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P. Grüning

H. Halloin

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AN ELECTRO-OPTICAL SIMULATOR OF THE SPACE BASED GRAVITATIONAL WAVE DETECTOR ELISA

P. Grüning¹, H. Halloin², P. Prat, S. Baron, J. Brossard, C. Buy, A. Petiteau
APC - Paris Diderot, France

¹*pierre.gruning@apc.univ-paris7.fr*

²*hubert.halloin@apc.univ-paris7.fr*

I. INTRODUCTION

The evolved Laser Interferometer Space Antenna (eLISA) is a space-based project which aims to detect gravitational waves in the frequency range 0.1 mHz to 1 Hz (see [1]). It consists of 3 spacecraft in a nearly-equilateral configuration, constantly following free-falling masses located at their center and orbiting around the sun as shown in Fig. 1. eLISA is the straw man concept proposed as an ESA L-class mission to fulfill the scientific objectives of 'The Gravitational Universe' proposed science theme. This theme has recently been selected by ESA for a launch in 2034. In the eLISA concept, a 'mother' spacecraft is located at the vertex of a V-shaped configuration, with two 'daughter' spacecraft at the end of the two arms. Laser beams are propagating along the arms, effectively forming a Michelson-type interferometer with 10^6 km arm lengths. The spacecrafts follow independent heliocentric orbits (without any station-keeping in the frequency range of eLISA measurements) and form a nearly equilateral triangle in plane that is inclined by 60° against the ecliptic (see Fig. 1.). Two interferometric measurements per arm are used to precisely monitor the distances between the inertial masses and, hence, to detect the tiny variation due to the pass of a gravitational wave. The goal of eLISA is to detect gravitational deformation as small as $\Delta L/L \approx 10^{-20} / \text{Hz}^{-1/2}$ (i.e 10 pm per million km) around 5 mHz. This expected performance of eLISA relies on two main technical challenges: the ability for the spacecraft to precisely follow the free-flying masses and the outstanding precision of the phase shift measurement between the spacecrafts.

This paper describes the LISA On Table (LOT) experiment developed at the APC laboratory in Paris which aim is to simulate eLISA and test noise reduction technics such as the Time Delay Interferometry algorithm.

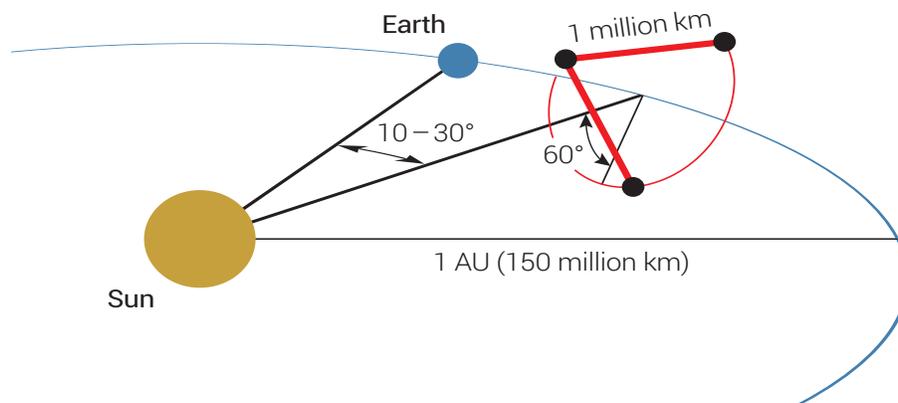


Fig. 1. eLISA on orbit

II. PRINCIPLES OF THE EXPERIMENT

The goal of the LOT experiment is to be able to simulate optical beat notes, as representative as possible of the signals that will be recorded by eLISA. The experimental setup should also be kept very flexible to allow different configurations and the use of hardware prototypes, so that it could be adapted to new technologies or algorithms developed for eLISA. Beyond the model of eLISA, the main challenge of such an experiment is to properly simulate delayed optical noise, while keeping the setup extremely stable on time scales of tens of seconds. The experimental setup presented here mainly focuses on the demonstration of the simulation principles and first results.

