Suppressing ghost beams: Backlink options for LISA

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Abstract. In this article we discuss possible design options for the optical phase reference system, the so called backlink, between two moving optical benches in a LISA satellite. The candidates are based on two approaches: Fiber backlinks, with additional features like mode cleaning cavities and Faraday isolators, and free beam backlinks with angle compensation techniques. We will indicate dedicated ghost beam mitigation strategies for the design options and we will point out critical aspects in case of an implementation in LISA.

1. Introduction

The laser interferometer space antenna (LISA) consists of three spacecraft (S/Cs) forming an equilateral triangle in space [1, 2]. Six laser links between the S/Cs establish the operation of three independent Michelson interferometers. Figure 1a shows the sketch of a possible LISA mission with 5 million km arm lengths and an angle of 60° between the laser links. Due to orbital motion the angle between the laser links will change by ±1.5° and the arm length mismatch will reach a maximum deviation of the order of 1% over the period of one year. Accordingly to these effects the interferometric phase measurement will be influenced significantly: First, the arm length mismatch of 50000 km causes laser frequency noise dominantly couple into the phase measurement. Second, without compensation the angle variation will lead to a complete loss of the intra-S/C laser links.

1.1. LISA with Telescope Pointing and Backlink

The current baseline for LISA foresees two movable optical subassemblies per S/C, each consisting of an optical bench (OB) mounted to the back of a telescope along with a proof mass, and equipped with a local transmitted laser beam, so called TX beams, such that the complete optical subassemblies including the OBs can independently follow the incoming beam and compensate the angular variations. This technique, also referred to as Telescope Pointing, ensures the preservation of full contrast within the inter-S/C interferometry by actuating the

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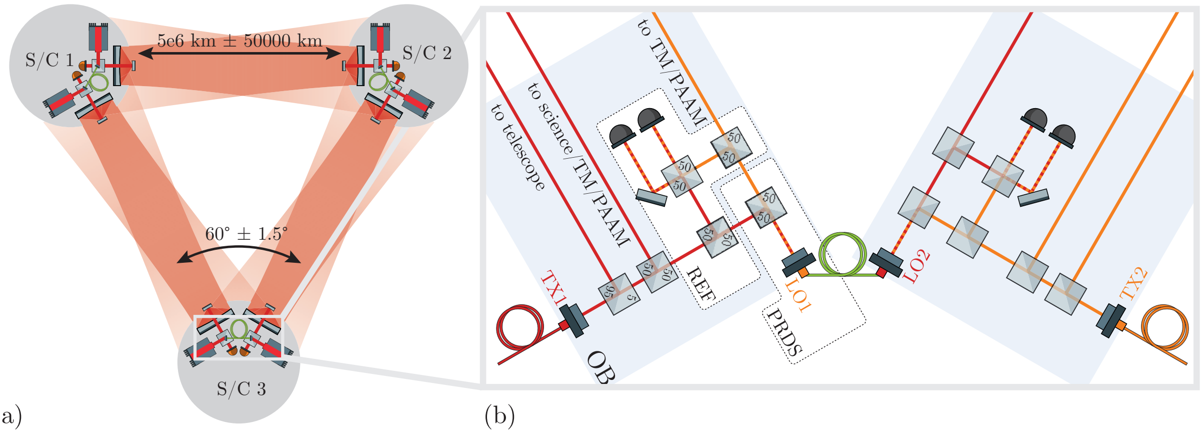


(a) (b)

Figure 1: (a) Sketch of the laser interferometer space antenna (LISA). (b) Magnified view of the two optical benches (OBs) within one S/C showing the phase reference distribution system (PRDS) including the injection of the local oscillator beam (LO) from the adjacent OB via backlink connection, the reference interferometer (REF) and the injection of the local laser light (TX beam). The interferometers per OB are namely the science, test mass (TM) and point ahead angle mechanism (PAAM) interferometer

