A Flight-Like Optical Reference Cavity for GRACE follow-on Laser Frequency Stabilization

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***Abstract*—We describe a prototype optical cavity and associated optics that has been developed to provide a stable frequency reference for a future space-based laser ranging system. This instrument is being considered for inclusion as a technology demonstration on the recently announced GRACE follow-on mission, which will monitor variations in the Earth's gravity field.**

I. Introduction

Launched in 2002, the Gravity Recovery and Climate Experiment (GRACE) mission [1] monitors changes in the Earth's gravity field by measuring changes in the distance between two spacecraft induced by that variable field. The distance variation is measured with a microwave ranging system with sub-micron precision. [2] The ranging measurement accuracy is limited by the signal-to-noise ratio and by the frequency stability of the microwave signal referenced to an ultra-stable oscillator (USO). [3] For the upcoming GRACE follow-on mission a laser ranging system with precision better than the GRACE microwave ranging system is under consideration as a technology demonstration. A laser ranging system easily provides improved signal-to-noise ratio over the microwave system. Laser frequency stability better than the GRACE USO stability has been demonstrated in several laboratories using thermally stabilized optical reference cavities. We are developing a space-qualifiable laser frequency stabilization system for the proposed GRACE follow-on mission. The system includes a ULE optical cavity with the associated optics and electronics and will be capable of providing a fractional frequency stability of better than 10^{-13} from 10 mHz to 1 Hz.

II. Cavity and Thermal Enclosure Design

A.

The goal for this development is to achieve a frequency noise power spectral density of less than 30 Hz/ $\sqrt{\text{Hz}}$ over the frequency range of interest, which is 10 mHz to 100mHz. For an orbital speed of 7 km/sec, this frequency range corresponds to distance scales on the Earth's surface of 700 km to 70 km. Below this frequency range accelerometer noise is expected to dominate the measurements, while measurements at higher frequencies are limited by data sampling.

The cavity is based on a design available from Advanced Thin Films, Inc., which has been used successfully in a number of laboratories around the world. [5,6] It consists of a 77.5 mm ULE spacer to which high reflectivity mirrors are optically contacted. The mirror substrates are also fabricated from ULE glass. The design finesse was 10000. The cavity is mounted to a vacuum flange using titanium flexures, which are bonded to the cavity spacer. The flange is attached to a titanium vacuum enclosure which forms the first stage of a two stage thermal isolation system. Laser light is injected into the cavity via an optical fiber, which is mounted along with the required mode-matching optics on a zerodur optical bench. The bench, in turn, is mounted to the cavity via additional titanium flexures. A 90/10 beamsplitter picks off a portion of the light reflected from the cavity, which is steered through a window on the bottom of the vacuum enclosure to a quadrant photodiode. Figure 1 shows the reference cavity and optical bench mounted on the vacuum flange, while Figure 2 shows the sealed thermal enclosure, which is mounted, again with titanium flexures to a baseplate. Also shown is the outer thermal shield. The outer surface of the vacuum can has been coated with gold to reduce radiative heat transfer. Heaters and RTD temperature sensors mounted directly to the outer shield, and also to an additional baseplate on which the entire cavity system is mounted are used to control the temperature at each end of the enclosure.

