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Measuring Earth: Current status of the GRACE Follow-On Laser Ranging Interferometer

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Abstract. The GRACE mission that was launched in 2002 has impressively proven the feasibility of low-orbit satellite-to-satellite tracking for Earth gravity observations. Especially mass transport related to Earth's hydrological system could be well resolved both spatially and temporally. This allows to study processes such as polar ice sheet decline and ground water depletion in great detail. Owing to GRACE's success, NASA and GFZ will launch the successor mission GRACE Follow-On in 2017. In addition to the microwave ranging system, GRACE Follow-On will be the first mission to use a Laser Ranging Interferometer as technology demonstrator to track intersatellite distance changes with unprecedented precision. This new ranging device inherits some of the technologies which have been developed for the future spaceborne gravitational wave detector LISA. I will present the architecture of the Laser Ranging Interferometer, point out similarities and differences to LISA, and conclude with the current status of the flight hardware production.

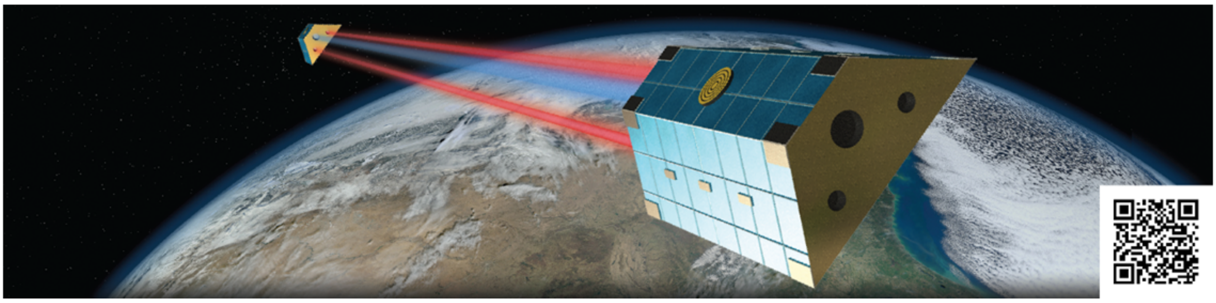

Figure 1. Artistic view of the GRACE Follow-On satellites. The microwave beam is shown in blue, the laser beams in red. Watch a brief animation about GRACE Follow-On and the Laser Ranging Interferometer by scanning the QR code or by going to www.gracefo.spacegravity.org/video1. Image credit: Satellites: AEI/Daniel Schütze, Earth: NASA

1. Introduction: Measuring Earth

The advent of modern satellite geodesy made it possible to monitor spatial and temporal variations in Earth’s global gravity field [1-3]. Especially the *Gravity Recovery and Climate Experiment* (GRACE, [3]) mission has proven that satellite geodesy is an outstanding tool to investigate processes that are vital to humankind: By sensing hydrological mass redistribution on a monthly scale, GRACE enables us to investigate climate change induced polar ice mass loss and human impact on ground water depletion [4-5]. A very nice online tool provided by the *Centre National d'Etude Spatiales* (CNES) and the *Groupe des Recherches de Géodésie Spatiale* (GRGS) at www.thegraceplotter.com illustrates the capabilities of GRACE's measurements.

The two identical GRACE satellites were launched in 2002 as a joint mission of the *National Aeronautics and Space Agency* (NASA) and the *Helmholtz Centre Potsdam – German Research Centre for Geosciences* (GFZ). They circle Earth in a common, freely decaying, low polar orbit of currently 380 kilometers altitude with an intersatellite separation of 170–270 kilometers, which is maintained by occasional orbit maneuvers. See the artistic impression in Figure 1.

Spatial variations in Earth's gravity field exert differential accelerations on the two satellites, which leads to length fluctuations in the intersatellite separation. These length fluctuations are tracked with micrometer precision with a microwave ranging device. In conjunction with *Global Positioning System* (GPS) measurements, the underlying gravity field of Earth can be derived [6]. Non-gravitational forces acting on the two satellites, such as atmospheric drag and solar radiation pressure from the sun and Earth's albedo, are removed from the measurements using an accelerometer [7]. After one month, the ground track of the satellites provides sufficient coverage of Earth to yield an update of the gravity field.

