

LASER RANGING INTERFEROMETER ON GRACE-C

M. Kaufer^{*a}, J. Bahr^b, N. Beller^a, V. Benitez-Casma^b, C. Dahl^a, T. Dauphin^a, S. Fischer^b, J. Flock^a, G. Heinzel^c, M. Herding^a, A. Kuchelmeister^a, T. Kuhn^a, P. Krause^b, M. Krzyk^b, M. Lehmann^a, V. Müller^c, A. Riede^a, N. Sprinkart^a, J. Thesinga^a, K. Voss^a, R. Wernitz^b

¹SpaceTech GmbH, Seelbachstraße 9-13, 88090 Immenstaad, Germany; ²Deutsches Zentrum für Luft- und Raumfahrt e.V., Raumfahrtagentur, Bonn, Germany; ³Albert-Einstein-Institut, Max-Planck-Institute for Gravitational Physics, Callinstraße 38, 30167 Hannover, Germany

ABSTRACT

Satellite gravimetry has revolutionized the observation of mass redistribution processes within the Earth system. The GRACE mission established Low-Low Satellite-to-Satellite Tracking as a key technique for monitoring temporal variations in Earth's gravity field, while GRACE Follow-On successfully demonstrated laser interferometric ranging with picometer-level performance. The next-generation mission, GRACE-C, is currently undergoing spacecraft integration and planned for launch in late 2028, with the Laser Ranging Interferometer serving as the sole ranging instrument. Building on the operational experience gained from GRACE-FO, the instrument design has been enhanced to improve performance, reliability, and robustness. This paper presents an overview of the mission and the LRI design and summarizes the results of the functional, performance, and thermal-vacuum tests of the German LRI flight units.

Keywords: Laser interferometry, Inter-satellite link, GRACE, Earth climate system

1. INTRODUCTION

Launched in 2002, the Gravity Recovery and Climate Experiment (GRACE) was the first mission to successfully employ high-precision Low-Low Satellite-to-Satellite Tracking (LL-SST) using a microwave ranging system. The measurement of the distance variations between two identical satellites in a polar low-Earth orbit in conjunction with the tracking of forces on test masses within these satellites enables an extremely precise recovery of the spatial and temporal variations of the Earth's gravitational field [1]. Its successor, GRACE Follow-On (GRACE-FO), launched in 2018, introduced a Laser Ranging Interferometer (LRI) jointly developed by NASA's Jet Propulsion Laboratory (JPL) and the German Research Centre for Geosciences (GFZ). The instrument significantly exceeded its original design goals, providing more than five years of successful on-orbit operation and demonstrating ranging performance at the level of approximately 200 picometers [6,7,8].

Building on the success of GRACE-FO, the next-generation mission, GRACE-C, has been developed within a renewed partnership between NASA and the German Aerospace Center (DLR), with launch planned for late 2028. In contrast to its predecessors, the LRI will serve as the primary inter-satellite ranging instrument, replacing the microwave ranging system as the baseline mission sensor. The GRACE-C LRI is being jointly developed by JPL and DLR, continuing the long-standing German-American collaboration in satellite gravimetry while incorporating lessons learned from the development and operation of the GRACE-FO instrument. To meet the increased demands on mission performance, reliability, and operational robustness, the instrument design has been further refined and matured for mission-critical operation.

This paper provides an overview of the current development status of the GRACE-C Laser Ranging Interferometer, including progress across the individual instrument subsystems and a discussion of the major German contributions. Furthermore, the achieved in-orbit performance of the GRACE-FO LRI is reviewed and compared with the heritage microwave ranging system, highlighting the benefits of laser interferometric ranging for future gravity missions.

* Marina.kaufer@spacetechn-i.com; phone 0049 7545 93284-41; spacetechn-i.com

2. LRI OVERVIEW

The Laser Ranging Interferometer (LRI) is operated on two spacecraft flying in a tandem formation in a near-circular, near-polar orbit at around 500 km height, with a distance approximately 220 km to each other. Both spacecraft are equipped with identical LRI payloads comprising hardware contributions from the United States and Germany. The U.S. segment includes the Laser Ranging Processor (LRP), the laser assembly (LAS), the Scaling Factor Unit (SFU) and the ultra-stable reference cavity (CAV). The German contribution consists of the Optical Bench Subsystem (OBS), comprising the Optical Bench Assembly (OBA) and the associated Optical Bench Electronics (OBE), as well as the Triple Mirror Assembly (TMA). Figure 1 shows an overview sketch of the whole instrument configuration.

