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OPTICAL BENCH OF THE LASER RANGING INTERFEROMETER ON GRACE FOLLOW-ON

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I. INTRODUCTION

The Gravity Recovery and Climate Experiment (GRACE) is a successful Earth observation mission launched in 2002 and consisting of two identical satellites in a polar low-Earth orbit. The distance variations between these two satellites are measured with a microwave ranging system located in the central axis with a precision down to several $\mu m/\sqrt{Hz}$. In data post-processing the spatial and temporal variations of the Earth's gravitational field are recovered. More than 1200 articles where published in the context of GRACE [1], yielding significant improvement in the understanding e.g. of the seasonal and long term development of Earth's water basins. Examples are the loss of ice masses on the north pole [2], articles on Ground water decrease in India [3] and California [4], and long term disaster prediction capability [5].

On GRACE Follow-On a laser ranging interferometer (LRI) will fly as a technology demonstrator to provide about 2 orders of magnitude higher ranging measurement precision, down to 80 $nm/\sqrt{Hz}$ in the measurement band between 2 mHz and 0.1 Hz.

The optical bench is a key unit of the LRI on-board the GRACE follow-on mission which will be launched in 2017 by the joint collaboration between USA (NASA) and Germany (GFZ).

The design, the performance analyses as well as the functional, performance and environmental tests results of the optical bench engineering model are discussed in this paper.

II. LRI OVERVIEW

The LRI is based on a laser interferometer evaluating the heterodyne signal of two near-infrared single frequency lasers (λ=1064 nm) with a frequency offset in the MHz range. The two lasers are located on the two GRACE FO satellites, which follow each other in a near polar orbit at 450 km height with about 220 km distance to each other.

The instrument hardware on both spacecraft is identical. It consists of a single frequency laser, a fabry perot reference cavity, a triple mirror assembly (TMA) and an optical bench subsystem (OBS, consisting of the optical bench assembly (OBA) and associated electronics (OBE)) and the instrument electronics, the so called laser ranging processor (LRP). Fig. 1 shows an overview sketch of the whole instrument configuration.

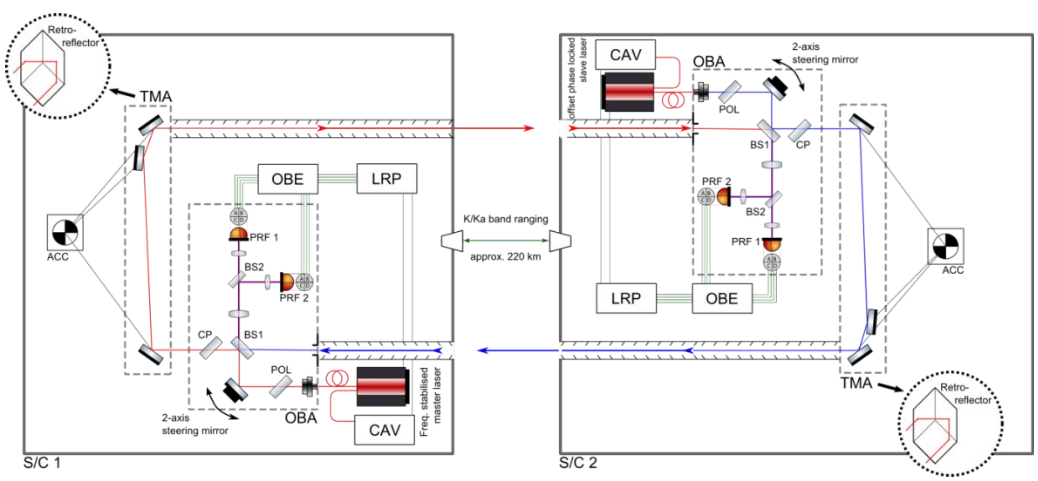

Fig. 1: LRI overview

On one spacecraft (the master S/C), the laser is frequency locked to the reference cavity via a fibre link and the beam is launched via the fibre injector onto the OBA. On the OBA it is directed to the quadrant photo receiver as well as to the other spacecraft by means of a beam splitter.

