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GRACE-Follow On Laser Ranging Interferometer: German contribution

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Abstract. The Gravity Recovery and Climate Experiment (GRACE) is a joint US/German mission that has been mapping the Earth's gravity field since 2002 by measuring the distance variations between two spacecraft using a micro-wave link. GRACE is reaching the end of its lifetime. For this reason and in order to minimize data gaps, an almost identical mission will be launched in 2017. This mission is called GRACE-Follow On (GRACE-FO) and it will include an additional instrument as a technological demonstrator to monitor distance changes between the spacecraft. This instrument is the Laser Ranging Interferometer (LRI), which is based on heterodyne laser interferometry at 1064 nm and takes advantage of many technologies developed for LISA. In this paper a short overview of the current status of the German contribution is presented.

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) mission has been measuring changes in the gravity field of the Earth since 2002 and has allowed the quantification of mass variations, such as the mass loss of polar ice sheets, the contribution of mass influx to sea level rise, and changes in the hydrological cycle [1]. GRACE consists of two spacecraft (SC) in circular polar orbits at 400 km altitude. The distance between the two SC is kept between 170 km and 270 km and a two-way microwave link (K/Ka band ranging) is used to measure the distance changes between them at the micro-meter level [2]. This signal, together with the on-board accelerometer data [3] and GPS signals [4], is used to reconstruct the gravity field of the Earth. GRACE was designed to be a 5-year-lifetime mission but subsequently was extended until the end of its orbit (in 2015 or 2016). Continuous and long-term monitoring of the spatial and temporal variations of the gravity field of the Earth is of paramount importance for understanding the processes and physics behind the observed changes. Therefore, to minimize the data gap between GRACE and



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future gravity field missions an almost exact replicate called GRACE-Follow On (GRACE-FO) will be launched in 2017 by the joint collaboration between the US (NASA) and Germany (DLR and GFZ).

GRACE-FO offers a unique opportunity to accommodate a second ranging instrument (Laser Ranging Interferometer, LRI) based on laser interferometry as a technological demonstrator, which should surpass the microwave instrument performance due to its smaller wavelength; and be the first intersatellite interferometric mission in space —see figure 1 [5, 6]. The LRI measurement principle is based on the LISA interferometry concept: a master SC and a slave SC with its laser offset phase-locked to the beam coming from the master SC. The beam is sent back to the master SC where phase changes, which correspond to distance changes between the SC, are measured by interfering the local SC beam with the incoming beam from the slave SC. The LRI ranging noise goal is $\approx 80 \text{ nm Hz}^{-1/2}$ for $f \geq 10 \text{ mHz}$ and relaxing as f^{-2} towards lower frequencies.

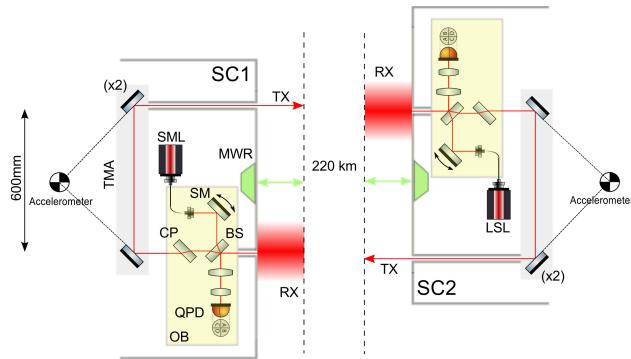


Figure 1. LRI concept. A detailed explanation can be found in [5]. SC1 sends light to SC2, which sends the light back to SC1 after being offset phase-locked to the incoming laser light from the distant SC. The change in the phase of the light is proportional to the SC distance change. The phase signal is measured by interfering the light from SC1 with the light coming from SC2. The steering mirrors correct the pointing of the beams using also the interferometric signal. SML: Stabilized Master Laser. LSL: Locked Slave Laser. SM: steering mirror. BS: Beam-splitter. QPD: Quadrant-photo Detector. CP: Compensation Plate. OB: Optical Bench. RX: Received Beam. TX: Transmitted Beam. MWR: Microwave Ranging. Cold gas tanks are not shown.

The German (AEI/GFZ/STI/DLR/Airbus) role in the LRI focuses on the optics, the triple mirror assembly, the beam steering mechanism and the photo-receivers. The US (JPL/Ball Aerospace/Tesat GmbH) side is responsible of the frequency stabilization system, phasemeter and payload processing electronics, and laser source [7]. Australia (ANU/EOS/CSIRO) contributes with triple mirror assembly prototyping and investigations on the link acquisition [8]. In this paper a short overview of the status of the German contribution is presented. In section 2 the Triple Mirror Assembly (TMA) is described. Section 3 focuses on the different subsystems within the so-called Optical Bench Assembly (OBA). Section 4 summarizes the German contribution status and future prospects.