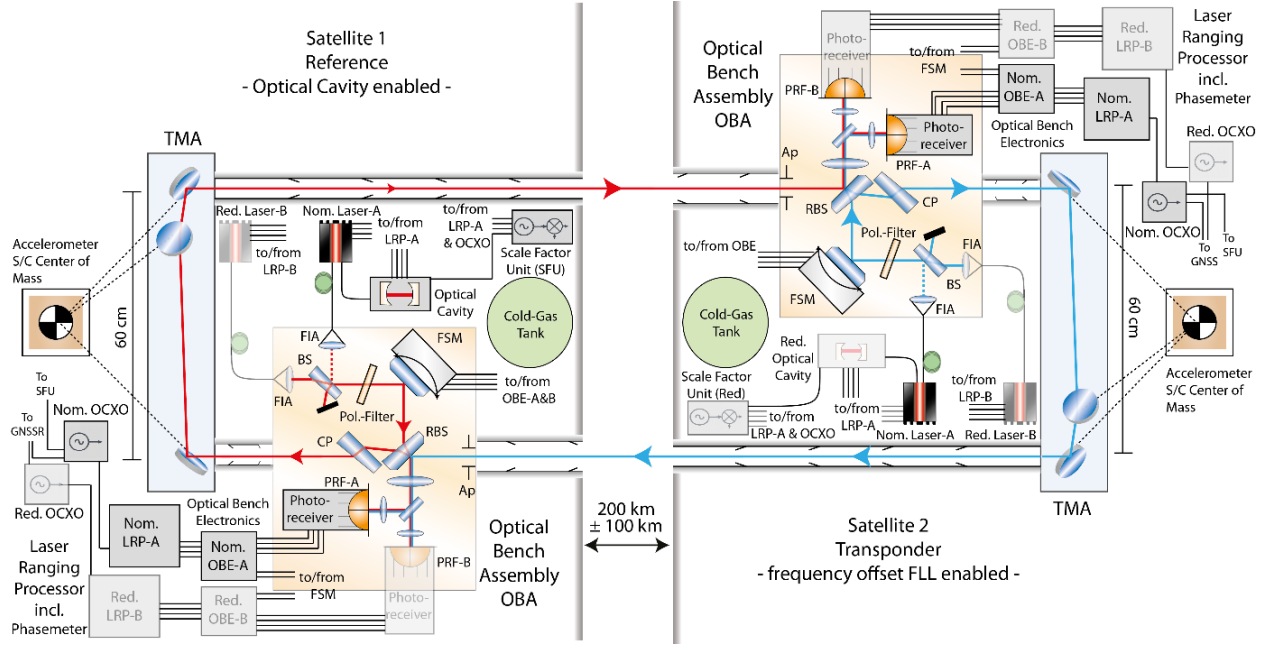


Figure 1: Simplified functional diagram of LRI (both satellites shown)

Inter-satellite ranging is achieved using heterodyne laser interferometry based on single-frequency laser light at a wavelength of 1064 nm. The instrument operates with an intentional frequency offset between the spacecraft lasers, typically in the range of 4 to 16 MHz. One spacecraft serves as the reference and stabilizes its laser frequency to the ultra-stable reference cavity. The main portion of the beam is injected into the optical bench, where a fraction of the light is retained as a local oscillator. This local oscillator beam is directed and imaged onto Quadrant Photo Receivers (QPR) (which consists of the Photo Receiver Frontend (PRF) at the OBA and one Photo Receiver Backend in the OBE). The remaining part is transmitted towards the second spacecraft via a beam splitter (RBS) and the TMA. This laser beam is called Transmitted (TX) beam.

The TX beam propagates through the TMA, which plays a central role in instrument architecture. Through its retroreflecting geometry and the placement of its vertex at the spacecraft center of mass, the TMA effectively enables ranging measurements referenced to the dynamical centers of mass of both satellites. In addition, the TMA accommodates platform-specific geometric constraints by providing a lateral displacement of 600 mm between the transmitted and received beam paths, thereby allowing the optical beam to bypass the cold gas tank while preserving the stringent beam co-alignment requirement of 50 μ rad.

On the second spacecraft, the incoming optical signal is received and used as the reference for an offset phase-lock of the local laser. The transponder spacecraft then transmits a frequency-shifted replica of the received signal back to the reference spacecraft. There, the returning beam is interfered with the local oscillator beam, generating a heterodyne signal that contains two times the Doppler shift of the relative motion of the two S/C. By precisely tracking the phase of this signal, sub-micrometer variations in the inter-satellite distance can be determined. These ranging measurements constitute the primary science observable and form the basis for the recovery of temporal variations in Earth's gravity field.

3. LRI-D DESIGN

This section presents the design of the German LRI units that are shown as CAD in Figure 2.

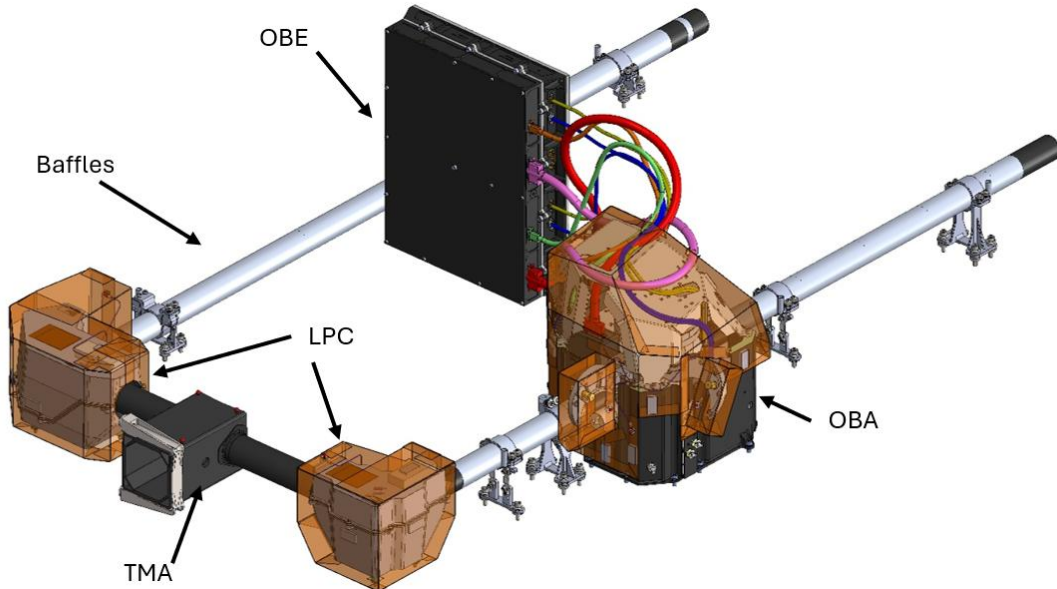


Figure 2: Overview of LRI-D units. Besides OBS (OBA and OBE) and TMA, the baffles and LPCs (light path closures) are part of the principal components of the LRI-D system.