A. Optical part

The optical part of the LOT is mainly based on a Mach-Zehnder interferometer combined to AOMs (acousto-optic modulator) to shift the laser frequency on the arms in order to obtain heterodyne interferences and also to inject the simulated noise with the appropriate delays corresponding to the arm length of eLISA (about 6,6s for a roundtrip of 10^6 km). The beatnotes are measured by photodiodes and sent to a phasemeter. Simultaneously, the simulated RF commands are electronically mixed, low-pass filtered, and sent to other channels of the phasemeter. Both, the AOMs and the phasemeter are controlled by a labview program with predefined mathematics used to generate the RF frequencies and the simulated noise used by the AOMs, including user-defined delays. The LOT's optical part is shown on Fig. 2. which represents one module of the simulator.

The LOT is presently composed of two of those modules, each one represents one satellite of the eLISA configuration. The third module, representative of the third satellite, will be implemented in future works. As for eLISA, the module representing one satellite has three interfering beams, one 'local' and two 'distant'. A single laser source at 1064 nm is used to produce these beams using a combination of polarizing beam splitters and waveplates so that optical paths of the distant beams follow the same optical path but with orthogonal polarizations. The local arm's frequency, which represents the laser beam inside the satellite used to interfere with the incoming distant beam, can be shifted with AOM 1. In the same way, AOM 2 and 3 induce the frequency shifts for the two distant arms. Each of these distant arms interferes with the local arm to produce a heterodyne signal detected by 48 MHz bandwidth photodiodes with power noise below 8 pW/pHz. This broad modulation bandwidth is particularly useful for simulations of the doppler effect. However, since a large frequency shift induces also a large angular shift after the AOM, a cat's eye configuration has been implemented for the frequency modulation. In such a configuration, the shifted outgoing beam makes a roundtrip following the same path than the incoming beam keeping the alignment between the lasers constant at any time and for any frequency.

All the experiment is performed in a clean room. The optical table is placed on an air cushion to reduce high frequency noise and all optical devices put under a box in order to reduce noises induced by air flow. Also, a heat device is fixed on the top to implement temperature layers so that air perturbation induced by eventual warm spots on the table are quickly absorbed.

