

LISA laser noise cancellation test using time-delayed interferometry

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ABSTRACT

The Laser-Interferometer-Space-Antenna (LISA) is a space-based interferometer with arm lengths of 5×10^9 m. Its design goal is to measure gravitational waves with a strain sensitivity of 10^{-23} at 10 mHz (for SNR=5 and 1 year integration). Unlike in earth-based interferometers the arm lengths can differ by up to 2% or 10^8 m. For that reason frequency noise in the $\lambda \sim 1 \mu\text{m}$ laser will not cancel in the direct interference signal. A laser locked to a ULE reference cavity (CTE $\sim 3 \times 10^{-8} / ^\circ\text{K}$) in a $1 \text{ } ^\circ\text{K}/\sqrt{\text{Hz}}$ environment will have about $10 \text{ Hz}/\sqrt{\text{Hz}}$ frequency noise. The LISA sensitivity goal requires for the laser noise of less than $10^{-5} \text{ Hz}/\sqrt{\text{Hz}}$, about a factor 10^{-6} below what has been achieved ⁽¹⁾. Cancellation of laser frequency noise can be achieved by time-delayed-interferometry (TDI) ^(2,3). We describe a laboratory test of TDI with an unequal arm interferometer. The intent is to ascertain the performance limitations and proof-of-concept for 6 orders of magnitude frequency noise suppression.

Keywords: LISA, time-delayed interferometry, gravitational wave detector, laser frequency stability

1. INTRODUCTION

The LISA mission sensitivity goal relies on the active stabilization of laser frequency. Depending on the residual frequency noise an additional suppression of 4 to 6 orders of magnitude will be necessary. A proposed ^(2,3) time domain method to achieve that, called TDI, processes separate measurements of the phase difference in each arm. In this scheme, the laser frequency noise cancels to the required level if the arm lengths are known with adequate accuracy, about 30 m. This paper deals with proposed laboratory experiments to apply TDI to data from an interferometer. These experiments are meant to provide insight into the technical limitations in the suppression of frequency noise.

2. EXPERIMENTAL SETUP AND PARAMETERS

2.1 Common phase noise measurement

A precursor experiment is to measure the phase of the beat note between two lasers with respect to the same RF source using two detectors and phasemeters. The setup is shown in figure 1. Two lasers (Nd:YAG NPRO's) with a 5-10 MHz frequency difference are interfered using a fiber splitter/combiner. We then split the light from one of these outputs again using a 50/50 non-polarizing cube beamsplitter. The two outputs of the second splitter are identical to first order. This experiment is expected to reveal sensitivity to synchronization differences in the two phasemeters.

2.2 Unequal arm fiber interferometer

The basic idea is to build two laboratory size interferometers with arms L_{12}, l_{12} and L_{13}, l_{13} with a large arm length difference $\Delta L = L_{13} - L_{12}$ (figure 2) conceptually similar to two adjacent LISA arms. The transfer function for laser frequency noise in an unequal arm Michelson interferometer vanishes at DC and at frequencies $f_n = n \cdot c / 2\Delta L$; i.e. noise at these frequencies is inherently suppressed (figure 3). Our measurements will characterize suppression of frequency noise by TDI at Fourier frequencies $f < f_n$.

The phase will be sampled ⁽⁴⁾ at a rate of $f_s = 20 \text{ kHz}$ giving a maximum Fourier frequency $f = 10 \text{ kHz}$. To achieve the necessary frequency noise suppression it is necessary to time-shift and subtract the signals from the two interferometers with precise timing resolution ⁽²⁾. The required timing resolution t_0 is given by: $S_{10}(f) \sim S_y(f)(2\pi f t_0)^{-2}$ ⁽⁵⁾ where $S_y(f)$ and $S_{10}(f)$ are the power spectral densities of the error before and after applying the TDI algorithm, respectively. Our goal is $(2\pi f t_0) = 10^{-6}$, requiring $t_0 < 16 \text{ ps}$ for $f = 10 \text{ kHz}$

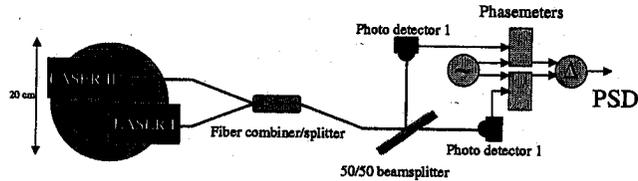


Figure 1: Setup for common phase noise subtraction test.

It is desirable to make the arm-length difference as long as practicable, to better simulate the LISA parameters. Our experiments will be based on optical fiber interferometers with an arm length difference of $\Delta L = 10$ km.

