LISACode : Simulating Lisa

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Abstract. A new LISA simulation code is presented. It is highly structured and programmed in C++. The simulator has the purpose to bridge the gap between the basic principles of LISA and a sophisticated end-to-end engineering level simulator. LISA sensitivity curves are presented for various configurations of the detector. This software package, which runs on most computer platforms, can be downloaded from the Lisa-France web site.

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INTRODUCTION

The LISA mission is aimed at detecting gravitational waves (GW) from space, using 3 detectors located on the summits of an equilateral triangle whose centre orbits around the sun, following the earth, at a distance of 50 10^6 km. The distance between the satellites is of the order of 5 10^6 km. The satellites are kept on geodesic orbits by a drag-free system (DFS) system that compensates for the external forces acting on the satellites. The triangular configuration, which depends on the orbits each satellite follows, is not rigid and will both rotate around its centre and "flex" (i.e. the distance between satellites will vary over time) with a period of one year.

On a much smaller scale (i.e. picometres), the distance between the satellites will be modified by the passage of a GW. The detection of such GW will be achieved by interference measurements giving the phase (frequency) difference between local and distant (i.e. coming from another satellite) laser beams on each satellite. There are, therefore, 6 independent laser beams and 12 interference measurements: 6 between local lasers and 6 between local and distant lasers.

The LISA detector system is complex and its sensitivity depends greatly on the different noise contributions coming from the DFS and the interferometric measurements. For these reasons and because a laboratory replica of the system is, as yet, not achievable, the exact evaluation of the performances of LISA can only be studied with computer simulations of the different processes involved.

Two such simulators have been elaborated in the US: Synthetic LISA [1] and LISA simulator [2]. The LISA-France group presents, in this contribution, a new simulator (LISACode) whose ambition is to achieve, through a very modular structure, a new

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degree of sophistication allowing to map, as closely as possible, the precise performances of the different sub-systems. However, LISACode is not a detailed simulator at the engineering level but rather a tool whose purpose is to bridge the gap between the basic principles of LISA and a (future) sophisticated end-to-end simulator. This is achieved by introducing, in a realistic manner, the different ingredients that will influence its sensitivity.

Due to the large distance between the satellites, the interference measurements are performed via independent (local and distant) lasers whose noise level does not allow to achieve the required sensitivity. This can only be obtained via the application of Time Delay Interferometry (TDI) method and which is included in LISACode.

A detailed description of LISA, of its method of principle and of the different noise sources, is given in the LISA Pre-Phase A Report [3]. An extensive description of the TDI method, and of the different combinations that can be used, can be found in M. Tinto, F. B. Estabrook, and J. W. Armstrong [4] and in S. V. Dhurandhar, K. Rajesh Nayak, and J.-Y. Vinet [5].

This contribution will not present in detail the structure or the use of the LISACode simulator but will give a few examples of the kind of results that can be obtained from it. The LISACode software package and a more detailed description of it can be downloaded from the web.

THE STRUCTURE OF LISACode

LISACode is written in C++ and has a very modular structure. The structure is presented in Fig.1. Its main components are: i) A variety of GW inputs, ii) a detailed description of the orbits [6] of the three satellites (including the breathing and rotation modes of the LISA triangle), iii) the different noise sources (lasers, DFS and the interferometric measurements), iv) the phasemetre measurements and v) the Ultra Stable Oscillator (USO) clock performances.