2. Triple Mirror Assembly

The TMA is a large lateral offset (600 mm) retro-reflector composed of three orthogonal mirrors [9, 10] and is a key element for the LRI since: (i) it routes the beam around the microwave ranging instrument and the cold gas tanks; (ii) it keeps the incoming and outgoing beams

anti-parallel and (iii) it allows to place its virtual vertex in the SC accelerometer reference point, and thus minimize SC jitter to path-length coupling, which is crucial due to the GRACE-FO low Earth orbit. The SC attitude jitter can be rather large: around $100 \mu\text{rad Hz}^{-1/2}$ in pitch and yaw and about $1 \text{ mrad Hz}^{-1/2}$ in roll. The residual jitter couples due to misplacement of the TMA vertex on the accelerometer reference point (assuming this coincides with the SC center of mass) and non-idealities of the TMA itself, i.e., co-alignment¹ imperfections [11]. While the SC attitude stability is good enough for the microwave ranging, it is not sufficient for the laser interferometer due to its narrower receiving field of view and smaller beam divergence. For this reason, a steering mirror together with Differential Wavefront Sensing (DWS) [12] is used to steer the laser beam: the local SC measures the tilt between the local beam and the received beam from the distant SC and sends a signal to the steering mirror, which corrects the local beam pointing accordingly —see section 3. The local beam is then sent to the far SC after passing through the TMA. The TMA coalignment also plays an important role in the beam pointing because an error is added only in the transmit beam path and cannot be corrected by the beam steering mechanism. Consequently, poor TMA coalignment (above $\sim 100 \mu\text{rad}$) can jeopardize the beam pointing control loop, due to the drop in power at the receiver due to the relative angle between the transmitted beam and the line-of-sight between the spacecraft. The received power for a relative angle of $100 \mu\text{rad}$ is around 30% of the transmitted one. For $200 \mu\text{rad}$ drops to $\sim 1\%$.

A Carbon Fibre Reinforced Polymer (CFRP) hollow tube (600 mm long and 39 mm in diameter) is used as the TMA mechanical frame due to its low coefficient of thermal expansion and its good strength/stiffness-mass ratio compared to other brittle materials such as Zerodur or Silicon Carbide. At the ends of the CFRP frame two Zerodur mirror assemblies (Zerodur pieces at both ends of the CFRP tube —see figure 2) were wrung and glued. The input Zerodur assembly holds one mirror while the output one holds the other two mirrors. The interface to the SC is a bracket made of CFRP. The TMA design (frame and mirrors), the materials processing, qualification and manufacturing of the CFRP frame has been carried out by STI, while the Zerodur mirror assemblies have been manufactured by Cassidian Optronics.

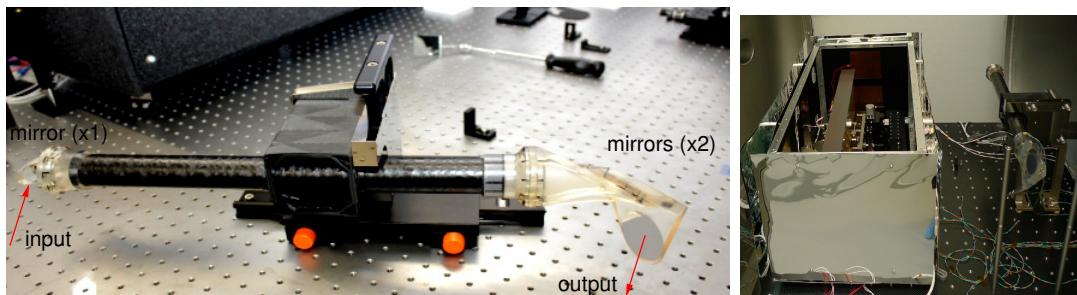


Figure 2. Left: QM TMA. Right: QM TMA co-alignment test campaign at STI facilities. The co-alignment is measured with the help of a Zerodur reference flat and an autocollimator (not shown).

The DM (Demonstrator Model) and QM (Qualification Model) have gone under performance (right panel on figure 2) and environmental tests in late 2013-early 2014. The TMA Critical Design Review (CDR) was passed successfully in March 2014. TMA Flight Models (FM) will go under performance and environmental tests in late 2014 and early 2015.

¹ Co-alignment is defined as the deviation from perfect anti-parallelism between the input and output beams of the TMA.

3. Optical Bench Assembly

The OBA includes all the necessary subsystems to

- launch the local beam onto the quadrant photo-receiver (QPR) and to the distant SC,
- provide the opto-electrical interfaces (photo-receivers and steering mirrors and their electronics) to the US-supplied Laser Ranging Processor (LRP), which ultimately
 - measures the phase difference change between the local beam and the incoming beam from the distant SC, which corresponds to the change in the relative distance between the SC,
 - measures the relative angle between the local beam and the incoming beam from the distant SC by means of DWS,
 - steers the local beam to align it to the beam coming from the far SC by zeroing the DWS signal since the SC pointing control is not sufficient to keep the heterodyne signal locked.

