Interferometric Range Transceiver for Measuring Temporal Gravity Variations

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The Gravity Recovery and Climate Experiment (GRACE) has ushered in a new era for satellite measurements of the Earth system. GRACE provides monthly estimates of the time-varying gravity field, which are largely due to the redistribution of water mass in the Earth system, with a spatial resolution of ~500 km and an accuracy of 1 cm equivalent water. This is accomplished via a suite of instruments including a microwave ranging system, precision accelerometers for measuring non-gravitational forces, and a GPS navigation system. The tremendous advances made by GRACE have led to an interest in launching a follow-on mission with even better performance. Improving the ranging performance, implementing a drag-free control system, and flying at a lower altitude can improve the spatial resolution. This presentation will describe our work towards proving an interferometric laser ranging system that we expect to perform near the 1 nm/sqrt(Hz) level or better from 10 to 100 mHz, which when coupled with other mission improvements, would improve the spatial resolution to ~100 km for 1 cm water equivalent accuracy. We will present our strawman design for the laser ranging system and a preliminary error budget. We will discuss the breadboard tests underway and our plans to build an engineering model of the instrument and demonstrate its accuracy in the laboratory over the next few years.

I. INTRODUCTION

The advances made by GRACE have led to an interest in launching a follow-on mission with even more ambitious scientific goals. The spatial resolution can be improved by reducing the ranging uncertainty, implementing a drag-free control system, and flying at a lower altitude. Such a mission, with improved ranging performance through the development of an interferometric laser ranging system has been proposed and would improve the spatial resolution to ~100 km for 1 cm water equivalent accuracy [1]. An example of the improved information such a GRACE follow-on mission might provide is shown in Figures 1a) and b).

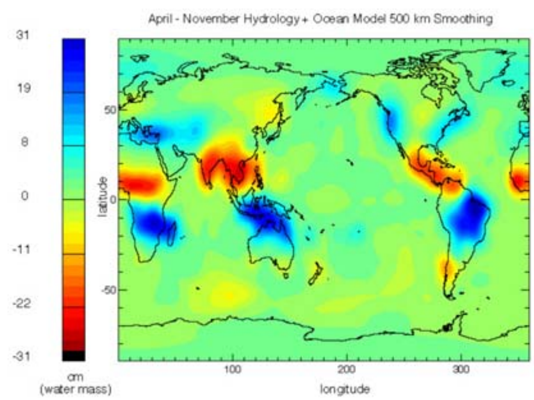

Fig. 1a) an example of current capabilities of the GRACE mission

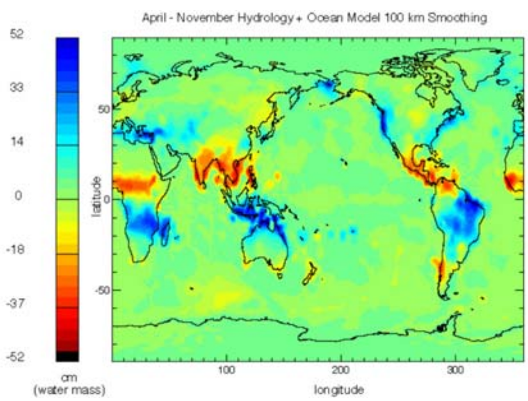

Fig. 1b) an example of the predicted capabilities of a GRACE follow-on mission

We are working towards proving the performance of a laser ranging system for the GRACE follow-on mission. We have developed a strawman flight design and an error budget for that design. Based on that work we have developed a design and test plan for a laboratory breadboard. The remainder of this paper describes the status of our laboratory development and our plans for follow-on work to advance the Technology Readiness Level (TRL) of interferometric ranging in low earth orbit.

II. STRAWMAN DESIGN AND ERROR BUDGET

Our strawman design, like that proposed in [1], is a laser heterodyne interferometric ranging system. This is an active metrology scheme that uses two separate lasers, with the laser on the local spacecraft phase-locked to the signal from the laser on the far spacecraft [2].