Optical Bench Subsystem

The Optical Bench Subsystem (OBS) comprises the Optical Bench Assembly (OBA) and the Optical Bench Electronics (OBE). Within the OBA, the principal electro-optical elements include two ultra-stable Fiber Injector Assemblies (FIAs) [5], a Fine Steering Mirror (FSM), beam combination optics, imaging optics, and the photo-receiver frontends equipped with quadrant photodiodes (QPDs). The key functions of the mentioned components are to

- Launch the laser beam to the other S/C (via the TMA)
- Direct the superimposed received TX beam and the local oscillator onto the QPD's of the PRFs
- Convert the optical heterodyne signal to electrical signals and provide them to the LRP, which calculates the longitudinal signal as well as the angular difference between the TX beam and LO beam
- Enable the beam steering (by LRP command) to cover the field of regard of the S/C
- Enable closed-loop beam steering (by LRP) to keep the received beam and the transmitted beam co-aligned
- Image the OBA entrance aperture and the FSM optical surface onto the PRFs (for beam size adaption, avoidance of beam walk, avoidance of diffraction rings)

The optical bench assembly design is driven by stringent requirements on optical efficiency, wavefront quality, thermal stability, pointing performance, and angular measurement accuracy. To meet the overall instrument performance targets, the OBS shall provide an overall ranging noise contribution below $5 \text{ nm}/\sqrt{\text{Hz}}$ within the thermal environment of the spacecraft while maintaining angular measurement errors below a few microradians at received optical powers of only a few tens of picowatts.

The OBA follows a highly stable opto-mechanical architecture in which the optical components are mounted within a titanium bench structure or attached to it, see Figure 3. The use of titanium provides a favorable combination of high thermal mass, structural rigidity, and geometric symmetry, resulting in reduced thermal sensitivity and enhanced beam-pointing stability. Furthermore, the optical elements are manufactured from BK7G18, a material with a coefficient of thermal expansion closely matched to titanium, thereby minimizing thermally induced optical path variations and preserving alignment stability over the mission lifetime.

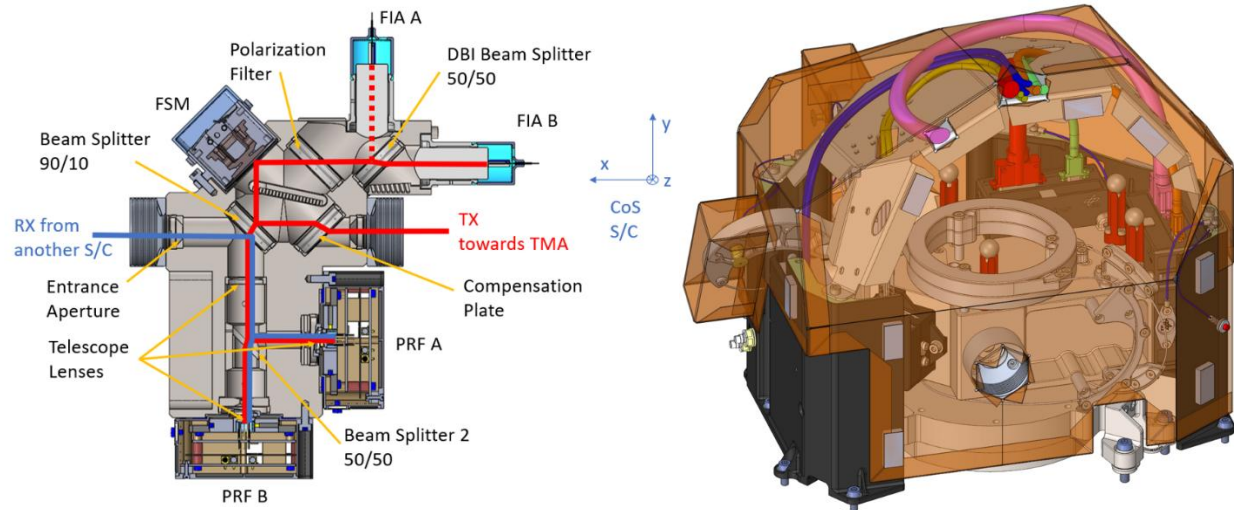


Figure 3. Illustration of the Optical Bench Assembly. Left: top down view, showing the optical path. Right: top side view, showing the mechanical parts, the MLI and the electrical harness.

The OBE provides the electronic functionality required for FSM closed-loop pointing control and analog signal conditioning of the photoreceiver frontend signals. Particular emphasis is placed on achieving high-bandwidth beam steering, with a small-signal bandwidth of at least 1 kHz, together with extremely low pointing noise of less than 12 $\mu\text{rad}/\sqrt{\text{Hz}}$. In parallel, the photoreceiver electronics are designed to achieve an equivalent input current noise below 5 pA/ $\sqrt{\text{Hz}}$ up to 16 MHz and differential phase offsets below 100 mrad between any two of the four AC measurement channels. These characteristics ensure highly accurate extraction of both ranging and attitude-related observables while maintaining consistent phase behavior across all measurement channels. See [2, 3, 4] for more details on the design of the OBS.

