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OVERVIEW OF THE LISA MISSION AND R&D DEVELOPMENTS AT THE APC

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Abstract. The study of the gravitational waves opens a new window for the observation of the universe. Completing the observations obtained from electro-magnetic waves, neutrinos and cosmic rays, the gravitational waves will provide informations on the most violent phenomena in the universe, as supernova explosions, collisions of binary systems or mergers of black holes. Their study will thus increase our knowledge in astrophysics, but also in cosmology and fundamental physics. This paper will make a short presentation of the future space interferometer LISA, aiming at detecting gravitational waves, and presents an overview of the R&D developments for LISA at the APC laboratory.

1 Introduction

The first idea of gravitational waves (GW) is attributed to Laplace in the early 19th century. It took a hundred more years to get the first formalism of a gravitational wave. This was done by Einstein as a consequence of general relativity. A GW is described as a distortion of space-time resulting by the relative movement of massive objects. It leads to such small distance variations that only GW emitted by extremely massive objects can potentially be detected. Due to their very weak interaction with matter, GW offers an incomparable tool for the study of the early Universe. So, they are a unique way to access features of massive objects, as binary systems of black holes, neutron stars or white dwarfs, at different stages of evolution.

The existence of GW has been indirectly proven but there is still no direct detection. The first detectors to emerge in the 60s were resonant bars. Since the 90s, ground interferometers have been built and began collecting data in the last decade: VIRGO and GEO in Europe, LIGO in the United States and TAMA in Japan. The detection band of these detectors is between a few tens of Hz to several thousands. The lower limit is mainly fixed by the seismic noise. So the idea of a space interferometer emerged in the early 80s. The Laser Interferometer Space Antenna will be able to detect gravitational waves below 1 Hz and will thus complement ground interferometers observations.

2 Mission and Technology

2.1 LISA

The LISA mission is a joint ESA-NASA spaceborne project, aiming at detecting gravitational waves in the frequency range 10^{-4} –1 Hz (Danzmann K. 2000). It consists of 3 spacecraft in a nearly equilateral configuration orbiting around the sun, about 20 degrees behind the Earth. The spacecraft 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. These interferometric measurements are used to precisely monitor the distance between the inertial masses and, hence, to detect the tiny variation due to the passage of a gravitational wave. So, the expected performance of LISA relies on two main technical challenges: the ability for the spacecrafts to precisely follow the free-flying masses and an outstanding precision of the phase shift measurement.

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The goal of LISA is to detect gravitational deformations as small as $\Delta L/L \approx 7 \times 10^{-21}/\sqrt{Hz}$ (i.e 7 pm per million of km) around 5 mHz. 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 :

Time Delay Interferometry : While each optical signal 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 (around 16 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), the application of this method is not perfect and the noise reduction factor is of the order of 10^8 .

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.

Pre-stabilization : Even with TDI and arm-locking, the light emitted by the laser sources needs to be very stable, at the level of 10^{-13} in term of relative frequency change. Up to now, pre-stabilization on a Fabry-Perot cavity has been considered (Jedrich N. 2006). However, another pre-stabilisation technique often used in metrology (Hall et al. 1999 and references therein), based on the use of a hyperfine transition of the iodine molecule as frequency discriminator, may be an interesting way.

2.2 LISA Pathfinder

The LISA Pathfinder (LP) mission is a preliminary technological mission in order to test the numerous technologies that will be used by LISA. The launch is planned for the end of 2011. LISA Pathfinder consists of a single spacecraft including two inertial masses and an optical bench. These masses are nearly perfectly free-falling, the imperfection is caused by residual forces that create disturbances (electric fields, gravity gradients, solar wind, charged particules, etc). The main objective of this preliminary mission is to validate different experimental techniques related to the inertial masses. First, LP should help us to quantify the acceleration noise due to these residual forces that will perturb the free-falling masses. Then, LP will test the capability of *drag free system* to correct the position of the satellite with respect to inertial masses. This involves testing the inertial sensors and the micro-propulsion system. The last main aim is to test the feasibility of laser interferometry at the level of accuracy envisaged for LISA (within one order of magnitude).

3 R&D developments at the APC

The R&D activities at the APC laboratory are focused on two main axes. The first one was to achieve a frequency stabilized laser system compatible with the pre-stabilization requirements of LISA. The second one is to design an optical simulator of LISA able to quantify the noise of the different instruments, to study the interactions of the different noises and to make the connection between physical measurements and reduction noise algorithms.

