

FREQUENCY DRIFT INTERFEROMETRY FOR STRAY LIGHT MEASUREMENT ON THE LISA SPACE INSTRUMENT

A. Roubeau-Tissot¹, M. Lintz¹, M. Nardello¹, M. Pichot¹ and J.-P. Coulon¹

Abstract. Coherent stray light in intricate optical systems such as interferometers, impacts measurement accuracy, particularly in interferometric space missions such as GRACE-FO. The aim of our project is to create an instrument inspired by the FMCW method, utilizing a frequency-swept laser to detect stray light in LISA's optical system. The current demonstrator accurately quantifies stray light and fulfills the precision challenges asked for the LISA space mission with a <2 mm resolution in OPD.

Keywords: LISA France, instrumentation, OGSE, prototype, stray light, interferometry, FMCW, frequency-drift interferometry

1 Introduction

On a complex optical system such as an interferometer, coherent Stray Light is a pitfall in many ways because it can affect the accuracy and resolution of the measurements or their dynamics. This is all the more true with space interferometers as in the GRACE (Gravity Recovery And Climate Experiment) Follow-On space mission, which uses the LRI (Laser Ranging Interferometer) to track the Earth's mass distribution across the planet (Abich et al. 2019). The GRACE-FO mission employs high accuracy and high resolution laser interferometry, similar to the LISA space mission. Achieving precise optical phase measurements requires addressing and reducing coherent stray light issues. This involves using a reliable method at the system level to ensure that stray light limits are not exceeded after instrument integration. Simply measuring overall amplitude isn't effective, as individual stray light amplitudes for different components must be determined. This is because these components have varying stability and noise allocations, and their contributions must be identified separately. For example, stable components connected to a Zerodur baseplate differ from less stable ones like movable wave plates, which have lower acceptable stray light amplitudes.

This work aims to develop the demonstrator of an instrumentation that can measure the stray light optical amplitude, whatever its origin, in the photoreceivers of the LISA (Laser Interferometer Space Antenna) space mission's interferometric system MOSA (Moving Optical SubAssembly) before sending it into space. The instrumentation is based on the method known under the name of FMCW (Frequency Modulated Continuous Wave, Zheng (2004)) but is of more general application.

2 Experimental set-up

2.1 Method used

Utilizing a single-mode laser source, we sweep the optical frequency over time and introduce this beam into the optical system under test. Throughout the optical frequency scan, we capture all outgoing signals, encompassing both optical and electrical signals. Should any of these signals exhibit a fringe-like pattern, we attribute this modulation to the existence of stray light amplitude, which interferes with the nominal light amplitude. The optical path difference (OPD) between the nominal and stray light (SL) is deduced from the frequency of these interference fringes (f_{itf}), as in coherent reflectometry, using:

$$f_{itf} = \frac{\Delta L}{c} \frac{\Delta \nu_{opt}}{\Delta t} \quad (2.1)$$

¹ Universit   C  te d'Azur, Laboratoire ARTEMIS, Nice

where $\Delta L = nL_{SL} - nL_{nom}$ the SL/nom OPD, n the medium index and $\frac{\Delta\nu_{opt}}{\Delta t}$ the frequency scan rate.

So by doing spectral analysis of the recorded photo signals, we will retrieve the list [**SL amplitude vs. OPD**] of the different SL contributions. The setup must fulfill the requirements for MOSA stray light tests by reaching a measurement floor in fractional amplitude SL/nom under **2, 2.10⁻⁶** on the measurement range [**0–200 Hz**] and by achieving a resolution in SL/nom OPD under **2 mm**.