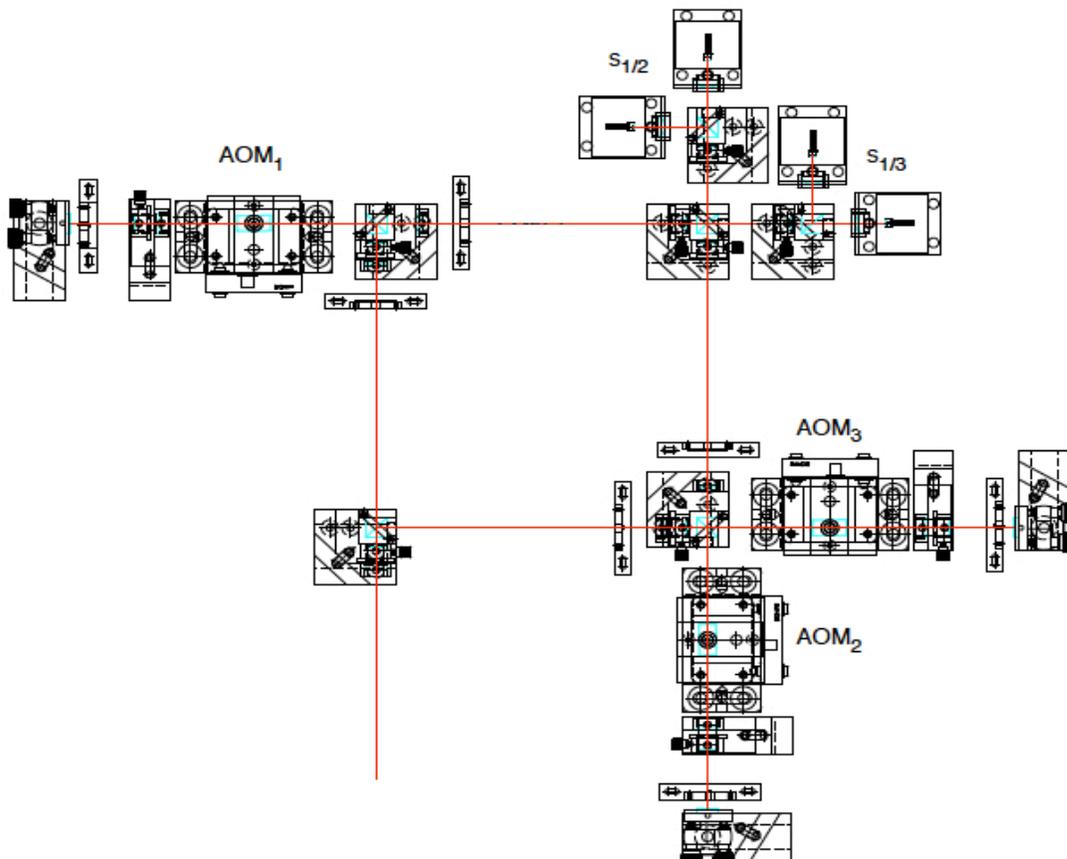


Fig. 2. One module of the optical LOT

B. Electronic part

The LOT's electronic part is composed of all necessary devices for control and measurement but also of an electronic version of the interferometer which recovers and combines the signals sent to the AOMs in order to analyze and compare them to the optical signals. The concept is illustrated on Fig. 3. The data streams for each channel (i.e. sent to the AOMs) are simulated (i.e. generated, delayed and interpolated), converted to digital commands and sent to a National Instrument PXIe 6537 communication board. The communication rate is controlled using a synthesized clock, up to 5 MHz, derived from a GPS disciplined oscillator. The communication card as well as the DDS can handle communication rates up to 50 MHz (i.e. a frames' rate of about 190 kHz), while it was set to 2 MHz in the present work (frames rate of 7.6 kHz).

Computer controlled DDS (Direct Digital Synthesizer, model Agilent AD9912) actuates the AOMs. The signal of each DDS channel is split, amplified and mixed before going through a low-pass filter and being measured by the phasemeter developed at the Albert Einstein Institute in Hanover Germany (see [2]). DDS channel 1 represents the local arm (i.e. the laser inside the satellite), channels 2 and 3 stand for the two distant arms. Just as the local laser shifted by AOM #1 interferes respectively with the distant lasers shifted by AOM #2 and #3, the signal generated by DDS #1 is mixed respectively with the DDS channels #2 and #3 before being sent to phasemeter channels 3 and 4 (while channels #1 and #2 get the signals from the photodiodes PD). The DDS are able to generate RF signal up to 400 MHz with an accuracy of 3.6 mHz and the possibility to adjust the phase of the signal with a precision of 0.38 mrad.

The electronics clocks are derived from a 10 MHz high stability, GPS disciplined oscillator to reduce the differential jitter noise. The output data are transmitted to the computer using a parallel port, at a rate of about 23.8 Hz.