The beam then passes the TMA, which enables the range measurement from CoM to CoM of the two spacecraft, due to its retro reflector properties and the placement of its vertex at the CoM of the respective S/C. While in principle a retroreflector is in general required to achieve this sort of ‘racetrack configuration’, on GRACE FO the TMA has the further purpose to route the beam around the Ka-Band Horn and the coldgas tank, which requires it to have a displacement of about 600 mm between the receive and transmit beam path. The very constrained space on the GRACE FO platform together with the required beam co-alignment in the range of 50 µrad makes this a challenge on its own. In Fig. 2 the approximate placement of the LRI units is shown exemplary in the GRACE BUS, which is very similar to the one GRACE FO will use. On the second spacecraft (the slave S/C) the hardware configuration is identical, but the laser is not locked to the reference cavity but frequency offset locked by 10 MHz to the received signal from the master S/C. The heterodyne signal of the superposition of the local oscillator of the master S/C and the received signal from the slave S/C yields two times the Doppler shift of the relative motion of the two S/C. This phase shift signal is the main science signal from which the distance variation is derived and ultimately the gravity field is reconstructed. For a more detailed description of the instrument principle see [6,7].

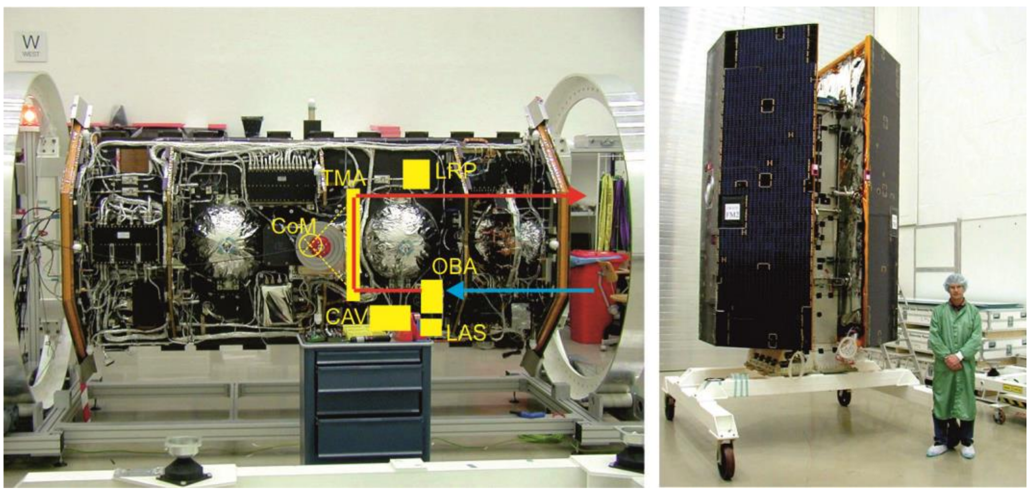

Fig. 2: Approximate placement of LRI in the GRACE BUS and the two satellites in launch configuration (original pictures from http://www.csr.utexas.edu/grace/)

III. KEY REQUIREMENTS

The top level instrument requirement is the ranging noise requirement of

$$\tilde{x}(f) < 80\,\frac{\mathrm{nm}}{\sqrt{\mathrm{Hz}}}\ \mathrm{x\ NSF(f)\ for\ 2\ mHz < f < 100\ mHz} \tag{1}$$

with

$$\mathrm{NSF(f)} = \sqrt{1+\left(\frac{\mathrm{f}}{3\ \mathrm{mHz}}\right)^{-2}} + \sqrt{1+\left(\frac{\mathrm{f}}{10\ \mathrm{mHz}}\right)^{-2}} \tag{2}$$

From this requirement several key and driving design requirements for the free space optics part of the LRI (which is the OBA, the TMA and the instrument baffles) and the OBA are derived and listed in Table 1.

Table 1 key and driving LRI optical design requirements

Parameter	Requirement LRI	Requirement OBA
Beam Diameter	5 +/- 0.5 mm	5 +/- 0.5 mm
Free Aperture (over FoR)	> 3 x beam diameter	> 3 x beam diameter
Beam propagation Factor M^2	< 1.2	< 1.2
Wavefront planarity ($1/e^2$)	< λ/8	< λ/12
Beam alignment error	< 50 µrad	< 10 µrad
Field of regard ($1/e^2$)	> 4.5 mrad	>4.5 mrad
Beam walk on QPR (over FoR)	-	< 10 µm
Ranging noise	< 80 nm/√Hz x NSF(f)	< 5 nm/√Hz x NSF(f)
Rotational coupling factor	< 200 µm/rad (in pitch an yaw)	< 80 µm/rad (in pitch an yaw)
Pointing stability	< 20 µrad over 1 orbit	< 15 µrad over 1 orbit

The beam diameter requirement is derived from the overall power budget, taking required power at the distant spacecraft and heterodyne signal loss under the influence of co-alignment errors into account. The same is true for M², the required wavefront planarity and the beam co-alignment. The field of regard defines the required laser beam steering range relative to the S/C because of pointing misalignments after launch (caused by uncertainty of the S/C pointing due to star camera errors, launch settling and optimized pointing for the microwave ranging system) and S/C AOCS pointing performance of about +/- 300 µrad.

