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Optical testbed for the LISA phasemeter

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Abstract. The planned spaceborne gravitational wave detector LISA will allow the detection of gravitational waves at frequencies between 0.1 mHz and 1 Hz. A breadboard model for the metrology system aka the phasemeter was developed in the scope of an ESA technology development project by a collaboration between the Albert Einstein Institute, the Technical University of Denmark and the Danish industry partner Axcon Aps. It in particular provides the electronic readout of the main interferometer phases besides auxiliary functions. These include clock noise transfer, ADC pilot tone correction, inter-satellite ranging and data transfer. Besides in LISA, the phasemeter can also be applied in future satellite geodesy missions. Here we show the planning and advances in the implementation of an optical testbed for the full metrology chain. It is based on an ultra-stable hexagonal optical bench. This bench allows the generation of three unequal heterodyne beatnotes with a zero phase combination, thus providing the possibility to probe the phase readout for non-linearities in an optical three signal test. Additionally, the utilization of three independent phasemeters will allow the testing of the auxiliary functions. Once working, components can individually be replaced with flight-qualified hardware in this setup.

1. Introduction

In order to detect gravitational waves in the low frequency regime (mHz-Hz), the planned space mission LISA (laser interferometer space antenna) [1, 2] will utilize inter-satellite heterodyne interferometry to detect distance changes between free-floating test masses [3]. The corresponding metrology system needs to provide an interferometer phase readout precision in the order of $\mathrm{\mu rad}/\sqrt{\mathrm{Hz}}$. Hardware to solve this task, a LISA phasemeter, was developed within the scope of an ESA technology development project by a collaboration between the Albert Einstein Institute, the Technical University of Denmark and the Danish industry partner Axcon Aps. It includes the actual heterodyne readout itself together with auxiliary functions to ensure its required high precision and provide additional information for post processing. Their necessity and requirements are dictated by the LISA design and its sensitivity. This will be explained in the following section. In addition to LISA, the phasemeter could also be used in other applications, like geodesy missions [4], or MHz heterodyne interferometry in general.

2. Requirements for the phasemeter

The distance between the LISA satellites will be of the order of several million km. This distance is too long to receive sufficient power from a dispersing laser beam which is directly

reflected from one of the remote spacecraft. To solve this problem, a local high-power copy of the beam is created. For this purpose, the received laser beam is mixed with a local laser on each spacecraft. The resulting beatnote is used as a sensor signal to phaselock the local laser to the received beam, thus creating the local high-power copy. The latter is then transmitted back to the opposite satellite. As the LISA constellation will fly on orbits with line-of-sight velocities between satellites in the order of several m/s, Doppler shifts in the order of MHz with both signs shift the beatnote up and down. To avoid zero crossing, a frequency offset must be applied in the lock. These circumstances lead to the requirements for the phasemeter to operate with the earlier stated precision within the MHz regime for the phase readout and to be able to control the local laser. The phasemeter presented in this paper handles the phase readout with a DPLL (digital phase locked loop) [5, 6], which tracks the MHz signal by mixing it with a digital copy. This also allows the implementation of the local laser control in the digital domain.

However, the digital systems and in particular the digital copies of the beatnotes on the satellites, are driven by USOs (ultra stable oscillators), also referred to as clocks in the following. They individually come with a timing jitter and the subsequent differential timing noise between different satellites distorts the phase measurement. This issue is addressed by measuring this differential noise by transferring and comparing the single clock noises, so the differential noise is known and can be removed in post processing [7, 8]. The actual implementation of this concept here is to use a GHz USO, which can directly be imprinted on the main carrier as a sideband and mixed down with its counterpart on a remote satellite [9]. The phasemeter therefore needs be able to downsample the GHz signal into the MHz domain to use it as a digital clock as well as tracking the sideband-sideband beatnote. The former is achieved with dedicated digital hardware called the clock module, while for the latter a DPLL is used. It should be mentioned here, that recent publications also show an alternative option for the clock noise removal [10].

A similar distortion occurs through the non-perfect analog-to-digital conversion. Jitter in its sampling times adds phase noise. However, it can be mitigated by adding a well-known pilot tone to the actual signal as a reference to track the distortion. The pilot tone is derived from the USO and therefore its distribution is incorporated on the clock module.

Finally, the most severe limitation of the LISA sensitivity is introduced by the huge differences in the interferometer arm lengths which lead to amplification of laser frequency noise about several orders of magnitude. To address this issue, the post-processing technique TDI (time delay interferometry) has been developed [8, 11, 12]. It makes use of the fact, that each triangular interferometer formed by the LISA constellation is broken down into measurements between single arms. These single arm measurements can then be artificially delayed during data analysis to compensate for the unequal arm length and to synthesis an equal arm length interferometer. However this requires the knowledge of the absolute arm length and the relative satellite distances, respectively, with sub-meter accuracy. Only then can the correct delays be applied in the TDI algorithm. The phasemeter implements a solution for this inter-satellite ranging [13, 14] by comparing locally generated PRN (pseudo random noise) codes with received ones from the remote spacecraft. The transmission is again achieved by sideband modulation of the main carrier. In a similar manner, data bits can be imprinted on the main carrier for data communication between the spacecraft. A desciption of the actual hardware and details of the implementations can be looked up in [15, 16].

