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LISA ON TABLE : AN OPTICAL SIMULATOR FOR LISA

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ABSTRACT

LISA, the first space project for detecting gravitational waves, relies on two main technical challenges: the free falling masses and an outstanding precision on phase shift measurements (a few pm on 5 Mkm in the LISA band). The technology of the free falling masses, i.e. their isolation to forces other than gravity and the capability for the spacecraft to precisely follow the test masses, will soon be tested with the technological LISA Pathfinder mission. The performance of the phase measurement will be achieved by at least two stabilization stages: a pre-stabilisation of the laser frequency at a level of 10^{-13} (relative frequency stability) will be further improved by using numerical algorithms, such as Time Delay Interferometry, which have been theoretically and numerically demonstrated to reach the required performance level (10^{-21}).

Nevertheless, these algorithms, though already tested with numerical model of LISA, require experimental validation, including 'realistic' hardware elements. Such an experiment would allow to evaluate the expected noise level and the possible interactions between subsystems. To this end, the APC is currently developing an optical benchtop experiment, called LISA On Table (LOT), which is representative of the three LISA spacecraft.

A first module of the LOT experiment has been mounted and is being characterized. After completion this facility may be used by the LISA community to test hardware (photodiodes, phasemeters) or software (reconstruction algorithms) components.

I. INTRODUCTION

The LISA (LIght Interferometer Space Antenna) mission is a joint ESA-NASA spaceborne project, aiming at detecting gravitational waves in the frequency range 10^{-4} -1 Hz [1]. It consists of 3 spacecraft in a nearly equilateral configuration orbiting around the sun, about 20 degrees behind the Earth.

The satellites are separated by 5×10^{6} km, constantly following free-flying masses located at their center. On each spacecraft, two laser beams are emitted towards the other satellites, resulting in six laser links (see Fig. 1).

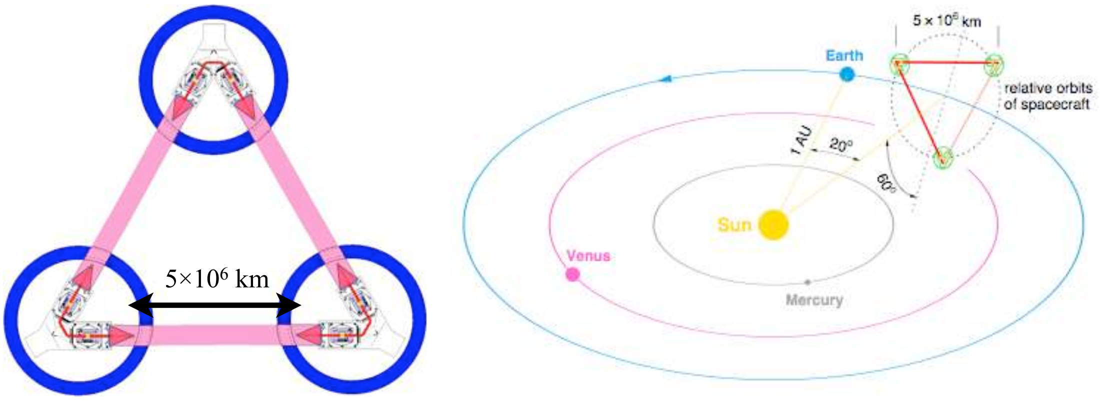

Fig. 1. The 3 LISA satellites with their laser links (left) and orbiting around the Sun (right)

These interferometric measurements are used to precisely monitor the distance between the inertial masses and, hence, to detect the tiny variation due to the pass of a gravitational wave. The goal of LISA is to detect gravitational deformation as small as $\Delta L/L \approx 7 \times 10^{-21}/\sqrt{\text{Hz}}$ (i.e 7 pm per million of km) around 5 mHz.

This expected performance of LISA 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. This latter constraint requires frequency stabilized lasers and efficient numerical algorithms to account for the redundant, delayed noise propagation, thus canceling laser phase noise by many orders of magnitude.