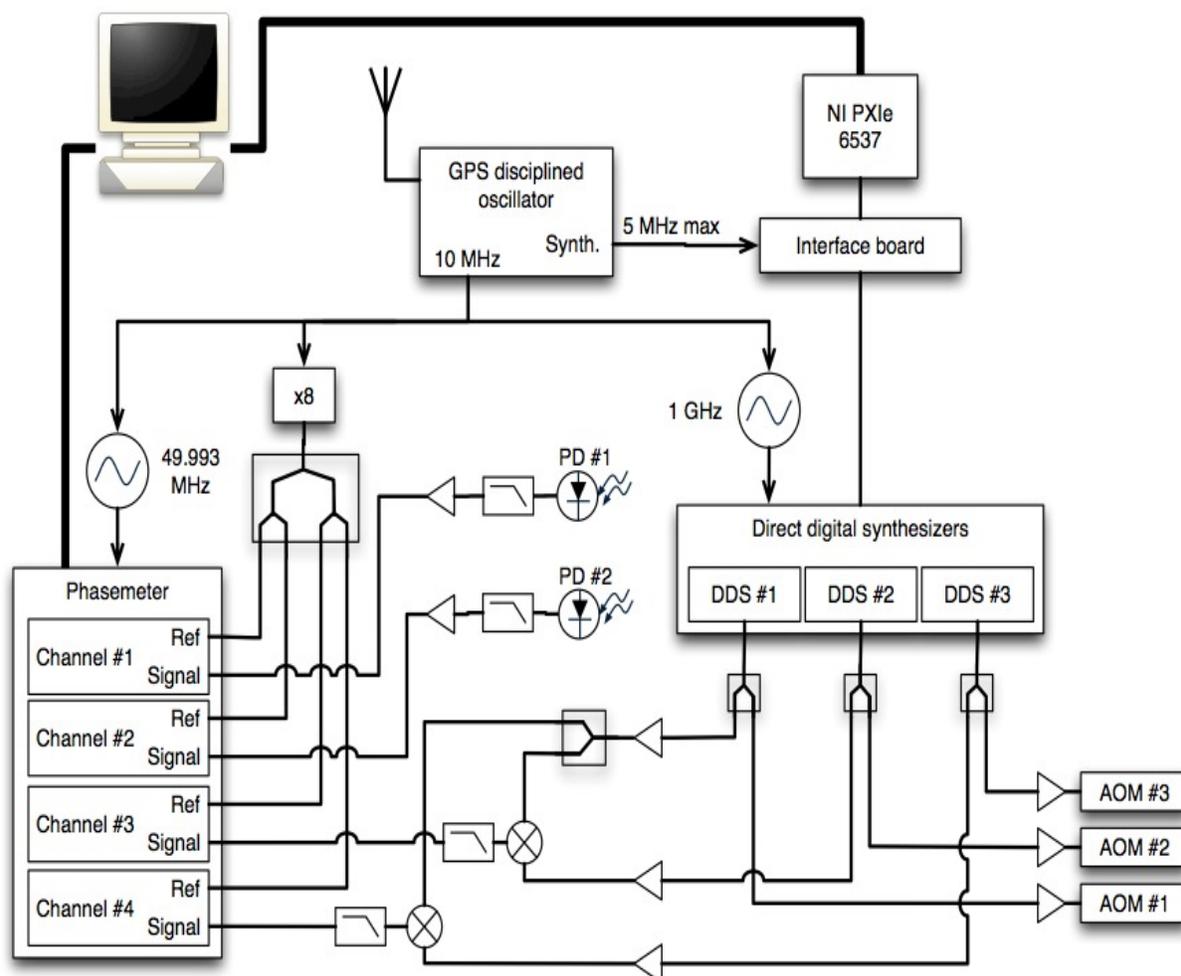


Fig. 3. Electronic LOT

C. Time Delay Interferometry

Time Delay Interferometry (TDI) [3,4] is a post-processing algorithm to avoid the coupling of the laser frequency noise with the science signal. The eLISA mission is composed of two arms, each of them linking one free-falling mass of the 'mother' spacecraft to the free-falling mass of each 'daughter' spacecraft. In practice, the variations of the arm length are computed from three interferometric measurements on each link : test mass to optical bench on the mother S/C, 'mother' optical bench to 'daughter' optical bench, optical bench to test mass on the daughter S/C. The sum of these 3 measurements cancels out the (large) movement of the S/C w.r.t the test masses. The principle and different measurements of the eLISA interferometry is represented on Fig. 4.

In the simplest configuration, neglecting all of the exterior perturbations and considering only the laser noise (which is the most important) we get the TDI first generation Equation (1) :

$$X_{1st} = (1 - D_{31'}D_{1'3})s_{TT;1} - (1 - D_{21}D_{12})s_{TT;1'} \tag{1}$$

D_{ij} being a delay operator : $D_{ij}\Phi(t) = \Phi(t - L_{ij})$ with L_{ij} the light time from payload i to j , about 3,3 s and S_{TT} corresponding to the measured signals. Also for our experiment, the delays have been held constant (static configuration). For a detailed development leading to Equation (1), see [5].

