9th *LISA Symposium, Paris*
ASP Conference Series, Vol. 467
G. Auger, P. Binétruy and E. Plagnol, eds.

LISA-like Laser Ranging for GRACE Follow-on

Daniel Schütze, Gunnar Stede, Vitali Müller, Oliver Gerberding, Christoph Mahrdt, Benjamin Sheard, Gerhard Heinzel, and Karsten Danzmann

Max Planck Institute for Gravitational Physics (Albert Einstein Institute) and Institute for Gravitational Physics, Leibniz Universität Hannover

Abstract. The *Gravity Recovery and Climate Experiment* (GRACE) mission successfully demonstrated that low-orbit satellite-to-satellite tracking is a powerful tool to analyze spatial and temporal changes in Earth's gravity field. Especially hydrological mass transports are well-resolved. To continue longterm observations, a GRACE follow-on mission is planned for 2017 which will almost be an identical copy of the GRACE mission. Additionally, for technological demonstration, a *Laser Ranging Interferometer* is planned supplementary to the conventional microwave ranging device to potentially improve the intersatellite range measurements. The frequency band of interest for Earth gravity observations coincides with the LISA frequency band, thus LISA technology can be inherited. We describe the basic concept of the *Laser Ranging Interferometer* for GRACE *follow-on* and present a testbed to investigate its functionality and key components.

1. Introduction

The GRACE mission is a joint DLR/NASA project which has been launched in 2002 (see e.g. Tapley et al. (2004)). Since then, it has been delivering valuable data about Earth's spatially and temporally varying gravity field proving the feasability of low-orbit satellite-to-satellite tracking. Especially changes in the gravitational potential due to hydrological mass transport could be studied in detail (see e.g. Schmidt et al. (2008)). GRACE consists of two identical satellites which circle the Earth in a freely decaying low polar orbit. The satellite separation is kept between $170 - 270$ km by occasional orbit maneuvers. Distance changes between the satellites are tracked with a mircowave ranging system (Dunn et al. (2003)). From these distance changes, the Earth's gravity potential can be derived. Additionally to the mircowave ranging system, each satellite has an accelerometer (Touboul et al. (1999)) to remove non-gravitational accelerations from the measurements. Since the ground tracks of the satellites give sufficiently dense coverage of the Earth's surface each month, GRACE yields a monthly update of the Earth's gravity field which can be used to observe longterm trends, e.g. for testing climate models (van den Broeke et al. (2009)). To continue observations, a GRACE *follow-on* (GFO) mission is scheduled for 2017. In addition to the mircowave ranging system, GFO will contain a *Laser Ranging Interferometer* (LRI, Sheard et al. (2012)) to improve the intersatellite distance measurements and to demonstrate the feasibility of laser interferometry for future geodesy missions based on high precision intersatellite ranging.

2. LISA heritage: *Laser Ranging Interferometer* for GRACE *follow-on*

The signal of Earth's gravity field is encoded in intersatellite distance changes at the orbit frequency and higher harmonics. The expected frequencies of $0.001 - 1$ Hz lie within the frequency band of the future spaceborn gravitational wave observatory LISA (*Laser Interferometer Space Antenna*, Danzmann & the LISA Science Team (2003); Danzmann & Rüdiger (2003); Heinzel et al. (2006)). The relative satellite motions for GFO of a few meters per second are of a similar order of magnitude as for LISA. Thus heterodyne laser interferometry with offset phase-locked lasers in the MHz-range can be used. The large distance between the GFO satellites, 170 – 270 km, infers the use of a LISA-like receiver-transponder principle (see e.g. Jeganathan & Dubovitsky (2000)) rather than a passive reflector approach. Since GRACE consists of one interferometric arm only, no frequency noise cancellation scheme such as *Time Delay Interferometry* (TDI, Tinto & Armstrong (1999)) as for LISA can be performed. Yet considering the noise requirements, GFO is much more relaxed aiming at 80 nm/$\sqrt{Hz}$ whereas LISA needs to reach 12 pm/$\sqrt{Hz}$ to meet design sensitivity at 100 mHz; thus, a laser frequency stabilization as demonstrated by Folkner et al. (2010) suffices. Due to the very similar architecture of GFO and LISA interferometry, the GFO *Laser Ranging Interferometer* profits from LISA developments such as highly stable optical setups and low-noise electronics. The basic concept of the GFO *Laser Ranging Interferometer* (LRI) is shown in fig. 1.

