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An electro-optical simulator for eLISA

LOT: Lisa On Table

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Abstract. This paper describes the progress on a hardware simulator of eLISA developed at the APC laboratory in Paris, France. It is designed to simulate realistic noise and the appropriate delays resulting from the huge distances the laser has to travel between the eLISA spacecrafts. We present the experimental setup consisting of an optical and electric interferometer. Also, the time delay interferometry noise reduction method and its performance on simulated signals in the simplest transponder case will be described.

1. Introduction

eLISA's capability to detect the tiny variations in space-time due to gravitational waves relies on many parameters such as accurate processing algorithms (TDI), precise feedback loops (arm-locking) and very low noise, extremely high performance instruments (phasemeters). Hardware simulators are necessary to characterize the detection devices, test the numerical models and study the influence of the hardware on the detection algorithms. The LOT (LISA On Table) experiment has been designed to address this issue. It is an electro-optical simulator composed of both, an optical and an electric interferometer.

The LOT is expected to be a very complete hardware simulator representative of eLISA, offering the additional flexibility to define ad-hoc fluctuations in the frequency, amplitude or phase of the laser and propagation delays. The control electronics also allows to accelerate the simulation, so that one year of data streams could be generated within a few days. The DDS channels are splitted in order to generate both, the electric beat notes and the optical ones using acousto-optical modulators (AOM) to shift the laser frequency and also to inject the frequency noise with the appropriate delays. Finally, the phasemeter recovers the signals from both interferometers.

Furthermore, in its final version, besides the fact of being able to perform measurements of realistic eLISA signals, the LOT will be extremely useful as a hardware in the loop simulator during eLISA's assembly, integration, testing and verification (AIT/AIV) phases where the interactions between different hardware devices will be studied.



2. Experimental setup

This part describes the main aspects of the LOT, on one hand the electric interferometer including the command-control devices, the signal generation and the phasemeter and on the other hand the optical interferometer.

2.1. Electronic LOT

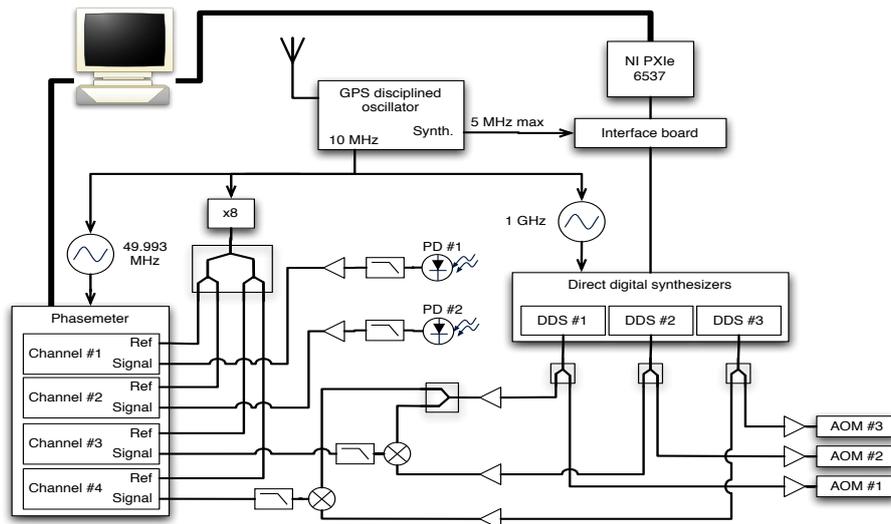


Figure 1: Overview of the electric part

Computer controlled DDS (Direct Digital Synthesizer, model Agilent AD9912) are used to generate the analog signals from the data streams generated by NI PXIe driven by a labview program. 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 electronic clocks are derived from a 10 MHz high stability, GPS disciplined oscillator to reduce the differential jitter noise.

