

A Michelson interferometer system for testing the stability of a piezo-electric actuator intended for use in space

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Abstract. The Laser Interferometer Space Antenna (LISA) experiment will search for gravitational waves generated by cataclysmic events far back in astronomical history. LISA is an interferometer formed by three spacecraft positioned five million km apart, and to observe gravitational waves, it must monitor test mass positions with picometre level resolution. One of the numerous technological challenges is to identify an actuator with appropriate accuracy, precision and stability for positioning of the optical fibres used to deliver LISA's laser sources. We have developed a Michelson interferometer system to determine the temporal and thermal stability of candidate actuators, with an emphasis on characterisation in the milliHertz frequency range required for gravitational wave detection in space. This paper describes the interferometer data logging and calibration and presents preliminary results in the form of a "noise spectrum" generated from the small perturbation of a nominally static mirror. The maximum displacement of the mirror was ~ 50 nm with sub-Hz noise levels of $0.1\text{--}1$ nm $\sqrt{\text{Hz}}$. This is within the LISA noise specification, and confirms that the apparatus is stable enough for the characterisation of the actuator.

1. Introduction: The search for gravitational waves and LISA

Gravitational waves are ripples in space-time caused by the interaction of massive objects such as galaxies and stars. Unlike electromagnetic radiation, gravitational waves are barely scattered or attenuated by matter and so they can propagate indefinitely throughout the universe. "Gravitational astrophysics", requiring measurement of gravitational waves is therefore a uniquely far-reaching kind of astronomy which can look back closer to the Big Bang than ever before [1]. Several experiments to search for gravitational waves are underway, though the waves have not yet been directly detected[2]. One ground-based technique is to use sensitive interferometers, with arm lengths of several kilometers, to detect small fluctuations in the recombined beam if a gravitational wave passes, *e.g.* the LIGO instrument[1]. The Earth's gravitationally noisy environment limits low frequency (sub-Hz) observations, and provides a strong motivation for carrying out the search for gravitational waves in space.

The Laser Interferometer Space Antenna (LISA) also operates as an interferometric detector, but the arms of the interferometer are formed by three spacecraft five million km apart. The LISA laser sources will be supplied to the optical benches by optical fibres, and a fibre positioning unit will be used as an actuator to enable fibre alignment and replacement of redundant fibres. As the detection of picometre displacements over millions of km is extremely technologically challenging, the low-

frequency stability of all the instrumentation in the optical chain has to be very well understood so that any gravitational wave signals can be unambiguously identified. Figure 1 shows the levels of displacement noise necessary to fulfil the LISA requirements. The laboratory interferometry experiment reported in this paper was motivated by the need to understand the low-frequency stability of candidate fibre delivery actuators.

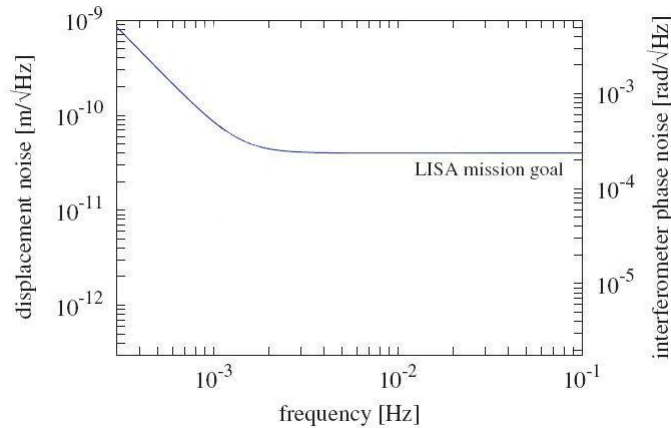


Figure 1: LISA mission goals, showing the displacement noise requirements on the left hand axis(after[3])