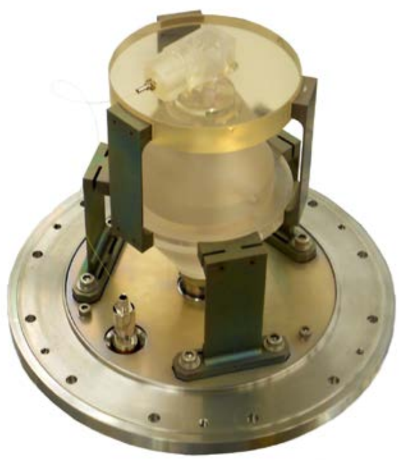

Figure 1. Reference cavity and optical bench mounted to a vacuum flange

Figure 2. Reference cavity assembly with outer thermal shield removed

III. PERFORMANCE TESTING IN A SIMULATED SPACE ENVIRONMENT

A neodymium:YAG laser with a non-planar ring oscillator (NPRO)configuration was used for performance tests of the cavity design. The laser was locked using a standard Pound Drever Hall technique [8], whereby the laser light is modulated (in this case at 5 MHz) and phase sensitive detection of the light reflected from the cavity generates the phase error signal as the frequency discriminator. A sketch of the setup is shown in Figure 3. A portion of the laser output was split off to beat with the output of a second, identical, laser which was locked to a second cavity. The beat signal was detected on a high bandwidth photodetector and then mixed with a stable rf source to provide a signal within the 20 MHz bandwidth of a high accuracy digital phasemeter developed originally for GRACE-2 [9] and further developed for the LISA instrument [10]. Results of these performance tests are described in [7].

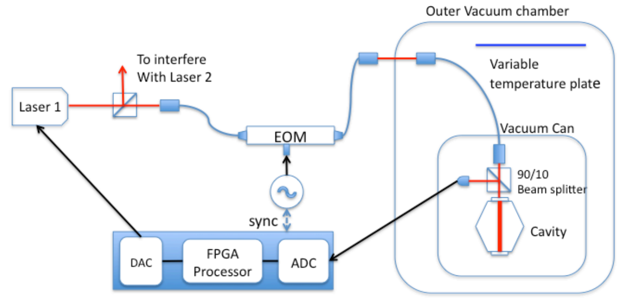

Figure 3. Test configuration for laser stabilization in simulated space environment

In the space operations, the cavity will need to meet its performance requirements in a varying thermal environment, as the spacecraft flies in and out of the sun over a ninety-minute orbit. To simulate this the spacecraft is placed in a large vacuum chamber containing an 8" by 10" sheet of aluminum with a heater and temperature sensor attached. A function generator drives the heater such that the plate temperature varies by 2 °C over ninety minutes, a variation which is greater than that expected on the spacecraft. During these tests the thermal control was applied to the baseplate of the cavity only. Comparisons of the cavity under these conditions to a second cavity are shown in Figure 4. While the results at low frequency are above our design goals, they meet the current requirements for the GRACE follow-on mission.

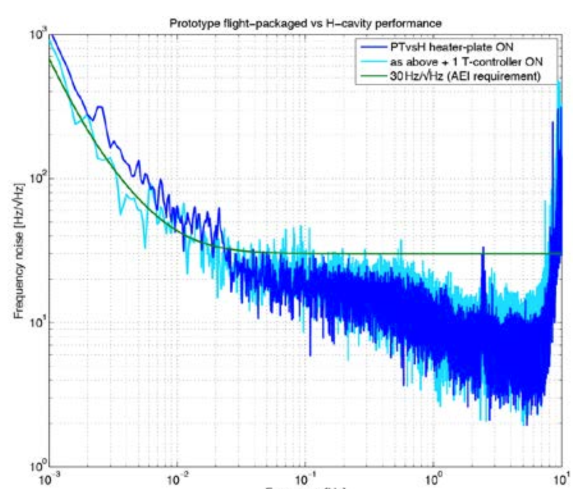

Figure 4. Power spectrum of difference frequencies of lasers locked to prototype and to a second cavity. The prototype is subjected a varying thermal environment as described in the text. Dark blue trace has no thermal control applied to the prototype, light blue: with thermal control. Green: 30 Hz/$\sqrt{\ }$Hz requirement.

IV. FUTURE WORK

The prototype cavity assembly will be subject to thermal cycling and launch vibration tests in order to establish its readiness for consideration for a future space flight. A complete system test including an Interferometric Range Transceiver developed under a previous IIP [4] will be performed.

ACKNOWLEDGMENT

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