As for eLISA, channel 1 (i.e. the local arm) is mixed respectively with channel 2 and 3 (i.e. the distant arms) in order to simulate the two local signals. These two data streams are recorded by the phasemeter on channel 3 and 4, the other channels being used for the optical signals recovered by the photodiodes (PD). The phasemeter is a prototype developed by the Albert Einstein Institut in Hanover, Germany [1] which transmits the output data at a rate of about 23.8 Hz. Both, the DDS and the phasemeter are controlled by a labview program with predefined mathematics models (computed by a separate C library for maximum efficiency) used to generate the RF frequencies and the simulated noise, including user-defined delays. These delays are held fixed in the present work, but will be representative of the eLISA orbits once the command program is combined with LISACode [8, 9].

2.2. Optical LOT

The optical part of the LOT is mainly based on a Mach-Zehnder interferometer combined with three AOMs (acousto-optic modulator) which are driven by the DDS to shift the laser frequency on the arms in order to obtain heterodyne interferences. The beatnotes are measured by photodiodes and sent to the phasemeter.

The optical interferometer 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

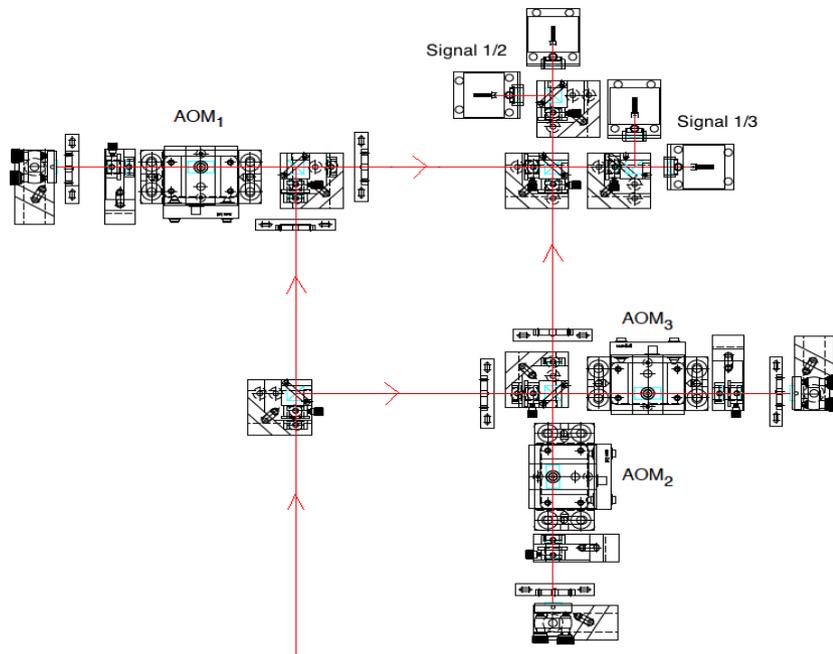


Figure 2: The optical interferometer

the eLISA configuration. For this study only one module has been used, representative of the mother spacecraft. As for eLISA, the module representing one satellite has three interfering beams, one local and two distant. A single laser source at 1064 nm (Innolight Mephisto 500) is used to produce these beams.

The local arm's frequency can be shifted with AOM 1 (driven by DDS channel 1). In the same way, AOM 2 and 3 (driven by DDS channel 2 and 3) induce the frequency shifts for the two distant arms. Free space A&A MT110-B50 TeO₂ AOMs have been used for the LOT. The maximum diffraction efficiency ($\geq 80\%$) is reached at 110 MHz, with a bandwidth of ± 15 MHz with an efficiency greater than 65%. This broad modulation bandwidth is particularly useful for simulations of the Doppler effect. 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 $8 \text{ pW}/\sqrt{\text{Hz}}$. Signal 1/2 is the resulting beatnote from the interfering beams shifted by AOM 1 and 2 and in the same way, signal 1/3 results from the interference between the beams shifted by AOM 1 and AOM 3 separated using orthogonal polarizations.

