

Test environments for the GRACE follow-on laser ranging interferometer

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Abstract. In the year 2017 a follow-on mission to the very successful joint German/US mission GRACE (Gravity Recovery And Climate Experiment) will be launched. As of this day the two GRACE satellites have successfully been mapping the spatial and temporal variations of the gravitational field of the Earth by satellite-to-satellite tracking for over a decade. The main science instrument on GRACE and its successor mission GRACE Follow-On which is used to measure the inter-satellite distance changes is a microwave link sensor. However, an additional instrument, the laser ranging interferometer (LRI), will be implemented into the architecture of the GRACE Follow-On satellites as a technology demonstrator. In this paper we will give a brief overview of a fiber-based test environment which is currently used during the assembly, integration and test of the LRI flight hardware.

1. Introduction

The Gravity Recovery And Climate Experiment (GRACE) has been a highly successful satellite mission. Launched in 2002, it has been mapping the gravitational field of the Earth for over a decade and has provided the science community with unprecedented insights into the spatial and temporal variations of the mass distribution of the Earth. The main contributor to these variations is water - as well in liquid as in solid form. Amongst the multitude of published results that could be obtained from GRACE data are publications on the Greenland ice sheet mass loss (e.g. [1], [2]), the global sea level rise which can be associated with the melting of ice caps and glaciers (e.g. [3]) or the depletion of groundwater in regions that notoriously suffer from a shortage of water like the California central valley ([4], [5]) or northern India ([6]). On GRACE a microwave ranging instrument has been used to determine a change in the inter-satellite distance. From this, together with global positioning system (GPS) and accelerometer data, one can derive the gravitational field below the two spacecraft (SC). A complete update of the Earth's gravity field is released about once per month. However, the tandem SC are way past their design mission time of five years and are suffering from battery fatigue. Hence, updates of the gravitational field were increasingly released on an irregular basis.

Anticipating the imminent end of the original GRACE mission the same US/German team has decided to launch a follow-on mission as soon as possible to keep the data gap to a minimum. In August 2017 the GRACE Follow-On mission is planned to be launched. The tight schedule



that is caused by this early launch date could only be fulfilled by flying an almost exact copy of the original GRACE SC. While a microwave instrument will remain the main science instrument that is used to determine the inter-satellite distance, a laser ranging interferometer (LRI) will be integrated into the SC as a technology demonstrator. The accuracy of the LRI is anticipated to be $80 \text{ nm}/\sqrt{\text{Hz}}$, which is more than one order of magnitude better than the accuracy of the microwave instrument [7].

Being able to test and calibrate this complex device on ground is crucial during its assembly, integration and test activities. While also subsystems require special test environments, the most sophisticated tests of the LRI can be performed when the two SC are enabled to exchange laser beams. This is referred to as *constellation level* tests. These tests require a test environment which experimentally simulates the complete laser link between the SC independently of their physical orientation in the laboratory. That is why a fiber-based set-up was designed that fulfils exactly these requirements. In the manner of space flight jargon it is referred to as fiber-based *optical ground support equipment* - or short Fiber OGSE. In the following section an overview of the functionality of the Fiber OGSE and a brief introduction into its architecture is given.

2. Description of the Fiber OGSE set-up

The task of the Fiber OGSE is to experimentally simulate the laser link between the two GRACE Follow-On SC. This includes beam properties (see e.g. [7]) as well as static and dynamic SC misalignments. Due to the SC separation of approximately 230 km the beam that is received by one satellite (RX beam) has a nearly spherical wavefront. Since only a small fraction of it eventually reaches the optical bench, the RX beam is well approximated by a top-hat beam. The maximum RX beam power is of the order of a few hundred picowatts and drops as a function of the misalignment between the transmitted beam (TX beam) and the line of sight (LOS):

$$P_{\text{RX}} = 2 \frac{P_0}{\omega_{\text{RX}}} r_{\text{ap}}^2 e^{-2((\alpha - \alpha_{\text{SC}})^2 + (\beta - \beta_{\text{SC}})^2) \ell^2 / \omega_{\text{RX}}^2}. \quad (1)$$

