Interferometric Range Transceiver for Measuring Temporal Gravity Variations

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We report on interferometric range transceiver technology demonstration. The goal of this work is to reduce risk for a follow-on gravity mission to the Gravity Recovery and Climate Experiment (GRACE) by demonstrating performance of a heterodyne interferometric laser ranging instrument appropriate for a follow-on gravity mission to GRACE at the NASA Technology Readiness Level (TRL) 6. In order to show readiness at TRL 6 we are constructing a brassboard interferometer from flight qualifiable material that we will run through vibration and thermal tests. We have demonstrated displacement noise performance of better than 1 nm/√Hz at frequencies greater than 30 mHz in a laboratory breadboard.

I. INTRODUCTION

By mapping the Earth's gravity field from space scientists can achieve global, continuous, and homogeneous high quality monitoring of the static and time variable components of the Earth's gravity field. The Gravity Recovery and Climate Experiment (GRACE) currently in operation provides estimates of the Earth's static gravity field as well as monthly estimates of the time-varying field [1]. This information is used in the field of solid earth sciences and geodesy to measure mantle viscosity and to improve navigation and orbit determination of low earth orbit (LEO) satellites; in the field of glaciology to monitor changes in the polar ice caps at the cm level; in the field of hydrology to monitor groundwater, soil moisture, and aquifers at the cm level; and in the field of oceanography to provide estimates of ocean currents and time-varying ocean bottom pressure. The tremendous advances made by GRACE have led to an interest in launching a follow-on mission with even better performance.

The GRACE mission measures the Earth's gravity field via ranging measurements between two identical satellites. The two satellites fly in the same LEO orbit, one ahead of the other, with a separation of approximately 200 km. As one satellite passes over a topographic feature, the corresponding change in the Earth's gravity field leads to a change in the orbit of the satellite, which leads to a change in the separation of the two satellites. A microwave ranging system detects the change in separation. In conjunction with this a precision accelerometer on each spacecraft measures non-gravitational forces (such as atmospheric drag) that affect the spacecraft, and a GPS navigation system determines the position of the spacecraft. GRACE is limited at low frequencies by accelerometer errors and at high frequencies by the microwave phase noise. The resolution of the GRACE measurement can be improved by implementing a drag-free control system, improving the ranging performance to the 1 nm/sec level through laser interferometric ranging, and flying at a lower altitude. An improved mission using this technology has been proposed as a follow-on mission to GRACE [2, 3].

The NASA Earth Science Technology Office (ESTO) has funded work to reduce risk for such a follow-on mission through the Instrument Incubator Program (IIP). One of the goals of the IIP program is to reduce risk by raising the TRL level of low-TRL technologies. Our IIP work focuses specifically on the interferometer subsystem. At the beginning of this IIP contract, the interferometer was judged to be at TRL 3. The breadboard validation we have completed in the laboratory has raised the TRL level to TRL 4, and we are building a flight-like subsystem model that we will test in a relevant environment to raise the TRL level to 6 within the next six months. In addition, we are performing a study of data analysis techniques designed to take advantage of the higher spatial resolution gravity field data provided by a follow-on mission.

II. STRAWMAN FLIGHT DESIGN

Like the GRACE mission, a GRACE follow-on mission would derive measurements of the Earth's static and time-varying field from changes in the separation of two or more satellites in LEO. An improved ranging performing at the 1 nm/sec level would be achieved through the use of laser heterodyne interferometric ranging between satellites flying at low altitude (~250 – 350 km) in a drag-free orbit. The satellites' separation is expected to be ~50 – 100 km. The drag-free control system incorporates a proof-mass accelerometer as a sensor and low-force thrusters that act as actuators to eliminate the effects of atmospheric drag on the satellites' orbit.