OBs via two moving optical subassemblies. The data post-processing technique, Time Delay Interferometry (TDI), can deal with the laser frequency noise caused by the unequal arm length interferometer, but it requires, amongst other things, the knowledge about the phase behavior between the two TX beams. As consequence of implementing both, Telescope Pointing and TDI in LISA, two challenges need to be met:

Firstly a flexible optical connection is required that provides the TX beam as local oscillator (LO) beam for the other OB. Secondly, the exchange of the TX beam is required to perform a phase reference measurement. Together, this is the so called backlink, or phase reference distribution system (PRDS). The absolute path length of the PRDS is not crucial, but the path length difference between clockwise and counter-clockwise traveling light, the so called non-reciprocity, is required to be less than $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ such that a single Michelson link is sensitive to about 10^{-20} in strain [4]. Earlier experiments have shown that this phase stability can be reached by using quasi-monolithic interferometers in a thermally stable low-pressure environment [3]. For the actual PRDS the optics are not invariably stable. Due to the rotating OBs the backlink connection is either flexible itself, or actively controlled, or it is insensitive to beam tilts.

1.2. The LISA optical bench

The PRDS will be implemented in the LISA OB and thus depends on the current LISA design. A magnified view of two OBs within one S/C is shown in Figure 1b. Each OB has a local laser source that provides the TX beam. The TX beams are frequency shifted relative to each other by a few MHz to perform heterodyne interferometry. The part of the OB shown here can mainly be separated into three segments: Firstly, as laser preparation we denote the splitting of the TX beam into the interferometers, namely the science, test mass and point ahead angle mechanism interferometer and into the telescope that takes the major share of the laser light (95%). Via the telescope the light is sent to the remote S/C and received by it. Secondly, the PRDS that is located on the OB and provides the transfer of the TX beams between the OBs. The TX beam from the adjacent OB is used as local oscillator (LO) beam on the regarded OB. Thirdly, the reference interferometer interferes the LO and TX beams and therefore delivers the phase information between the two 5 million km Michelson links required for TDI.

Both, the engineering and the optical requirements, make the search for an optimal PRDS challenging. This article lists a selection of potential backlink candidates and we briefly estimate their complexity, their applicability for LISA (implementation and redundancy opportunity) and the parasitic noise influences, e.g. caused by ghost beams.

2. The classic fiber

The straight forward approach to achieve a flexible PRDS is the usage of a fiber that exchanges the TX beams between the benches. Figure 2a shows a layout of two OBs hosting a fiber backlink and the reference interferometer, but not the full LISA OB for simplification. Experiments, comparing a fiber backlink connection with an ultra stable quasi-monolithic optical connection implemented on one OB, have shown that a fiber-based PRDS is limited in its phase measurement by so called ghost beams that cause unwanted interferences. By applying designated correction and stabilization methods, like balanced detection for a ghost beam correction in post-processing and the usage of a fiber length stabilization to reduce the dynamic motion of ghost beams generated inside the fiber, the classic fiber backlink is able to achieve the desired LISA performance [4, 5]. But the balanced detection method requires photodiodes on both output ports of the recombining beam splitter and needs to provide about three orders of magnitude of suppression. For keeping the redundancy in LISA the number of photodiodes would increase by a factor of two. Furthermore, the active feedback control loop for the fiber length stabilization requires additional control electronics on board of the S/C. Most of the approaches that reduce ghost beams only increase the signal to ghost beam power ratio but do not fully remove the ghost beams from the set-up. At this point it is crucial to consider the complete LISA OB design including the telescope. Only the total number of ghost beams of each part of the LISA OB counteracting with the interferometers gives a valid estimation of the overall interferometer performance.

2.1. Fiber ghost beam

In general a ghost beam denotes a spurious beam traveling through the set-up in addition to the nominal beams that are used for the interference. There is a large variety of possible sources for ghost beams, like beams occurring due to secondary reflections at non-perfect anti-reflecting (AR) coatings, but this article will only focus on those ghost beams that are potentially limiting the performance in the classic fiber backlink experiment.