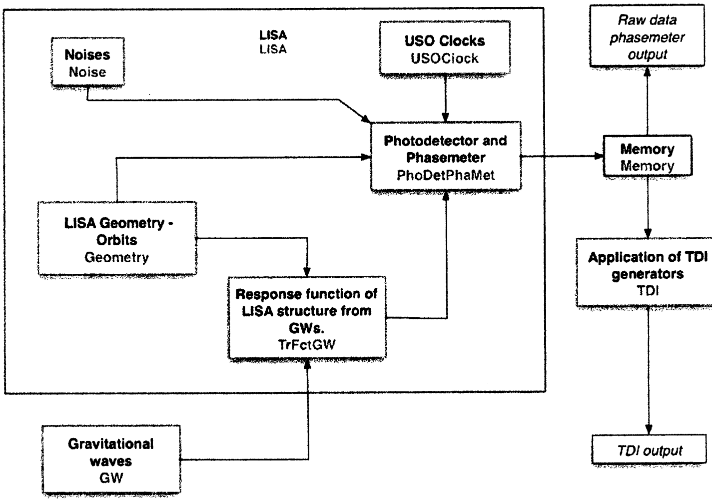

FIGURE 1. Schematic diagram of the LISACode software simulator.

The interference measurements yield the frequency shifts between the 12 local/distant laser beams at a fixed rate (typically 10Hz). These measurements are then filtered to deliver the 12 frequency measurements at a rate of the order of 1 Hz. LISACode operates thus in the time domain very much like Synthetic LISA.

LISACode can then either output the results of the phasemetre measurements or process them through various, user definable, TDI combinations, which will allow to suppress, by a factor of 10^7 or more (see Fig 11, for example), the laser noise.

Because of the rotation of the LISA triangle, the frequency signal delivered by LISA will have a complicated time structure with a periodicity of 1 year. Figure 2 shows an example of such signals as given by a GW source, whose parameters are displayed in the figure.

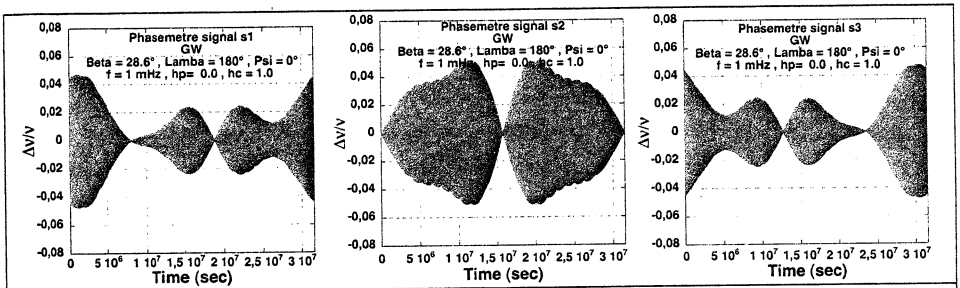

FIGURE 2. Phasemetre output of each LISA satellite for a year long observation of a (noiseless) monochromatic gravitational wave. Left: the relative frequency shift between the local laser of satellite 1 and the (distant) laser coming from satellite 2. Middle: same as left but for satellites 2 and 3. Right: same as left but for satellites 3 and 1.

THE LISA SENSITIVITY CURVES

One of the first goals of the development of LISACode is to estimate quantitatively the sensitivity of LISA in various configurations and to compare these to previous calculations, if existent.

The sensitivity of LISA is defined by the following formula:

$$h = 5\sqrt{\frac{Noise}{Yr * Resp_{GW}}}$$

Where $Resp_{GW}$ is the response function of LISA to the GW signal and *NOISE* is the noise power distribution. The sensitivity is calculated for a one-year ($Yr = 3\ 10^7$ sec) observation period and corresponds, by convention, to a Signal to Noise ratio of 5.

Figure 3 and 4 present (full line, in blue) the noise and GW response of the TDI X1s1 (first generation Michelson combination centered on satellite 1: a rigid, non-rotating, LISA configuration) compared to standard semi-analytical calculations (dotted line, in red). Figure 5 shows the corresponding sensitivity. The oscillations at high frequencies are introduced by the TDI method. One observes that up to ≈ 0.02 Hz the agreement is very good. The slight discrepancy observed at the higher frequencies is attributed to the effect of the phasemetre filter algorithm, which cannot be included in semi-analytical calculations.