The mission described above requires advances in the technology for the drag free control system, frequency-stabilized lasers for the ranging system, and the interferometry itself. This work focuses on the challenges of nm-level range measurement between satellites in LEO, in particular the development of an interferometric system and error budget for the ranging. Development of the drag-free control system and associated technologies (the accelerometer and the low-force sensors) will rely heavily on the work done for the LISA

Technology Package (LTP) payload on the LISA Pathfinder mission. A laser with the very high level of frequency-stabilization required for such a mission (~5 x 10^{-14} Hz/√Hz at 0.01 Hz) has been demonstrated laboratory environments [4, 5] but much work remains to space-qualify such a laser system.

The laser interferometric ranging instrument is an active metrology scheme that uses two separate lasers, with the laser on one spacecraft phase-locked to the signal from the laser on the other spacecraft. The measurement is from accelerometer proof-mass to accelerometer proof-mass. Any residual motions between the optical bench and the proof mass not removed by the drag-free system do not affect the ranging signal to first order. The interferometric instrument includes two 1.06 um frequency-stabilized lasers, phase meters capable of precision heterodyne phase measurement in the presence of large Doppler shifts, and a quadrant photodiode for detection of the range rate and spacecraft pointing offsets through measurement of phase differences between the quadrants (Fig. 1)

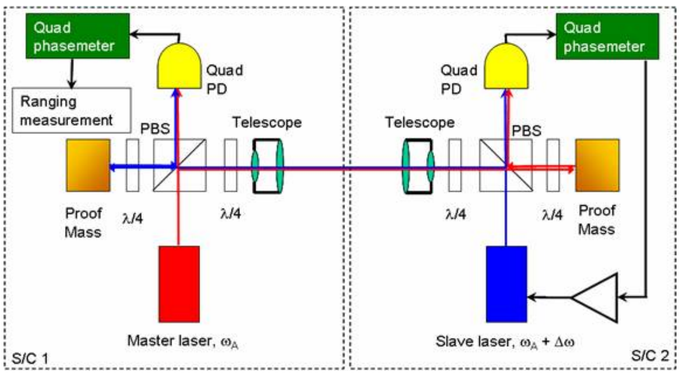

Figure 1. Inter-satellite interferometric ranging concept for a GRACE follow-on mission. A small amount of the light from the laser on S/C 1 leaks through the S/C 1 PBS and hits the quadrant photodiode, the rest is transmitted to S/C 2 where it bounces off the proof mass (part of the accelerometer) and then reaches the S/C 2 quadrant photodiode. A small amount of the light from the laser on S/C 2 leaks through the S/C 2 PBS and hits the quadrant photodiode, creating a beat signal with the light from S/C 1. The laser from S/C 2 is phase-locked to the signal from S/C 1. The majority of light from the laser on S/C 2 is transmitted to S/C 1 where it bounces off the accelerometer proof mass and reaches the S/C 1 photodiode. The signal on S/C 1 provides the inter-satellite ranging measurement.

Figure 2 shows our concept for the optical bench on a single spacecraft. Light from the laser is coupled onto the optical bench via an optical fiber. A single refractive telescope is used to both transmit the light from the local spacecraft and to receive light from the distant spacecraft. A spatial filter and bandpass filter are used to limit the effects of sunlight in the aperture on instrument performance. A quadrant photodiode at the output of the interferometer detects spacecraft pointing offsets through measurement of phase differences between the quadrants.

Important terms in the error budget include laser frequency noise, accelerometer noise, thermal effects, coupled wavefront distortion/pointing jitter effects, clock noise, and phase detection noise [3], [6]. The overall performance of a GRACE follow-on mission will be limited at low frequencies by the accelerometer noise and at higher frequencies by the laser frequency noise [3]. Control of those noise sources is not included in this effort. Our project goal is to ensure that all other ranging error sources related to the optical interferometry are less than the expected noise from the laser and the accelerometer. In addition, the interferometer must provide the capability to acquire and maintain the laser pointing accuracy.