Due to the backlink path a direct connection between two fibers exists. Under the assumption that the fiber coupler and the fiber itself reflect a small amount of the light, a low finesse cavity is induced between the fibers. The reflection is caused by direct back reflections at the fiber coupler interface due to non-perfect AR coatings or by the fiber due to e.g. Rayleigh scattering or cladding modes. Both, nominal and ghost beams traveling collinearly inside this cavity, interfere among each other and spoil the phase performance. In the following we will distinguish between two ghost beam sources:

(i) **A ghost beam from the injection** denotes a beam coming from the fiber and fiber output coupler injecting the TX beam onto the optical bench.

(ii) **A ghost beam from the backlink** denotes a beam coming from the PRDS. Regarding a non-fiber PRDS the ghost beams due to the backlink fiber are eliminated.

2.2. Ghost beam coupling

When a spurious beam interferes with one of the nominal beams, or another ghost beam, the resulting signal might influence the phase detection. The level of the phase disturbance depends on the beam power, the polarization state, the beat frequency and the heterodyne efficiency of the ghost beam signal.

An optical signal can be described as a vector, decomposed in phase and amplitude in the complex plane. A signal contaminated with a ghost beam is described by the vector addition of the non-contaminated signal (amplitude a and phase φ) and the ghost beam signal, with an amplitude, a^{SL}, and a phase, φ^{SL}. The phase error φ^{err} caused by only one ghost beam signal can be calculated with simple trigonometry (here $\varphi = 0$ without loss of generality):

$$\tan(\varphi^{\mathrm{err}}) = \frac{a^{\mathrm{SL}} \sin(\varphi^{\mathrm{SL}})}{a + a_{\mathrm{SL}} \cos \varphi^{\mathrm{SL}}}. \tag{1}$$

Under the assumption that the ghost beam signal is a small vector noise its amplitude is negligible in comparison to the non-contaminated amplitude, $a^{\mathrm{SL}} \ll a$, and for small phase errors $\varphi^{\mathrm{err}} \ll 1$. Using these assumptions Equation 1 can be rewritten as

$$\varphi^{\mathrm{err}} = \frac{a^{\mathrm{SL}}}{a} \cdot \sin(\varphi^{\mathrm{SL}} - \varphi) \tag{2}$$

with $\varphi \neq 0$. By including n ghost beams, Equation 2 can be extended to

$$\varphi^{\mathrm{err}} = \frac{1}{a} \sum_{i}^{n} a_i^{\mathrm{SL}} \cdot \sin(\varphi_i^{\mathrm{SL}} - \varphi) \tag{3}$$

with $a = \sqrt{\eta P^{\mathrm{TX}} P^{\mathrm{LO}}}$ and $a_i^{SL} = \sqrt{\eta_i^{\mathrm{SL}} P_i^{\mathrm{SL}} P^x}$, while $P^x = \{P^{\mathrm{TX}}, P^{\mathrm{LO}}, P_i^{\mathrm{SL}}\}$. The decomposition of the amplitudes in heterodyne efficiencies, η, and laser powers, P, shows the coupling of ghost beam amplitudes into phase error in dependency on the mode overlap of ghost beam and local oscillator beam, and the contributing laser powers. However, this model neither includes non-clean polarization effects, which could indeed reduce the resulting coupling, nor does it include the small vector noise dynamics that couple non-linearly, leading to effects like frequency up-conversion of out-of-band signals.