Actually, contrary to a classical Michelson interferometer, the optical signal is obtained from two different laser sources. As a consequence the beam phase noise does not vanish and the relative frequency stability of the lasers must be at the same level as the expected sensitivity ($\Delta L/L = \Delta\nu/\nu$). This requirement is far beyond any standard stabilization technique developed on ground and foreseeable for a future space mission.

Nevertheless, this stability can be achieved for LISA thanks to three successive stabilization stages :

- **Pre-stabilization** : Even with TDI and arm-locking (see below), the light emitted by the laser sources need to be very stable, at the level of 10^{-13} relative frequency change. The foreseen technique is based on a Fabry-Perot cavity [2]. Recently, another technique had been proposed, based on molecular iodine as a frequency reference [3,4]. This approach demonstrated to be compatible with the LISA requirements and space constraints [4,5].

- **Arm-locking** : In the interesting frequency range of LISA (10^{-4} - 1 Hz), the distance between the free-falling masses is very stable. Consequently, it can be used as a length (i.e. frequency) reference. This technique requires the frequency reference of the pre-stabilization to be slightly tunable [6,7,8].
- **Time Delay Interferometry** : While each optical signals is the combination of two laser sources, the frequency noise of each source is also propagating on two laser links. Thus, by correctly combining the interferometric signals, taking into account the propagation delays (about 16.7 s between two spacecraft), it is possible to cancel the laser noises (and, so, recover a 'Michelson-like' signal). However, due to the finite precision of the time stamps (drifts of the ultra stable clocks), this method is not perfect and the noise reduction factor is of the order of 10^8.

Some of these noise-reduction techniques require the precise knowledge of the inter-satellites distances as well as precise synchronization of the onboard ultra-stable clocks. For these purposes, GHz sidebands of the laser links are modulated to send data from one spacecraft to another. These data, as well as the «science» signal need to be very precisely recovered by the phasemeter.

Hence, the capability of LISA to measure very small displacements relies (among other things) on accurate processing algorithms (TDI), precise feedback loops (arm-locking) and very low noise, extremely high performance instruments (phasemeters). Simulation software can simulate the Doppler effects, the propagation delays, reconstruction algorithms, etc. Nevertheless, the development of 'hardware' detectors are desirable, in order to characterize the detection devices, validate the numerical models and study the influence of the hardware on the detection algorithm. this is the purpose of the LOT (LISA On Table) experiments developed at the APC and described in the next sections.

II. DESCRIPTION OF THE EXPERIMENT

The main challenges when developing an optical simulator for LISA are :

- simulate the propagation delays (16 s!) from one satellite to another
- keep the phase noise of the simulated beat notes at a very low level

A. Principle of the experiment

Each LISA spacecraft encloses 2 Nd:YAG lasers (one for each telescope). These lasers are combined with the incoming (delayed) light from the 2 other satellites. In order to compensate for the relative motions of the spacecraft (Doppler effect) and keep the beat notes frequencies within the bandwidth of the photodetectors (1 - 20 MHz) these two lasers may have different slightly different optical frequencies. Moreover, these lasers are phase-locked (with a constant frequency offset) on each other, so that it is functionally equivalent to consider that there is only one laser source on each spacecraft contributing to the phase noise of the recorded beat notes. Consequently, when simulating 'realistic' optical signals, it is sufficient to consider only 2 beat notes on each satellite, results of the interference between the 'local' laser and the 'distant' ones.

Obviously, the travel time of the light from one spacecraft to another (more than 16 s) cannot be reproduced on ground. Nevertheless, in order to simulate the LISA signals, only the phase of the laser beams needs to be delayed, not the carrier (only the phase is carrying information). Moreover, the beat measurements can be splitted into low and high frequency contents. The low frequency part contains all the Doppler effect (varying on timescales of months or more) as well as the main part of the laser frequency noise. The incoming optical frequency (at a time t in a inertial frame) of a laser beam can then be formally written as :

$$f_{meas}(t) = f_0 + \Delta f_{offset} + \Delta f_{Doppler}(t-\tau(t)) + \frac{d\Phi^{LF}}{dt}(t-\tau(t)) + \frac{d\Phi^{HF}}{dt}(t-\tau(t)) \tag{1}$$

In this equation, the following terms are used :