Triple Mirror Assembly

The Triple Mirror Assembly (TMA) enables optical measurement of the distance between the spacecraft centers of mass (CoMs). Since the direct beam path between the CoMs is obstructed by spacecraft hardware, the optical path is folded by a three-mirror retroreflector whose vertex is located at the spacecraft CoM. This arrangement provides a stable geometric reference between the interferometric measurement and the spacecraft inertial center.

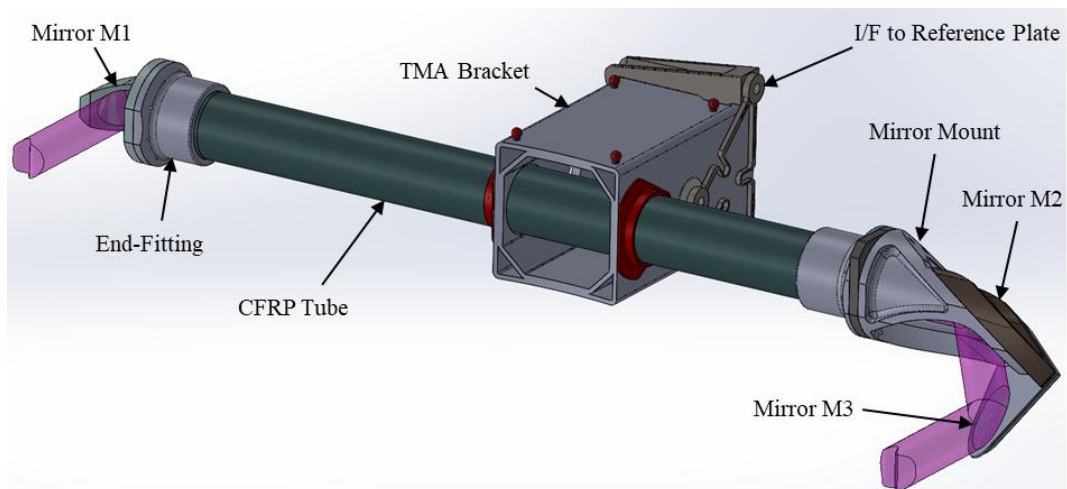


Figure 4. Opto-mechanical design of the TMA

It comprises a lightweight structural frame, two mirror units, and a reference plate used exclusively during ground verification activities. The supporting structure consists of a carbon-fiber-reinforced polymer (CFRP) tube connected to a spacecraft interface bracket. At both ends of the tube, mirror assemblies are attached via bonded end fittings. Each assembly carries three planar mirrors mounted through dedicated glass fittings, forming an orthogonal arrangement in which the reflective surfaces intersect at a common vertex.

To support alignment and performance verification, an Invar reference plate is mounted to the interface bracket during testing. The material was selected because its coefficient of thermal expansion closely matches that of the CFRP bracket, thereby minimizing thermally induced distortions. The reference plate is removed after completion of the ground test campaign and is not part of the flight configuration.

The optical functionality of the TMA is based on the retroreflector principle. In an ideal configuration, an incident beam entering the assembly is reflected such that the outgoing beam remains parallel to the incoming beam, independent of any rotation of the TMA about its vertex. This property is achieved through the precise orthogonality of the three mirror surfaces. Any deviation from the nominal mirror alignment introduces angular errors and results in a non-zero offset between the incident and reflected beam directions. Therefore, the Beam Co-Alignment (BCA) error, defined as the half-cone angle of the reflected beam, must be tightly controlled. For the intended mission application, the optical BCA error is required to remain below 50 μrad over the entire operational lifetime and throughout the full field of view.

In addition to the angular performance, thermal stability of the optical path is a key design driver. Temperature-induced variations of the optical path length (OPL) within the TMA directly affect the interferometric measurement, as they cannot be distinguished from actual path length changes between the spacecraft terminals. Consequently, the thermal sensitivity of the internal OPL must be minimized, with a requirement of less than 1000 nm/K.

4. FUNCTIONAL, PERFORMANCE AND THERMAL-VACUUM TEST RESULTS

This section presents the most important functional, performance and thermal-vacuum tests results of the German LRI flight units. Since the FM test campaign for the OBS flight models are currently ongoing, the paper focuses on the key results obtained during the function and performance test campaign in ambient.

A: Test of the Triple Mirror Assembly

The BCA error of the TMA was measured at room temperature for horizontal and vertical (g-compensated) orientations of the TMA as well as in a thermal vacuum environment for horizontal orientations of the TMA. In Fig. 5 the test setup for the measurement of the BCA error over temperature is shown. The TMA and a reference flat are installed on an ultra-stable CFRP plate inside the TV chamber. The reference flat is made of ZerodurTM and has two reflecting surfaces, which are parallel on the μrad level to each other. The reference flat enables the angular measurement of a test beam