IV. OPTICAL BENCH

The optical bench features the ultra-stable fibre injector (FIA), the beam fine steering mirror (FSM), superposition of the laser signal, imaging optics as well as the photoreceiver frontends (PRFs) with the quadrant photodiodes. Its key functions are to

- launch the laser beam to other S/C (via TMA)
- superimpose the received beam and the local oscillator on the PRFs
- convert the optical heterodyne signal to electrical signal and provide to LRP
- enable the beam steering (by LRP command) to cover the field of regard
- 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 onto the PRFs (for beam size adaption, avoidance of beam walk, avoidance of diffraction rings)

Fig. 3 shows the setup of the optical bench and the beam path and Fig. 4 shows the actual EM hardware during the assembly and test campaign at STI. The individual components are either placed in or attached to the optical bench body out of titanium. This approach has been selected to achieve a low thermal noise (due to the high thermal mass enclosing the components) and high beam pointing stability (due to the symmetry of the titanium body with respect to the plane containing the beam). The optical components are out of BK7G18, which is well CTE-matched to titanium, further improving the thermal stability of the OBA.

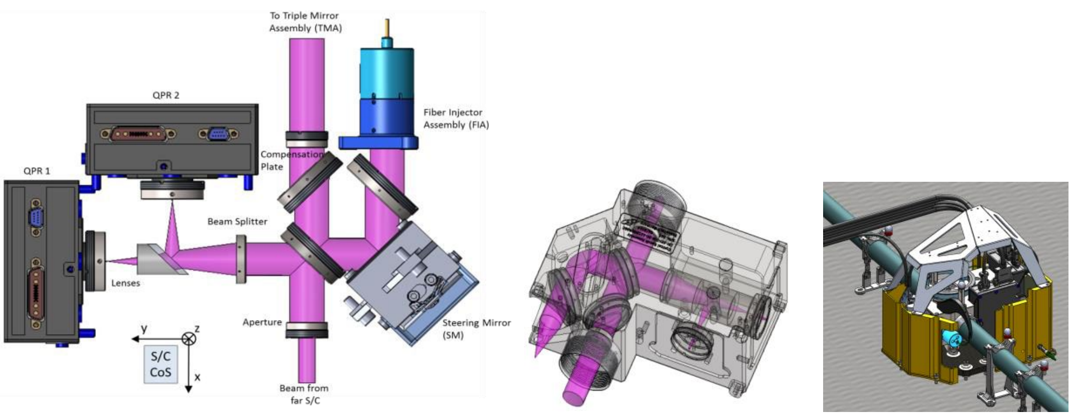

Fig. 3. Optical bench illustration, left: top down view, showing the optical path; middle: with graphical representation of the titanium body; right: with thermal shields, cable support and attached baffle tubes

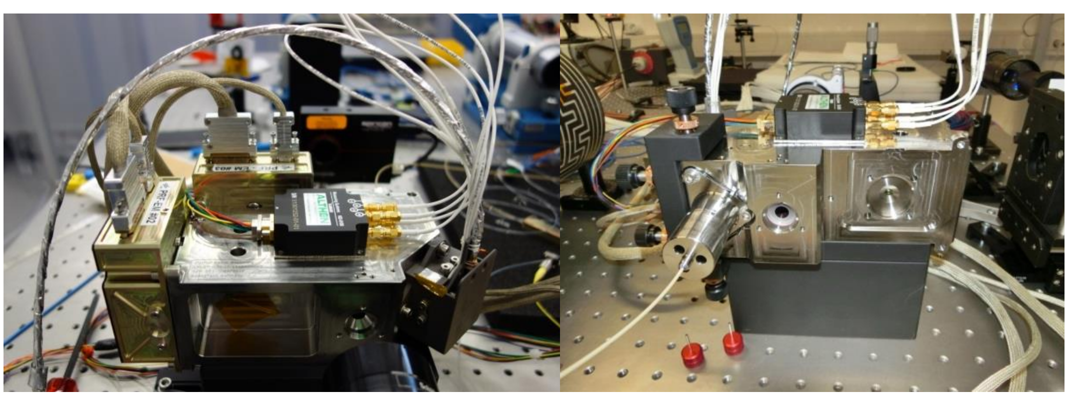

Fig. 4. EM optical bench at STI facilities, left: fully integrated with PRFs and FSM; right: during assembly, with view on FIA