- $\tau(t)$ is a slowing varying function describing the propagation delay from the distant spacecraft
- f_0 is the mean frequency of the master laser, common to all the beams (about 280 THz for a Nd:YAG laser emitting at 1064 nm)
- Δf_{offset} is a constant value taking into account the mean offset of the phase locking (w.r.t the master laser)
- $\Delta f_{Doppler}(t)$ is the frequency shift due to the Doppler effect (measured in the inertial frame). Δf_{offset} + $\Delta f_{Doppler}(t)$ is typically between -20 and 20 MHz.
- $\Phi^{LF}(t)$ is the low frequency part of the phase noise
- $\Phi^{HF}(t)$ is the high frequency part of the phase noise

The purpose of LISA being to measure gravitational waves with frequencies lower than a few Hertz, the corner frequency between 'low' and 'high' frequencies is typically 10 Hz. For simulations, the last term can then be discarded and the evolution of the resulting optical phase can easily be sampled and stored electronically. The idea of the LOT experiment is then to generate a realistic evolution of the laser frequency (i.e. $f_{meas}(t)$-f_0 in the equation above) and imprint it on different 'arms' from the same laser through the use of acousto-optic modulators. This development is strongly linked to a simulation software (LISACode [10]) that has already been developed in our lab, trying to stay as close as possible to the 'real' design of LISA. This software can efficiently simulate the Doppler effects, the propagation delays, reconstruction algorithms, etc. LISACode is now one of the 3 simulation softwares used for the Mock LISA Data Challenges [11].

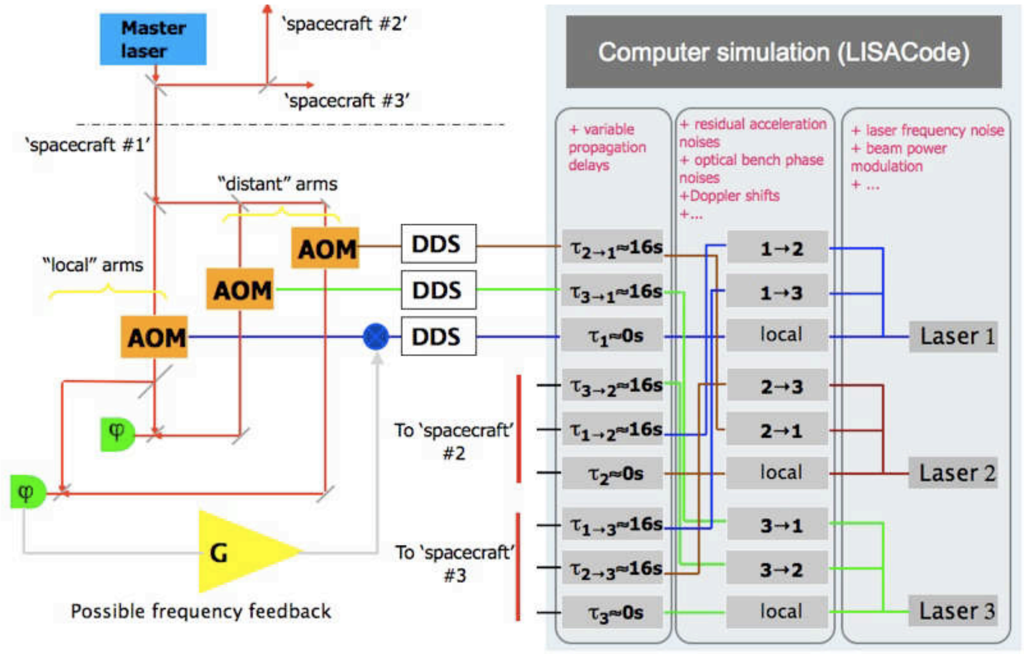

Fig 2. Principle scheme of the LISA On Table experiment

The principle of the experiment is summarized on Fig 2. A common laser source is split into 3 modules, representative of the 3 LISA satellites. In each module, the beams are split again into one 'local' and two 'distant' beams. Adequate frequency noises are added to these beams thanks to acousto-optic modulators (AOM). Two beat notes are then recorded for each module, corresponding to the mixing of the local beam with each of the distant ones. The AOMs are driven by direct digital synthesizer (DDS), generating RF signals whose frequencies, phase and amplitude are calculated and transmitted from a computer simulation. Optionally, a feedback on the RF frequency driving one or more AOMs can be added to account for arm-locking or phase locking on a distant laser.