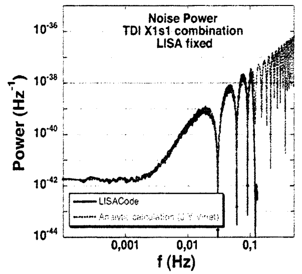

FIGURE 3. Power distribution of LISA noise obtained from 1st generation Michelson TDI combination.

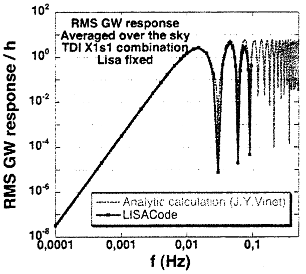

FIGURE 4. "averaged over the sky" GW response obtained from 1st generation Michelson TDI combination.

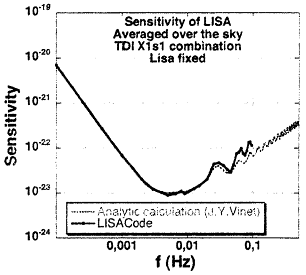

FIGURE 5. "averaged over the sky" LISA sensitivity response obtained from 1st generation Michelson TDI combination.

A more realistic calculation can be performed by including the "Sagnac" rotation and the flexing of the LISA triangular configuration. This implies the use of 2nd generation TDI combinations. Figures 6-8 shows the noise function, the GW response and the LISA sensitivity (full line, in blue) for the TDI X2s1 combination.

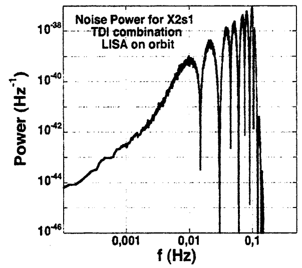

FIGURE 6. Power distribution of LISA noise obtained from 2nd generation Michelson TDI combination.

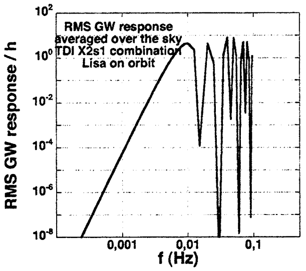

FIGURE 7. "averaged over the sky" GW response obtained from 2nd generation Michelson TDI combination.

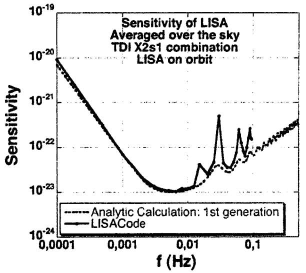

FIGURE 8. "averaged over the sky" LISA sensitivity response obtained from 2nd generation Michelson TDI combination.

Modifying the arm lengths of LISA

Once the sensitivity of LISA is calculated for its nominal configuration, it is possible to study how it evolves when modifying some of its parameters.

One of the question that arise when discussing the optimal LISA configuration, in terms of performance versus cost, is the optimum length (L) of the LISA arms. Nominally, this length is 5 10^6 km. LISACode has the possibility to parameterize this distance. Based on the noise sources as given in table 4.1 of the LISA Pre-Phase Report [3], it is concluded that only the detector shot noise will depend on L. Figure 9 shows the sensitivity curves for L= 5 10^6 km (dotted line, red) and 2 10^6 km (full line, blue). As expected, a deterioration of the performances at the lower frequencies is clearly observed.

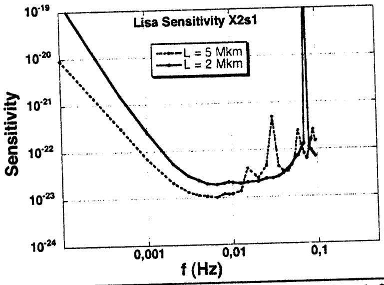

FIGURE 9. LISA sensitivity response obtained from 2^{nd} generation Michelson TDI combination when varying the LISA arm lengths.

