Laser Frequency Stabilization for GRACE-2

W. M. Folkner, G. deVine, W. M. Klipstein, K. McKenzie, R. Spero, R. Thompson, N. Yu
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109

M. Stephens, J. Leitch, R. Pierce
Ball Aerospace and Technologies Corporation
PO Box 1062, Boulder, CO 80306-1062

T. T.-Y. Lam, D. A. Shaddock
Australian National University
Canberra 0200, Australia

Abstract— **The GRACE mission monitors changes in the Earth's gravity field by measuring changes in the distance between spacecraft induced by that changing field. The distance variation is measured with a microwave ranging system with sub-micron accuracy. 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). For GRACE-2 a laser ranging system is envisioned with accuracy better than the GRACE microwave ranging system. A laser ranging system easily provides improved signal-to-noise ratio over the microwave system. We have developed a prototype optical cavity and associated optics and electronics to provide a stable frequency reference for the laser ranging system, with performance a factor of 20 better than the GRACE USO.**

I. Introduction

The GRACE mission [1] has been monitoring variations in the Earth's gravity field since launch in 2002. A microwave ranging instrument is used to measure changes in distance between two dedicated spacecraft in polar circular orbits at an altitude of about 450 km with separation of about 200 km [2]. An accelerometer on each spacecraft is used to measure atmospheric drag forces to remove the drag signature from the ranging data [3]. The spacecraft orbits have a 30-day repeat cycle, and a new gravity field is determined each month. The GRACE system accuracy is sufficient to determine a change in mass equivalent to a volume of water with depth 1 cm over a radius of about 400 km [4].

The GRACE microwave ranging instrument accuracy is limited primarily by the signal-to-noise ratio and by microwave frequency stability derived from an ultra-stable oscillator [5]. The other significant source of system noise is the accuracy with which atmospheric drag and other non-gravitational forces are calibrated with the accelerometer.

A future GRACE-2 mission may achieve significantly improved system accuracy by replacing the microwave ranging instrument with a laser ranging instrument. Because of the shorter wavelength a laser ranging system can easily provide a higher signal-to-noise ratio than the GRACE microwave ranging system [6]. Frequency stability of a laser locked to a thermally stabilized cavity has been shown in laboratory experiments to be better than the GRACE USO stability [7,8]. A technology demonstration of a laser ranging instrument is being considered for a recently announced GRACE Follow-On mission.

Below we describe the development and performance of a thermally stabilized optical cavity suitable for use as a frequency reference for a laser ranging instrument in the GRACE-2 or GRACE-Follow-On missions. This continues work described in an earlier paper which also gave an example of an overall description of a laser ranging instrument architecture for the GRACE Follow-On technology demonstration [10].

II. Laser Frequency Stabilization Design

A common means to provide a stable laser frequency is to form an optical cavity by attaching mirrors to the ends of a 'spacer' made of a material of with a very low thermal expansion coefficient. The laser frequency is locked to the length of the cavity by comparing the laser output frequency with light which has resonated in the cavity. Glasses such as zerodur or ULE have thermal expansion coefficients of order 3×10^{-8}/K. The optical cavity can be insulated from external sources of heat, so that temperature fluctuations experienced by the cavity are reduced.

The laser frequency stabilization goal adopted for this development is a frequency noise power spectral density of 30 Hz/√Hz over the frequency range of interest, 10 mHz to 100 mHz, corresponding to length scales of 700 km to 70 km. Performance at lower frequencies (longer length scales) is also of interest but is expected to be limited more by atmospheric drag calibration than by laser frequency stability. Frequency stability is limited by brownian motion noise of the spacer [11] to about one order of magnitude lower than the adopted goal. Performance approaching the brownian-noise limit has been achieved in laboratories [7,8]. We have adopted a less ambitious goal to ensure that the system can survive launch vibration and on-orbit thermal extremes.