Moreover, RF signal can be mixed electronically after the DDS and fed directly to the phasemeters. This configuration allows to separate the optical effects from the electronics ones.

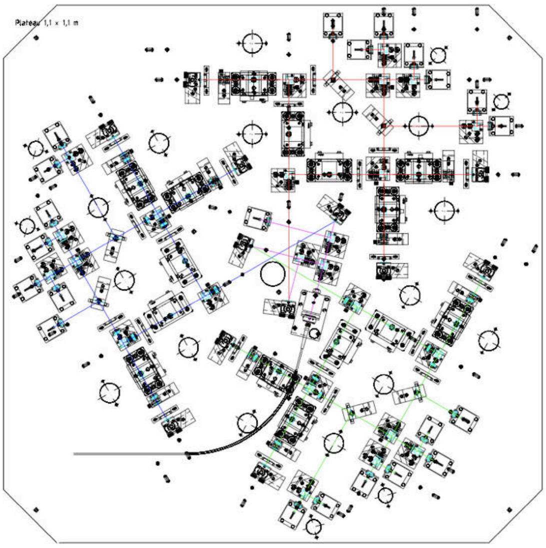

Fig 3. Mechanical layout of the 3 interferometers designed for the LISA On Table experiment.

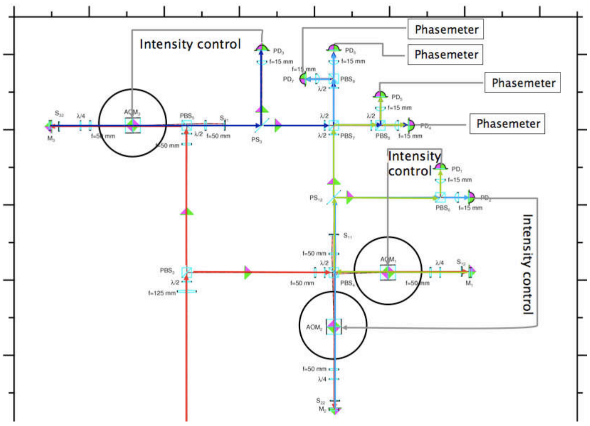

Fig 4. Optical design of one 'module', simulated with OptoCAD.

B. Optomechanical design

The mechanical and optical layouts of the LOT experiment is represented on Fig. 3 and 4. Fig. 3 shows the mechanical layout of 3 identical modules. The modules are essentially Mach-Zehnder interferometers, with AOMs used for frequency shifting the laser frequency. A well-known configuration of the AOMs, called ”cat's eye configuration”, allows to change the frequency of the laser beam over a high range (>20MHz) with only little angular deviation. The AOMs are driven with a 110 MHz RF signal (the frequency shift of the laser beam is 220 MHz due to the double pass of the cat's eye configuration). Moreover, the use of AOMs allows to control the power beam by acting on the RF power. The chosen optical configuration also allows the two ”distant” beams to follow the same optical path on perpendicular polarizations.

More generally a careful attention had been put to ensure that each laser beam propagates with exactly the same optical path and components (beam splitters, wave plates, etc.). In fact, below 1 Hz, the predominant phase disturbances are due to the thermal dilatation of the bench. Because of the identical optical path, the phase is therefore insensitive to isotropic dilatation due to homogeneous temperature variations. Furthermore, the final optical bench will probably be made of Invar plates glued on an aluminium honeycomb. Finally, the whole optical bench can fit within our 1.1x1.1x0.4 m^3 vacuum enclosure to reduce turbulence effects and ease the thermal regulation.

III. STATUS OF THE EXPERIMENT AT THE APC

Since the beginning of 2010, one module had been mounted on a temporary aluminium breadboard. The purpose of this mounting is to validate the electronics, mechanics and optics design, before the final design of the Invar plate. Fig 5 and 6 show the mounting of the first module on the aluminium plate.