2.2 Demonstrator Implementation

The current demonstrator is composed of five main parts:

- **Frequency swept laser:** 1064 nm fibered laser diode to be swept over at least 1 nm (swept optical frequency $\Delta\nu_{opt} = 265$ GHz) allowing a resolution of 1 mm on the OPD SL/nominal
- **Frequency Ramp Control:** Offset phase-locked loop that achieves linear optical frequency drift ($\frac{d\nu_{opt}}{dt} = \text{Cte}$) using an unbalanced fibered heterodyne Mach-Zehnder interferometer. (Kéfélian et al. (2009) and Jiang et al. (2010))
- **Frequency Scan rate measurement:** Measurement of the beat frequency between the frequency swept laser and a fixed frequency laser (method inspired by Chiodo et al. (2013)).
- **Frequency Ramp Monitoring:** A fibered interferometer to check the quality of the frequency ramp by doing a real-time interference measurement simultaneously with the MOSA tests.
- **MOSA simulator:** Free space setup where stray light contributions with known OPD and amplitude are used to test the efficiency and accuracy of our demonstrator.

The work presented here will focus on measurements made on the MOSA simulator test bench. This bench, as shown in Fig. 1, is composed of a silica wedge plate allowing us to generate multiple reflections/transmissions in $R \approx 4\%$ and $T=1-R$ (SL beams), mirrors M1 and M2 reflecting the stray beams: some reflections finally reach the photoreceiver placed on the nominal beam and thus appear as "stray light contributions".

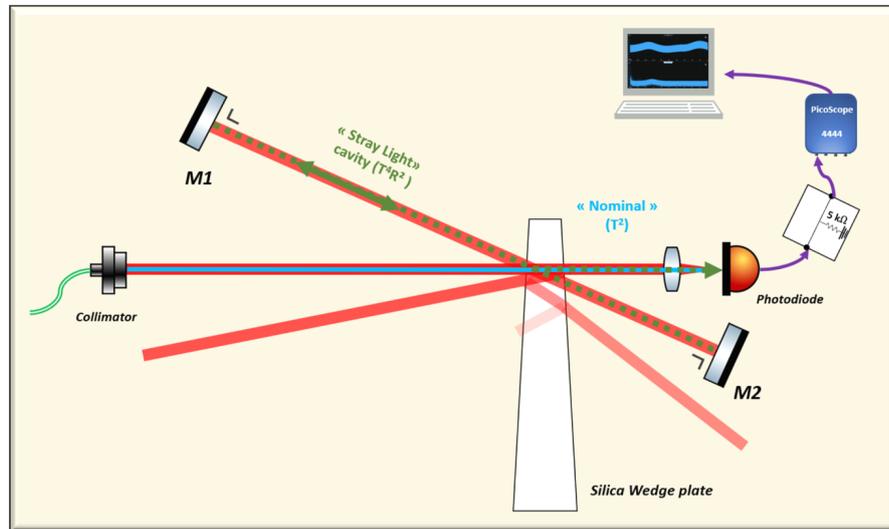


Fig. 1. Scheme of the MOSA simulator with a nominal optical path and several stray light contributions coming from the first reflection on the wedge and the M1-M2 cavity

In our scenario, we have a primary beam as the initial transmission through the wedge's output (depicted as light blue in the scheme, with a power ratio of T^2). Additionally, there's a stray light contribution from the first wedge reflection (green path, power ratio T^2R^2), and echoes of this stray light within the M1-M2 cavity (resulting in a T^2 power loss in the round trip).

The anticipated optical path difference (ΔL) between the stray light and the nominal beam is 1,402 2 m. This value is derived from the reconstruction of the optical path in the FRED simulation software, using measurements conducted with a mechanical arm on the optical bench.

3 Results on the MOSA simulator

After recording the photo signals, we calculate the FFT (Fast Fourier Transform) using a Python code and we obtain the spectrum shown in Fig. 2Left. We're making all our measurements with two frequency ramp velocities: 5,1 GHz/s (510 GHz in 100 s) or/and 5,3 GHz/s (530 GHz in 100 s) to scan the laser over around 2 nm and improve the OPD resolution.

