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Laser interferometer for spaceborne mapping of the Earth's gravity field

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Abstract. The Gravity Recovery and Climate Experiment (GRACE) is one of the present missions to map the Earth's gravity field. The aim of a GRACE follow-on mission is to map the gravitational field of the Earth with higher resolution over at least 6 years. This should lead to a deeper insight into geophysical processes of the Earth's system. One suggested detector for this purpose consists of two identical spacecraft carrying drag-free test masses in a low Earth orbit at an altitude of the order of 300 km, following each other with a distance on the order of 50 to 100 km. Changes in the Earth's gravity field will induce distance fluctuations between two test masses on separate spacecraft. These variations in the frequency range 1 to 100 mHz are to be monitored by a laser interferometer with nanometer precision. We present preliminary results of a heterodyne interferometer configuration using polarising optics, demonstrating the required phase sensitivity.

1. Introduction

Various geophysical processes generate gravity anomalies with extensive spatial variations over the surface of the Earth. The resulting gravity field is known as the long-term average (or mean) gravity field. Measurement of these gravity anomalies provides, for example, a better understanding of the structure of the solid Earth. Shorter-term mass fluctuations like the variation in water content of the Earth's crust are known as the time-variable gravity field. It helps, among other things, to study the global sea level changes or the polar ice sheet balance. These changes have a significant impact on relevant climatic issues.

The Gravity Recovery and Climate Experiment (GRACE) was successfully launched in 2002 to monitor these changes [1]. GRACE consists of two identical satellites, one 220 km ahead of the other in the same orbit at an altitude of approximately 500 km. Temporal and spatial changes in the Earth's gravity field cause small variations in the inter-spacecraft separation, which is measured in order to determine the Earth's gravity field. The relative distance and velocity changes are measured with a microwave interferometer in the K-Band with an accuracy of 1 μm . The information gained about the global gravity field from GRACE raised an interest in developing a follow-on mission with better performance to improve our knowledge of e.g. the cryosphere and hydrological or atmospheric phenomena affecting the Earth's system. To achieve this, the metrology system for the distance measurement between the satellites needs to be improved, for example, by using laser satellite-to-satellite interferometry (SSI) [2–5] and it is beneficial to reduce the inter-satellite distance to improve spatial resolution [6]. Furthermore,

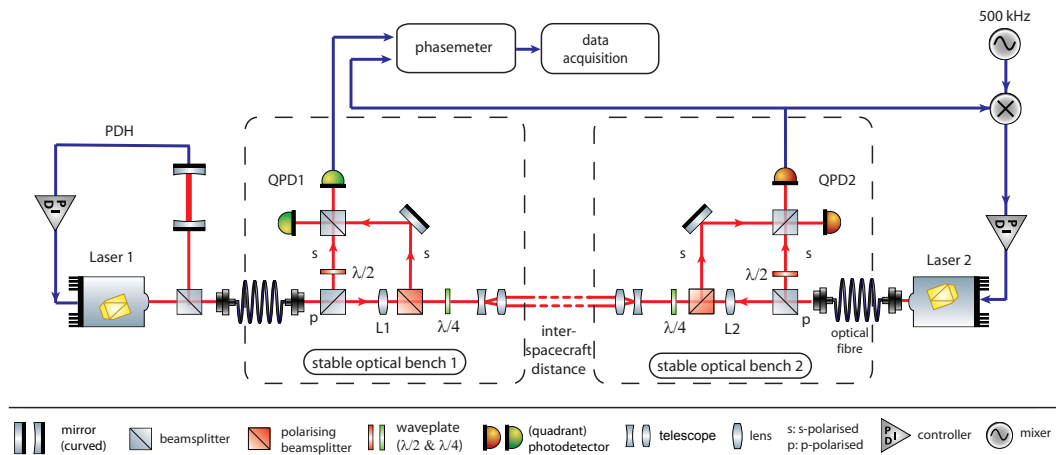


Figure 1: Baseline design for the SSI: a symmetric system of two heterodyne Mach-Zehnder interferometers with lasers and detectors on both spacecraft.

it is also desirable to choose a lower altitude since the gravity field diminishes with increasing height. The disadvantage of a lower orbit is the significant atmospheric drag which must then be compensated. Therefore, a suitable drag-free control system needs to be developed. In order to provide a constant thermal environment and to avoid sunlight radiation coupling onto the optical axis between the two satellites, a sun synchronous near-circular orbit would be suitable.