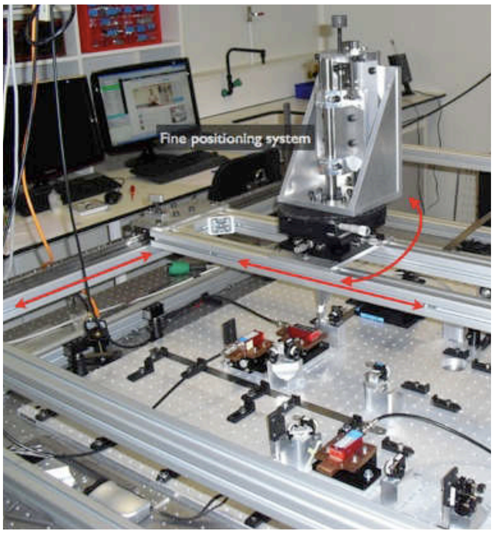

Fig 5. Positioning of the optics components on the aluminium breadboard.

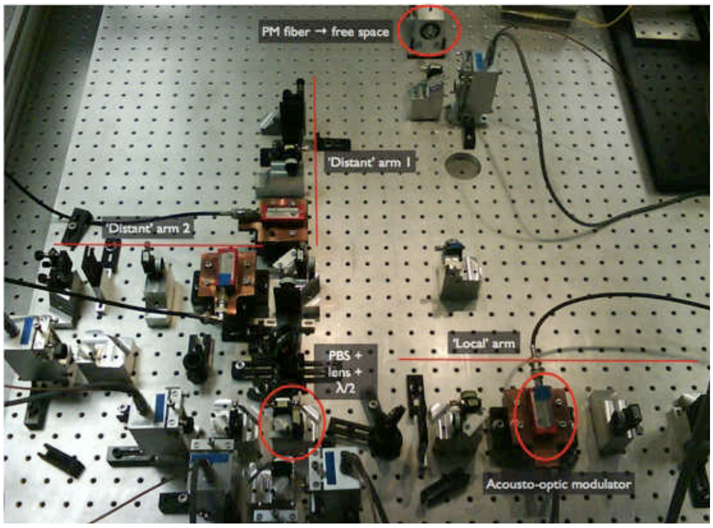

Fig 6. The first module mounted on the breadboard.

In order to avoid mechanical relaxations and maximize phase stability of the optical path, optical components (beam splitters, lenses, wave plates, etc.) are mounted on monolithic support, with the minimum number of tuning degrees of freedom. An external fine positioning system has then been developed (see Fig. 5). It consists of two coarse translations over the size of the plate (1.1×1.1 m) with an accuracy of about 0.5 mm. Based on measurements of optical measurements (such as beam position or size at reference points, beam intensity, etc), the supports can then be finely positioned with a two axes fine translation stage (accuracy of about 1/100 mm over 13 mm) and a fine rotation stage (sensitivity of about 100 µrad). Once at the correct position, the support is glued on place and the tuning system removed. Beam position monitoring showed no degradation of the positioning due to the gluing process.

The command electronics is based on direct digital synthesizer (model Agilent AD9912). These components are able to generate RF signals up to 400 MHz with an accuracy of 3.6 µHz (48 bits frequency tuning word) and the possibility to adjust the phase of the signal with a precision of 0.38 mrad (14 bits phase word). The phase and frequency words are set via a serial port communication, at a maximum speed of 50 Mbits/s, allowing for frequency and phase updates up to 250 kHz. Measurements of the phase noise induced by the DDS show a white noise at a level of 2×10^{-6} rad/√Hz above 500 Hz and a 1/f behavior below 500 Hz. The RF power stabilization cards (used to control the optical intensity after the AOMs) do not add significant phase noise. All the electronics clock are derived from the same 1 GHz high stability oscillator in order to cancel the differential jitter noise between the DDS. The same clock is also used to synchronize the frequency, phase and amplitude updates. Fig. 7 and 8 show the prototype of the control electronics for one module and the associated phase noise.