A. Fibre Injector

The key requirements for the fibre injector are the 5 mm collimated beam diameter with a wavefront planarity of better than λ/15 for the full operational temperature range of 10 to 40 °C, a free aperture of 3 times the beam diameter and a pointing stability of better than 5 µrad/K. Furthermore the fibre injector return loss for signals entering the injector in the reverse direction shall be higher than 50 dB. An optically fully monolithic design, with the fibre directly spliced to the aspheric lens body by CO2 splicing technology [8], has been developed to achieve these requirements. The design combines an extremely high thermal stability with high return losses, but requires very precise manufacturing capability. It has been performance tested over the full operational temperature range and successfully passed thermal cycling, vibration and shock testing. The engineering model met all requirements, except for the beam diameter, due to a conversion error of the fiber numerical aperture. The flight model design has been modified to achieve the required 5 mm beam diameter.

The design is adaptable to other fibre NAs and beam diameters and considered an attractive design of various collimator applications with high stability requirements. Fig. 5 shows the fibre injector EM, the wavefront measurement in vacuum and the beam profile in the focus.

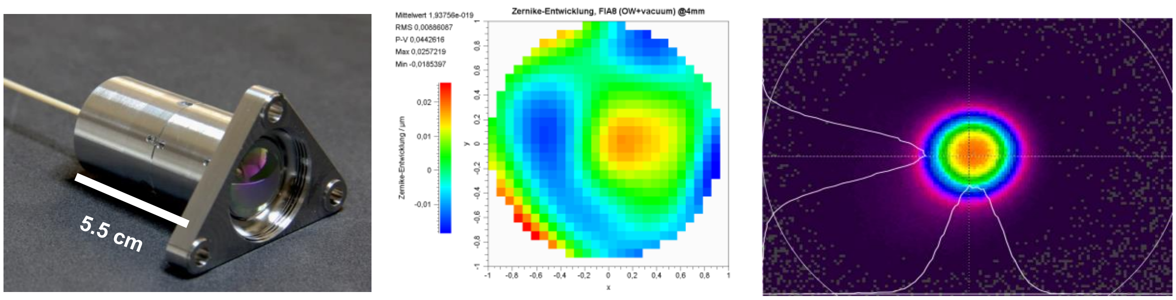

Fig. 5. Left: Fibre Injector EM ; middle: Wavefront measurement; right: Beam profile in Focus)

B. Internal Optics

The internal optics consists of a polarizer after the FIA, a beamsplitter and compensation plate and the imaging optics.

The beam splitter is a wedged plane optic with a 90:10 splitting ratio and a surface figure error of better than 3/0.2(0.2), corresponding to approx. λ/18 at the design wavelength of 1064 nm. The beamsplitter is the element, where the received beam and the local oscillator are superimposed. The planarity of the beamsplitter is of key importance, as any deviation in planarity leads to a loss of heterodyne signal due to a wavefront mismatch between the received beam and the local oscillator on the local spacecraft as well as a loss of signal on the distant spacecraft due to a change in the far field divergence. The submount design and the gluing process had to be optimized to ensure the required planarity of about λ/15.

The compensation plate has identical dimensions like the beam splitter, but is coated with AR coatings on both sides. Its function is to reduce the linear rotation-to-pathlength coupling by about three orders of magnitude (from about 2300 µm/rad to less than 40 µm/rad).

The imaging optics are comprised of 3 lenses and a beam splitter. The function of the imaging optics is to image the entrance aperture and the plane of the steering mirror onto the two redundant quadrant photodiodes of the PRFs. They provide a demagnification factor of 8.4 to reduce the 8 mm entrance aperture to about 0.95 mm to fit the 1 mm diode aperture and eliminate any beam walk on the PRFs during rotation of the individual spacecrafts.