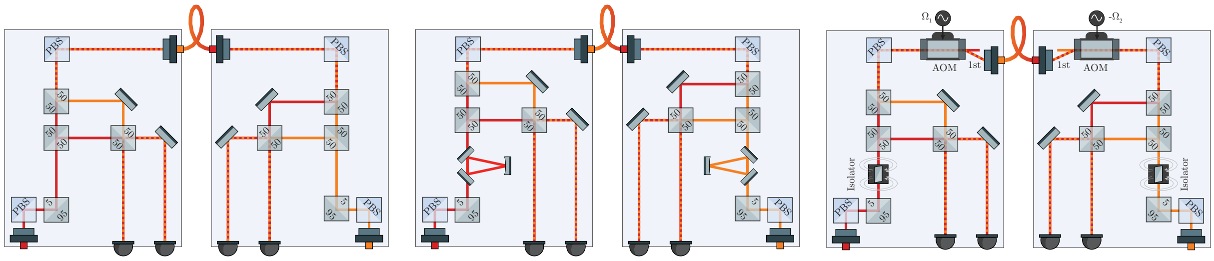
3. Modifications of the fiber backlink

Regarding the classic fiber backlink a reduction of ghost beams can be achieved by improving the signal to ghost beam power ratio by installing attenuation beam splitters on the OB. While the nominal beam enters the interferometer only once the ghost beam passes the attenuation stages several times. A 5/95 beam splitter is envisaged to be implemented in LISA for the power splitting for the telescope. Due to the limited laser power consumption in the LISA telescope and the local interferometry the implementation of additional attenuation stages is not desirable.

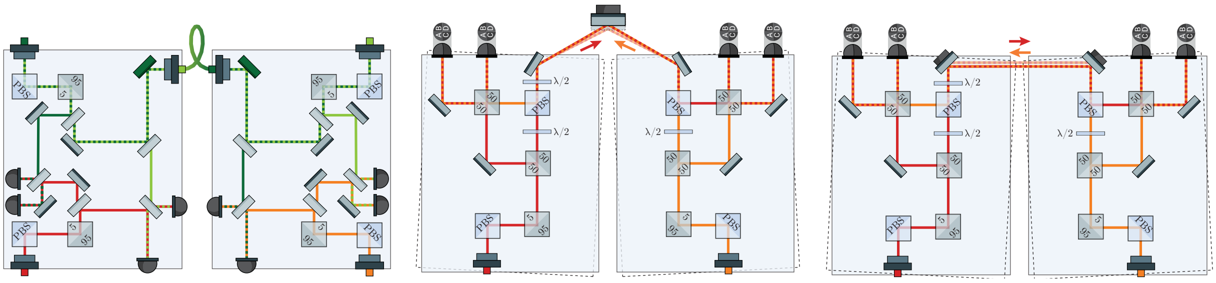
Figure 2b shows an alternative design of a fiber-based backlink with a mode cleaning cavity implemented behind the injection fiber. The cavity has a narrow bandwidth and is matched to the laser frequency of the TX beam and thus filters the frequency shifted LO beam from the backlink. The generation of ghost beams from the injection is prevented. Due to the triangular cavity shape direct back reflections from the cavity itself can be avoided. However, an additional cavity would increase the complexity on the LISA OB and requires further locking electronics for stabilizing the cavity length. Furthermore, this solution only handles ghost beams coming from the injection fiber, not from the backlink.

Avoiding ghost beams from the injection can also be realized with a Faraday isolator that is inserted in the path from the injection fiber output coupler to the backlink as shown in Figure 2c. Back traveling light from the PRDS will be separated by the Faraday isolator and thus cannot be reflected at the injection fiber. Critical aspects in this design are the phase stability of the rotator and its magnetic field effecting the free floating test masses in the LISA S/C.

Also shown in Figure 2c is the installation of two acousto-optic modulators (AOMs) in front of the backlink fiber. The AOMs use the acousto-optic effect to shift the laser frequencies of the TX beams before they are coupled into the backlink fiber. The frequency shifts have a different



(a) Classic fiber BL. (b) Cavity BL. (c) AOM BL with Faraday BL.



(d) Frequency shift BL. (e) Mirror in the middle BL. (f) Free beam BL.