GRACE has already greatly exceeded its initially allocated lifetime of 5 years. Battery fatigue on both satellites limits the mission operation time until 2017 to early 2018. Owing to GRACE's great success and the urgent need to continue the observation of Earth's gravity field, NASA and GFZ are currently preparing the GRACE Follow-On satellites, which will be launched in 2017.

While the main science instrument on GRACE Follow-On will still be a microwave ranging device, the two satellites will additionally carry a Laser Ranging Interferometer (LRI, [8]) as a technology demonstrator. This novel instrument will greatly improve the intersatellite range measurements by more than one order of magnitude and additionally deliver highly accurate beam pointing information. Moreover, the LRI will prove the feasibility of interferometric laser ranging technology for next-generation geodesy missions based on high-precision intersatellite ranging.

2. GRACE Follow-On and the Laser Ranging Interferometer

2.1. The LRI project team

The LRI onboard the GRACE Follow-On satellites is a joint project with US and German contributions. On the US side, developments are carried out by NASA and the *Jet Propulsion Laboratory* (JPL), with major components being delivered by *Ball Aerospace* and *Tesat-Spacecom* GmbH & Co. KG. The US contributions include the phasemeter and payload processing electronics, the laser frequency stabilization [9], and the laser source.

The German side of the project team consists of GFZ, the *Max Planck Institute for Gravitational Physics* (*Albert Einstein Institute*, AEI), the *Deutsches Zentrum für Luft- und Raumfahrt* (DLR), *SpaceTech* GmbH, and *Airbus Defence & Space* GmbH, SAS, SA & Ltd. The German responsibilities are the optics, the Triple Mirror Assembly, the beam steering method including electronics, and the quadrant photo receivers with electronics. According to the cooperative project plan, the AEI provides the German LRI instrument manager and STI the German LRI implementation manager.

Additional support for the LRI project was provided by the *Australian National University* (ANU), *Electro Optic Systems* Pty. Ltd., and the *Commonwealth Scientific and Industrial Research Organisation* (CSIRO), where the first Triple Mirror Assembly prototypes were built and tested [10, 11].

2.2. Comparison between LISA and GRACE Follow-On laser ranging

Advanced interferometric intersatellite ranging technologies have been developed for the *Laser Interferometer Space Antenna* (LISA, [12]), which is going to observe low-frequency gravitational waves in the millihertz regime. Since GRACE Follow-On relies on high-precision intersatellite ranging as well, it is worthwhile to consider relevant similarities and differences between the laser ranging technologies applied in the respective mission scenarios, which are listed in Table 1.

The baseline ranging technology for both LISA and the GRACE Follow-On LRI is heterodyne laser interferometry with frequency offset phase-locked lasers. In both cases, relative intersatellite line-of-sight velocities are several meters per second, so that an offset frequency of several megahertz has to be applied to keep the ranging signal unambiguous under changing Doppler shifts.

Although the intersatellite separation is quite different for LISA and GRACE Follow-On, being 1 Mio. kilometers and 200 kilometers, respectively, the received light power levels of 100 picowatts are quite similar. This is due to the fact that GRACE Follow-On uses much lower laser powers to start with and employs no telescope for weight and space constraint reasons.

A major difference between LISA and GRACE Follow-On can be found in the orbit environmental conditions. While LISA will be launched into a heliocentric orbit with very stable environmental conditions, GRACE Follow-On is operating in a low-Earth orbit with considerable atmospheric drag and changing solar radiation. This requires an active beam steering scheme to counteract spacecraft attitude jitter.

Table 1. Similarities and differences between LISA and GRACE Follow-On laser ranging technologies.