Noise pickup is expected to increase with increasing fiber length. The two long fibers $L_{12} = 10$ km and $L_{13} = 20$ km will be wrapped on a common spool inside a vacuum chamber, insulated from acoustical noise to minimize phase noise. At 10 kHz, fiber induced phase noise is expected to be dominated by acoustical pickup.

We plan to build two heterodyne fiber interferometers and measure the phase of the two signals with respect to the phase of the mixer output f_H . An NPRO laser @ 1319 nm will serve as the light source for the interferometers. Its free-running frequency noise at 10 kHz is < 10 Hz/ $\sqrt{\text{Hz}}$. If necessary for improved output signal, we will add frequency noise by applying a broadband signal to the laser PZT input. For signal calibration, we will insert fiber stretchers in the long arm of each interferometer. The goal is to measure the SNR improvement in the power spectral density (PSD) of the two phase measurements once the time delay arithmetic is applied. Figure 2 shows the setup and depicts generic frequency-domain spectra of the two outputs of the phasemeters and a spectrum after TDI has been applied to the time-domain data. In this case of two interferometers the algorithm that will be applied to the phase data is as follows ⁽²⁾:

$$\begin{aligned}
 X(t_0) &= s_{12}(t - 2L_{13}/c) - s_{13}(t - 2L_{12}/c) - s_{12}(t) + s_{13}(t) \\
 &= \Phi_N(t - 2L_{13}/c - 2L_{12}/c) - \Phi_N(t - 2L_{13}/c) + h_1(t - 2L_{13}/c) + n_1(t - 2L_{13}/c) \\
 &\quad - [\Phi_N(t - 2L_{12}/c - 2L_{13}/c) - \Phi_N(t - 2L_{12}/c) - h_2(t - 2L_{12}/c) + n_2(t - 2L_{12}/c)] \\
 &\quad - [(\Phi_N(t - 2L_{12}/c) - \Phi_N(t) + h_1(t) + n_1(t))] \\
 &\quad + [(\Phi_N(t - 2L_{13}/c) - \Phi_N(t) - h_2(t) + n_2(t))] \\
 &= h_1(t - 2L_{13}/c) + h_2(t - 2L_{12}/c) - h_1(t) - h_2(t) + n_1(t - 2L_{13}/c) - n_2(t - 2L_{12}/c) - n_1(t) + n_2(t)
 \end{aligned} \tag{1}$$

The laser frequency noise Φ_N contributions in the signals of the two interferometers cancel when the signals are combined with the proper time-delays. The signal will be attenuated depending on its frequency but so will the remaining noise n_1, n_2 , i.e. the SNR is constant ⁽²⁾:

$$S_{X(t)}(f) = 4 [h_1(f) - h_2(f)]^2 \sin^2(2\pi f L_{12}) + 4 [S_{n_1}(f) + S_{n_2}(f)]^2 \sin^2(2\pi f L_{12})$$

By modulating the arm length and the laser frequency at different frequencies laser frequency noise suppression and SNR can be determined at these frequencies. This is shown in figure 3 where the plots on the right hand side show the power spectral densities of the phasemeter outputs directly and after TDI has been applied, respectively. The arm length modulation simulates a gravitational wave signal in the long-wave limit where the effect of the wave is equivalent to forces local to the end mirrors. That is, at low frequencies the interferometer response to gravitational waves is independent of frequency, and can be approximated by the PZT frequency-independent dashed line in figure 3.

