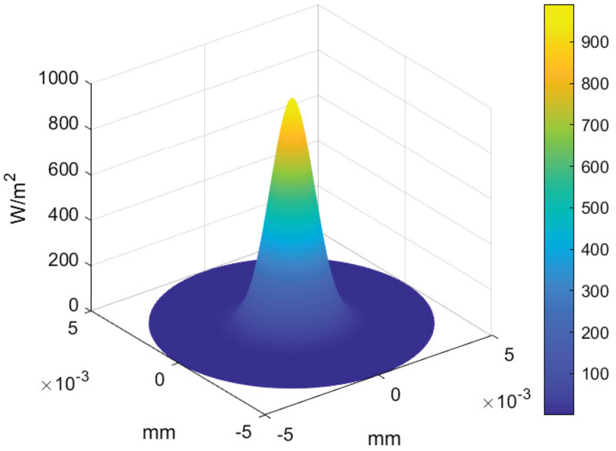
The detector will be a Hamamatsu InGaAs PD (model G10899-03K), 3 mm of diameter, with high efficiency at the wavelength and power range of interest,[7] the responsivity at 1064 nm is in fact 0.7 A/W. The PD will be positioned 3 mm behind the pinhole; since the half divergence of the beam is approximately 15°, this is the maximum distance from the pinhole allowing to keep the whole beam inside the PD's surface (the fraction of power that escapes detection with this configuration is $4 * 10^{-6}$).

3. STRAY LIGHT OPTICAL BUDGET

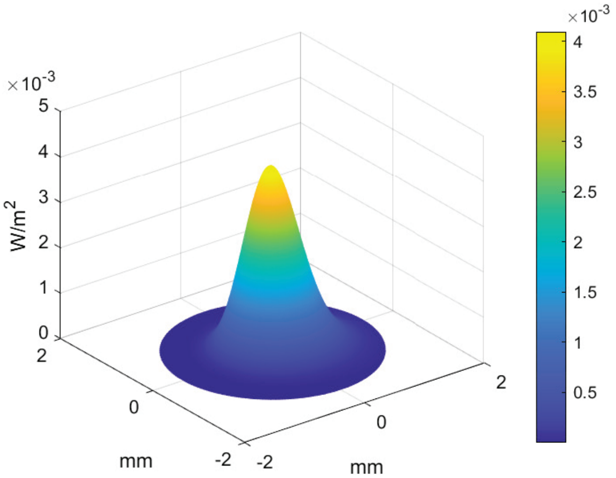
The SL-OGSE instrument will measure stray light levels in LISA interferometers (where stray light affects the phase of the heterodyne beat-notes during the LISA mission) and also in the CAS (Constellation Acquisition Sensor), the camera that will be used to search the weak signal coming from the distant spacecraft and allow the correct orientation of the 3 spacecraft in the constellation.

Stray light returning from the TAP to the interferometers will give rise to an unwanted interference signal, in the MOSA's photoreceivers, with a frequency proportional to the distance between the MOSA photoreceivers and the TAP. For this reason, positioning the TAP far enough (1.5 m is the minimal acceptable distance), from the telescope aperture will allow to reject the corresponding fringe signal away from the frequency range that is relevant for detecting stray light sources in the MOSA optics.

On the contrary, stray light directed from the TAP toward the CAS will directly superpose to the stray light originated in the MOSA, thus influencing the stray light measurements. Requirements regarding the amount of stray light permitted from the TAP are not yet available, but for this preliminary design we can compare it directly to the stray light originated by the telescope mirrors, which will be the biggest stray light source from



(a) Spot intensity profile on the focal plane



(b) Spot intensity profile on the PD, located 3mm after the focal plane

Figure 5: Beam intensity profiles on key positions: focus plane and detector. The areas represented in the two plots correspond to the hole size of the pinhole and the active area of the PD, respectively.