Figure 2: An overview of backlinks (BLs) for LISA.

sign such that the total frequency shift collected by the beams is kept in the detection bandwidth. A ghost beam passes the same AOM two times and thus collects the same frequency shift twice. Consequently ghost beams from the backlink are frequency shifted to non-detectable frequencies. Since the AOM cannot fully preserve the Gaussian beam quality both the heterodyne and the coupling efficiency will drop. Putting the AOM at a different position, such that the backlink fiber can be used as mode cleaner, can restore the interference quality. Unknown is the thermal behavior of the AOM, a significant heat source on the OB, and the electro magnetic crosstalk between two of these devices.

Another approach is shifting the resulting ghost beam beat note out-of-band by using additional laser sources, so called additional local oscillators (ALO). A possible layout is depicted in Figure 2d. The ALO beams are used for the light exchange between the two OBs. The four laser sources are all offset phase locked to each other such that they are all in the detection band. This ensures a minimal coupling of ghost beams from both sources, the injection and the backlink, into the interferometric measurement. However, the induced cavity between ALO and LO fiber generates ghost beams of second order, meaning laser beams that are reflected at both fibers. After two reflections the ghost beam power is significantly, but potentially not sufficiently, smaller. This alternative requires an additional single sideband, for example from another laser, and a third fiber output coupler per OB, further increasing the complexity of the LISA OB.

4. Free beam solutions

The exclusion of a fiber in the backlink connection eliminates the ghost beams from the backlink fiber itself and is therefore an attractive alternative.

The so called mirror in the middle backlink, shown in Figure 2e, demonstrates one thinkable design. To compensate the angular variations of the incoming beam due to the rotation of the two OBs a mirror is placed in the middle of the OBs such that the preservation of heterodyne efficiency in the local interferometry is ensured via the Law of Reflection. This alternative requires that the rotation axis of both OBs is at the laser reflection point on the mirror surface. The engineering complexity and the controlling of the moving optical subassemblies within the S/C would increase. Any significant deviation from the rotation axis would cause a parallel beam shift and the mirror needs to be controlled in its translational axis. Finally, with one mirror in the middle at one specific point the redundancy opportunity is not trivial and, additionally, the mirror needs to be installed outside of the OB at a fixed point. However, with the usage of polarizing optics in the backlink path, the backlink beam does not travel to the injection fiber, which makes this solution, theoretically, ghost beam free except for the uncertainties of the suppression properties of the polarizing optics. In earlier experiments the required $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ phase stability of polarizing optics had been demonstrated for the LISA OB and test mass readout [3].

A second, more likely, approach for a free beam backlink is the usage of two steering mirrors, one per OB, that will actively be actuated for compensating the angle of the incoming beam. A sketch is shown in Figure 2f. By controlling both, the horizontal and vertical degree of freedom, any bench motion and therefore beam rotation can be compensated. The challenge in this set-up is the implementation of two coupled active feedback control loops for steering the mirrors. The scattering due to the backlink fiber is eliminated and the reduction of back reflections from the LO beam at the injection fiber is feasible by using polarizing optics, as described before.

5. Conclusion

In this article we discussed the impact of the backlink on the LISA optical bench that is required when using Telescope Pointing. In this context ghost beams generated in the backlink and injection fiber were described as the critical noise source for the backlink and the phase reference measurement with a non-linear coupling depending on the ghost beam amplitude and phase.

While a previous experiment with a classic fiber backlink demonstrated $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ reciprocal phase stability, it required dedicated correction methods like balanced detection that are not desirable for LISA. Two approaches were pointed out as an alternative to a simple fiber backlink: One uses additional optics to reduce the relevant ghost beam power with a fiber solution. The other one relies on a steered free beam connection. Further studies and experiments are needed to determine the optimal implementation. To perform these studies under realistic conditions one critical aspect will be to measure the fiber backscatter after radiation, revealing the ghost beam power levels expected during the mission. It would be advisable to try to eliminate the possibility of cladding modes as a source of ghost beams with a direct measurement or by probing the influence of alignment on the ghost beams.

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