3.1 Laser Frequency Stabilization

The Fabry-Perot (FP) pre-stabilization technique, as planned for LISA, is based on a fixed-length, ultra stable optical resonator. It was proved to meet the LISA requirement in terms of intrinsic frequency stability (Jedrich N. 2006). Nevertheless, some limitations can be identified with this technique. First, the performance of the FP cavity is very sensitive to mechanical, but also to thermal disturbances. Additionally, they do not provide an absolute frequency reference. Finally, the performance of the arm-locking algorithm can be increased with the precise knowledge of the Doppler frequency shift (consequence of the relative drift of one spacecraft w.r.t another one). The pre-stabilization method presented here proposes an interesting alternate technique, based on molecular spectroscopy, that can circumvent these issues. It offers the required performance with very good long-term stability (fixed frequency reference). The knowledge of the Doppler shift is therefore directly

measured from the beat frequency. The position of a molecular transition is also much less sensitive to thermal perturbations than a cavity, the constraints being typically relaxed by about 3 orders of magnitude.

These systems have to both meet the spatial constraints (simplicity, compactness, minimizing the consumption of energy) and achieve frequency stability comparable to those obtained in metrology. In order to perform a precise analysis of the frequency stability of our iodine stabilized laser, we decide to build two identical systems allowing frequency comparisons. Consequently, the stability of the systems is determined by the measurement of the joint performance.

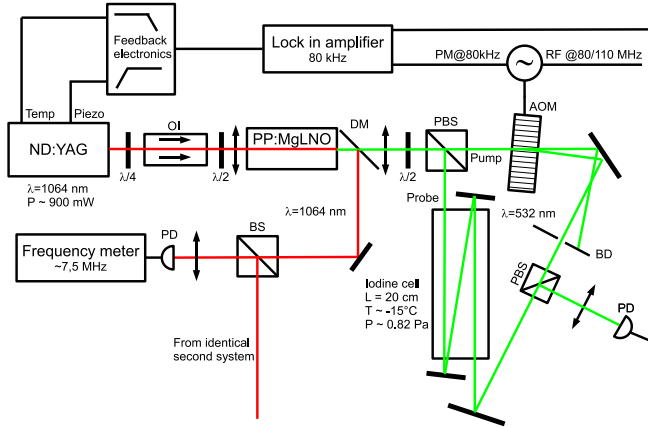


Fig. 1. Experimental layout of the iodine laser stabilization. OI: Optical Isolator, DM: Dichroic Mirror, BS: Beam Splitter, PBS: Polarization Beam Splitter, AOM: Acousto-Optic Modulator, PD: Photodiode, BD: Beam Dump, PM: Phase Modulation, RF: Radio Frequency

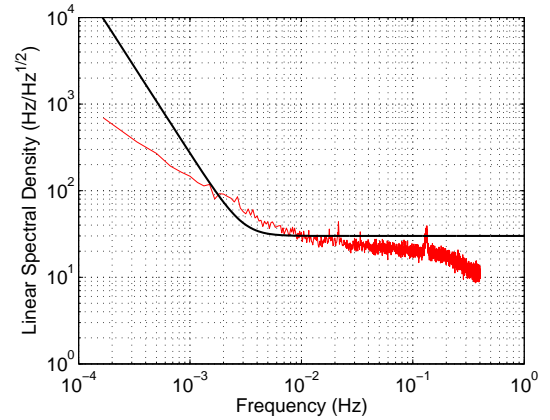


Fig. 2. Frequency stability of one system: in red, the linear spectral density corresponding to our data ; in black, our objective (see text for details).

The experimental setup of one of our system can be seen on figure 1. A complete description of the experience will be given in Argence et al. (in preparation). We use commercial NPRO Nd:YAG lasers that produce about 1W light power at 1064 nm, the wavelength chosen for LISA. Unfortunately, there is no known strong molecular resonance to lock the lasers around 1064 nm. However, iodine provides strong, narrow hyperfine transitions around 532 nm corresponding to the second harmonic of Nd:YAG laser. Thus, the frequency of the laser is doubled with a single pass through a non-linear crystal. A dichroic mirror is then used to separate the two wavelengths. The infrared parts of the two systems are then recombined with a beam splitter and sent to a fibred photodiode. The frequency noise of the beat is assumed to be the (quadratic) sum of the frequency noises of each of the systems.