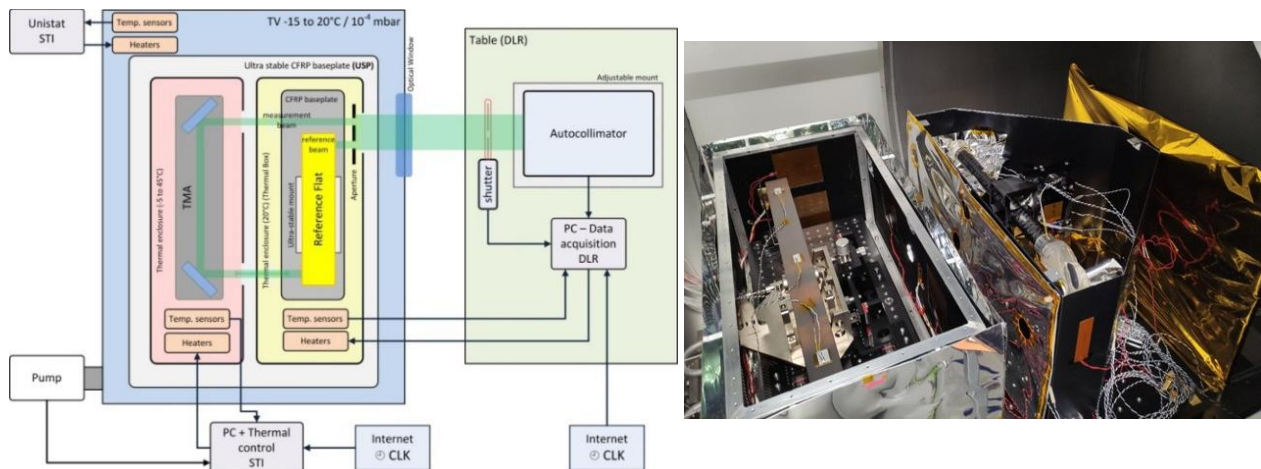


Fig. 5. Left: Test setup for the measurement of the beam co-alignment error of the TMA over temperature. Right: Picture of the TMA FM1 set-up within the TV chamber.

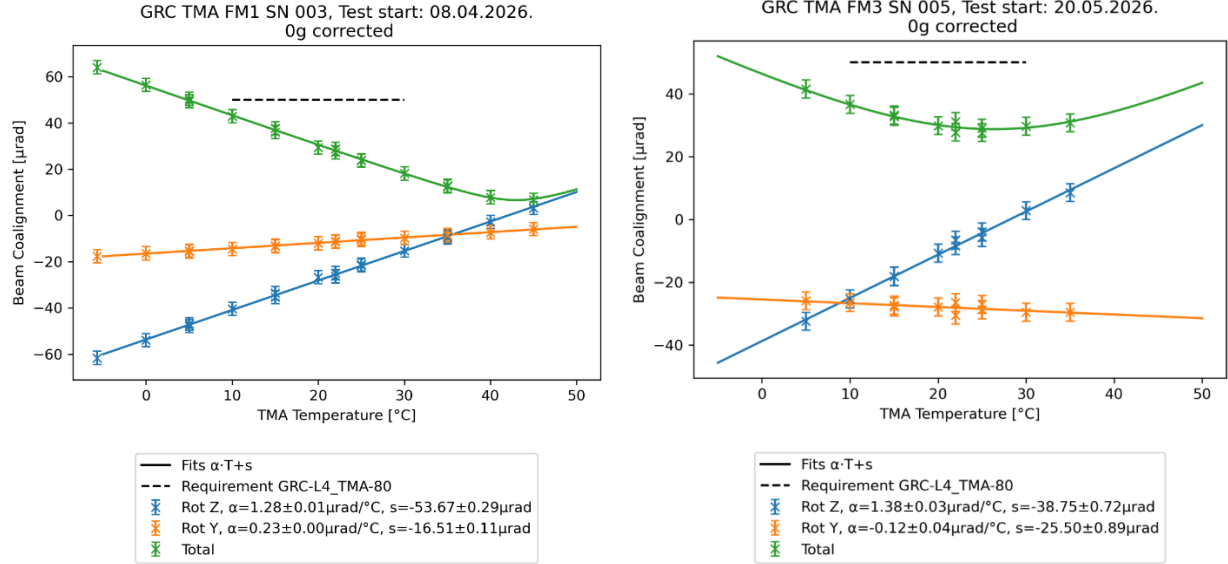


Fig. 6. Beam co-alignment mathematically 0g corrected. The correction is based on a co-alignment offset of $40.7 \pm 3.7 \mu\text{rad}$ (rotation around y) and $0.6 \pm 3.7 \mu\text{rad}$ (rotation around z) under ambient conditions. Left: BCA stability for the first flight model of the TMA. Right: BCA stability for the second flight model of the TMA.

before and after it passes twice the TMA. The angular misalignment between the direct reflection from the reference flat (reference beam) and the indirect reflection via the TMA (measurement beam) yields the information about the BCA error of the TMA. The measurement is performed by an autocollimator (ACO) in combination with a shutter that allows for an individual investigation of the measurement and reference beam. The TMA is located inside the TMA thermal enclosure, which controls the TMA temperature over the operational flight temperature range to measure the temperature coefficient of the BCA error. The reference flat is mounted inside the OGSE thermal box, which keeps the OGSE at room temperature to minimize angular misalignments of its reflecting surfaces. Both compartments are thermally controlled by heaters and temperature sensors in a closed-loop control. The TMA was oriented horizontally inside the TV chamber during the measurements. This causes a slight bending of the carbon tube due to gravity, and consequently an offset of the measured BCA values. This can be mathematically corrected by subtracting the offset compared to measurements in 0g-configuration, where the TMA is mounted vertically. Fig. 6 shows the 0g corrected BCA dependence over temperature including error analysis and the 50 μrad top level requirement for OBS and TMA together. From this data the TMA FM1(FM2) BCA linear thermal coefficients were determined to be 0.23 μrad/K (-0.12 μrad/K for FM2) for rotation around y and 1.28 μrad/K (1.38 μrad/K for FM2) for rotation around z in a temperature range of $-5^\circ\text{C} \leq T \leq 45^\circ\text{C}$ ($5^\circ\text{C} \leq T \leq 35^\circ\text{C}$ for FM2).