One possible GRACE follow-on mission can benefit from the current developments for the joint ESA-NASA space-based gravitational-wave detector “Laser Interferometer Space Antenna” (LISA) [7] and its precursor mission LISA Pathfinder (LPF) [8, 9], such as a precise drag-free technology and the interferometric readout. Interferometric length measurements in the frequency band of interest from 1 to 100 mHz, that meet the required phase sensitivity, have been demonstrated with the LPF configuration [10]. Our goal is to show that the following proposed measurement system containing polarising optics can be implemented with the proposed pathlength sensitivity of a possible GRACE follow-on mission.

2. Measurement system

The relative velocity between the spacecraft induces a Doppler shift in the interferometer beatnote. This effect together with the large variations in the inter-spacecraft separation make heterodyne interferometry ideally suitable as the pathlength readout scheme. A symmetric active system with lasers and detectors on both spacecraft would be appropriate, since this enables to maintain the heterodyne frequency away from DC. We assume from an early strawman design that the required interferometer sensitivity is $2.5 \text{ nm}/\sqrt{\text{Hz}}$ between 10 mHz to 100 mHz, increasing with $1/f$ between 10 and 1 mHz. The round-trip Doppler shift introduces variations in the interferometer beatnote up to a few 100 kHz. A suitable heterodyne frequency is, therefore, between several hundred kHz and a few MHz, with the lower limit given by the maximal Doppler shift and the required control bandwidth of the offset phase lock. The upper limit is given by technical considerations concerning the photodiodes and the phasemeter. The preliminary baseline is a heterodyne frequency on the order of 500 kHz.

2.1. Polarising optics in heterodyne interferometer

For the heterodyne interferometer, we have selected a polarising layout as preliminary baseline (Fig. 1). We decided to separate the incoming and the outgoing beam on each optical bench with

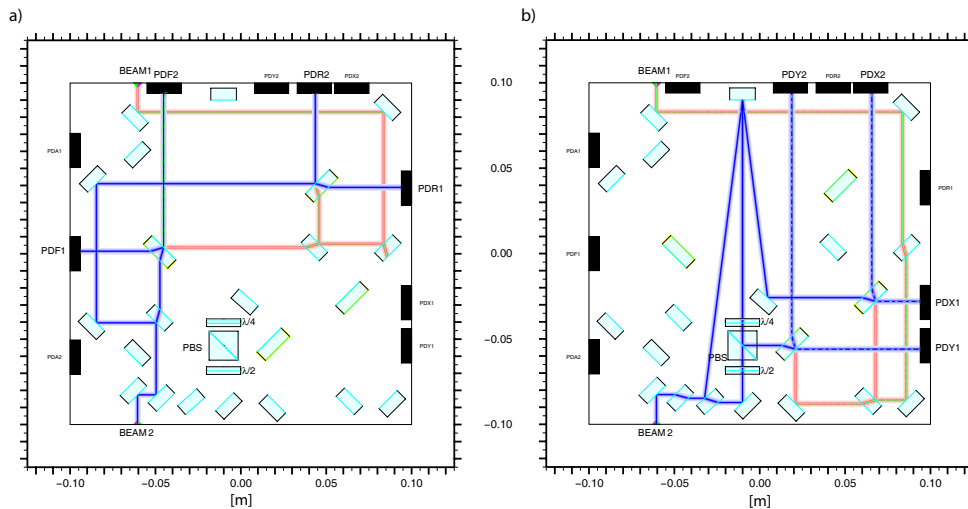


Figure 2: OptoCad models of the laser interferometer for a comparison between polarising and non-polarising optics: a) reference and frequency noise interferometer (unequal armlenghts) b) non-polarising and polarising interferometer.