Introducing an offset on the TDI delays

The application of TDI depends on the precision with which the laser flight path distances between the LISA satellites, and hence the TDI delays, are estimated. For example, an offset of 300 m in the estimation of the laser flight path, will induce a delay offset of 1 μsec. Figure 10 shows the TDI X2s1 sensitivity curve for delay offsets of 0, 0.5 and 1 μsec. As the predicted precision on the knowledge of the flight path is considered to be much smaller than these values, it can be seen that LISA will not suffer from this effect.

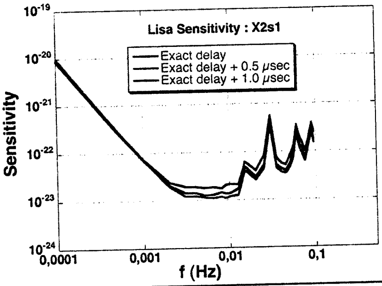

FIGURE 10. LISA sensitivity response obtained from 2^{nd} generation Michelson TDI combination when introducing an offset on the laser flight path between satellites.

AN EXAMPLE OF A GRAVITATIONAL WAVE SIGNAL

As stated above, the direct output of a phasemetre contains the different instrumental noise, including the laser noise that overwhelms the intensity of the physical signal of a GW. Figure 11 shows (upper curve, in red), as a function of the frequency, the power spectral density of the output of a phasemetre. Imbedded in this spectrum is a GW signal of frequency 1 mHz and power 10^{-18} $Hz^{-1/2}$. Processing this data with a second generation TDI combination (i.e. X2s1: Michelson based on satellite 1) the GW signal is revealed (lower curve in blue) showing that TDI is able to suppress the Laser noise by a factor 10^{-8} in this frequency domain.

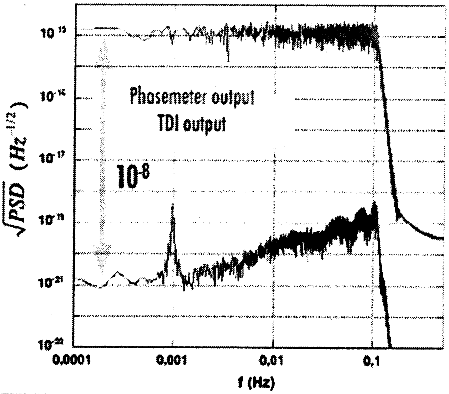

FIGURE 11..LISA response in the presence of a GW signal. Upper curve: The PSD of a phasemetre output prior to TDI processing. Lower curve: after TDI processing.

STATUS AND EVOLUTION OF THE CODE

The present version of LISACode (version 1.2) contains the following features:

- A variety of simple GW signals for inputs and the possibility to introduce more sophisticated GW signals via ASCI files.
- The calculation of realistic orbits that include SAGNAC and flexing of the LISA satellite configuration.
- The noise sources corresponding to laser, drag free control, optical path noise [3] and the USO.
- The standard TDI combination of first and second generation as well as a procedure to define any combination of the TDI basis.
- The possible modification of most of the parameters that define the LISA configuration.

All these parameters, and many more, are inputted to the program by an ASCI file. The outputs (phasemetres, TDI, satellite positions…) are also ASCI files.

The program executes on most platforms (Mac, UNIX, Windows…) and the source code, together with a compilation script, can be obtained on request, by emailing to: antoine.petiteau@apc.univ-paris7.fr .

In the future, the outputs and inputs will become XML compatible following the structure defined by the LISA mock data challenge [7]. More realistic noise functions as well as more complex GW signals (MBHB, EMRIs...) will be implemented.

Also in the near future, the Galactic Confusion Noise will be introduced in the code at the phasemetre level.

A more complete presentation of this code can be found on the following web site: http://www.apc.univ-paris7.fr/LISA-France/analyse.phtml

SUMMARY

A new and sophisticated LISA simulator (LISACode) is now available for the GW community. Its performances and ease of use should make it a useful tool for the study of LISA performances in different configurations. It is hoped that it will be made use of in the context of the present LISA Mock Data Challenge [7] as well as for future analysis and optimization of the LISA detector.

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