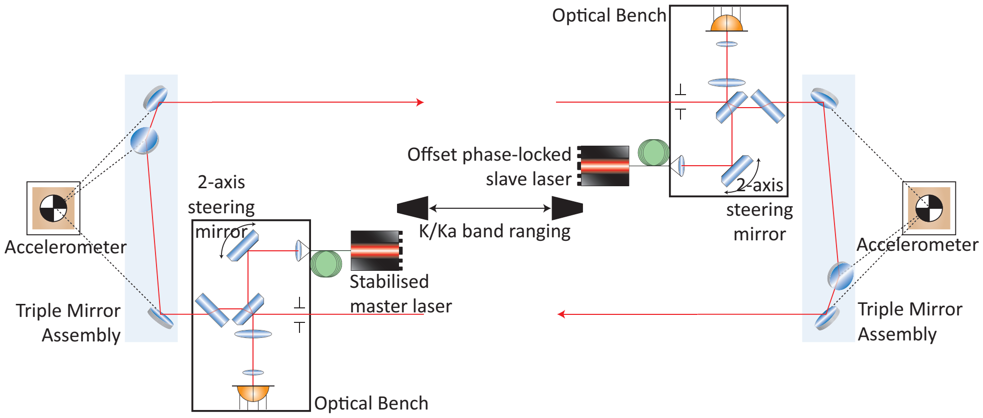

Figure 1. Layout of the LRI for GFO. Lefthand side is the master spacecraft, righthand side the slave spacecraft. The axis between both satellites is occupied by the microwave ranging system. The frequency stabilisation subsystem is not shown.

The laser interferometer hardware on each satellite will be identical and can work in master or in slave mode. The beam coming from the distant slave spacecraft is overlapped with the local beam on a quadrant photodetector on the *Optical Bench* of the master spacecraft. Any beamtilt between the two beams results in non-zero *Differential Wavefront Sensing* signals (DWS, see e.g. Anderson (1984); Heinzel et al. (1999)). The DWS signals are kept close to zero by feeding them back to a steering mirror in a closed loop. In this way, the local beam stays overlapped with the received beam. The telescope is needed to image both aperture and steering mirror surface on the quadrant photodiode and to reduce the beam size to an appropriate size for the photodiode. In this way, beamtilt-induced beamwalk and diffraction effects caused by the aperture are suppressed on the surface of the quadrant photodiode. Leaving the optical bench, the master beam is retroreflected by the 60 cm *Triple Mirror Assembly* (TMA) establishing an off-axis interferometric racetrack between the two satellites. The TMA comprises of three perpendicular mirrors that virtually act as a hollow retroreflector. By placing the virtual intersection point of the TMA in the center of the accelerometer, the beam behaves as if being reflected at a surface perpendicular to its propagation direction and going through the accelerometer center. The geometrical properties of the TMA ensure that the retroreflected beam is antiparallel to the incoming beam and that it has the same distance from the intersatellite axis assuring that the outgoing beam reaches the distant satellite. The main reason for using the TMA instead of an on-axis interferometer design is that the axis between the centers of mass of the two satellites is blocked by the cold-gas tanks and the mircowave ranging systems. In addition to that, the properties of the TMA enable to probe the accelerometer reference point, nominally co-located with the satellite center of mass, without physically having to access it. Thus any non-gravitational accelerations measured by the accelerometer can be effectively removed from the interferometric measurements. A caveat of the TMA is that a misplacement of its vertex with respect to the accelerometer reference point leads to coupling of satellite rotations into the length measurement. In a linear approximation, the deviation δL of the length measurement can be described as (Sheard et al. (2012))

$$\delta L \approx 2\theta_{\mathrm{pitch}} V_{\mathrm{z}} - 2\theta_{\mathrm{yaw}} V_{\mathrm{y}}. \tag{1}$$

Here, θ_{pitch} and θ_{yaw} are the pitch and yaw angles of one satellite. The x-axis of the coordinate system is defined by the axis connecting both satellites. The displacement of the TMA vertex in that coordinate system is denoted as V_{z} and V_{y}, respectively. To reach the allocated noise requirements, the TMA has to be placed with an accuracy in the order of 10^{-4} m with respect to the y- and z-axis. Displacements along the x-axis can be neglected in first order. When reaching the slave spacecraft, the master laser beam is overlapped with the slave laser beam on the *Optical Bench* of the slave spacecraft. By a phase-locking scheme, an offset phase-copy of the received master laser beam is produced and send back to the master spacecraft. In this way, the quadrant photodiode on the master spacecraft measures phase differences between master and slave beam corresponding to the round-trip distance changes which can be converted to intersatellite distances.