3. Electrical testing
Naturally, all previously mentioned functions of the phasemeter have to be tested. In particular, a sufficient phase readout performance had to be shown for the successful completion of the ESA project, within which frame the phasemeter was developed. This was done by a null measurement with LISA-like signals, which were generated with a dedicated digital signal simulator (DSS). Performing a null measurement means splitting a given signal and feeding it to

separate phasemeter channels. The difference in the measured phases then yields the estimate of the readout performance and can be utilized to search for noise sources in the readout channels. Null measurements carried out utilizing the pilot tone correction described in the last section showed sufficient performance below the requirement of $8.5\,\mu\mathrm{rad}/\sqrt{\mathrm{Hz}}$ for frequencies up to 25 MHz [16].

4. Advanced optical testbed - a hexagonal interferometer

Despite the proof of performance with the described electrical null measurement, a more advanced testbed is currently under construction at the Albert Einstein Institute. The leading thought for it is to be able to perform a three signal measurement utilizing optical signals [5]. In contrast to a null measurement, the three signal measurement provides the possibility to search for non-linearities common in the phasemeter channels. This is achieved by generating three signals that, while being different from each other, cancel out when adding their phases. Performing this scheme with optical signals puts it closer to a realistic environment. Besides the test of the phase readout itself, the testbed also provides the capability to test the whole LISA metrology chain including the auxiliary functions.

In detail, the testbed consists of a laser preparation, a hexagonal ultra-stable optical bench as well as the unit under test, the phasemeter itself. At the heart of the testbed is the hexagonal optical bench, a sketch of which can be seen in Fig. 1. It consists of a Zerodur® baseplate and six beamsplitters and beamcombiners, respectively. They were positioned in a way that allows the pairwise mixing of three beams under ultra-stable conditions, effectively implementing an optical three signal test. The beatnotes generated are read out by external photodetectors and fed via cables to the phasemeter. To mitigate angular jitter from the fiber injectors, special quasi-monolithic FIOSs (fiber injector optical assemblies) are under construction and about to be bonded to the bench. Furthermore, the bench will be deployed in a vacuum tank with thermal shielding to avoid distortions due to air fluctuations and to reduce temperature changes.
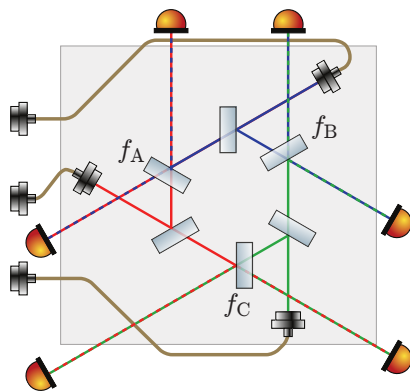

Figure 1. Sketch of the hexagonal ultra-stable optical bench. Three beams injected via fiber injectors are mixed pairwise to implement an optical three signal test.
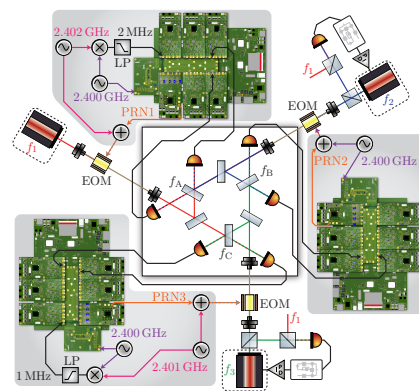

Figure 2. Sketch of the planned final setup, showing three phasemeters and three EOMs with exemplary frequencies for tests of the auxillary functions.

To make sure that the beatnotes generated on the ultra-stable optical bench stay within the bandwidth of the phasemeter, the associated lasers have to be controlled. The final goal is to do this with the same LISA phasemeter used for the actual read out. As an intermediate step, a laser preparation bench has been built, on which once more beatnotes between the lasers are generated and used for locking. This provides the possibility to control and lock the lasers

independent from the readout. The loop gain of the laser locks can intentionally be changed to vary the laser frequency noise to show phasemeter performance under different conditions.

To be able to also test the auxiliary function of the phasemeter, it is planned to use three individual phasemeters together with a dedicated GHz source and an EOM each. The EOMs are interconnected at the fibers between preparation and ultra-stable bench. In this constellation, every single phasemeter will read out one beatnote. Additionally, the GHz clocktone used for one single phasemeter will be imprinted together with ranging and data communication via the EOMs to one of the laser carriers. To assure a non-DC beanote signal between sidebands, slightly offset GHz frequencies will be used. The whole setup can be seen in Fig. 2. In this final version, the three mentioned individual assemblies can be interpreted as LISA satellites. In contrast to other testbeds set up to test primarily the TDI algorithm [17–19], the LIME (LISA metrology experiment) presented here is designed to test and analyze the whole LISA metrology chain from the precise phase readout up to the auxiliary functions in great detail.

5. Conclusions & Outlook

The LISA phasemeter implements phase readout and auxiliary function for the LISA metrology chain. A breadboard model of a LISA phasemeter developed in the scope of an ESA contract was successfully tested for phase readout performance in an electrical null measurement. This technique however cannot reveal non-linearities common in the used channels. For this purpose, an advanced testbed is under development. It utilizes an ultra-stable hexagonal optical bench to implement an optical three signal test. Besides the phase readout, the whole LISA metrology chain including the auxiliary functions can be tested. The well-tested phasemeter itself could then not only be used for LISA, but also in similar applications, like future geodesy missions. In future work, the testbed would serve as a reference and parts can be replaced with corresponding engineering or flight models to be verified.

Acknowledgments

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