The green beam is divided in two non-equivalent power parts: the pump beam and the probe beam. Both beams counter propagate within the iodine cell. This configuration allows to get rid of the Doppler broadening effect due to the thermal movements of the molecules. One of these beam (the pump) is strong enough to 'saturate' the line (i.e. a large part of the molecules on its path are in a excited state). The other beam (the probe), of much weaker intensity, is used to scan the absorption profile. The molecules that have already been excited by the pump beam cannot absorb the probe beam and then cause a dip in the absorption profile. With the two beams being of the same wavelength (or shifted by a constant value, see below), only molecules with a given velocity (projected on the light path) are simultaneously saturated by the pump and scanned by the probe beam.

The pump beam is frequency shifted and modulated by an acousto-optic modulator (AOM). The method used here is the modulation transfer spectroscopy (MTS), which already demonstrated very good results on similar experiments (Hall et al. 1999 and references therein). By four waves mixing, the modulation is transferred to the probe beam. The carrier side-bands interference produces a beat on the probe beam whose amplitude is roughly proportional to the derivative of the line profile and can then be used as an error signal for the feedback electronics. After demodulation with a lock-in amplifier, the error signal is fed through the feedback electronics, acting on the temperature and piezo-electric actuator of the laser crystal. The temperature is used for correction

of large deviations on long timescales (below about 70 mHz), whereas the piezo-electric actuator handles higher frequencies, up to about 1 kHz.

The estimated linear spectral density for a single laser is plotted in figure 2. The solid line corresponds to the laser stability requirements fixed for the LISA mission and therefore our objectives of frequency stability (Jedrich N. 2006). Thus the frequency noise in terms of linear spectral density has to be below $30 \cdot \sqrt{1 + \left(\frac{3mHz}{f}\right)^4} Hz/\sqrt{Hz}$ between 10^{-4} and 1 Hz. Above 10 mHz, the spectrum is roughly flat, below our objective of $30 Hz/\sqrt{Hz}$, with a slight tendency to decrease toward $10 Hz/\sqrt{Hz}$ at higher frequencies. Below 10 mHz, the frequency noise increases. This is probably due to thermal environment fluctuations. The forthcoming move in a clean room, temperature-stabilized, should provide better results in this frequency range.

3.2 LISA On Table (LOT): Optical Simulator of LISA

Besides the technology of the inertial masses which will be tested with LISA Pathfinder, the success of the LISA mission depends on its capacity to measure very small displacements (i.e. for LISA, measuring phase difference variations). The measurement of this phase shift changes mainly relies on very good performance of the three stabilization stages: algorithms accuracy (TDI), precise feedback loops (arm-locking) and frequency pre-stabilization but also on extremely low noise of the different instruments (as phasometers or photodiodes). Although the performance of these different key points can (at least partially) be tested in the lab, their interaction is difficult to simulate and predict. Especially, the travel time of the light from one spacecraft to another (16s) 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). Given the low frequency range of phase variations, storing the phase information requires only moderate amount of memory.

Consequently, we are developing an optical simulator of LISA called LOT for LISA On Table. It will be able to test noises and interactions of different instruments and to apply on physical data the noise reduction algorithms as TDI. The LOT is divided into three parts corresponding to the three spacecraft. Each part contain one "local" beam and two "distant" ones. Initially, the same laser source will be used for the 9 beams, this allows to cancel the relative laser frequency noise. The phase (i.e. frequency) variations are introduced by acousto-optic modulators (AOM) with appropriate delays. 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 (>10MHz) with no angular deviation. The chosen configuration also allows the two "distant" beams to follow the same optical path on perpendicular polarisation. Then photodiodes connected to phasometers (prototype developed at the AEI, Hanover) measure the beat between the "local" beam and the two "distant" ones. These beat signals can then be used for post-processing as TDI algorithm or frequency control (arm-locking).

4 Conclusion

The LISA mission is planned for launch in 2020. However, its future depends on the success of the LISA Pathfinder mission. Besides, the R&D developments at the APC are in progress, the laser pre-stabilisation on iodine shows results compatible to LISA requirements. With the help of others LISA teams, the APC is currently developing hardware simulator of LISA aiming at testing interaction between numerical algorithms and instruments.

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