Here $P_0 \approx 20 \text{ mW}$ is the TX beam power, $\omega_{\text{RX}} \approx 35 \text{ m}$ is the beam radius at the receiving SC, $r_{\text{ap}} = 4 \text{ mm}$ is the radius of the receiving aperture on the OBs and $\ell \approx 230 \text{ km}$ is the separation of the satellites [8]. α_{SC} and β_{SC} describe the mispointing i.e., the angle between the TX beam and the LOS. The actual ranging signal is a frequency modulation of the laser beam, with power P_{RX} , due to Doppler shifts and is of the order of $\pm 4 \text{ MHz}$ [7].

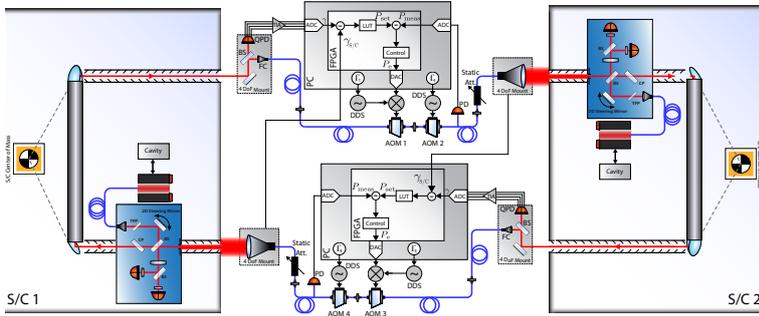


Figure 1. Schematic of the Fiber OGSE as it is mounted between the two (simplified) GRACE Follow-On SC [9].

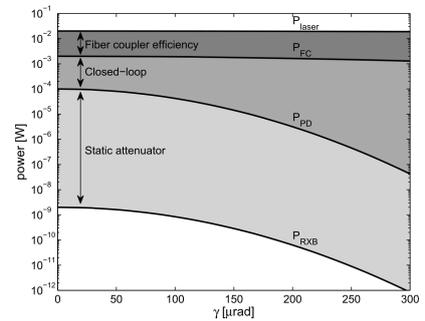


Figure 2. The different attenuation stages of the DPA [9].

Figure 1 shows a schematic of the Fiber OGSE as it will be used between two SC. On the left and right hand side of the figure simplified sketches of the SC with the main parts of the LRI are shown. The upper and lower units of the Fiber OGSE are identical and represent the

dual link between the SC. In the upper link the transmitted beam (TX beam) leaves the SC on the top left and is immediately coupled into a fiber. This part of the Fiber OGSE is referred to as the *transmitted beam assembly*. At the top right the light exits the Fiber OGSE through a fiber collimator which generates a laser beam with approximately 2 cm waist radius. The collimator with its tip/tilt and translation mount is called *received beam assembly*. In between these two units is the *dynamic power attenuation unit* (DPA). This contains two acousto-optical modulators (AOMs) and an FPGA-based control loop which controls the AOMs in such a way that the RX power matches the far-field power that the SC on the right side of the picture would detect if both satellites were separated by approx. 230 km (see eq. 1 and [9]). Hereby the AOMs serve as actuators and the power of the radio-frequency (RF) signal that controls them is the controlled variable.