Also, each AOM produces two beams, one frequency shifted to produce the beat note for the heterodyne interferometer (order 1 beam), and one unaffected beam (order 0) which will be used for optical path length compensation using a dark fringe stabilization scheme.

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 are placed under a box in order to reduce noises induced by air flow and temperature fluctuations. 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.

3. Time Delay Interferometry tests

This section explains briefly the TDI principle in the simplest case of a transponder type configuration. First results of noise reduction in this case will be shown in the second part on simulated delayed signals, both on the electric and optical LOT.

3.1. TDI principle

The dominant noise in eLISA is, by many orders of magnitudes, the laser phase fluctuations. These noises are however transported from one spacecraft to another and appear as differences between the local laser and the distant, delayed one. Their contribution can be canceled by properly delaying and combining the signals: this method is known as time delay interferometry (TDI) (see e.g. [2,3,10–15]). TDI however requires a precise knowledge of the light time between spacecraft (at the meter level over 10^6 km). Moreover, these equations assumed perfect clocks on each spacecraft, with no relative drifts nor jitter. Ranging and clock noise transfer can be performed by adding auxiliary modulations on the laser links [4]. After TDI and clock noise corrections [7], the residual phase noise should be due to the test masses (residual acceleration noise at low frequency) and the optical noise (including shot noise and path length fluctuations on the optical benches).

For the first experimental measurements performed on the LOT, the simplified, 'transponder' equation (which require only two simulated data streams), has been used with the additional constraint of a static constellation (i.e the delay operators $D_{2'1}D_{12'}$ and $D_{31'}D_{1'3}$ are constant and commute). In that case, the simplest TDI combination (X, first generation) leads to:

$$X_{1st} = (1 - D_{31'}D_{1'3})s_{TT;1} - (1 - D_{2'1}D_{1'2})s_{TT;1'} \quad (1)$$

$s_{TT;1}$ and $s_{TT;1'}$ being the two simulated data streams. This combination synthesizes an equivalent Michelson interferometer with equal arms.

3.2. TDI test on delayed signals

To perform a first test of TDI with the LOT in a realistic configuration, a white noise (amplitude $280 \text{ Hz}/\sqrt{\text{Hz}}$) was simulated and applied on the local arm, as well as on the distant (delayed) arms 2 and 3. This setup is representative of a static 'transponder' eLISA used by equation 1. The signal sent to the local arm is not delayed, whereas the signal on arm 2 is delayed by 6.502081 s and arm 3 by 6.502081 s (equal arm lengths configuration).

A second test is performed with the same configuration as above but with different delays on the distant arms. The signal on arm 2 is delayed by 6.502081 s and arm 3 by 6.711826 s (unequal arm lengths configuration). These delays corresponds to the round-trip time of the laser between the eLISA spacecrafts. The resulting amplitude spectral densities are shown on figure 3 and 4.

For these tests, frequencies of 108 MHz, 112.5 MHz and 112.7 MHz have been applied respectively on the local arm, on the distant arm 2 and 3 resulting in beat notes of 4.5 MHz and 4.7 MHz for the electric interferometer and twice that for the optical one due to a double pass of the laser through the AOMs.

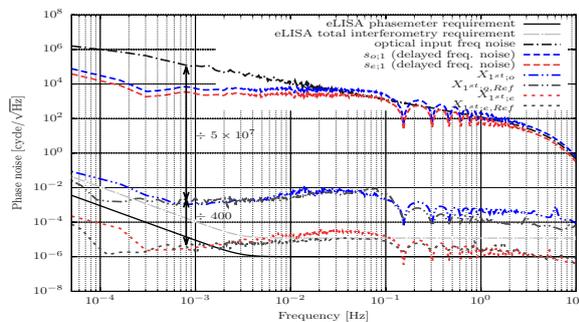


Figure 3: TDI on equal delayed signals (6.502081 s)