2. Laboratory interferometer system

2.1. Description

In the laboratory interferometer system (Figure 2), the path lengths are equalised so that the common mode displacement noise will largely cancel out. A pick-off beamsplitter is mounted at the interferometer input, before the main beamsplitter, to direct 33% of the laser power to a photodiode, which acts as a power monitor for the 633 nm 5 mW HeNe laser. A spatial filter is used to improve the quality of the beam and enlarge it to ~ 7 mm diameter before it enters the interferometer. The interferometer beamsplitter divides the laser beam into two paths, at right angles to one another and to the incoming beam. The beamsplitter is adjustable for rotation in two axes (tip and tilt). Measurements are made by mounting a mirror to the actuator stage, and using the mirror as one arm of a Michelson interferometer. A similar mirror is mounted in the reference arm of the interferometer. The reference mirror is also adjustable for rotation in the tip and tilt axes. The recombined beams are aligned to be co-linear and directed to a photodiode. Movements of either mirror, along the beam axis, cause a change in fringe intensity which can be enhanced by using a slit in front of the photodiode and introducing tilt so that transverse fringes can be scanned across the detector. The aim of the experiment is to cycle the actuator under test through several fringes in order to check resolution, range of travel, linearity and stability. Fringe counting is used to measure the actuator's position. In the preliminary apparatus described in this paper, a micrometer stage is used in place of the actuator for calibration (Figure 2).

Silicon photodiodes operated without reverse bias (to reduce noise[4]) are used for monitoring the laser power and interferometer signal. Photodiode currents are measured using a bespoke i-V converter with a nominal sensitivity of $0.1 \pm 0.0015\%$ V/mA, and a National Instruments DAQ 6023E board for analogue input to a PC, with National Instruments LabVIEW software used for data logging and calibration. So that drift in the laser power is not mistaken for the interferometer signal, the signal is written as a normalised ratio of the interferometer power and laser power. The dimensionless interferometer signal s is given as

$$s = \frac{1}{2} \left(\frac{V_i - c_i}{V_p - c_p} \right) \frac{m_p}{m_i} \quad \text{Equation 1,}$$

where V is the measured output voltage, m is the i-V converter sensitivity (in mA/V), c the i-V converter offset (in V) and the suffixes i and p represent the interferometer and power monitor photodiodes/channels respectively. (The factor of 0.5 in Equation 1 accounts for the different fractions of the signal being passed to the power monitor and interferometer photodiodes) Calibration of the i-V converter with a Fluke 715 precision mA current generator indicates that s can be measured to $\pm 0.2\%$.