The OPL temperature coefficient of the TMA was interferometrically measured in a thermal vacuum environment for horizontal orientation of the TMA. The test setup is shown in Fig. 7. The TMA and a corner cube are mounted to an ultra-stable CFRP plate inside the TV chamber. The corner cube vertex coincides with the TMA vertex and thus the corner cube is used to reference the OPL change to the TMA vertex position. The interferometer mirrors (reference mirrors with holes M1 and R1 and plane target mirrors M2 and R2) are installed on a separate CFRP plate and located in a thermally stabilized housing to achieve the required measurement accuracy of better than 200 nm/K. The laser head, the phasemeter and the two Differential Plane Mirror Interferometer (DPMI) which evaluate the TMA and the corner cube phase signals are located on an optical table outside of the TV chamber and the light is routed via a view port to the setup inside the TV chamber. The DPMIs are rotated by 45° w.r.t. each other to reach the corner cube behind the TMA (beams have to be routed around the TMA tube and through the TMA bracket). This set-up benefits of a high common-mode rejection ratio since the main noise sources are to some degree common to both interferometers, i.e. laser frequency noise and common mode displacement/mechanical vibrations.

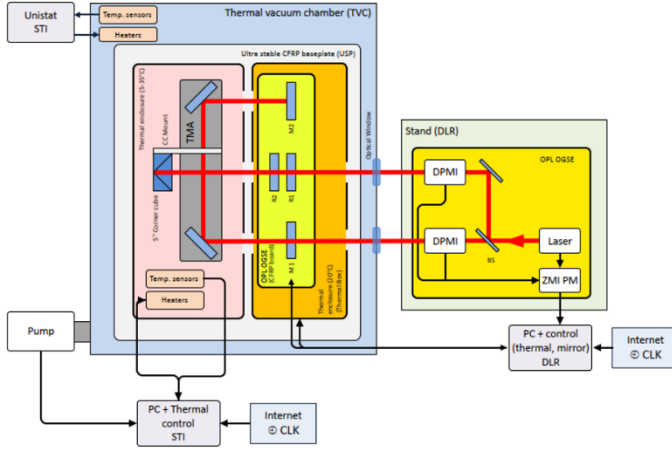


Fig. 7. Left: Test setup for the measurement of the optical path length error of the TMA. Right: Picture of the TMA FM1 with corner cube installed at the reference plate within its test enclosure.

The OPL coefficient has been measured for different temperature ranges. The resulting coefficients are for FM1 $532 \text{ nm/K} \pm 49 \text{ nm/K}$ for temperatures between -5°C and $+45^\circ\text{C}$ and for FM2 $563 \text{ nm} \pm 64 \text{ nm/K}$ for temperatures between $+5^\circ\text{C}$ and $+35^\circ\text{C}$, which is sufficiently below the mission's requirement of 1000 nm/K .

B: Test of the Optical Bench Subsystem

Both flight models of the OBS have seen the same tests with similar results. For the sake of brevity key results for one OBS are presented.

Schematics of the OBS performance test setup are shown in Figure 8. For all tests an LRI-D EGSE mimicking the function of the LRP is used. It controls the OBS functions, and reads-out its monitor signals as well as the phase information of the OBS. Using a Fiber Coupled Laser Diode (FCLD) as a GSE light source, the position of the LO on the QPD's can be measured as well as the TX beam properties. Its beam angle is measured by an autocollimator (ACO), its beam diameter by a CCD camera and its wavefront by a Shack-Hartmann sensor (SHS). The ACO is also used to measure the angular alignment of a reference surface at the TX beam output of the OBA and of the reference targets in front of the OBA. Using both alignment information it is possible to derive the angular information of the TX beam w.r.t. the OBA and to suppress angular misalignments between the ACO and the OBA.

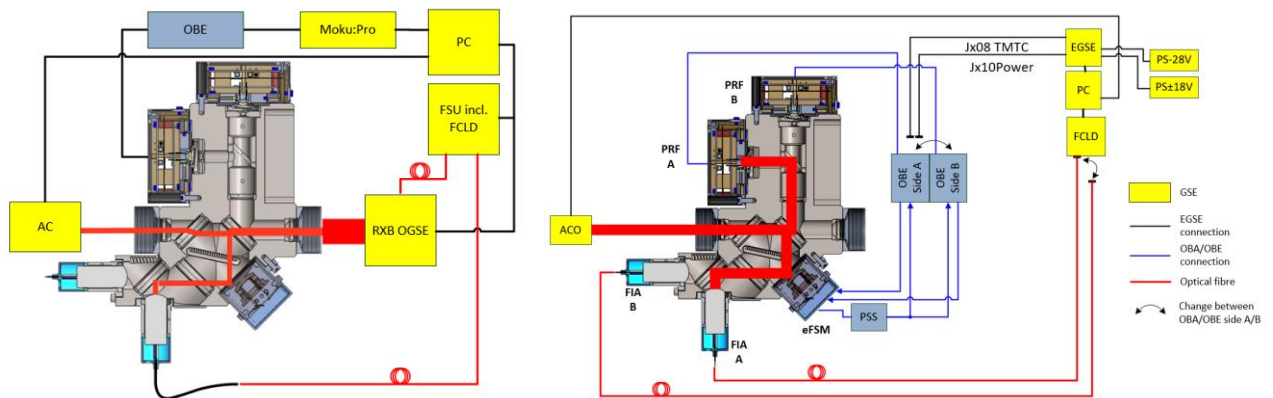


Figure 8: Key setups for OBS functional and performance measurements. Left: Setup for DWS coupling factor and heterodyne efficiency. Right: Setup for Fine Steering Mirror pointing stability.