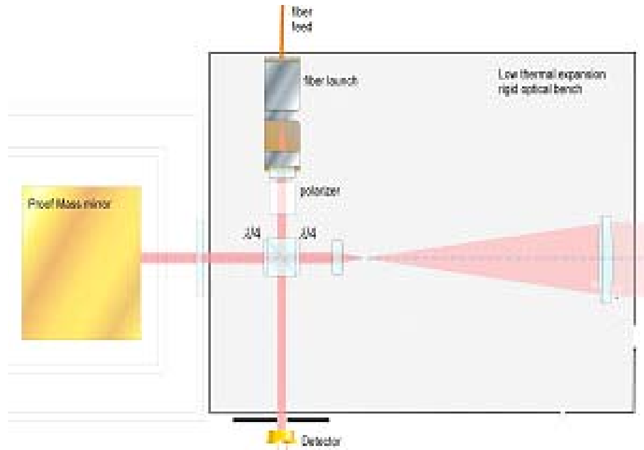

Figure 2. Concept for single optical bench for interferometric range transceiver.

III. BREADBOARD DESIGN AND PERFORMANCE

We have built a laboratory breadboard that has demonstrated laser ranging performance over laboratory distances near the 1 nm/√Hz level from 30 mHz to 10 Hz. The laboratory breadboard is composed of commercially available parts. We have used this breadboard to validate our calculation of the contribution to the error budget from laser frequency noise, clock noise, phase-locked-loop residuals, and our pointing detection capability.

Two Lightwave Electronics 1.064 um lasers are phase-locked together to form a coherent optical transponder [7]. Two flat mirrors are used to simulate the proof masses that would be part of the drag-free mission. For the breadboard (Fig. 3), commercial beamsplitters, neutral density filters, and waveplates are used. A BlackJack phasemeter or a commercial high-speed digital lock-in amplifier measures the phase output of the photodetectors at a specified beat frequency set by the frequency offset of the phase lock between the two lasers. The breadboard does not include a telescope. Simulated Doppler shifts can be introduced into the system through the laser phase lock electronics. Additional optical elements can be introduced between the two beam splitters in order to attenuate the beam or simulate pointing misalignment between the spacecraft. Measurements are performed in a dedicated vacuum chamber. Fig. 4 shows the displacement noise performance of the laboratory breadboard.

Measurements of the pointing offset of the laser beam from the distant spacecraft are made at the interferometer output port by a quad cell phase detector. The phase measurement in the four quadrants is made separately using different channels on the BlackJack phasemeter. The average of the phase measurements gives the science measurement of the overall fringe phase between the signal arriving from the other spacecraft and the local laser. The normalized difference between the fringe phases measured in opposing quadrants gives a beam pointing offset between the local beam and the one received from the other spacecraft. We have demonstrated this measurement concept in the laboratory breadboard demonstration by inserting a beam steering optic between the two simulated spacecraft.

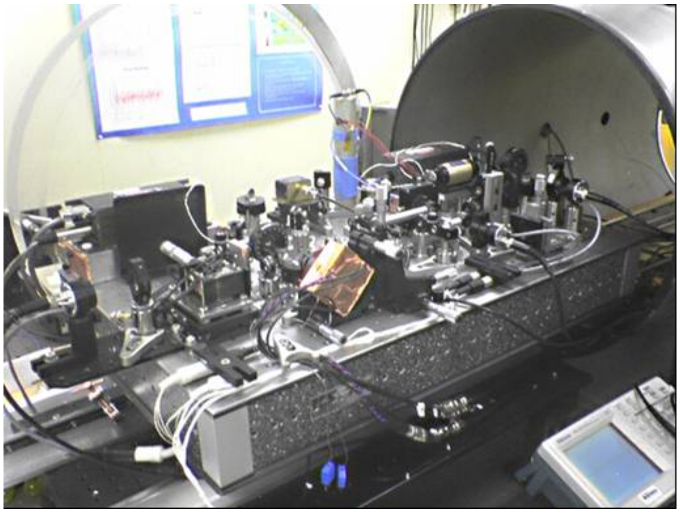

Figure 3. Breadboard demonstration of interferometric ranging.