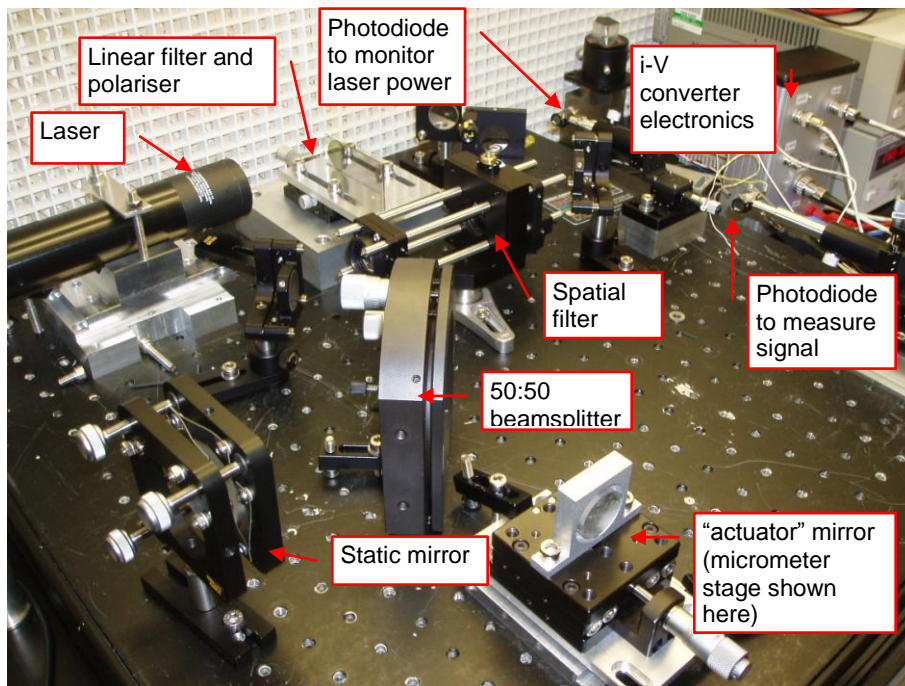


Figure 2: Photograph of actuator test system

2.2. Calculation of Displacement

The interferometer signal s calculated from Equation 1 needs to be converted into a displacement. Firstly the amplitude A of the fringe is determined by manually observing and differencing the maximum s_{max} and minimum s_{min} interferometer signal. If λ is laser wavelength, s is a function of the mirror position (displacement) x given by

$$s(x) = A \cos^2 \left(\frac{2\pi x}{\lambda} \right) + s_{min} \quad \text{Equation 2.}$$

This can be inverted to give the displacement in terms of the signal:

$$x = \frac{\lambda}{2\pi} \cos^{-1} \left(\sqrt{\frac{s - s_{min}}{A}} \right) \quad \text{Equation 3.}$$

The error in the displacement measurement results from a combination of errors in s and λ . Fluctuations in the wavelength of the unstabilised laser used in the preliminary experiments are the

dominant source of error, $\sim \pm 2\%$. It is intended to reduce this error by replacing the laser with a frequency stabilised model.

The contribution at different frequencies to the noise power is given by the power spectrum of the displacement, in m^2/Hz . However, for comparison with the LISA specification in Figure 1, the displacement spectrum must be stated, in units of $\text{m}/\sqrt{\text{Hz}}$, given by the square root of the power spectrum. The simplest case is to use a static mirror in place of the actuator, so that all the displacement observed is due to local environmental fluctuations. This “noise spectrum” determines whether the experimental apparatus can measure the actuator stability to an appropriate sensitivity for the LISA mission. Figure 3 shows the results from a noise spectrum measurement sampled at a frequency of 100Hz. It is clear from (a) and (b) that the correction for laser power fluctuations is necessary, and the displacement in (c) indicates that the “static” mirror actually moves $\pm 50\text{nm}$ over the experiment. This could be due to thermal or acoustic noise, and will be discussed further in Section 4.