polarising optics for the following reasons: A non-polarising setup simplifies the optical path but results in a significant loss of incoming light. This light must be removed with a Faraday isolator in order to avoid laser instabilities. By contrast, with a polarising layout one has the freedom to select the optimal local oscillator level and to utilise all the light power. On the other hand, thermal sensitivity of polarising components being used in transmission, are able to modify the optical pathlength, the extinction ratio and the polarising plane. For these reasons, the influence of polarising optics on the interferometer sensitivity is currently under investigation.

In the proposed layout shown in Fig. 1 the outgoing p-polarised beam is transmitted through the polarising beamsplitter (PBS). Therefore, the incoming light must be s-polarised to be reflected by the PBS. This could be realised by adding two quarter wave plates to the optical path. The two beams in each Mach-Zehnder interferometer are finally recombined at a beamsplitter. Apart from the interferometers, two telescopes are included for both transmitting and receiving the laser beams between the two spacecraft. The lens (L1 or L2 as illustrated in Fig. 1) in the outgoing beam path can be used to adjust the divergence of the outgoing beam because it does not affect the beam of the receive path.

Alignment control signals can be obtained by the technique of differential wavefront sensing (DWS) [11]. For this purpose, we intend to use four-quadrant photodiodes (QPD) since longitudinal information can be ascertained over the sum of the quadrants. The obtained DWS signals contain the information about the angle between the two interfering wavefronts.

Before implementing the setup illustrated in Fig. 1, an optical bench containing four heterodyne Mach-Zehnder interferometers has been designed for a trade-off study between polarising and non-polarising optics in interferometry. The four interferometers with equal number of transmissions and reflections presented in Fig. 2 can be described as follows:

- (i) *Reference interferometer*: gives a reference phase containing all environmental noise contributions such as mechanical and thermal fluctuations, which occur outside the stable optical bench and are common to all four interferometers (Fig. 2 a).
- (ii) *Frequency noise interferometer* with intentionally unequal arm lengths: senses laser frequency noise. Its output signal can be used for active frequency stabilisation of the laser (Fig. 2 a).

- (iii) *Non-polarising interferometer*: to be used for a relative length measurement on the bench (Fig. 2 b).
- (iv) *Polarising interferometer*: to be applied for the same purpose as (iii). The beam path of these two interferometers (Fig. 2b) has been designed to cover a similar area on the bench, in order to reduce effects of thermal gradients on the length measurement.

2.2. Frequency-stabilised laser system

We expect a strong coupling of laser frequency noise $\tilde{\delta\nu}$ into the interferometric readout of the phase due to the large inter-spacecraft separation L of about 50 km. To keep the optical pathlength noise $\tilde{\delta s}$ under the allocated budget of $1 \text{ nm}/\sqrt{\text{Hz}}$, the laser has to have a laser frequency stability of

$$\tilde{\delta\nu} \approx 3 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \cdot \left[\frac{\tilde{\delta s}}{1 \text{ nm}/\sqrt{\text{Hz}}} \right] \cdot \left[\frac{2L}{100 \text{ km}} \right]^{-1}, \quad (1)$$

which follows from $\frac{\tilde{\delta\nu}}{\nu} = \frac{\tilde{\delta s}}{\Delta L}$. Laser frequency stabilities near this level have already been demonstrated using Fabry-Perot cavities [12] or transition in molecular iodine [13]. Because of the frequency noise coupling via the large pathlength difference, both laser frequencies must be stabilised. In our proposed configuration the first laser will be locked to a reference cavity using the Pound-Drever-Hall (PDH) scheme [14] while the second laser will be phase-locked to the incoming light from the remote spacecraft with an offset on the order of the desired nominal heterodyne frequency [15]. A number of experiments have already demonstrated the two techniques described here with the performance required for the LISA mission, which is also sufficient for the SSI.