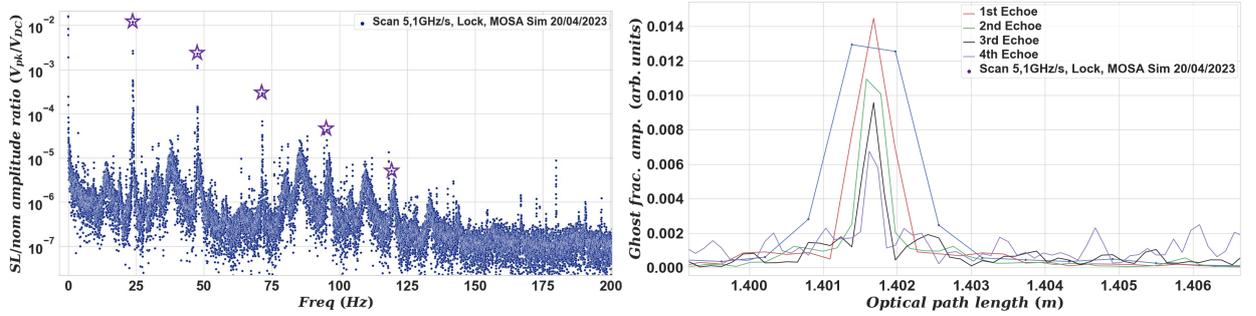


Fig. 2. Left: Example fractional amplitude spectrum of the photoreceiver signals recorded on the MOSA-simulator set-up as a function of the Fourier frequency during a **5,1 GHz/s** laser frequency scan. Stars indicate expected SL peaks at the output of the MOSA Sim. **Right:** The N-th Echoes, at $N * \Delta L_{M1M2}$ overlaps with the main SL contribution as a function of the OPD computed from 2.1

We retrieve the expected main SL contribution and his echoes in the M1-M2 cavity with an amplitude loss of factor 6 due to the beam's divergence (purple stars). And if we overlap all the echoes over the main SL peak as a function of the OPD and we compute their barycenters we see that, first, the peaks overlap pretty well on Fig. 2Right ($\leq 0,1$ mm accuracy and then that the mean barycenter, 1,401 6 m, is 0,6 mm away from the theoretical value which is one of the main proof of the precision quality of our measurement.

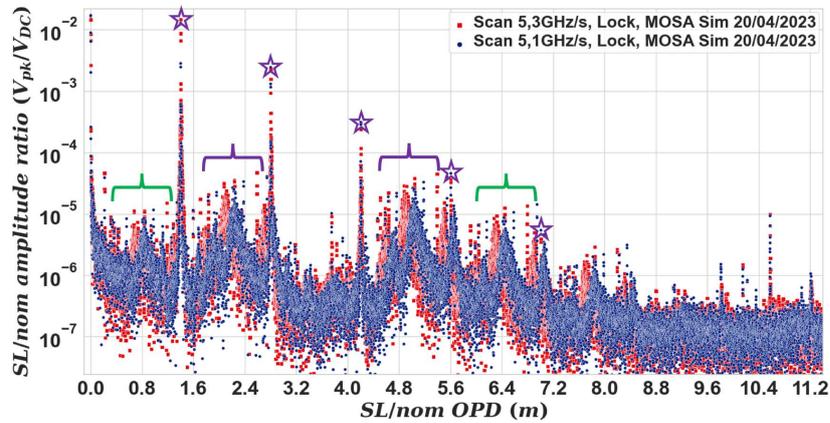


Fig. 3. Fractional amplitude spectra as a function of the OPD (computed from 2.1) during two laser scans. In red (resp. blue): data obtained with an optical frequency ramp rate of **5,3 GHz/s** (resp. **5,1 GHz/s**). Stars indicate SL peaks and brackets parasitic noise peaks

The presence of additional peaks related to mechanical noise, such as acoustic and seismic disturbances, can be observed alongside the stray light (SL) peaks. By employing a straightforward technique (Roubeau-Tissot et al. 2022), which involves overlaying spectra from two sequential measurements with varying frequency scan rates (**5,1 GHz/s** and **5,3 GHz/s**) as illustrated in Fig.3 in terms of optical path difference (using 2.1 to convert the Fourier frequency), it becomes possible to differentiate authentic SL peaks from the rest (parasitic peaks). Peaks that overlap are stray light contributions, while others represent noise contributions (depicted within brackets). Importantly, these noise patterns are exclusively evident in the MOSA simulator's output and do not directly affect our fiber instrument (e.g., the output of frequency ramp monitoring, a fiber interferometer). This distinction arises because mechanical noise only perturbs the cavity's optical path (mirrors or wedge).