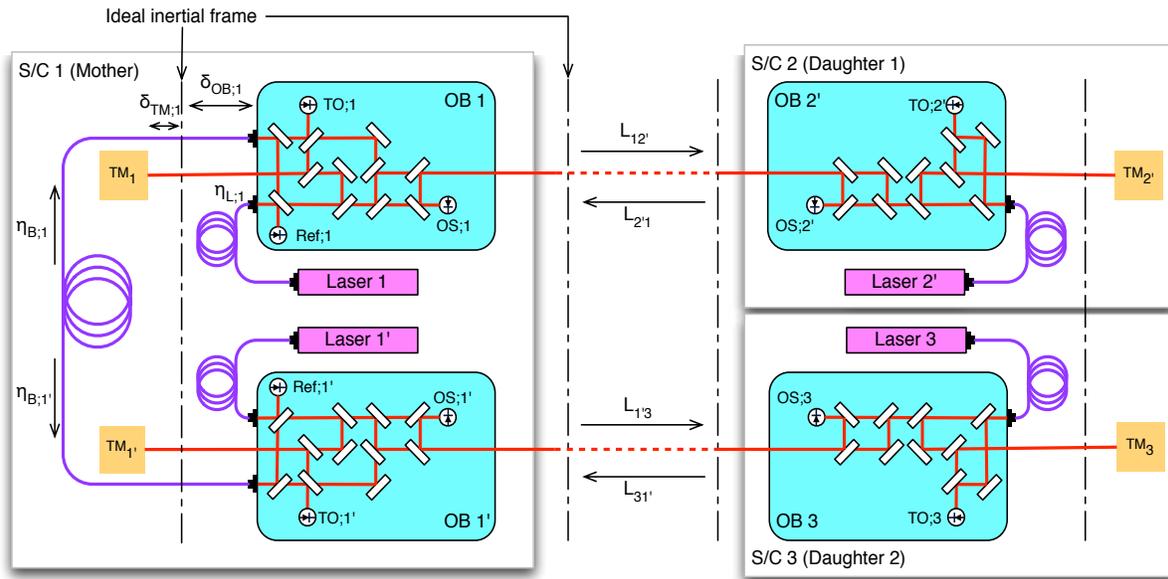


Fig. 4. Principle of the eLISA interferometric measurements

III. MEASUREMENTS AND FURTHER WORK

Here we present some results, showing the reference noise level of the LOT, some TDI tests and upcoming improvements to lower the intrinsic noise level of the interferometer.

A. Reference noise level

First, the intrinsic noise level of the phasemeter has been estimated using a single RF source split on the 4 input channels of the phasemeter. The ASD (Amplitude Spectral Density) of data recorded on channel 1 and the ASD of the difference between channel 1 and 2 are represented on Fig. 5. The ASD of raw values and differences between other channels give very similar results. These results show that the raw data are slightly above the eLISA requirements for the phase measurement noise, while the differential measurement between two channels is marginally compatible with the requirement. The difference between the two curves are due to a relatively strong common mode between the channels, whose origin unclear for the moment, but could be due, e.g. to a residual phase jitter between the reference and the synthesized signal. However, the intrinsic phase noise of the phasemeter is well below the other noise sources of the LOT experiment and will not be a concern

in the present work. For reference, the requirements for the interferometric measurement (including shot noise, optical bench noise, electronics, etc.) are also plotted on Fig. 5.

On a second configuration, the 3 DDS were configured with no modulation, and carrier frequencies at 108 MHz ('local' arm), 112.5 MHz ('distant' arm 1) and 112.7 MHz ('distant' arm 2). The ASD of the resulting beat notes $s_{o;1}$ (optic), $s_{e;1}$ (electronic) and the combinations $s_{o;1} - s_{o;1'}$, $s_{e;1} - s_{e;1'}$ are represented on Fig. 5. ($s_{o;1'}$ and $s_{e;1'}$ have similar spectra as, respectively, $s_{o;1}$ and $s_{e;1}$). As expected, the 'optical' beat notes are dominated by optical pathlengths fluctuations, due to thermal expansion of the aluminum support plates, the air turbulences, etc. The two optical signals are mostly uncorrelated except for the 2 resonant peaks at 0.04 and 0.08 Hz (maybe related to the air damping of the optical table).