2.3. Phase readout scheme

The proposed readout scheme measures the relative pathlength changes δL between the satellites using heterodyne interferometry. These variations translate into phase fluctuations $\tilde{\delta\phi}$ of a sinusoidal beatnote at the heterodyne frequency. Pathlength changes of one wavelength measured by photodetectors correspond to a phase variation of one cycle or 2π rad. The purpose of the phase measurement system (PMS) is to faithfully extract the phase of the photocurrent generated in the photodetectors without limiting the sensitivity of the length measurement by adding significant extra noise. In LISA Pathfinder a Discrete Fourier Transform (DFT) method has been chosen as baseline [16], which is ideal if the signals have nearly constant frequency.

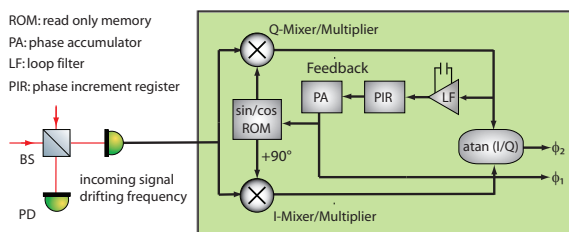


Figure 3: Phase measurement method: digital PLL as it is currently planned to be implemented on LISA.

In contrast to this, the measurement scheme for the interferometric phase readout chosen for LISA is a digital *phase locked loop* (PLL) that tracks the signal frequency and phase [17]. Figure 3 shows a schematic of such a phase readout system. Here, the photodiode signal is sampled by an analog-to-digital converter, and then multiplied with a sine and cosine signal of correct frequency. The output of the multiplication is used to track the signal's frequency and to compute the phase change. Since it is ideal for a variable heterodyne frequency, the digital PLL method has been chosen as preliminary baseline for a possible GRACE follow-on mission. Additionally, we benefit a lot from the ongoing LISA study. The algorithm will have to be implemented in hardware to make the phase readout fast and reliable. Hardware development based on Field Programmable Gate Arrays (FPGA) as

main technology platform seems to be suitable. The requirements for the SSI phase measurement system are considerably relaxed compared to the LISA requirements [7]. The noise budget for the phase measurement is only $1 \text{ mrad}/\sqrt{\text{Hz}}$ compared to $6 \mu\text{rad}/\sqrt{\text{Hz}}$ for LISA.

3. Performance of the laboratory breadboard

For breadboarding, we used standard laboratory laser-diode-pumped, monolithic Nd:YAG lasers (*Innolight Mephisto lasers*, 500 mW @ 1064 nm) [18]. These lasers generate single frequency, linear-polarised light with low intrinsic noise. In order to compare the behaviour of polarising and non-polarising optics in interferometry, we have set up three interferometers on an aluminium baseplate. The resulting optical scheme is shown in Fig. 4. All interferometers are divided into the two following functional parts:

- *The modulation bench* provides the beam preparation. The laser beam is split into two parts by a beamsplitter. The two beams are then modulated each by acousto-optical modulators (AOMs) driven at approximately 80 MHz with a frequency difference f_{het} of 1.6 kHz. The frequency shifted beams are coupled into optical fibres and injected into the optical bench.
- *The optical bench* contains the three interferometers. The polarising and non-polarising interferometers, with equal armlengths on the optical bench, perform the length measurements. In order to assess their performance, the obtained phases are to be compared to the phase reference obtained from the remaining non-polarising interferometer.

The experimental breadboarding has been performed with a digital phasemeter implemented on a PC as in LTP [16]. The heterodyne signals measured at the photodiodes are digitized and acquired by a computer. In order to extract the phase information, a DFT-Algorithm is applied as software post-processing of the data. This LTP based readout has been demonstrated to have sufficient sensitivity to measure. Therefore, it is used to assess and compare the opto-mechanical performance of our breadboard. In order to reduce coupling of acoustic and thermal effects into the phase readout, the measurement was conducted in a vacuum environment.