C. Fine Steering Mirror

The fine steering mirror is a flight proven design from LCT. It provides an optical steering range of +/- 8.1 mrad and allows a fast initial link acquisition over a range of +/- 3 mrad at 150 Hz, which is the initial alignment uncertainty of optical axes of the LRIs on the two spacecraft with respect to each other. The steering mirror will be operated throughout the whole mission to cancel out the spacecraft angular movement in pitch and yaw (in the order of +/- 300 µrad) with an accuracy of a few µrad.

D. Photoreceivers

The photoreceivers are comprised of a frontend (PRF) and a backend(PRB) and has been designed by DLR Adlershofen. The PRF contains the quadrant photodiode and the preamplifier electronics, while the PRB contains the main amplifier and the power. The whole design has been optimized to ensure a high sensitivity and low noise in the heterodyne measurement band between 4 and 16 MHz. The PRF is positioned laterally to the optical beam to µm accuracy by carefully hammering and to 30 µm accuracy longitudinally by shimming.

IV. OPTICAL DESIGN AND ANALYSIS

The major part of the optical design is based on a detailed nonsequential optical raytracing model incorporating a full representation of OBA optics, including aberrations and the local oscillator as well as the received beam. It has been used to derive PRF shimming accuracy by worst case element misalignments, applied to derive single element tolerances (driven by beam walk) and delivers the qualitative heterodyne signal efficiency behaviour under alignment changes. Fig. 6 shows the optical design and tolerance analysis flow, the optical raytracing model and some evaluation features.

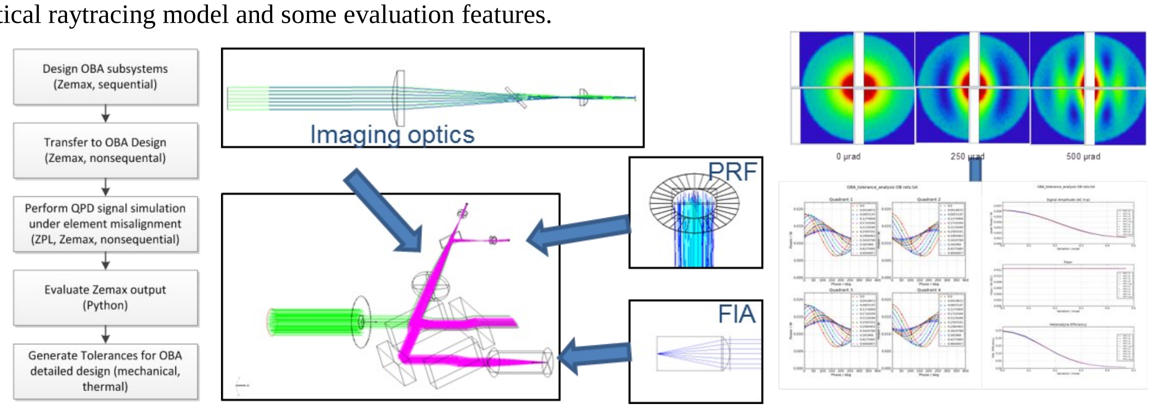

Fig. 6. Left: Optical design and tolerance analysis flow; middle (optical bench representation in raytracing mode; top right: coherent irradiation on QPR for different angle between wavefronts; bottom right: postprocessing of raytracing model for qualitative heterodyne signal evaluation

IV. THERMAL DESIGN AND ANALYSIS

The thermal design of the OBA has to ensure three constraints: 1. the allowable operational temperature limits for all components are kept during all times on orbit. 2. the thermal noise is low enough to support the allocated ranging noise of less than 5 nm/√Hz x NSF(f). 3. the angular alignment of the beam out of optical bench is better than 15 µrad over one orbit (for initial acquisition reasons). For 2. and 3. the design approach with the titanium structure with high thermal capacity into which the optical components are inserted or attached to has been selected. It provides high thermal mass and a good thermal symmetry with respect to the plane of the optical axes.

To first order the thermal noise couples into the ranging noise only via the thermal dependency of the optical properties of the beamsplitter and the compensation plate[6] and electrical noise of the PRFs and PRB with a coupling factor of 2.1 nm/K. The coupling factor of the BS and CP is 74.4 nm/K and of the PRFs and PRB is 2.1 nm/K. From this one calculates a required thermal noise of less than 0.065 K/√Hz x NSF(f). The assumed worst case thermal environment for GRACE FO is based on actual thermal noise measurement data from GRACE, which yielded 0.3 K/√Hz x NSF(f) and a +/-3 K sinusoidal temperature variation at orbit frequency.

Fig. 7 shows the assumed temperature time series for the analysis and the resulting ranging noise from the detailed transient thermal analysis of the OBA.