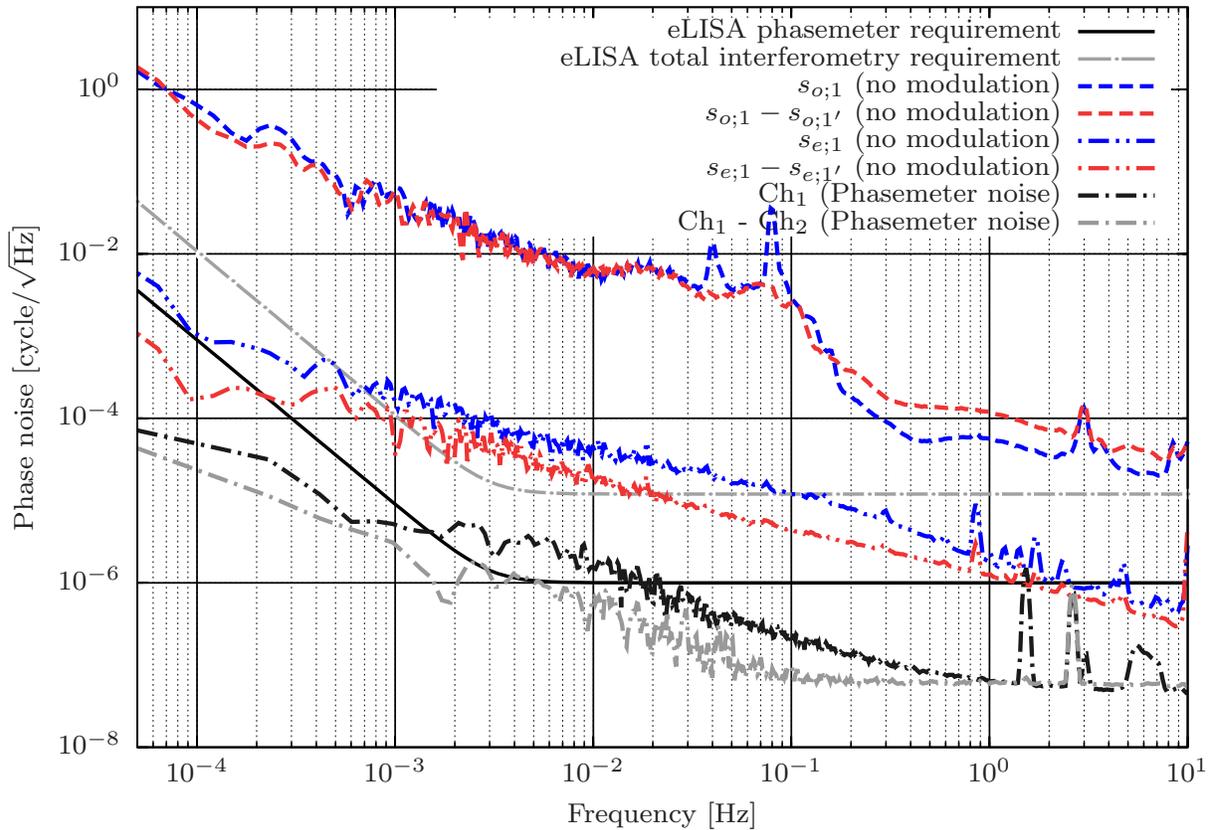


Fig. 5. Reference noise level

B. Time Delay Interferometry on unequal arms

The same analysis as described above is performed, using the TDI combination given in Equation 1 and the results are given on Fig. 6. (unequal arm lengths configuration). The injected frequency noise is a white noise at a level of $560 \text{ Hz/Hz}^{-1/2}$ up to 1 Hz (about twice the expected level of frequency noise of the stabilized laser source). The noise reduction factor after TDI for unequal arm lengths, at 1 mHz, is at the level of $5 \cdot 10^7$ for optical signals, and 10^9 for electronic signals, compared to $2 \cdot 10^{10}$ for equal arms. This degradation could be due to phase jitter between the synthesized clocks driving the noise injection (1 GHz for the DDS operations) and the timestamps of the recorded phases (49.993 MHz for the phasemeter synchronization).