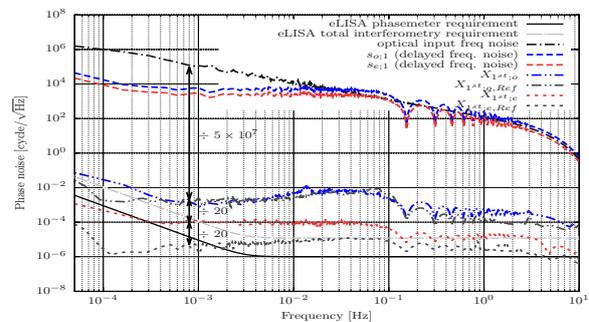


Figure 4: TDI on unequal delayed signals (6.502081 s and 6.711826 s)

$s_{o,1}$ and $s_{e,1}$ are the measured signals, 'o' stands for optic and 'e' for electric. $X_{1^{st};o}$ and $X_{1^{st};e}$ are the signals after TDI has been applied. The $X_{1^{st},Ref}$ shows the reference level after application of TDI on signals without WN modulation.

For equal arm length we get a noise reduction of 5×10^7 on the optical signals at 1 mHz and 2×10^{10} for the electric one. The lower performance for the optical LOT is expected due to the optical path length fluctuations. For the unequal arm case the optical noise reduction is unchanged but limited to 10^9 for the electric one. 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).

4. Comparison between the LOT and eLISA

This section is intended to make a brief comparison between the LOT and eLISA regarding the main parameters adjustable on our simulator and also some performances.

	LOT (current version)	LOT (final version)	eLISA
Laser frequency noise	$560 \frac{Hz}{\sqrt{Hz}}$ (simulated and adjustable)	$560 \frac{Hz}{\sqrt{Hz}}$ (simulated and adjustable)	$280 \frac{Hz}{\sqrt{Hz}}$
Laser power	Up to 0.5 W (3mW on photodiodes on standard operation mode)	Up to 0.5 W (3mW on photodiodes on standard operation mode)	2W (a few pW on the photodiodes)
TDI performance	5×10^7	At least 10^8	10^8
Delays	6.5s and 6.7s (adjustable but constant)	variable eLISA-like delays	Between 6.47s and 6.87s
Doppler shift	none	eLISA-like Doppler shift	amplitude up to 4MHz with frequency less than $10^{-7} Hz$

Table 1: Comparative table between the current version of the LOT, the final version and eLISA

In our case we simulated a laser frequency noise with twice the value of the expected eLISA laser frequency noise, also, regarding the laser power, a certain level had to be maintained in order to keep the dark fringe stabilization scheme working (see 5. Next steps). With this stabilization scheme implemented, eLISA-like TDI performances are expected. Concerning the delays, the command/control software allows only constant delays but in the future, pre-calculated delay variations (using realistic orbital models) will be used. These same models will also allow Doppler shift simulation. Currently, only a "pseudo-realistic" Doppler shift simulation is possible by adding a simple frequency modulation on the signals.

5. Next steps

The results of the first measurements, as described above, demonstrate the validity of the concept but also clearly show evidence of the major sources of noise: jitter in the simulated delays and optical path-length noise. The next steps and future works will address these two points and also increase the representativity of the simulation.

- An FPGA (Field Programmable Gate Array) board will be inserted right after the NI PXIe 6537 communication board to 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 to mimic the phase lock of the laser sources on the distant spacecraft as well as the implementation of the arm-locking (see [5]) stabilization scheme. Additionally, a ranging pilot tone (frequency modulation around 1 Hz) will be implemented to monitor the effective delay of the frames (this technique has already been successfully used in [6]).
- 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 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 [8,9] 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.
- 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 (see [16]). However, the current architecture of LOT only allows clock noise transfer between the two daughter and the mother spacecraft and not between the two daughter spacecrafts.

6. Conclusion

This paper reported the current status of the LISA On Table experiment. The principle has been validated, with beatnotes recorded both on optical and electronic interferometers. The limited performance due to time jitter will be resolved soon, the FPGA card being under development. Also, the active compensation is about to be installed to improve the noise reduction of 5×10^7 for the optical frequency noise.

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