Figure 2 shows an example of a heterodyne interferometer. A spatial filter, and a bandpass filter are used to limit the effects of sunlight on the instrument performance.

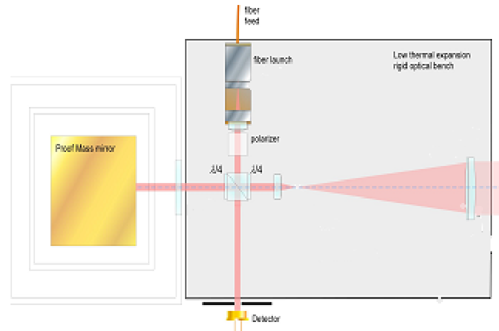

Fig. 2 Strawman design for laser ranging using heterodyne interferometry

Using a quadrant photodiode at the output of the interferometer derives the spacecraft pointing signal.

Important terms in the error budget include laser frequency noise, accelerometer noise, thermal effects, wavefront distortion – pointing jitter coupling, clock noise, and phase detection noise [3], [4]. 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 [1]. Control of those noise sources is out of the scope of this effort. *Our goal in this work is to ensure that all other ranging error sources related to the interferometry are less than the expected noise from the laser and the accelerometer.*

III. LABORATORY BREADBOARD RANGING SYSTEM

We have designed and are in the process of building a laboratory breadboard of a ranging system, composed of commercially available parts, that will validate some, but not all, of the error terms. In addition, we will demonstrate the integrity of the spacecraft pointing signal and demonstrate phase detection in the presence of Doppler shifts.

A breadboard is under construction. Two Lightwave Electronics 1.064 μm lasers are be phase-locked together [2]. They are coupled into a vacuum chamber with single-mode, polarization preserving fiber. Inside the vacuum chamber are two flat mirrors that simulate the proof masses that would be part of the drag-free mission, beamsplitters, neutral density filters, waveplates, and the photodetectors. A phasemeter will measure the output of the photodetectors. Doppler shifts can be introduced into the system through the laser phase lock electronics.

Elements can be introduced between the two beam splitters in order to attenuate the beam or simulate pointing mis-alignment between spacecraft.

The work we are currently carrying out includes

- Validation of system performance
- Phase measurement in presence of Doppler shifts
- Demonstration of integrity of spacecraft pointing signal
- Pointing acquisition range verification
- Verification of clock noise error terms
- Measurement of thermal stability on a component level
- Discovery of unexpected error signals

We do not expect to obtain significant information with this breadboard about wavefront distortion – pointing jitter coupling effects, sunlight effects, or pointing acquisition range with a flight-like telescope. We will address those issues in following years after the design and construction of a flight-like system.

IV. CONCLUSIONS

An interferometric range transceiver is a key component to a GRACE follow-on mission with enhanced spatial resolution in the measurement of the Earth's time-varying gravitational field. We are working to advance the technology of interferometric ranging in low Earth orbit. An error budget based on a simple design for a heterodyne interferometer has guided the development of a laboratory breadboard that will validate our error budget and pointing scheme. Future work will include building a flight-like brassboard of such a ranging system and subjecting it to testing in relevant space-like environments.

III. ACKNOWLEDGEMENTS

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[2] Muthu Jeganathan and Serge Dubovitsky, "Demonstration of nm-level Active Metrology for Long Range Interferometric Displacement Measurements, " in Interferometry and Optical Astronomy, Pierr J. Léna, Andreas Quirrenbach, Editors, Proceedings of SPIE Vol. 4006 (2000) pp. 838-846.

[3] P. L. Bender, J. L. Hall, J. Ye and W. M. Klipstein, "Satellite-satellite laser links for future gravity missions," Space Sci. Rev. 108, 377-384 (2003).

[4] Final Technical Report (FTR) of the (Phase A) Study of the Laser Interferometer Space Antenna (Dornier Satellitensysteme GmbH-Matra Marconi Space – Alenia Aerospazio), ESTEC Contract no. 13631/99/NL/MS, Report No. LI-RP-CD-009 (April 2000).