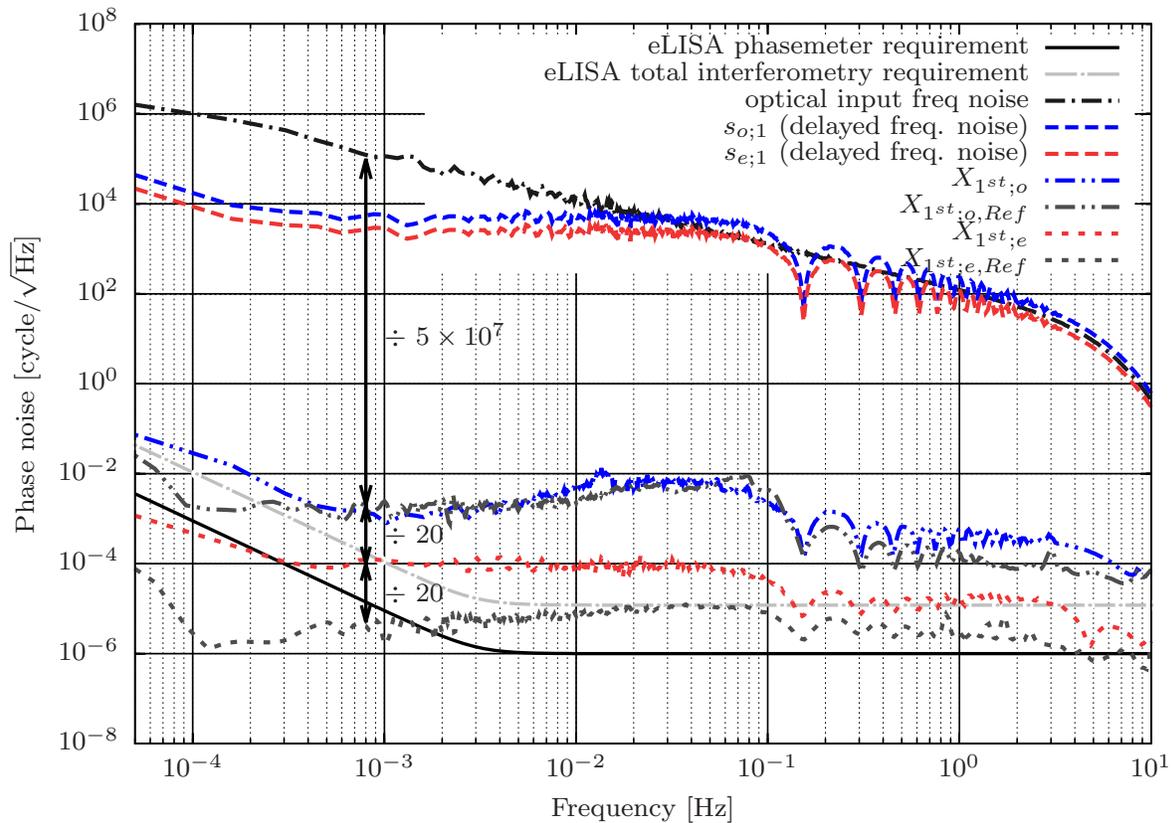


Fig. 6. TDI test with unequal arm configuration

IV. FURTHER DEVELOPMENTS AND CONCLUSION

The time jitter of the simulated delays will be addressed by inserting an FPGA (Field Programmable Gate Array) board right after the NI PXIe 6537 communication board. This FPGA will take charge of buffering, delaying and synchronizing the command frames to the AOMs. It will also allow to add frequency corrections, taken from digital or analog error signals. With the appropriate delays, this capability will mimic the phase lock of the laser sources on the distant S/C, as well as the implementation of the arm-locking stabilization scheme.

The optical bench phase noise will be actively compensated using the interference of 'direct' (i.e. order 0) beams. Actually, these beams are unaffected by the RF signals on the AOMs and can be used to form an homodyne interferometer. The LOT interferometer arm lengths can therefore be stabilized using mirror dithering (above 1 kHz, i.e. outside the frequency band of eLISA) and dark fringe stabilization scheme. The homodyne and heterodyne interferometers will share (almost) the same optical paths (they only slightly differ between the AOMs and the end arm mirrors) and the compensation is expected to approach the interferometry requirement of eLISA.

Another effort is currently being made to couple the present command-control system for the LOT, to the LISACode simulation software [6] also developed in our laboratory. Once achieved, this work will allow the simulations of realistic propagation delays, taking into account Sagnac effect, variable delays and Doppler shifts. It will also be possible to directly compare the 'numerical' results of TDI (as given by LISACode) to the same algorithm applied on optically or electronically simulated beat notes. Finally, some space has been saved on the optical bench to insert electro-optical modulators. These modulators are planned to simulate the implementation of clock noise transfer and ranging.

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