3. Testbed for GRACE follow-on

A testbed for GRACE *follow-on* (GFO), commonly referred to as *Optical Ground Support Equipment* (OGSE), is currently under development at the *Max Planck Institute for Gravitational Physics (Albert Einstein Institute)* and the *Institute for Gravitational Physics, Leibniz Universität Hannover.* It is meant to be a flexible setup that can easily be adjusted to test concepts, prototype components and sets of components of the GFO *Laser Ranging Interferometer* (LRI). It could also function as a tool for experimental testing of aquisition procedures which are required to establish the initial inter-satellite laser link after launch. Fig. 2 shows a possible OGSE configuration to test the functionality of the *Laser Ranging Interferometer.* In the left part of the picture, the *Triple Mirror Assembly* (TMA) and the *Optical Bench* (OB) are installed on a hexapod which can move in all six degrees of freedom to simulate satellite motions. The right part of the picture contains the offset phase-lock of the lasers, the interferometry to read out pathlength changes of the setup, and a far-field simulator which produces a beam with a flat wavefront as if it had travelled from a distant spacecraft. Currently, the testbed is split into two parts which have been realized consecutively to investigate the TMA and the OB separately before combining both units into one setup.

We have established a method for determining the position of the vertex of the TMA relative to the coordinate system of the hexapod. This is necessary so that the TMA can be placed correctly inside the satellite once it is being assembled. Eq. 1 implies that the vertex coordinates V_{y}, V_{z} can be obtained by rotating the TMA around different pivot points, recording the resulting length changes, and infering the coupling factors V_{y} and V_{z}. Since a displacement along the beam axis V_{x} couples only quadratically, it is not easily determined. On the other hand, this also relaxes the required vertex alignment accuracy for V_{x}. Most likely, no elaborate method is needed to determine V_{x}. The prototype TMA is being developed at the *Australian National University* (ANU) in Canberra, Australia, in cooperation with the *Commonwealth Scientific and Industrial Research Organisation* (CSIRO). For preliminary tests, we are using a commercial hollow retroreflector to simulate the TMA. We rotate the hexapod around varying pivot points and measure the resulting length changes interferometrically. Hexapod rotations and pivot points are set by the hexapod controller. By performing a least squares fit on the data, we obtain the vertex coordinates V_{y} and V_{z} down to an accuracy of about 200 μm. The limiting factor is the accuracy of the hexapod. To improve the determination of the TMA vertex position down to even higher accuracy, we are currently working on an independent 6 d.o.f. interferometric readout of the hexapod position and orientation. This auxiliary readout will comprise of

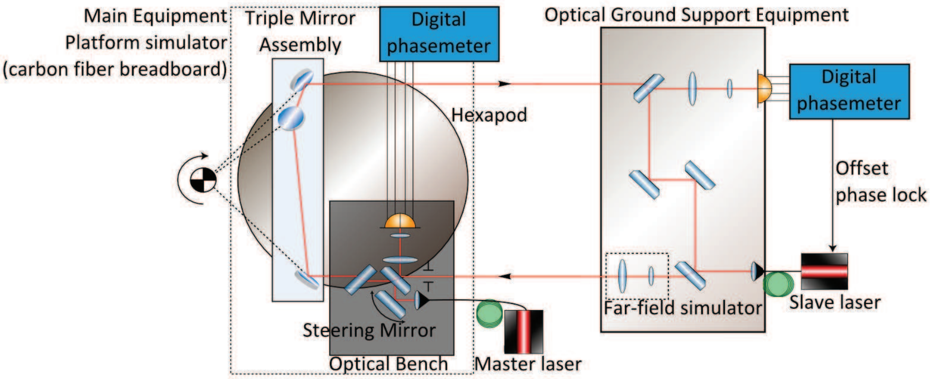

Figure 2. Testbed for GFO. On the lefthand side, the TMA and the OB are installed on a hexapod resembling the LRI for one satellite. The righthand side features the offset phase-lock of the lasers, interferometry to readout pathlength changes in the setup, and a far-field simulator.