The cavity is based on a design available from Advanced Thin Films and used successfully in laboratory tests. The spacer is made out of ULE. The spacer cross-section tapers from the middle towards each end and is designed to be mounted vertically to reduce distortions due to ground vibration. While mounting in the center is not as important for use in space, the vertical mounting has potentially improved performance when testing prior to launch. The length of the spacer is 77.5 mm. End mirrors were attached using optical contacting. The mirror coating was chosen to achieve a finesse of about 10,000. This is lower than typical for laboratory use, but eases requirements on alignment of the injection optics, which must survive launch and the space thermal environment. The cavity is mounted from a flange by titanium flexures bonded to the spacer, as shown in Figure 1. The flange is part of a titanium vacuum enclosure which serves as the first stage of a two-stage thermal isolation enclosure. It provides a controlled vacuum environment to reduce fluctuations of refraction within the cavity and eliminates convection between the cavity and the vacuum enclosure. Laser light is injected into the cavity via a single-mode optical fiber. An optical bench made out of zerodur contains optics to match the spatial mode from the output of the fiber into the cavity. The optical bench is also made of zerodur and is mounted to the cavity using titanium flexures. A photodetector is mounted to the vacuum flange to allow the alignment of the injection optics to be checked using light transmitted through the cavity. Light output from the cavity is mixed with the input light from the laser with a beam-splitter and transmitted through a window on the bottom of the vacuum enclosure to a second photodetector.

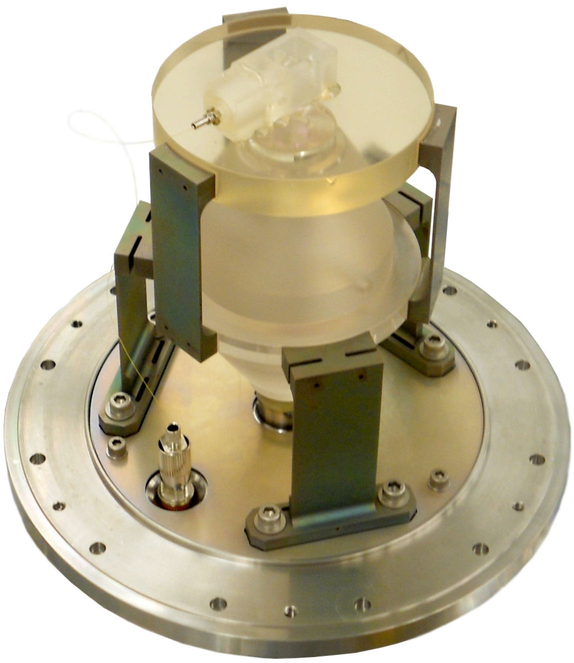

Figure 1. Laser frequency stabilization cavity and optical bench mounted on vacuum flange.

Figure 2 shows the cavity mounted within the titanium vacuum enclosure which has been coated with gold to reduce radiative heat transfer between the cavity and the enclosure can and also between the vacuum can and the external aluminum thermal shield shown next to the cavity. The current implementation includes a vacuum valve and ion gauge on the vacuum flange for testing purposes. For the planned flight unit, the valve and gauge will be removed to reduce volume and mass. Heaters and temperature sensors are attached near the top and the bottom of the outer aluminum enclosure to control the temperature of the ends of the enclosure.

