A simulation of weak-light phase-locking for space laser interferometer

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A simulation of weak-light phase-locking for space laser interferometer

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Abstract. A simulation was investigated to better understand the impacts and effects of the additional technical noises on weak-light phase-locking for space laser interferometer. The result showed that the locking precision was limited by the phase readout noise when the laser frequency noise and clock jitter noise were removed, and this result was then confirmed by a benchtop experimental test. The required space laser interferometer noise floor was recovered from the simulation which proved the validity of the simulation program.

1. Motivation

The space-borne gravitational wave (G.W.) antennas were designed to use space laser interferometers to detect the G.W. signal at the frequencies from 0.1 mHz to 1 Hz. The LISA (Laser Interferometer Space Antenna) mission, due to the long distance transmission and the finite aperture of the telescope, only very few fraction of the transmitted light ($\approx$100 pW) can be received by the remote satellite [1]. A technique called'weak-light phase-locking' (WLPL) is adopted by the remote satellite and makes it a 'phase-transponder' with the local satellite [2]. In this paper, a simulation was performed to better understand the impacts and effects of the additional technical noises on WLPL for LISA.

2. Investigation of noises

To simulate WLPL for LISA in a systematic manner, the noise sources categorized have to be taken into account as the interferometric measurement system (IMS) noise and the acceleration noise. The IMS noise mainly includes shot noise, beam pointing noise, laser frequency noise, clock jitter noise and so on [3-7]. Since the simulation will be run in time series, the above LISA noises given by smooth function in ASD (Amplitude Spectral Density) should be converted into random noise in time domain. An algorism based on Fourier transform was invented to convert the
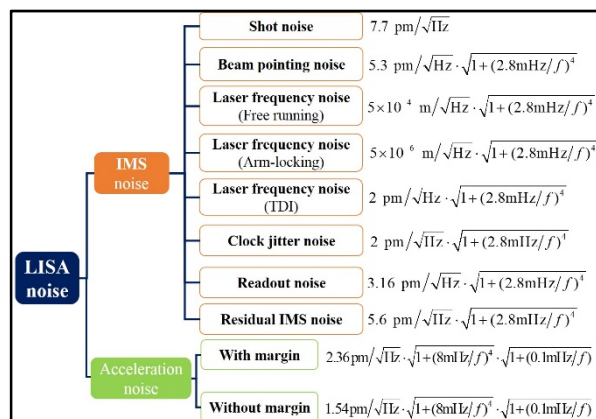

Fig.1 Diagram of the LISA noise

noise function into real time data with random characteristics.

3. Condition and simulation

A simulation program using Matlab Simulink is established and the schematic diagram of the program is shown in Fig. 2. The transmitting light received by the remote satellite is represented by 'add1'. A single frequency 'G.W. signal' (100 pm/√Hz at 30 mHz) is also added as an indicator to analyze the impacts of various noises. The slave laser in the remote satellite is given as 'add2'. The slave laser and the received light "interfere" at 'add3' and the phase difference is sent to and read out by a phasemeter which is represented by 'add4'. Then, the PID (Proportional-Integral-Derivative) controller is introduced to feedback control the slave laser to phase-locking the transmitting light.

Considering all of the noises in Fig.1, supposing the frequency noise and the clock jitter noise have been well suppressed by arm-locking, TDI (Time Delay Interferometer) and other post process technics.

Fig.2 The Simulink model of WLPL

It could be seen from the Fig.3 that the out-of-loop signal is mainly limited by the readout noise and the in-loop signal is well below 10^{-12} m/√Hz. Under this situation, the 'G.W. signal' emerges out.

An experimental demonstration is also performed in order to test the control scheme. The schematic diagram and the result of the experimental test are given in Fig. 4. Here, the beat frequency is 1 MHz, and the power of the slave laser and the master laser are about 1 mW. Limited by the readout noise and optical pathlength noise, the phase lock loop is working at nanometer level. It could be seen that the phase difference between the slave laser and the master laser is suppressed from 10^{-7} to 3×10^{-10} m/√Hz at 1 mHz after the phase locking loop is turned on. This directly demonstrates the functionality of our control scheme.

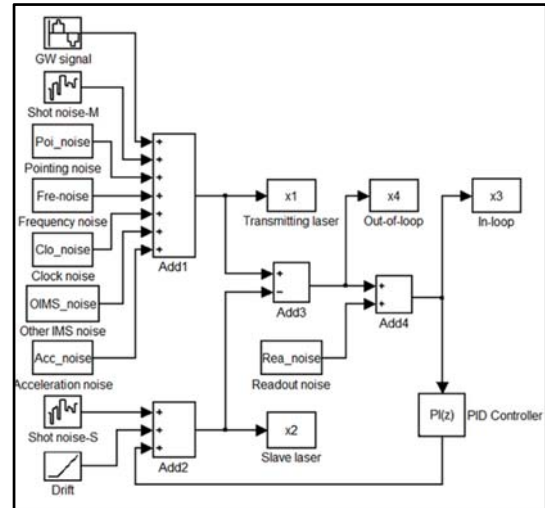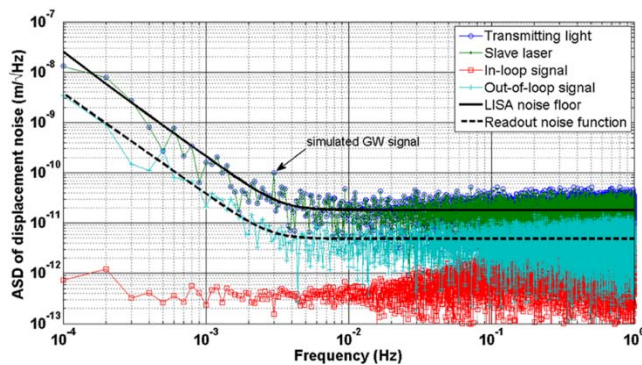Fig.3 ASD noise performance of the simulation

Fig.4 Schematic diagram (a) and result of the experimental test (b)

4. Results

The result showed that the locking precision was limited by the phase readout noise when the laser frequency noise and clock jitter noise were removed, and this result was also confirmed by a benchtop experimental test. The required LISA noise floor was recovered from the simulation which proved the validity of the simulation program.
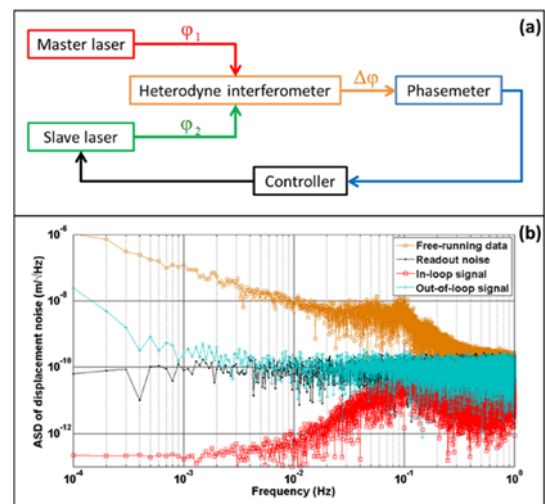
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