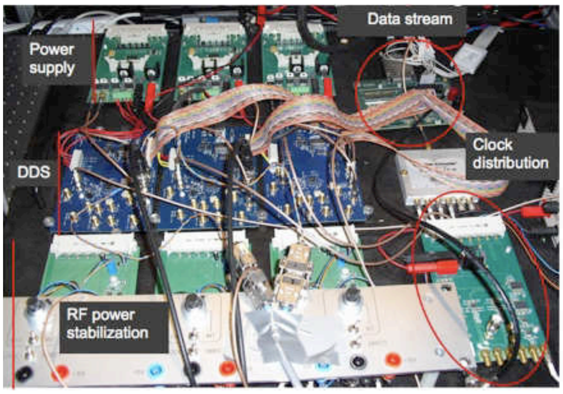

Fig 7. AOMs control electronics

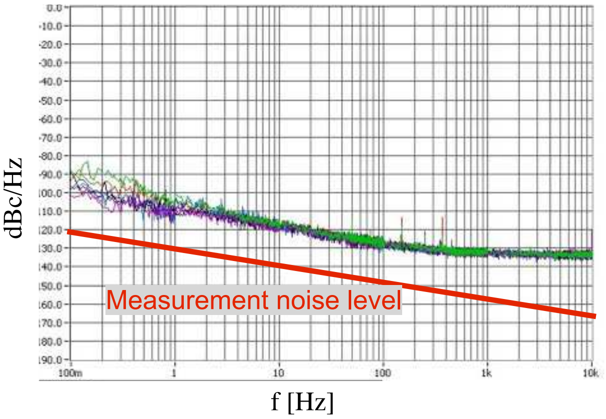

Fig 8. Control electronics phase noise

In order to optimize the communication speed and keep the system easy to use, simulations data (i.e. frequency, phase and amplitude commands) are first pre-processed and stored in binary files on a standard PC machine. The binary file is then fed to the DDS and amplitude control electronics through a 32 channels serial communication card (NI PXI-6937e) programmed under Labview. The card allow a transfer rate up to 50 Mbits/s (on 32 channels) but the communication speed is limited by the access and reading time on the hard disks. Tests have been performed using 2 hard disks in striped mode (RAID 0). 120 Mo/s transfer rate (corresponding to a communication speed of 30 MHz on 32 channels) has been measured allowing frequency, phase and amplitude updates at 150 kHz. This high update frequency allows to either accelerate the simulation (the acceleration factor is limited at about 50 by the phasemeter) and/or reduce the spectral distortions of the RF signal by using a large over-sampling factor.

The beat notes are measured with 48 MHz bandwidth photodiodes, exhibiting a low power noise f less than 8 pW/√Hz between 2 and 20 MHz (expected bandwidth of the beat notes). The recorded signal is then fed to a FPGA-based, numerical PLL, phasemeter that should have a noise performance of 1 µcycle/√Hz above 3 mHz.

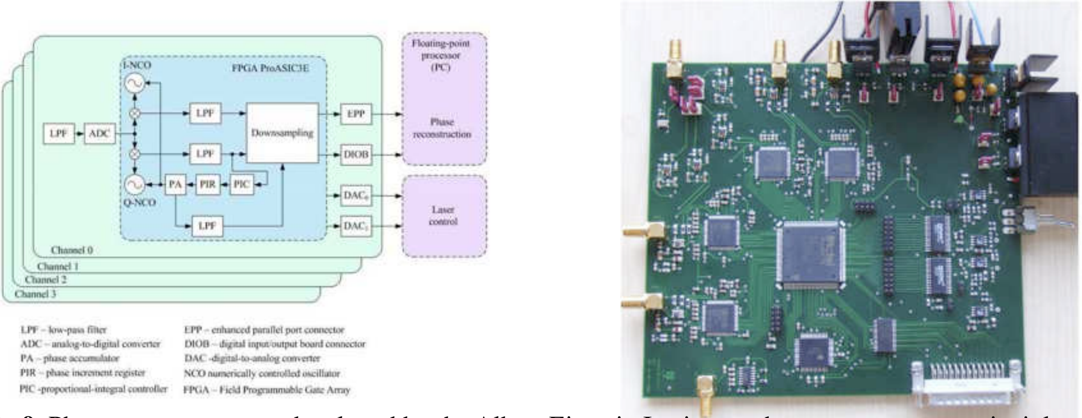

Fig 9. Phasemeter prototype developed by the Albert Einstein Institute : phase measurement principle (left) and realization (right).