The OBA is shown in figures 1 and 3: the light from the laser is delivered to the OBA by means of a fibre injector that creates a collimated 5 mm beam in diameter. The output of the fibre is routed via the steering mirror, which is able to tip and tilt it. This is necessary to keep the beams from both SC aligned and maintain the heterodyne efficiency to operational levels. A tiny fraction of the light is transmitted through a beam splitter while most of it ($\approx 20 \text{ mW}$) is reflected and directed to the TMA and sent out to the far SC. Before the beam reaches the TMA it is guided through a compensation plate, which is used to reduce linear attitude jitter-pathlength coupling [5]. The transmitted part of the light ($\approx 2 \text{ mW}$) is directed to redundant QPRs. An imaging system is used to image both the local beam and the received beam, which is mostly reflected by the beam-splitter into the QPR aperture. The local beam is used as the local oscillator that generates the beat note when interfering with the beam coming from the far SC ($\approx 100 \text{ pW}$). The beat note heterodyne frequency is in the 4-16 MHz range² and is detected by a LISA-like phasemeter in the LRP [13] that also measures the relative angle between them using the DWS technique. This information is used to drive the steering mirror and keep both beams co-aligned. The subsystems needed to perform all these tasks are:

- Fibre injector assembly (FIA): it is a fully monolithic design developed by STI, with the fibre directly spliced to the aspheric lens body, thus allowing an extremely high thermal stability (both for pointing and wavefront planarity) while minimizing ghost reflections. The wavefront planarity error is less than $\lambda/15$ over the full operation temperature range.
- Quadrant photoreceivers: they are 1 mm in diameter InGaAs quadrant photo-diodes with suitable electronics to detect beat notes in the frequency range from 4 MHz to 16 MHz. The photo-receiver equivalent input current noise is $5 \text{ pA Hz}^{-1/2}$ and has a responsivity around 0.6 A W^{-1} . Two QPRs are present in each OBA for redundancy.
- Fast steering mirror: it has a large optical angle dynamic range ($\pm 8.1 \text{ mrad}$) in conjunction with a large bandwidth: $\pm 3 \text{ mrad}$ at 150 Hz (equivalent to a speed of about 2 rad s^{-1}). Both are especially needed for the initial acquisition procedure [14] where an uncertainty space of $\pm 3 \text{ mrad}$ has to be quickly scanned. Such requirements are met by using voice coil actuators together with eddy current sensors (Kaman) in a closed-loop configuration.
- Imaging optics, beam-splitter and compensation plate.

The OBA CDR was successfully passed in May 2014. In early 2015 the FM OBA will be delivered and tested.

² Doppler shifts due to relative velocity of the SC are about $\pm 3 \text{ MHz}$.

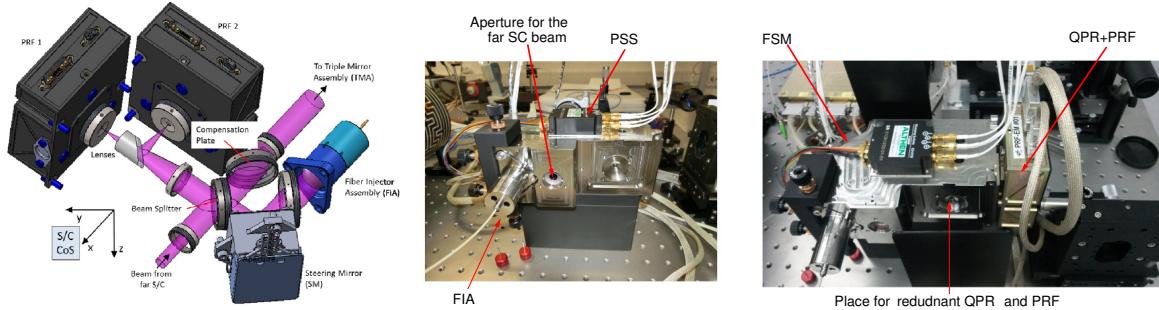


Figure 3. Left: OBA drawing. Middle and right: QM OBA during the last test campaign in 2014 at STI facilities. FSM: Fast Steering Mirror. PSS: Position Sensing System (eddy current sensors). QPR: Quadrant-photo-receiver. PRF: Photo-receiver Front-End.

4. Conclusion

The status of the German contribution for the LRI has been presented. All the systems have passed CDR in 2014 and the flight models will be delivered by the end of 2014 and beginning of 2015. The LRI performance will be about one order of magnitude better than the current GRACE microwave ranging and it will also provide SC attitude information via the DWS and the fast steering mirror Kaman sensors. The LRI is intended to pave the road for the next generation of gravity field missions based on intersatellite ranging. Moreover, it will also provide very valuable information for LISA since they have many elements in common, i.e., the frequency band (milli-Hertz), the received power by the far SC (pico-Watt) and the Doppler shifts (mega-Hertz).

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