	LISA	**GRACE Follow-On**
Intersatellite distance measurement	Heterodyne laser interferometry (receiver-transponder) with offset phase-locked lasers and phasemeter readout	
Intersatellite distance	1.000.000 km	• 200 km
Orbit	Heliocentric (1 au)	Polar low-Earth orbit (490 km initial altitude)
Orbit environment	No atmospheric drag, thermally stable	Atmospheric drag, large thermal disturbances
Attitude & orbit control system	Drag-free with µN-thrusters	Attitude control with magneto-torquers & cold gas thrusters
Measurement band	• mHz…Hz	
Single-link noise goal	12 pm/$\sqrt{\text{Hz}}$ (×frequency dependence)	80 nm/$\sqrt{\text{Hz}}$ (×frequency dependence)
Telescope aperture diameter	38 cm	8 mm (no telescope, just clipping by aperture stop)
Transmit beam waist diameter	34 cm	5 mm
Transmit power	1 W	30 mW
Effective received power at photo receiver	• 100 pW	
Maximum relative line-of-sight velocity	±15 m/s	±5 m/s

However, the ranging requirements are much relaxed for GRACE Follow-On compared to LISA, aiming at 80 nm/$\sqrt{\mathrm{Hz}}$, while LISA requires 12 pm/$\sqrt{\mathrm{Hz}}$ for gravitational wave observation. Due to GRACE's orbit period of about 90 minutes, the observation frequency band falls into the millihertz regime as for LISA.

In summary, the LRI for GRACE Follow-On is an adaptation of LISA technology to quite a different mission scenario in terms of environmental noise sources and required ranging precision. This relaxes much of LISA's requirements, however, new challenges arise from the much rougher orbit environment.

2.3. Architecture of the GRACE Follow-On Laser Ranging Interferometer

A schematic of the LRI [8] on one of the two GRACE Follow-On spacecraft is shown in Figure 2. The LRI is identical on both spacecraft, so we can focus our explanations on one spacecraft. For the constellation of the two satellites, keep in mind the artistic view shown in Figure 1. Additionally, this short video clip gives you a better idea of the geometry inside one of the GRACE Follow-On spacecraft: www.gracefo.spacegravity.org/video2.

The LRI uses an active transponder principle, which means that the weak incoming received (RX) beam is replaced by a strong local oscillator (LO) beam. This beam is then retroreflected by the Triple Mirror Assembly (TMA) and sent to the distant spacecraft.

The TMA is a passive retroreflector which consists of three perpendicular mirror sections – for a better visualization, watch the animation at www.gracefo.spacegravity.org/video3. Originally, the TMA was introduced to solve space constraint challenges and to route the laser beam around the cold gas tank and the microwave ranging system, which are blocking the direct axis between the two spacecraft's center-of-masses (CoM). However, it turned out that the LRI architecture using the TMA allows for a simple implementation of closed-loop beam steering, while the TMA's geometrical properties suppress coupling of spacecraft attitude jitter into the pathlength measurement [13].