We are currently using a phasemeter prototype, developed by the Albert Einstein Institute in Hanover (see Fig 9.). Two main phase noise sources have been identified on the phasemeter : sampling jitter noise and temperature dependent transfer function of the anti-aliasing filters. The jitter noise is corrected by following simultaneously (sampled with the same ADC) a reference frequency (at 22 MHz) and the 'science' signal (varying between 2 and 20 MHz).

The measured phase noise of the reference signal is then subtracted from the 'science' one. To improve the temperature stability of the antialiasing filters, active components have been used. With these improvements, the phase noise requirements are met, with a phase noise floor of about $8{\times}10^{-8}$ cycle/√Hz above 0.1 Hz. The photodiodes signals are sampled at 50 MHz and its phase can be read at a frequency up to about 200 Hz (limiting the simulation bandwidth at 100Hz).

Once all these elements have been mounted on the temporary optical bench (see above), preliminary measurements of the relative phase noise between the 2 beat notes of the module have been performed. THe results of these measurement are shown on Fig. 10. For the moment, the phase noise is about 100 times above our objective (around 1 nm/√Hz at 10 mHz). Many improvements will be made to improve this performance :

- protection of the bench from temperature fluctuations and turbulence (ultimately it will be put into a vacuum chamber)
- carefully tune the optical components to get equal optical path at the mm level.
- mounting on an Invar plate to reduce the thermal dilatation
- add a reference frequency on the RF driving the AOM for path length correction (similarly to what is done to correct the jitter of the phasemeter ADC.
- correlation (and correction) of the phase noise with calibrated temperature sensors put on the optical bench

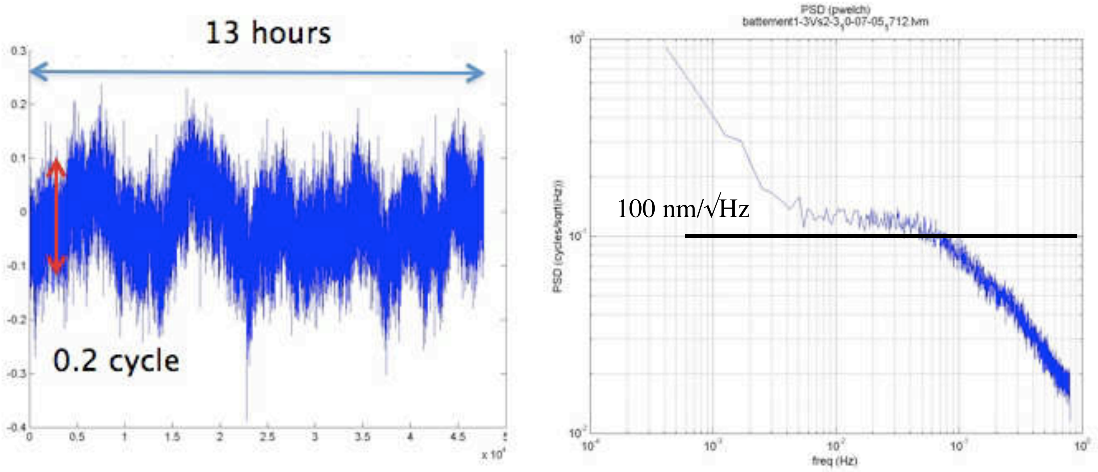

Fig 10. Preliminary differential phase noise measurements of the first module mounted on the temporary breadboard

CONCLUSION

The first module of an optical simulator for LISA has been mounted at the APC. The optomechanical and electronics designs have been validated and the whole system is currently being characterised and calibrated. Future work include the reduction of the path length noise (Invar breadboard, vacuum chamber, reference beat note, correlation with temperature, etc.), the mounting of another module (by the end of 2010) and first tests of TDI and/or arm-locking (beginning of 2011). Once completed and validated, the LISA On Table experiment will offer a test facility for the LISA community, including the validation of photodiodes, phasemeters and reconstruction algorithms.

ACKNOWLEDGMENTS

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