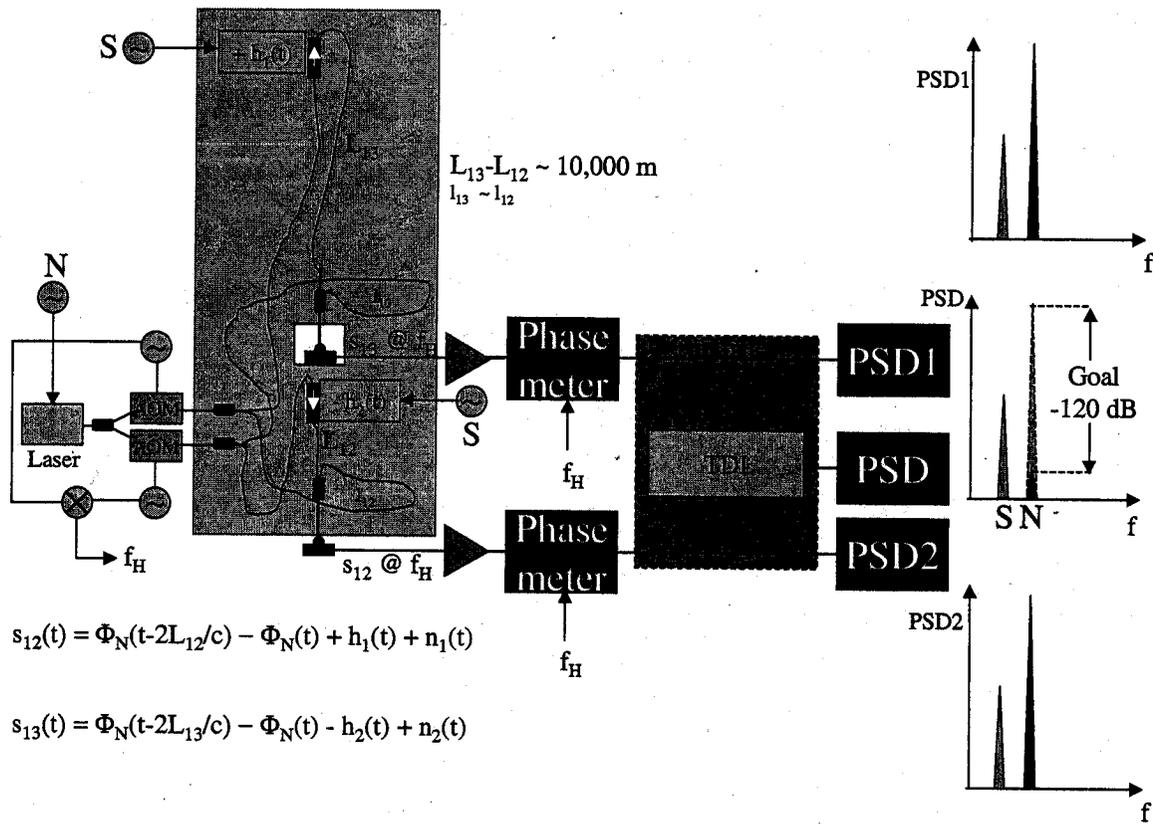


Figure 2: Unequal-arm fiber interferometer for testing of TDI

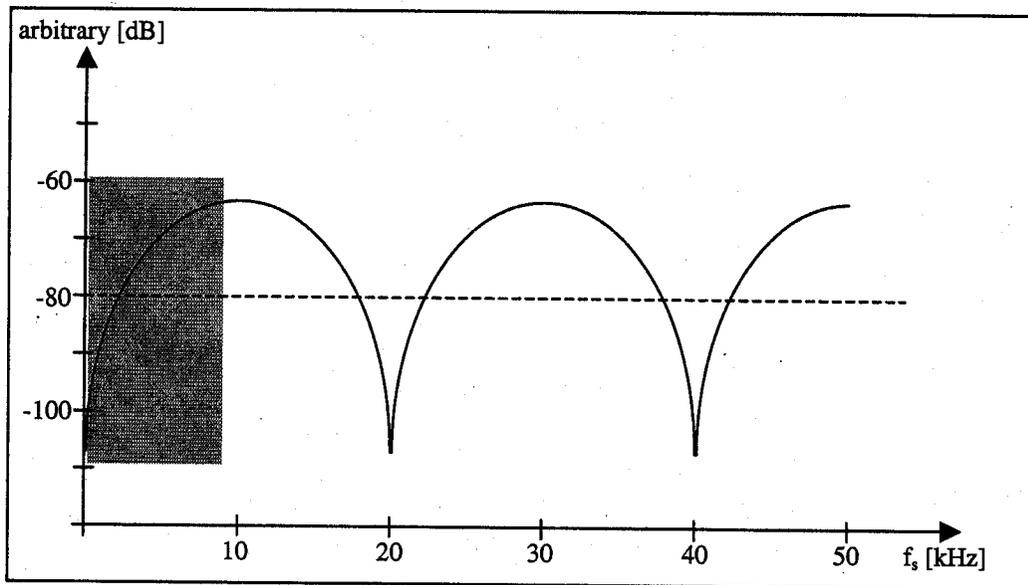


Figure 3 Transfer functions for laser frequency noise (solid) and arm length modulation (dashed) at frequency f_s for an unequal arm Michelson interferometer. Arm length difference $2\Delta L = 10 \text{ km}$, $f_n = 20 \text{ kHz}$. Gray outline is region of measurement.

3. RESULTS

We do have preliminary results from the common phase noise measurement. -----results from daniel follow-----

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