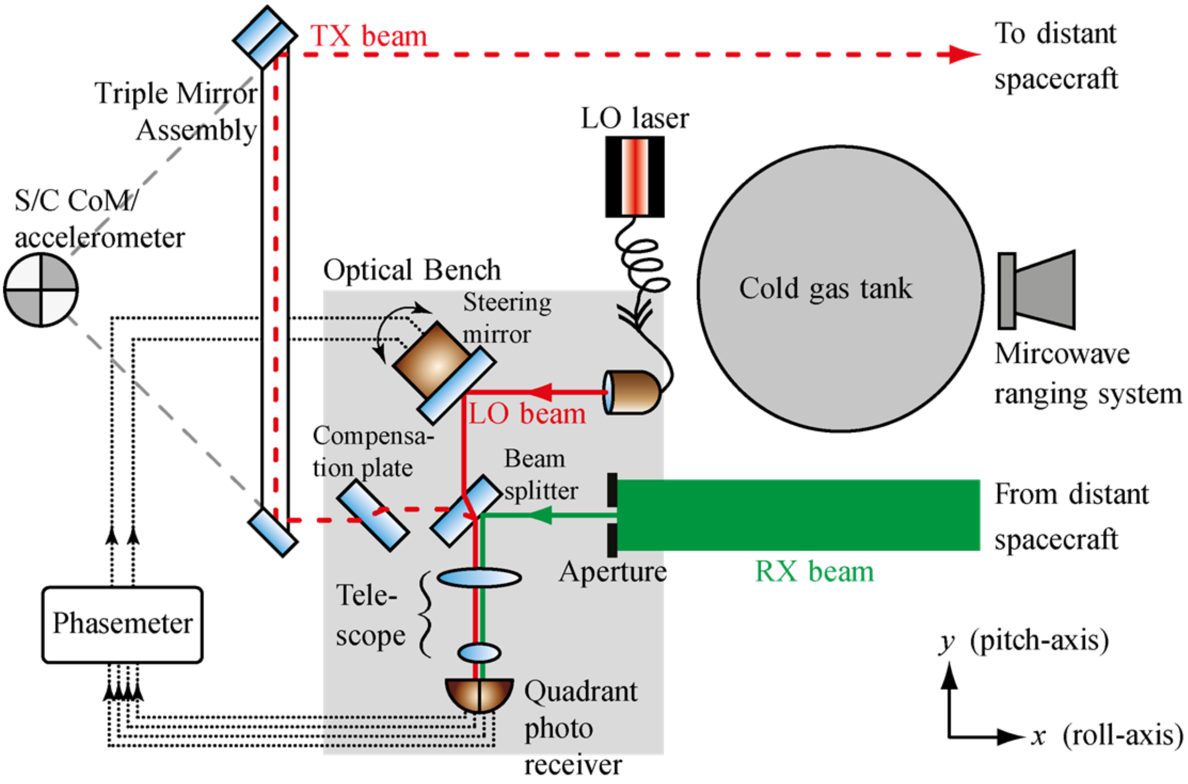

Figure 2. Schematic of the LRI on one of the two GRACE Follow-On satellites. The LRI is identical on both satellites.

The light received from the distant spacecraft (RX beam) is clipped at an 8 millimeter diameter aperture on the Optical Bench. This clipped beam is superimposed with a strong local oscillator (LO) beam and imaged with a telescope on the quadrant photo receiver (QPR).

The four phases of the QPR channels are recorded with a phasemeter. The average phase serves as error signal to drive the offset phase-lock of the LO laser on the slave spacecraft. On the master spacecraft, the average phase contains the intersatellite ranging information. By adding and subtracting the four QPR channels appropriately, signals sensitive to 2-dimensional relative wavefront tilt between LO wavefronts and RX wavefronts can be generated, which is known as Differential Wavefront Sensing (DWS). A control loop is implemented in the phasemeter, which feeds back the DWS signals to a 2-axes steering mirror. By this, local spacecraft attitude jitter, which leads to a tilt of the RX wavefronts with respect to the LO wavefronts, is actively counteracted [14].

3. In three years from prototypes to flight hardware

The LRI is quite a unique space project. As a technology demonstrator, some of the test and redundancy requirements, which are usually applied to space missions, are relaxed. This made it possible for this innovative and ambitious project to evolve from sheer design studies in 2010, to first prototypes and breadboard level verifications in 2012, to construction and test of engineering models thereafter, and ultimately to the construction and test of flight units in 2014/2015. Currently, the last flight subsystems are being assembled and tested. In a next step, the LRI flight units will be integrated into the GRACE Follow-On satellites.

4. Conclusion

The GRACE Follow-On satellites, which will be launched in 2017, will continue GRACE's quest of monitoring spatial and temporal variations in Earth's gravity field. For the first time, the intersatellite range displacements, from which the gravity potential is deduced, will be measured with a Laser Ranging Interferometer. This novel device promises an improved ranging precision compared to the conventional microwave ranging system by more than one order of magnitude to achieve 80 nm/$\sqrt{\mathrm{Hz}}$ in the measurement band of 0.002…0.1 Hz.

Flight hardware production for the Laser Ranging Interferometer is currently being finished. Most flight hardware has already successfully passed the test procedures. In the next step, the Laser Ranging Interferometer will be integrated into the two GRACE Follow-On spacecraft to be ready for launch in 2017.

Acknowledgments

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