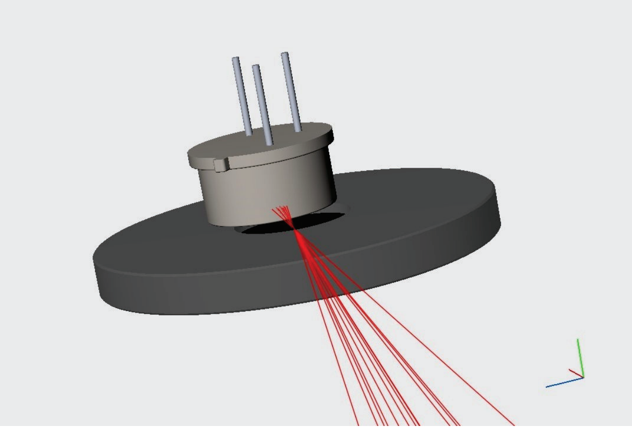


Figure 6: Optical rays passing through the pinhole and arriving on the PD. The two elements are tilted with respect to the chief ray, to minimize the optical return, and are therefore laterally shifted between each other.

the MOSA to the CAS, and whose contribution has already been estimated to be of $4 * 10^{-9}$ W thanks to FRED simulations (for a 2 W Tx beam and CL300 contamination, at the CAS interface).

The main contributions to stray light from the TAP will come from the parabolic mirror, which receives the full 2 W beam and will scatter some of it according to its roughness and contamination characteristics, and the PD, which could reflect directly part of the light back to the MOSA unless the PD is appropriately tilted. The following paragraphs analyse the two contributions.

3.1 Scattering from mirror

Scattering expected from the mirror surface is simulated with the optical setup shown in Fig. 3. In this case, the coherent source is substituted by a grid of 100x100 rays, on a surface as wide as the telescope pupil, and following the same propagation path. On the TAP mirror surface, 50 scattered rays (in green in Fig. 3) are created for each incident ray. They are directed into a cone 0.02° wide around the back-scattering direction, enough to cover the whole 30 mrad CAS field of view.

Scattering due to roughness from mirror surface is modelled with a Harvey-Schack model whose parameters are chosen to simulate an optical quality surface of 15 Å RMS roughness ($b_0 = 2.51\ sr^{-1} \quad l = 0.001 \quad s = -1.8$). Scattering due to contamination is handled according to Mie theory and the IEST-STD-1246D standard for a cleanliness level of 300, a reasonnable value for an instrument that should be maintained permanently under clean conditions.[8]

Results indicate that the power going back to the optical pupil is $1.1e - 11$ W. Since between the telescope pupil and the CAS system there is a 90/10 beamsplitter, the power reaching the CAS interface will be of 1 pW, which is a power level well below the values expected from the telescope to the CAS.

3.2 Reflection from PD

Given the high divergence of the beam reaching the PD, part of the tail of the gaussian intensity distribution can be reflected back through the pinhole and to the CAS. If we want the reflected light on the CAS to be lower than 1 pW, we must limit back-reflection to 5 nW (reflection from the mirror, assumed 0.2 %, and the beamsplitter, 10 %, will bring it to the target value). To reach this goal the PD surface is not perpendicular to the chief ray propagation direction; this 22° tilt will result in a 60 pW reflection inside the pinhole area. This creates a misalignement between the pinhole and the center of the PD, which will be shifted 1.16 mm from the center of the pinhole (see Fig.6).

4. CONCLUSIONS

As a part of the test campaign for the LISA mission, it was necessary to create a setup able to handle a 2 W, 300 mm wide beam, dumping most of the beam while measuring its power fluctuations and avoiding the return of stray light towards the other parts of the setup.

The task will be performed by a three elements instrument, composed by a parabolic mirror, a pinhole and a photodiode. Particular care was taken in the choice of the materials and geometry of the mirror, since the power had to be reduced to an acceptable level for the photodiode and stray light strongly depended on the beam reflection direction and divergence.

The chosen material is KG3 and the mirror will be an off-axis parabolic surface 388 mm wide.

ACKNOWLEDGMENTS

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