A fraction of the main light source is directed via a fiber system and via a frequency shifting OGSE to the RX beam OGSE. The RX beam OGSE consists of a large fiber collimator, whose alignment can be changed in the $y_{S/C}$ and $z_{S/C}$ directions and along the rotational degree of freedom around these axes. Thus, the frequency shifted beam of the RX beam OGSE mimics the RX beam onboard of the real satellites and generates a heterodyne beat note with the LO beam inside the OBA. This is used to measure the differential wavefront sensing (DWS) coefficients of the OBA to be for side A 32215 rad/rad for x and 33481 rad/rad for y. For the redundant side B the DWS factor has been calculated to be 31449 rad/rad for x and 33609 rad/rad for y. The heterodyne efficiency was tested in a homodyne setup to be 0.63 for side A and 0.65 for side B. The main light source can be exchanged with an amplitude modulated laser diode to measure the differential phase offsets between the QPR channels.

The phase of the science signal will be provided to the LRP via the 4 AC channels of the QPR. The LRP will process the phase and will generate the average of all four phase signals as well as the DWS combinations of the four phase signals. The latter one is used to control the optical pointing of the TX beam via the FSM. Thus, the differential phase error between the 4 AC channels of the QPR will have a similar influence on the TX beam pointing like the BCA error of the TMA; see Subsection 4. A. From the phases obtained during the ambient AC transfer function measurements, the phase differences between the individual channels can be calculated. The results for Side A and B for high case modulation at -30dB gain attenuation are shown in Figure 9 and lay sufficiently below the missions 50 mrad requirement. The differential phase stability between any 2 of the 4 AC channels of the QPR needs to be below 20 mrad/K in the frequency range of the science signal, which is 4 to 16 MHz. Preliminary results of the ongoing TV tests show a temperature coefficient for the differential phase offset far below 1 mrad/K. The average phase contains information about the distance variation between both S/C. Therefore, the average phase stability of the 4 AC channels of the QPR will have a similar influence on the ranging signal like the OPL stability of the TMA; see Subsection 4. A. The average phase stability of the four AC channels of the QPR has to be better than 74 mrad/K. Preliminary results indicate an average phase stability of about 1 mrad/K.

The angular stability of the TX beam was measured with the autocollimator over an extended period, for both Side A and Side B. The RMS pointing noise was evaluated in the time domain, and the amplitude spectral density (ASD) of the x and y pointing noise was evaluated in the frequency domain. Figure 10 shows the result for Side A. The RMS pointing noise is 0.70 microrad on the x axis and 0.61 microrad on the y axis, corresponding to a total RMS half cone angle of 0.93 microrad, well below the 4 microrad limit. In the frequency domain, the relative in-band accuracy of the steering mirror positioning is below the required $12 \mu\text{rad}/\sqrt{\text{Hz}}$.

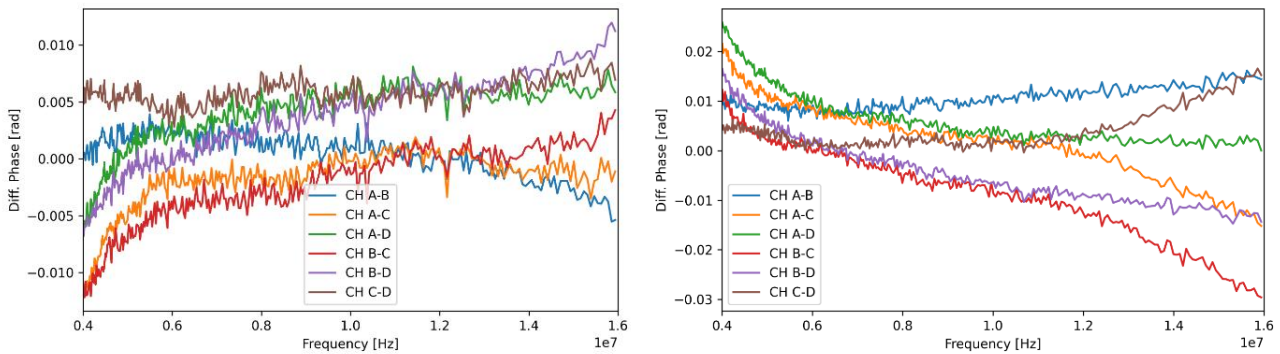


Figure 9: QPR AC Channel Differential Phase Offset Left: Side A with -30dB gain attenuation. Right: Side B with -30dB gain attenuation.