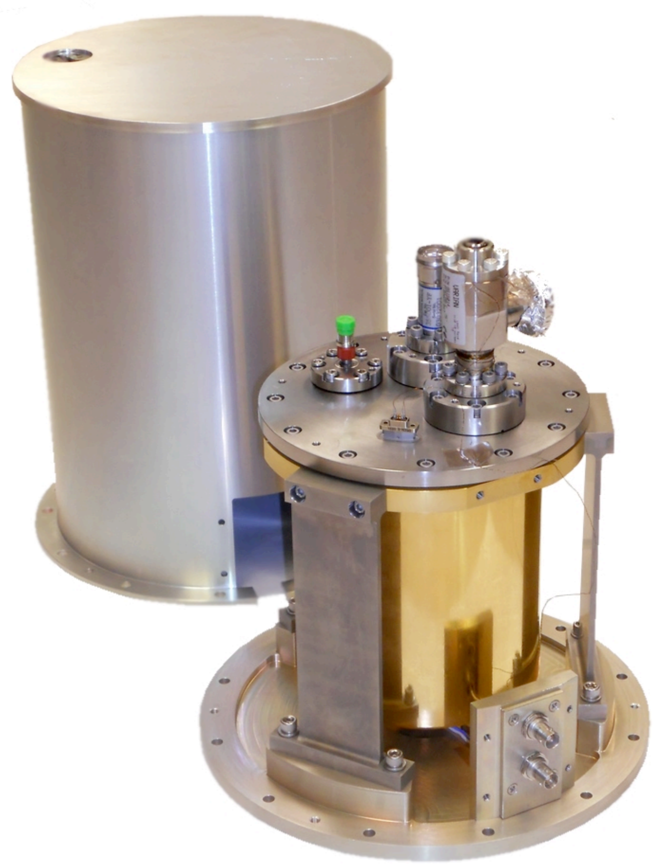

Figure 2. Laser frequency stabilization cavity installed in vacuum can, with external thermal shield shown adjacent.

III. LASER FREQUENCY STABILIZATION TESTING

A. *Frequency stability test configuration*

In order to evaluate the frequency stability of the cavity/enclosure assembly, a laser was locked to the prototype cavity and compared with a second laser locked to an earlier breadboard cavity and thermal enclosure. Two non-planar ring oscillator lasers with wavelength 1064 nm were locked to the cavities using the Pound-Drever-Hall (PDH) locking technique [12]. The laser light into the cavity was phase modulated with a frequency of ~1.4 MHz applied using fiber-coupled electro-optical modulators driven by external function generators. The output interference signal from the cavity photodetector was sampled at 40 Msps by a 12-bit Analog to Digital Converter (ADC). The demodulation and control system were implemented in an field-programmable gate array (FPGA) and the control signals were applied via 16-bit Digital to Analog Converters (DAC) at a rate of 1 Msps to the piezoelectric and thermal control frequency adjust inputs of the laser [13]. The locking configuration is shown in Figure 3.

The outputs of the two stabilized lasers were interfered on a free-space beam-splitter. The resulting beat note was detected with a high-bandwidth photo detector. The frequency difference between the lasers locked to the independent cavities was of the order of hundreds of MHz to several GHz (depending on which longitudinal cavity mode and/or which laser-cavity combination was selected). The beat signal was mixed down with a microwave signal generator and double-balanced analog mixer. This placed the frequency of the beat note within the 20 MHz bandwidth of high-accuracy phase measurement electronics developed originally for GRACE-2 [12] and further developed for the LISA instrument [13]. The beat note was typically mixed down to 5 MHz, with the phase measurement electronics tracking the phase of this signal and recording data at 100 Hz. The recorded phase was differentiated to produce frequency data for stability analysis.

The best laser frequency stability results from the laboratory environment are shown in Figure 4. The frequency stability achieved is better the performance goal for the signal frequency range of 10 mHz to 100 mHz. The white noise level of 1.5 Hz√/Hz is from front-end electronic noise, and the 1/f increase at low frequency is driven by laboratory temperature variations. At frequencies below 4 mHz the frequency noise sharply increases, probably due to a spurious interference outside the vacuum enclosure. Work is in process to determine and remove the cause of this excess noise.

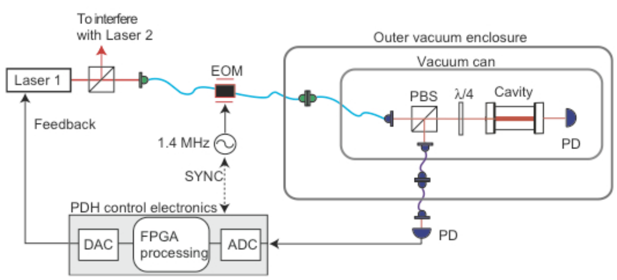

Figure 3. Test configuration using the Pound-Drever-Hall technique.

Figure 4. Square-root of the power spectrum of difference of frequencies of laser locked to prototype and breadboard cavities in laboratory environment.

IV. FUTURE WORK

Frequency stability performance tests of the prototype cavity assembly in a simulated spacecraft environment are in progress. These will be followed by thermal cycling tests and launch vibration tests to establish a technology readiness level of 6 for the cavity assembly.

ACKNOWLEDGMENT

This work was sponsored by the NASA Earth Science Instrument Incubator Program. This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. T. T.-Y. Lam and D. A. Shaddock were supported under the Australian Government's Advanced Space Research Program.

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