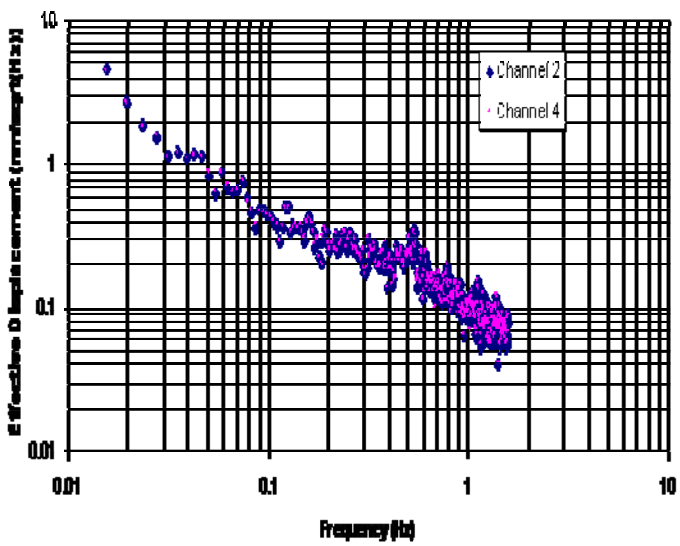

Figure 4. Displacement noise performance in nm/sqrt(Hz) as a function of frequency in Hz for the breadboard ranging demonstration.

This work has moved the TRL level from TRL 3 (analytical and experimental critical function and/or characteristic proof-of concept) to TRL 4 (component and/or breadboard validation in laboratory environment).

IV. BRASSBOARD TESTING FOR TRL 6

We have designed and are in the process of constructing a flight-like unit of the optical bench that will allow us to test performance of a flight-like system including performance in the presence of thermal fluctuations and non-operational survival (thermal and vibration). We plan to bring the optical bench including the fiber launch, low-distortion telescope, polarization optics and the photodiode to TRL 6. A frequency-stabilized laser and a flight-like phasemeter are not included. A precision, laboratory phasemeter built and supplied by JPL will be used.

We have chosen manufacturing processes and optical components that are flight-qualifiable or already have flight heritage for our design. The optical bonding process used for the majority of the parts is a proprietary Ball Aerospace process for these types of glass with flight heritage (Deep Impact, HIRISE). The choice of glass also has flight heritage. The telescope body and bench are Zerodur, while most of the remaining optics are fused silica. The design for our fiber launch has heritage from lasercom applications. Fig. 5 shows the concept for the flight-like unit.

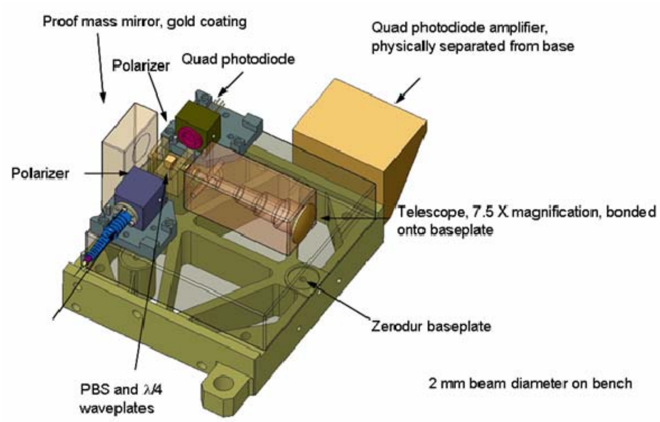

Figure 5. Concept for flight-like unit for interferometric ranging optical bench.

The majority of the parts for the brassboard have been manufactured and assembly is currently in process. The first of the optical components have been bonded.