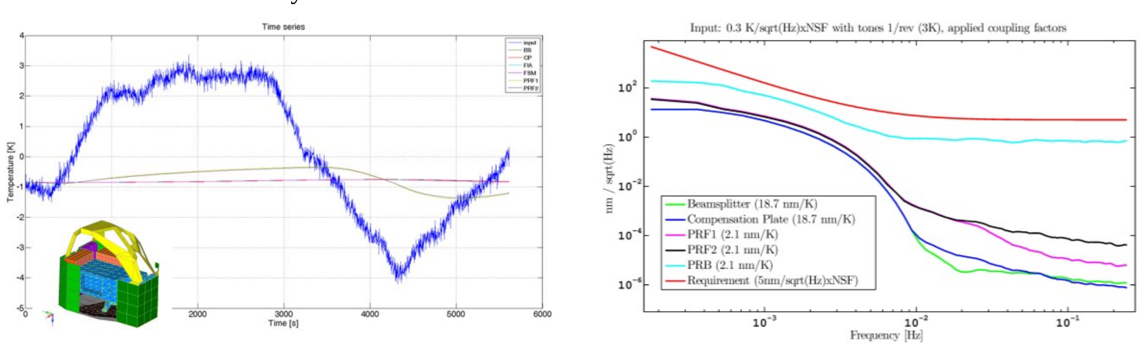

Fig. 7. Left: Assumed worst case thermal environment on GRACE FO; right: corresponding ranging noise

The analysis predicts thermal noise performance of less than 1 nm/√Hz x NSF(f), significantly better than required. The PRB shows up as the greatest contributor, which is caused by the worst case assumption of no thermal mass of the PRB in comparison to the detailed transient thermal modelling of the OBA.

IV. EXPERIMENTAL RESULTS

Extensive tests have been performed with the engineering model of the optical bench and its subsystems during assembly and in the final configuration. For most tests a single frequency laser signal was applied either via the FIA or the RX OGSE serving as far field simulator, providing plane wavefronts as would be received from the distant satellite. Especially for the wavefront planarity measurements a careful calibration of the Shack Hartmann sensor is required to achieve an absolute accuracy of better than λ/15. This calibration is repeated for each measurement with a point source setup providing a spherical wavefront with 1 m radius. Fig. 8 shows the test setup schemes and some photos of the integration and tests during integration.