The noise measurements obtained using this system are presented in Fig. 5. The graph shows the measured interferometric phase noise as a linear spectral density in comparison to the total pathlength noise budget of SSI and LISA. We reach a phase readout sensitivity of $1 \times 10^{-2} \text{ rad}/\sqrt{\text{Hz}}$ that corresponds to $1.7 \times 10^{-9} \text{ m}/\sqrt{\text{Hz}}$ longitudinal fluctuations. One can see that the required longitudinal sensitivity for the SSI interferometer has been demonstrated with this simple setup. Thus, a polarising interferometer can reach the required length stability. The

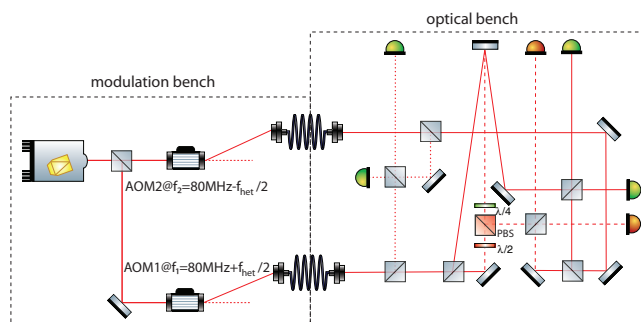


Figure 4: Schematic of the current setup. Left: the modulation bench. Right: the optical bench containing the reference (dotted), non-polarising (dashed) and polarising (solid) interferometer.

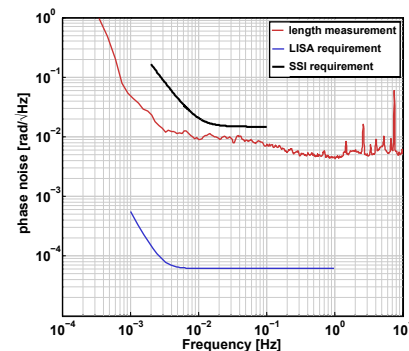


Figure 5: First pathlength noise measurements in a vacuum environment in comparison to the total pathlength noise budget of SSI and LISA.

sensitivity can be significantly increased by improving the mechanical and thermal stability of the optical bench, for example, by hydroxide-catalysis bonding the optical components onto an ultra-stable baseplate made of Zerodur[®] or Clearceram[®], among other materials [19]. Clearceram[®], as well as Zerodur[®], is a material with low coefficient of thermal expansion of about 10^{-7} . Thus, it could be possible to further improve the length stability for the SSI and to even reach the longitudinal sensitivity requirements for LISA.

4. Conclusions and Outlook

First results of our investigations on a laser interferometer for spaceborne mapping of the Earth's gravity field are presented. Laboratory activities have demonstrated the feasibility of heterodyne interferometry containing polarising optics as metrology system for a possible GRACE follow-on mission. First performance measurements on the laboratory prototype, set up on a metal breadboard, show that we are able to reach the required longitudinal sensitivity of $2.5 \text{ nm}/\sqrt{\text{Hz}}$ for SSI. To obtain a significant improvement of the thermal and mechanical stability of the interferometer, we will bond the designed optical bench presented in Fig. 2 onto an ultra-stable glass-ceramic baseplate made of Clearceram[®]-HS. This leads to a more reliable and stable optical setup, suitable for a space application.

We are also planning to operate this bonded optical bench with a heterodyne frequency of 500 kHz. We have developed a modified version of our current phasemeter, which is able to operate at this frequency. However, it will be necessary to adapt the hardware phasemeter to their frequency, in order to track the Doppler shift of the beatnote in the measurement.

This effort will be expanded as part of the newly founded Center for Quantum Engineering and Space-Time Research (QUEST).

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