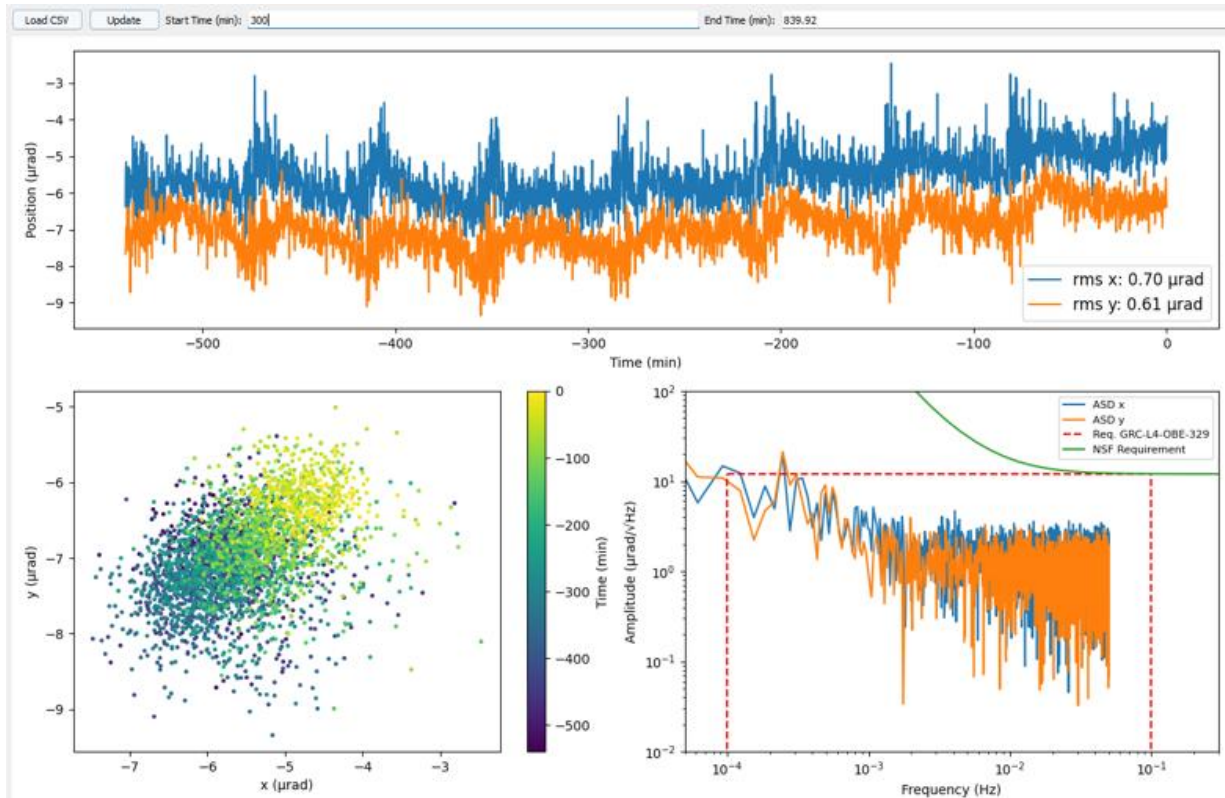


Figure 10: Side A fine steering mirror pointing stability, time series, x/y scatter, and amplitude spectral density vs. requirement.

5. SUMMARY

We have presented the design of the German units of the laser ranging interferometer on GRACE C and the test results of the key electro-optical requirements achieved with the flight models so far. It was verified that the flight models will enable the LRI to establish an optical link between the two GRACE C satellites and to perform ranging measurements with the required precision. The LRI will ensure the continuity of gravity data with an even higher accuracy that has profound importance in the monitoring, modelling and understanding of the climate system.

The delivery of the German LRI units to the S/C has started in summer 2026. The German LRI units will be completely integrated on both S/C next year. The launch is scheduled for end of 2028.

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REFERENCES

- [1] <http://www.gfz-potsdam.de/grace>
- [2] G. Heinzl, B. Sheard, N. Brause, K. Danzmann, M. Dehne, O. Gerberding, C. Mahrtdt, V. Mueller, D. Schuetze, G. Stede, W. Klipstein, W. Folkner, R. Spero, K. Nicklaus, P. Gath, D. Shaddock, "Laser Ranging Interferometer for GRACE follow-on", International Conference on Space Optics, 2012.

- [3] B. S. Sheard, G. Heinzel, K. Danzmann, D. A. Shaddock, W.M. Klipstein, W. M. Folkner, "Intersatellite laser ranging instrument for the GRACE follow-on mission", *Journal of Geodesy*, vol. 86, pp. 1083-1095, 2012.
- [4] K. Nicklaus, M. Herding, A. Baatzsch, M. Dehne, C. Diekmann, K. Voss, F. Gilles. B. Guenther, B. Zender, S. Boehme, V. Mueller, D. Schuetze, G. Stede, B. Sheard, G. Heinzel, "Optical Bench of the Laser Ranging Interferometer on GRACE Follow-On", *International Conference on Space Optics*, 2014.
- [5] S. Boehme, S. Fabian, A. Kamm, T. Beschel, E. Beckert, A. Tünnermann, K. Nicklaus, M. Dehne, "High Reproducible CO2 Laser Spliced Fiber-Collimator for a Space Borne Laser System", *International Conference on Space Optics*, 2016.
- [6] K. Abich et al., "In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer", *Physical Review Letters*, 123, 2019.
- [7] K. Abich et al., "Triple mirror assembly in the GRACE Follow-On laser ranging interferometer", *Phys. Rev. Applied* 24, 2025.
- [8] K. Ghobadi-Far, S. Han, C. M. McCullough, D. N. Wiese, D. Yuan, F. W. Landerer, J. Sauber, M. M. Watkins, "GRACE Follow-On Laser Ranging Interferometer Measurements Uniquely Distinguish Short-Wavelength Gravitational Perturbations", *Geophysical Research Letters*, 47, 2020.