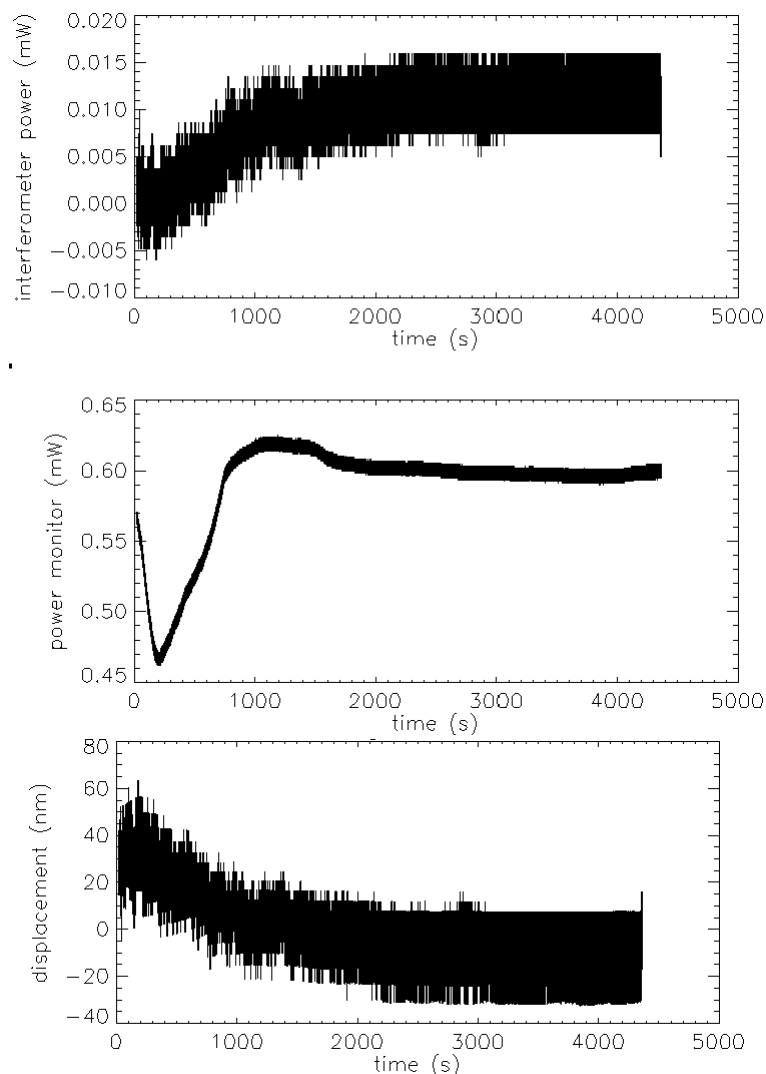


Figure 3. Power and displacement measurements. Top: measured interferometer power. Middle: power monitor signal showing laser power fluctuations. Bottom: Displacement of a “static” interferometer arm, calculated from Equations 1 and 3.

3. Preliminary results

A noise spectrum (Figure 4) has been calculated for the data shown in Figure 3 using a Fast Fourier Transform (FFT) algorithm. Linear trends were not removed from the data before the FFT calculation, as this could remove slow drift in the displacement. The calculation was verified using different software packages and also by computing the mean square power in the signal by two methods. It can be seen that at 0.1-1 mHz, the typical noise level is 0.1-1 nm $\sqrt{\text{Hz}}$, comparable to the levels shown for the LISA mission in Figure 1.

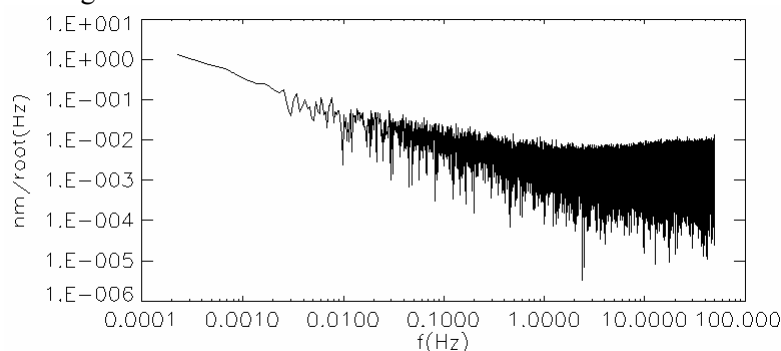


Figure 4. Noise spectrum of the displacement data shown in Figure 3.

4. Conclusions

These initial results are promising as they indicate that the noise spectrum (Figure 4) is similar to the LISA requirements (Figure 1). The data shown in Figure 4 is a “worst case” noise scenario which includes effects from thermal, acoustic and laser wavelength fluctuations. This suggests that the system is capable of detecting actuator displacement at the necessary frequencies.

The errors in the displacement calculation (Equation 3) will be substantially reduced by use of a frequency-stabilised laser. Thermal effects will be quantified by using an array of thermistors in thermal contact with each of the optical components to detect temperature fluctuations synchronously with the optical measurements. If thermal effects are causing the variations shown in Figure 3, the fluctuations in photodiode signal (expressed either as a time series or as a power spectrum) should be correlated with temperature changes. Temperature measurement will also permit estimation of any thermal drift in the i-V converter, for instance from changes in the op-amp input bias current[5]. Further characterisation and calibration will still be required, in particular to identify and minimise sources of acoustic noise.

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