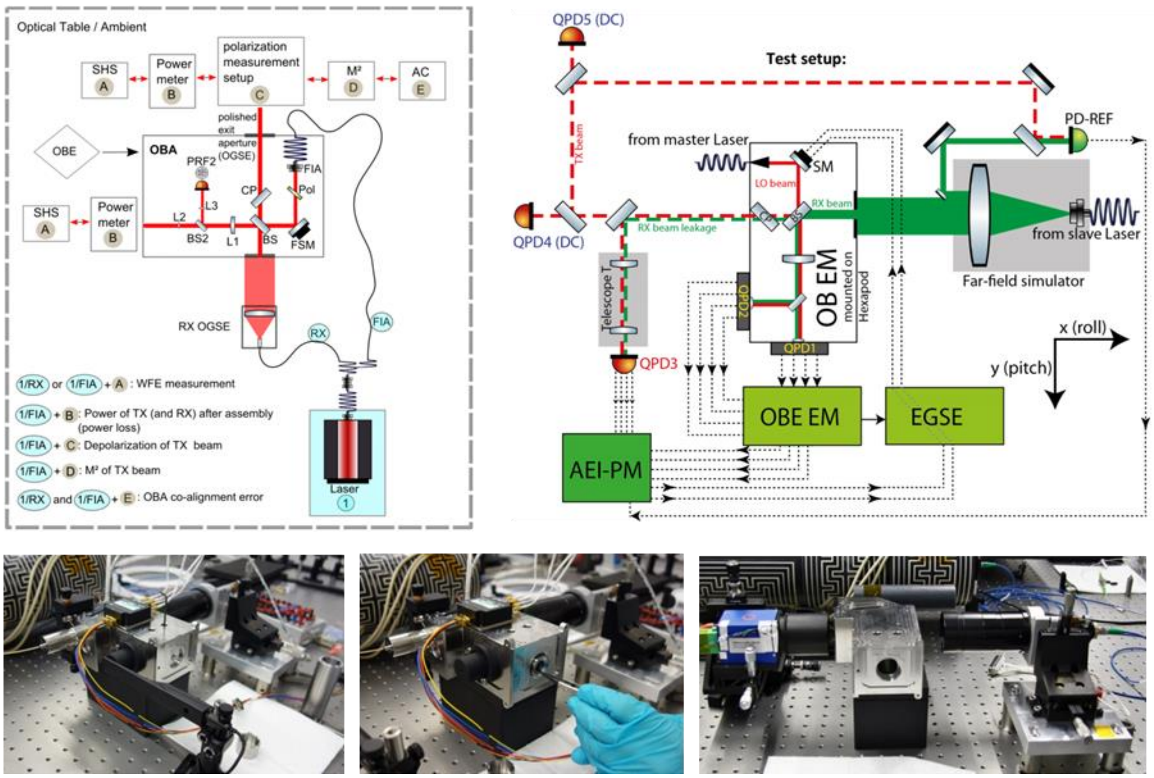

Fig. 8. Top: Test setup schemes for tests during assembly and final configuration; Bottom: some photos during assembly and testing

Fig. *9* shows a measurement of the beam position on the Photodiode when the steering mirror driving over the full field of regard and a measurement of the tilt to length coupling verifying that the compensation plate reduces the coupling by several orders of magnitude.

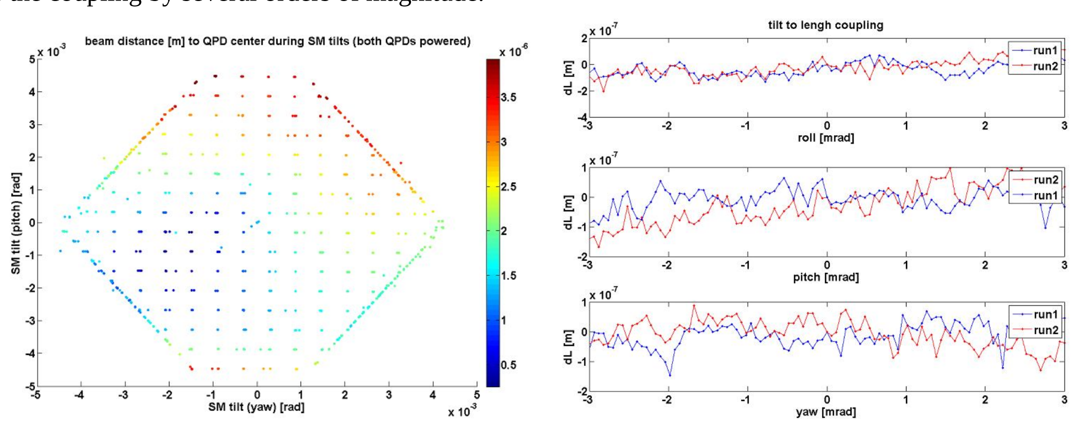

Fig. 9. Left: beam position color plot (in m) over Field of Regard; Right: Rotational Coupling factor measurements

Table 2 summarizes the achieved results of the key and driving optical requirements. Apart from the about 16 % too small beam diameter out of the FIA, all requirements are fulfilled with the EM. The ranging noise and the rotational coupling factors are currently based on analysis. The corresponding tests as well as the vibration and shock tests will be performed in the next months.

Table 2 test results of the key and driving optical design requirement for the optical bench

Parameter	Requirement OBA	Test/analysis result
Beam Diameter (4sigma)	5 +/- 0.5 mm	4.3 mm
Free Aperture	> 3 x beam diameter	> 3 x beam diameter
Beam propagation Factor M^2	< 1.2	M^2_x=1.16 M^2_y=1.15
Wavefront planarity ($1/e^2$)	< λ/12	< λ/14
Beam coalignment error	< 10 µrad	α=1.1 µrad (yaw) β=0.7 µrad (pitch)
Field of regard ($1/e^2$)	>4.5 mrad	> 4.5 mrad (will be 8 mrad for PFM)
Beam walk on QPR (over FoR)	< +/-10 µm (over 2 mrad)	< +/- 3 µm (over 4.5 mrad)
Ranging noise	< 5 nm/√Hz x NSF(f)	< 1 nm/√Hz x NSF(f)*
Rotational coupling factor	< 80 µm/rad (in pitch and yaw)	Yaw: <20 µm/rad (< 42 µm/rad*) Pitch: <30 µm/rad (<23 µm/rad*
Pointing stability	< 15 µrad over one orbit	Yaw: <2.41 µrad** Pitch: < 1.31 µrad**