V. TEST PHILOSOPHY

In order to determine the tests required to prove a Technology Readiness Level of TRL 6 the elements of the subsystem and the relevant environment must be determined. The NASA definition of TRL 6 is “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”. For this IIP project we have defined the system under test to include:

- A prototype optical bench built from flight-qualifiable components and materials
- Optical fiber mounts for injecting light from the laser into the IRT (and focusing mechanism if one is deemed necessary)
- A telescope built from flight-qualifiable components and materials

- A flight-qualifiable photodetector and signal amplifier
- Interferometric ranging capability
- Pointing detection capability

It does not include

- Flight-qualifiable lasers fiber-coupled onto optical bench
- Flight-qualifiable phasemeter
- Gravitational Reference Sensor (GRS)
- Drag free control
- Pointing and acquisition control
- Payload thermal control

Critical inputs to the determination of the relevant environment include launch environments, natural radiation expectations, orbital conditions, mission lifetime, man-made conditions, and performance restrictions. Because the GRACE follow-on mission is in the very early stages of planning, many aspects of the relevant environment are uncertain (for example, the launch environment). We have made assumptions in order to move forward with the advancement of the IRT TRL level and will identify these assumptions and the basis for them.

In order to define the thermal environment on the spacecraft, we have made the assumption that the IRT subsystem and the Gravitational Reference System (GRS) will be housed in an Al tube 30 cm in diameter actively stabilized to 288 K +/- 0.1 K. The GRACE mission has demonstrated the capability of active temperature stabilization to this level in LEO. The dimension of the tube is based on preliminary design for enclosures for the GRS and optical bench for the LISA mission. The IRT optical bench is assumed to be conductively isolated from the environment and radiatively coupled. We assume that the laser is in a separate enclosure and that there is no heat load from the laser; however, there will be a transient thermal load on the optical bench caused by sunlight impinging on the telescope.

For non-operational thermal requirements we use –30 to +40 C, typical numbers for LEO missions.

It is difficult to discuss a launch environment at this early stage in the GRACE follow-on mission. In order to determine vibration levels for testing we relied on the NASA General Environment Specification for STS and ELV Payloads, Subsystem, and Components (Rev. A).

Tests will include vibration and thermal testing of subassemblies in order to ensure the fidelity of the bonding process, interferometric ranging capability over the operational temperature range, pointing detection capability, non-operational thermal test, and vibration tests.

Figure 6 shows our test concept. The ranging performance will be tested using two optical benches to simulate two spacecraft. Only one optical bench will be subjected to environmental testing. The success criteria will be verification of ranging performance in the test configuration after the single breadboard has completed environmental test.

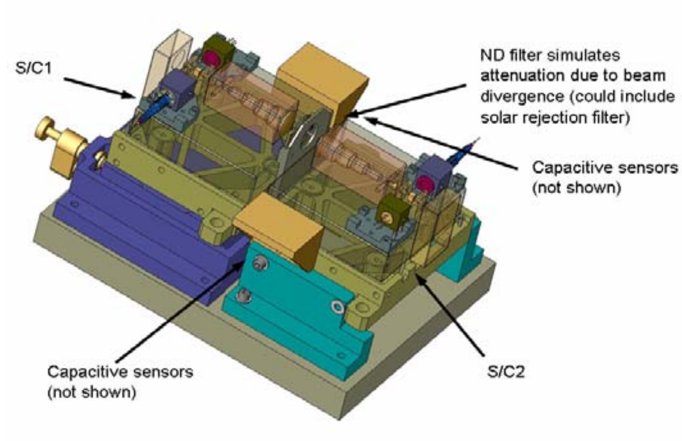

Figure 6. Test concept for brassboard interferometer.

VI. Conclusions

A GRACE follow-on mission has the potential to provide even better estimates of the Earth's static and time-varying gravity field. The technical challenges associated with such a mission include nm-level interferometric ranging between satellites in LEO, frequency-stabilized lasers, high-sensitivity accelerometers, and drag-free control of satellites in LEO. We are working raise the TRL level for interferometric ranging between satellites. A breadboard version has already demonstrated the necessary displacement sensitivity above 30 mHz and has raised the TRL level from 3 to 4. A flight-like model has been designed and is under construction. Tests are planned to bring the TRL level to 6.

Acknowledgments

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