LISA Benchtop Experiment

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The Laser Interferometer Space Antenna (LISA) is expected to launch in the middle of the next decade. LISA will detect gravitational waves generated by sources ranging from galactic sources like neutron star and white dwarf binaries to mergers between super-massive black holes in the centers of colliding galaxies. LISA will consist of six freely-falling proof masses shielded by three identical spacecraft. The spacecraft will be steered around the proof masses and laser interferometer will monitor the distances between the proof masses. One of the main challenges to test LISA interferometry on the ground is the long light travel time of 16 s between the spacecraft. At UF, we developed a technique to experimentally simulate the light travel time that enables us to build a LISA benchtop interferometer and test many aspects of LISA interferometry. We plan to test time delay interferometry, stabilize the laser frequency to a LISA arm, generate LISA-like signals, verify on-board data reduction schemes, and host mock data challenges well before LISA is launched. In this report we will give an overview of LISA interferometry and discuss the status and future plans of our experiment.

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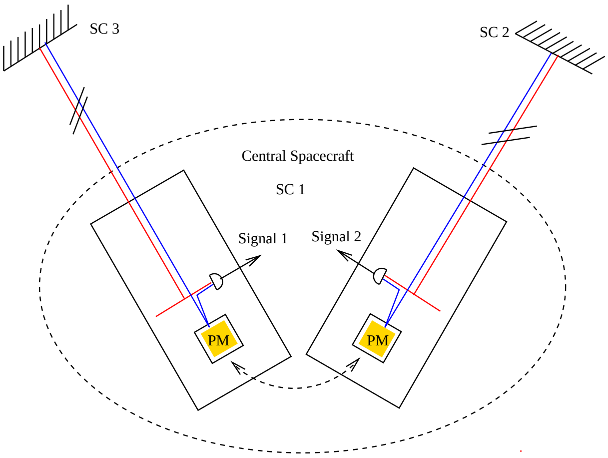

Figure 1: A very simplified version of the LISA interferometer: The central SC sends laser beams to both far SC. Phase-locked lasers will return the beam back to the central SC where the returned beam will be measured against the local laser. In this oversimplified picture the far SC act as simple transponders.

1. Introduction

The Laser Interferometer Space Antenna (LISA), a joint NASA/ESA mission scheduled to launch in 2014, will detect gravitational waves generated by highly accelerated masses [1]. This will open a completely new window to the universe. LISA's science goals are the measurement of gravitational waves from mergers between supermassive black holes and extreme mass ratio inspirals, the test particle case of strong field gravitational radiation. Signals from galactic binaries can be used to survey neutron star binary population and, more importantly, to calibrate the instrument. It is also very likely that signals from currently unknown and probably even more exciting sources will be discovered.

LISA will consist of three spacecraft (SC) in a triangular formation. Each SC is in a heliocentric orbit trailing earth by 20°. The distances between the SC are 5 million km with annual variations of 50,000 km. Each SC will contain two freely falling proof masses (PM). These PM act as gravitational reference sensors while the SC will shield them from all external forces [2]. The laser interferometer measurement system (IMS) is used to measure the distances between the PM. One of the main challenges associated with the interferometry is the overwhelming laser frequency noise. Time Delay Interferometry (TDI) and arm-locking are two techniques which have been discussed to supress the laser frequency noise in the LISA signals. Both technologies need to be verified during ground tests. In the first section of this paper, we will review TDI and arm-locking in LISA. In the second part we will describe experimental techniques which allow us to test LISA interferometry including TDI and arm-locking on the ground and discuss our future plans [3].

2. Interferometer Measurement System

The IMS will monitor the distances between the PM on the different SC. This is done by phase locking the lasers on the far SC (SC 2 and SC 3 in Fig. 1) to the laser field coming from SC 1. The far SC then act as transponders. Each incoming field on SC 1 will then be superimposed with

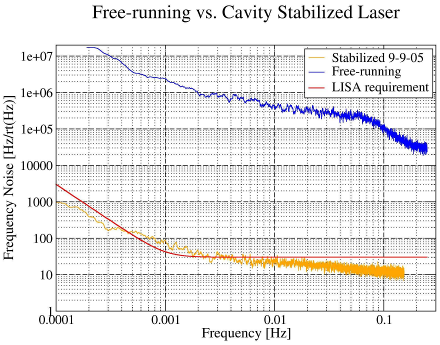

Figure 2: Laser frequency noise. The upper curve: free running, lower curve: stabilized.

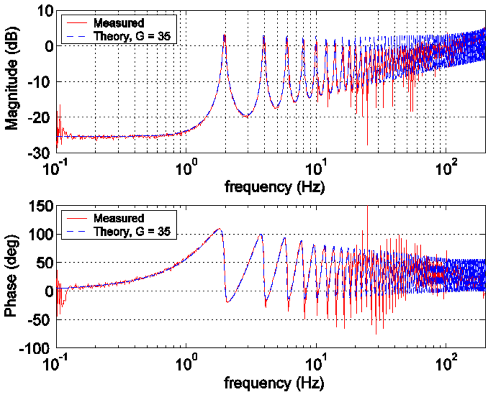

Figure 3: The frequency noise of a voltage controlled oscillator locked to a 0.5s long arm.