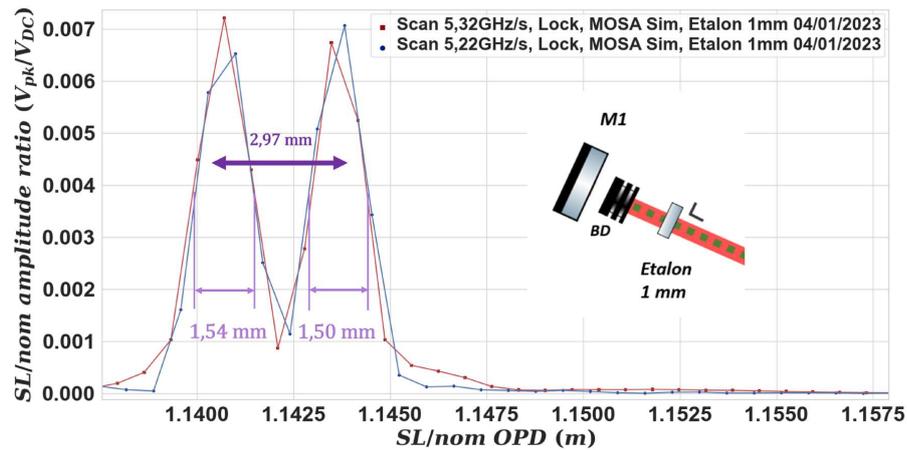


Fig. 4. Main stray light contributions in the MOSA simulator with the mirror M1 in Fig.1 replaced by an 1 mm silica etalon

To assess the demonstrator's OPD resolution (minimum discernible distance between two nearby stray light peaks), the M1 mirror is substituted with a 1 mm silica etalon. This introduces two SL contributions: one from the etalon's front reflection and another from the rear. The anticipated OPD between these peaks is **2,9 mm** (twice the thickness of the etalon multiplied by the silica index 1,45). Notably, in Fig.3, the experimental OPD measures **2,94 mm**, providing an adequate data points for the desired differentiation of the two peaks.

4 Conclusions

The spectral analyses of the MOSA simulator signals show the existence of the SL beams that we have prepared, and allow the measurement of the SL/nominal path difference, confirming the device's functionality for the measurement of the coherent stray light amplitude and OPD. The resolution in OPD is at the expected level of **2 mm** considering the amplitude **>500 GHz** of the frequency sweeps. The measurement floors demonstrate that we reach the currently required **$2, 2 \cdot 10^{-6}$** in SL/nom fractional amplitude above **1 Hz**. The residual noise at low frequency could possibly be removed by normalizing the photoreceiver signal by the laser power signal, obtained from a pick-up of the incoming laser beam.

We observe the presence of stray peaks (due to acoustic and seismic perturbations) and parasitic SL contributions coming from our fibered setup which we have to study and, if possible, remove. Also, we must understand and take into account all the physical phenomena which can affect the linearity of frequency ramp such as: the chromatic dispersion, the slow dependence in temperature and humidity of the fiber's effective optical index, the polarization variations in a strong birefringence medium as the fibers that we use. . .

Acknowledgements: This work is carried out within the LISA France Collaboration, and benefits from the funding of the Région Sud and the CNES (Centre National d'Etudes Spatiales) for the AIVT (Assembly, Integration, Validation and Test) of the MOSA of the LISA mission.

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