*from analysis **measurement supported by analysis, without OBA isostatic mounts

In addition to the requirements listed below the heterodyne efficiency of the optical bench is a direct measure to check the quality of the optical and electrical system. The heterodyne efficiency γ_{het} is defined as:

$$\gamma_{het} = \left(\frac{P_{max}-P_{min}}{2*(P_{max}+P_{min})} * (P_1 + P_2)/\sqrt{P_1 P_2}\right)^2 \qquad (3)$$

With P_{max}, P_{min} being the maximum respectively minimum power detected in the coherent superposition of the two laser sources with individual powers P_1, P_2. The theoretical maximum of the heterodyne efficiency of the superposition of an 8 mm tophat beam (the received beam) and a 4.3 mm Gaussian beam (the local oscillator) on the used quadrant photodiode with the same power (P_1=P_2) is $\gamma_{het,id}$=0.54. A homodyne measurement with one single frequency laser signal split and applied to the entrance aperture as a 50 mm diameter Gaussian beam and to the FIA has been performed and a $\gamma_{het,meas}$=0.56 has been achieved in average over the 4 segments. That the measured value is actually slightly higher than the theoretically expected value is attributed to the non-perfect representation of a tophat beam by the 50 mm Gaussian beam and minor deviations from the perfect Gaussian beam out of the FIA. Nonetheless the result shows that the optical bench system is basically achieving the maximum signal efficiency.

VI. SUMMARY

The design of the optical bench for the laser ranging interferometer on GRACE FO and test results of the key and driving optical requirements achieved with the already nearly flight like engineering model have been presented. Apart from the slightly too small beam diameter, which will be adapted in the PFM design, all requirements have been met. The engineering model is currently used in further tests on subsystem level and in combination with the LRP provided by JPL/NASA for risk mitigation for the Protoflight Model(PFM) in development. The formal qualification will happen with the PFM begin of 2015.

As part of the development a new highly stable fibre collimator (here called fibre injector) has been developed that has the potential to be adapted to a variety of other systems with the demand for a highly thermally stable diffraction limited output beam with excellent wavefront planarity. Furthermore a low noise quadrant photoreceiver and low stress optical mounting technology has been developed and is available for future projects.

The LRI on GRACE FO is expected to successfully demonstrate a significantly reduced ranging noise compared to the microwave instrument and to enable even higher accuracy measurements of Earth's gravity field in future missions such as GRACE 2 or NGGM.

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REFERENCES

[1] http://www.gfz-potsdam.de/grace
[2] Sasgen, I., van den Broeke, M., Bamber, J. L., Rignot, E., Sørensen, L. S., Wouters, B., Martinec, Z., Velicogna, I., and Simonsen, S. B.,. “Timing and origin of recent regional ice-mass loss in Greenland”. Earth and Planetary Science Letters, 2012, DOI: 10.1016/j.epsl.2012.03.033
[3] Tiwari, V. M., Wahr, J., and Swenson, “Dwindling groundwater resources in northern India, from satellite gravity observations”, Geophys. Research Lett. 36, L18401 (2009).
[4] Famiglietti, J. S., Lo, M., Ho, S. L., Bethune, J., Anderson, K. J., Syed, T. H., Swenson, S. C., de Linage, C. R., and Rodell, M., 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophysical Research Letters, 38:3403–+, doi:10.1029/2010GL046442
[5] J. T. Reager, B. F. Thomas, and J. S. Famiglietti, “River basin flood potential inferred using GRACE gravity observations at several months lead time”, Nature Geoscience. doi:10.1038/ngeo2203, 2014
[6] Gerhard Heinzel, Benjamin Sheard, Nils Brause, Karsten Danzmann, Marina Dehne, Oliver Gerberding, Christoph Mahrdt, Vitali Mueller, Daniel Schuetze, Gunnar Stede, William Klipstein, William Folkner, Robert Spero, Kolja Nicklaus, Peter Gath and Daniel Shaddock, “Laser Ranging Interferometer for GRACE follow-on”,ICSO 2012
[7] 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 2012, DOI: 10.1007/s00190-012-0566-3
[8] S. Boehme ; E. Beckert ; R. Eberhardt ; A. TuennermannProc. SPIE 7202, Laser-based Micro- and Nanopackaging and Assembly III, 720205 (February 24, 2009); doi:10.1117/12.808161