six interferometers in a rigid, three-dimensional L-shaped configuration.
Additionally, we have assembled an *Optical Bench* prototype following the design concept shown in fig. 1. All components except the fiber coupler and the quadrant photodetector are rigidly mounted to an aluminum baseplate. We read out the quadrant photodetector with a phasemeter and feed the DWS signals back to the steering mirror. The DWS noise floor of the phase measurement system (photodiode, amplifiers, phasemeter) was independently measured, $0.1\,\mathrm{mrad}/\sqrt{Hz}$ at $0.001-1$ Hz, using an amplitude-modulated beam. Due to the large magnification of beamtilt into DWS signal of about $10,000$, this corresponds to an angular noise floor of $10\,\mathrm{nrad}/\sqrt{Hz}$. We placed the OB prototype on the hexapod and rotated the hexapod which effectively tilts the incoming beam. We can observe that the outgoing beam remains fixed during hexapod rotations by closed loop control of the steering mirror via the DWS signals. In a next step, we need to improve the beam quality of the simulated far-field beam and the local oscillator beam and then confirm that the coalignment of incoming and outgoing beam meets requirements during hexapod rotations.

4. Summary

The *Laser Ranging Interferometer* (LRI) for GRACE *follow-on* is a promising technology demonstrator that will open a new era of unprecedented accuracy in intersatellite distance measurements and Earth gravity exploration. For a GRACE-like satellite pair, the signal of Earth's gravity field is concentrated around the orbit frequency and its harmonics. Thus the frequency band of interest is in the 1 mHz to 100 mHz band which has significant overlap with the LISA frequency band. Therefore, the LRI can build upon the highly advanced low-noise LISA technology. We have presented a testbed with which key concepts and components of the LRI can be tested.

Acknowledgments. This work was partly funded by the *Deutsche Forschungsgemeinschaft* (DFG) within the *Cluster of Excellence* QUEST (*Centre for Quantum Engineering and Space-Time Research*).

References

Anderson, D. Z. 1984, Applied Optics, 23, 2944
Danzmann, K., & Rüdiger, A. 2003, Classical and Quantum Gravity, 20, S1

Danzmann, K., & the LISA Science Team 2003, Advances in Space Research

Dunn, C., Bertiger, W., Bar-Sever, Y., Desai, S., Haines, B., Kuang, D., Franklin, G., Harris, I., Kruizinga, G., Meehan, T., Nandi, S., Nguyen, D., Rogstad, T., Thomas, J. B., Tien, J., Romans, L., Watkins, M., Wu, S. C., Bettadpur, S., & Kim, J. 2003, GPS World, 14, 16

Folkner, W. M., deVine, G., Klipstein, W. M., McKenzie, K., Shaddock, D., Spero, R., Thompson, R., Wuchenich, D., & Yu, N. 2010, Proceedings of the 2011 Earth Science Technology Forum

Heinzel, G., Braxmaier, C., Danzmann, K., Gath, P., Hough, J., Jennrich, O., Johann, U., Rüdiger, A., Sallusti, M., & Schulte, H. 2006, Classical and Quantum Gravity, 23, IUPAP; Okinawa Prefecture; Inoue Fdn Sci; Fdn Promot Astron

Heinzel, G., Rüdiger, A., Schilling, R., Strain, K., Winkler, W., Mizuno, J., & Danzmann, K. 1999, Optics Communications, 160, 321

Jeganathan, M., & Dubovitsky, S. 2000, Interferometry In Optical Astronomy, Pts 1 and 2, 4006, SPIE; European SO Observ; DFM Engn Inc

Schmidt, R., Flechtner, F., Meyer, U., Neumayer, K. . H., Dahle, C., Koenig, R., & Kusche, J. 2008, Surveys In Geophysics, 29, 319

Sheard, B., Heinzel, G., Danzmann, K., Shaddock, D. A., Klipstein, W. M., & Folkner, W. M. 2012, Journal of Geodesy

Tapley, B. D., Bettadpur, S., Watkins, M., & Reigber, C. 2004, Geophysical Research Letters, 31, L09607

Tinto, M., & Armstrong, J. W. 1999, Physical Review D, 59, 102003

Touboul, P., Willemenot, E., Foulon, B., & Josselin, V. 1999, Bollettino di Geofisica Teorica ed Applicata, 40, 321

van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., van Meijgaard, E., Velicogna, I., & Wouters, B. 2009, Science, 326, 984