the local laser and the phases of the beat signals will be measured with phasemeter [4]. Each of these configurations is equivalent to a Mach-Zehnder interferometer with a 5 million km long arm length difference. The Mach-Zehnder or phasemeter signals (Signal 1 and Signal 2 in Fig. 1) will be dominated by laser frequency noise. If we first assume that the light travel times in the two long arms are identical, both signals could be subtracted from each other to cancel the laser frequency noise. This requires the phasemeter to have a resolution of 10^{-5} cycles/$\sqrt{\text{Hz}}$ and a dynamic range that enables them to handle the laser frequency noise and the several MHz Doppler shifts associated with the relative velocities between the SC. In practice, the arm lengths will change and will differ by up to one percent during the year long orbit. In this case, linear combinations between the instantenous phasemeter signals and earlier (time delayed) phasemeter signals can, in principle, cancel the laser frequency noise synthesizing an equal-arm Michelson interferometer. Time delay interferometry (TDI) depends on a precise knowledge of the light travel time and precise timing of all phasemeter signals [5].

The requirements TDI places on the linearity of the phasemeter, on timing, and on ranging scale with the laser frequency noise. LISA's laser frequency stabilization system will use ultra-stable optical resonators based on spacer materials with very low thermal expansion coefficients like ULE and Zerodur. The low thermal expansion coefficient and the very low expected temperature variations inside the LISA spacecraft would allow a frequency stability of a few Hz/$\sqrt{\text{Hz}}$. However, material internal processes or processes in the optical bonds might compromise the stability. The requirement on the laser frequency noise in LISA is set to 30Hz/$\sqrt{\text{Hz}}$ above 3 mHz to allow for some margin. Fig. 2 shows the frequency noise between two independently frequency-stabilized laser systems measured in our laboratory using Zerodur spacers inside a temperature stable vacuum tank. These results show that such a setup will meet the LISA requirements.

An additional method has been proposed to further reduce the laser frequency noise. Arm-locking uses the interferometer arms between the SC as these are the most stable frequency references in the frequency band of interest. However, the unusual transfer function of the Mach-Zehnder interferometer with such an extremely long reference arm requires a specially shaped feedback loop and will not suppress the laser frequency noise at all Fourier frequencies [6]. Several options for implementing arm-locking are currently studied to adapt it to a realistic LISA interferometer.

3. LISA Benchtop experiment

A test of all aspects of TDI and arm-locking requires a way to simulate the 16 s light travel time between the SC. An optical delay of this magnitude is impossible to create in the lab. However, it is important to understand that the laser phase (and amplitude) is the only information that needs to "travel" 5 million km to simulate the long LISA arm. Our group developed an electronic phase delay unit which uses a second reference laser to demodulate the laser phase into the low RF-range where we can digitize the signal, delay it electronically, and then regenerate it 16 s later. A first low frequency version has been built that can handle beat frequencies up to 50 kHz [3]. After a series of initial tests the EPD unit was then used to demonstrate arm-locking of a voltage controlled oscillator to a 0.5 s long arm. The results (see Fig. 3) agree very well with the theory [6] and show that an arm-locking controller can be stable and can suppress the laser frequency noise in most frequency bands. We are currently improving the bandwidth of the EPD unit and developing fast phasemeters. Both components have to handle the laser beat signals of 10-30 MHz. The new EPD units, phasemeter, and the frequency stabilized lasers are the key components of our LISA benchtop experiment. In a first stage, the experiment will consist of a total of four lasers, one for each SC and a reference laser to demodulate the laser phase. One SC-laser and the reference laser will be stabilized to the Zerodur cavities. A beat signal between these two lasers will be delayed by 16 s and demodulated with a second beat between the reference laser and one of the far SC-lasers. The mixer output will then be used to phase lock the far laser. The second beat signal will also be delayed and demodulated with the instantenous beat signal of the first beat. This demodulated signal is identical to one of LISAs Mach-Zehnder signals. An identical setup with different time delays will be used to simulate the second Mach-Zehnder arm. These signals will allow us to test TDI, study the phasemeter, and many other aspects of LISA interferometry. The Mach-Zehnder signals can also be used to lock the local SC-laser to the delay time and test arm-locking. In a second stage we will add Dopler shifts and gravitational wave signals to the interferometer to further test the dynamic range of the LISA interferometer and study data reduction techniques.

References

[1] Danzmann K. et al 1998 LISA: Laser Interferometer Space Antenna Pre-Phase A Report 2nd edn MPQ 233 (Garching, Germany: Max Planck Institut fuer Quantenoptik)

[2] Achieving geodetic motion for LISA test masses: ground testing results, L. Carbone, A. Cavalleri, R. Dolesi, C.D. Hoyle, M. Hueller, S. Vitale, W.J. Weber, Phys. Rev. Lett. **91(15)** 1501101 (2003)

[3] Electronic Phase Delay - A first step towards a bench-top model of LISA, J.I. Thorpe, R.J. Cruz, S. Sankar, G. Mueller, Class. Quant. Grav. **22(10)** (2005) S227-S234

[4] Status of LISA phase measurement work in the US, S.E. Pollack, O. Jennrich, R.T. Stebbins, P. Bender, Class. Quant. Grav. **20** (2003) S193-S199

[5] Cancellation of laser noise in an unequal-arm interferometer detector of gravitational radiation, M. Tinto, J.W. Armstrong, Phys. Rev. D **59** 102003 (1999)

[6] Experimental verification of arm-locking for LISA using electronic phase delay, J.I. Thorpe, G. Mueller, Physics Letters A **342** (2005) 199-204