2.1. The Received Beam Assembly

The RX beam assembly consists of a fiber collimator with a lens of focal length $f = 200$ mm in a four degree of freedom mount. The beam that is generated by this collimator has a waist radius of 18 mm ($1/e^2$). The corresponding wavefront curvature was measured with a Hartmann-Shack-sensor and deviates by less than $\lambda/15$, where $\lambda = 1064$ nm from a flat wavefront within the receiving aperture. The power drop in this area is about 10 %. The motorized rotation mount allows for a tilt in yaw and pitch of the collimator of ± 26 mrad. This is more than sufficient to simulate static misalignments of the SC as well as SC attitude jitter. To properly align the unit with respect to the SC a two degree of freedom linear stage is also used. A readout mechanism that is based on calibrated potentiometers which are attached to the motors of the rotation mount is used to monitor the angular motion of the unit [9]. When SC jitter is simulated, this information is forwarded to the DPA which takes it into account for the calculation of the AOM gains (see eq. 1).

2.2. The Transmitted Beam Assembly

The TX beam assembly serves two purposes: launch the TX beam into the fiber setup and measure the TX beam angle. The latter is being done with a DC measurement of the TX beam centroid on a 10 mm diameter quadrant photodiode (QPD). The QPD currents are transformed to voltages by a transimpedance amplifier (TIA). These are then fed to analog-to-digital converters (ADC) and then to the FPGA (see fig. 1). Here the voltages of the individual QPD segments are combined to yield the position of the TX beam centroid on the QPD. By applying calibration factors that denote the lever arm of the TX beam the horizontal and vertical angles of the TX beam are obtained. The TX beam assembly is also mounted to a four degree of freedom rotation/translation stage for alignment of the unit and to simulate SC misalignments.

2.3. Dynamic Power Attenuator

The core of the Fiber OGSE is the DPA. A closed-loop control with approximately 50 kHz bandwidth that is implemented in an FPGA is used to generate the correct power level at the receiving SC [9]. For this the FPGA evaluates the TX beam angle and its predefined set-point to eventually apply an amplitude modulated RF signal to one of the AOMs. When Doppler shifts are applied the other AOM is operated in a feed-forward control to keep it at constant gain (with respect to the optical power) and can therefore be neglected for the control-loop. The dynamic attenuation of the laser power is a multi-step process (see fig. 2). The first angle-dependent gain is introduced by the fiber collimator of the TX beam assembly. In order to keep this nonlinear gain to a minimum, a collimator was chosen whose coupling efficiency is rather insensitive to a tilt of the laser beam. The control-loop in the DPA then dynamically attenuates the laser power to the microwatt level and a static attenuator further reduces the signal power to the picowatt

range. With this scheme the control-loop can be operated above the electronic noise floor with signal-to-noise ratios of $10 - 10.000$ in an angular range of $0 \leq \gamma \leq 225 \mu\text{rad}$ [9]. This implies that SC jitter, which is a varying misalignment of the SC, could be simulated with an amplitude of up to $225 \mu\text{rad}$ by shifting the set-point of the DPA control-loop. The static part of the SC misalignment (which is in a range of a few mrad [14]) is introduced by deliberately misaligning the RX and TX beam assemblies by using their motorized rotation mounts. However, larger amplitudes of the SC jitter could also be introduced by synchronously varying the tilt of the RX and the TX assemblies with respect to the SC. Because the repeatability of the used rotation stages would not suffice for this, only the home-made read-out mechanism of the rotation mounts renders this possible.

3. Conclusion

In this paper we gave an overview of the design of the Fiber OGSE which is a test environment that is currently being used during AIT of the GRACE Follow-On LRI. It realistically simulates the laser link between the two SC and allows for the introduction of static and dynamic SC tilts. Due to its flexibility, the setup can also be used to study future mission concepts. The performance of the Fiber OGSE was already proven and the results published [9]. This reference may also be considered by the reader for a more detailed description of the Fiber OGSE. Recently, tests of the LRI initial link acquisition procedure were performed using the Fiber OGSE with mock-up OBs. While this was done before in a similar way ([14],[15]), up to now these tests have been the most realistic of their kind. Especially the accurate imitation of the far-field power as well as the generation of a flat wavefront with homogeneous intensity profile of the RX beam is unprecedented. The results of these tests will be published soon in another paper.

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