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End-to-end measurement of tilt-to-pathlength coupling effects for LISA

N.F. Hasselmann[1], C. Brugger[1], E. Fitzsimons[2], U. Johann, G. Heinzel[3], D. Weise[1], A. Sell[1]
[1]Airbus Defence and Space, 88090 Friedrichshafen, Germany; [2]UK Astronomy Technology Centre, Royal Observatory Edinburgh, Edinburgh EH9 2PY, UK; [3]AEI, 30167 Hannover, Germany

Abstract

In this proceeding, we will present the first end-to-end TTL measurements performed with a setup featuring a LISA-representative telescope, interferometer and pointing mechanism, as well as an experimental demonstration of active beam pointing control using the In-Field Pointing (IFP) concept.

Introduction

LISA seeks to observe gravitational waves from space in a measurement band from ~0.1 mHz to 0.1 Hz, which is so far not accessible to ground-bourne detectors, and consists of a triangular formation of satellites separated by ~2.5 Gm that will be trailing earth on a heliocentric orbit [1]. Annual orbital dynamics result in varying angles of the triangle, demanding an actuated field of view of the telescopes for the links, while maintaining the pm/Hz$^{1/2}$ noise levels in the interferometric readout that are required for gravitational wave detection.

The coupling of angular jitter of the spacecraft and pointing mechanisms to the measured piston (TTL) is among the key contributors to the overall measurement noise, consequently limiting the allowable angular noise to a ~10 nrad/Hz$^{1/2}$ level [2]. IFP is one of the advanced payload architectures studied by Airbus [3], which go beyond LISA. Here, beam pointing is implemented via a tiltable mirror positioned in an intermediate pupil plane of a wide field off-axis telescope. In comparison to the LISA baseline architecture Telescope Pointing; where the whole telescopes are repositioned continuously, only small components are actuated with a minimum impact on self-gravity [4]. The results, knowledge and methods obtained from experiments with the IFP setup can often be transferred to other payload schemes employed in space-based gravitational wave observatories and therefore remain highly interesting. For example, the prototype mechanism [5] also serves as example for various mechanisms proposed for different LISA payload architectures, which will likely employ a similar actuator technology.

More importantly, the setup allows for on ground validation of tilt-to-length coupling performance as well as breathing angle compensation demonstrations. In order to perform such measurements for the baseline instrument architecture, Telescope Pointing, one would have to ensure that gravity offloading methods do not interfere with previously mentioned measurements.

Experimental setup

The setup, shown in Fig. 1, features an off-axis wide field reflective all Zerodur telescope with a 5x magnification followed by a 5x refractive stage. The entrance pupil is 150 mm in diameter. In this pupil, a plane mirror is positioned, reflecting back the light transmitted to the distant spacecraft. This mirror can be actuated in order to reenact the changes in the apex angles of the LISA formation caused by orbital mechanics. It is thus also referred to as “Space-Craft-Simulator” (SCS) and allows TTL measurements over the whole field of view. In the intermediate pupil of the system between refractive and reflective stages, the actuated mirror for beam steering is positioned (IFPM). This mirror is responsible for pointing (i.e. compensating the tilt introduced by the SCS). Following the telescope is the interferometer (IFO) bench containing all infrastructure required for routing of local oscillator and measurement beams and the phase detection using various quadrant photo diodes (QPDs) and single element diodes. Auxiliary interferometers for tracking thermal expansion and measuring laser frequency noise are not shown. A unity magnification refractive relay stage is positioned behind the beamsplitter overlaying local oscillator and measurement beams in order to complete pupil imaging of the entry pupil onto the detector plane. For characterizing the pupil imaging performance, currently only one out of two QPDs is equipped with this relay optics.

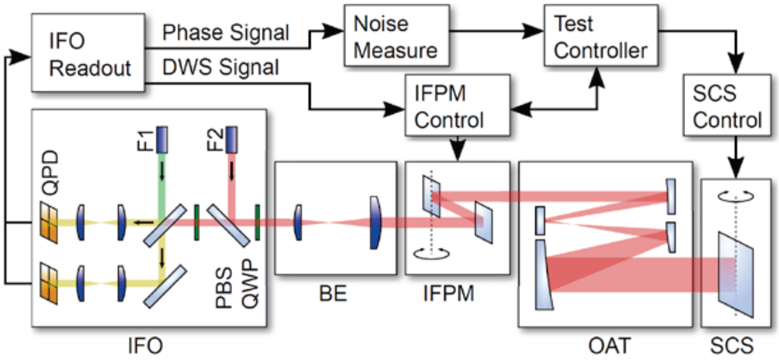

Figure 1: Schematic of the setup. SCS: Space-Craft-Simulator, OAT: Off-Axis reflective telescope, IFPM: In-Field-Pointing actuated mirror, BE: Beam expander, QWP: Quarter-wave plate, PBS: Polarizing beam splitter, F1/2: Fiber launchers 1/2, QPD: Quadrant photodiode, IFO: Interferometer (bench).

Results

By scanning the IFPM and keeping the SCS static while recording the angle of the light incident on the QPDs with respect to the local oscillator beam using differential wavefront sensing (DWS) as well as recording the change in optical pathlength for a double pass through the setup, the TTL coupling can be experimentally determined. The dependency of change in optical pathlength from the angle introduced can be approximated with a function the shape of a 2nd order polynomial for small field angles [6].

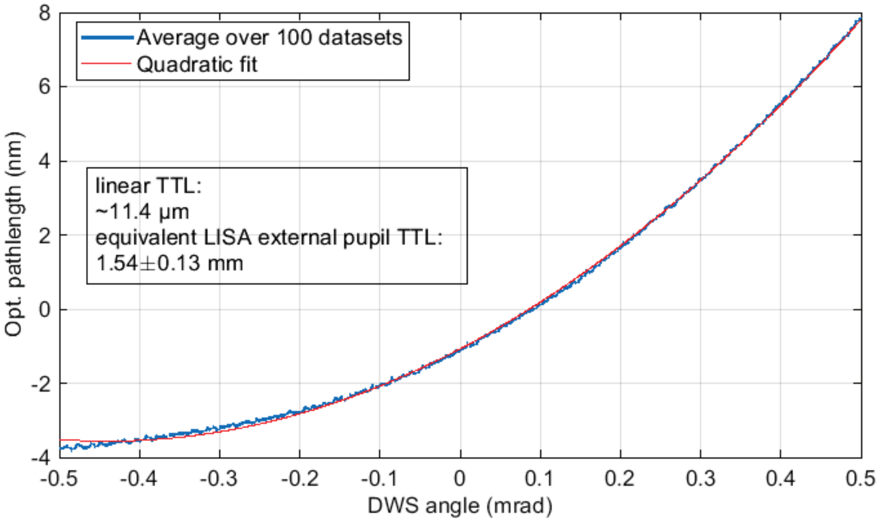

Figure 2: Early TTL-measurement during the alignment of the setup; plotted is the optical pathlength versus the DWS angle (blue) as well as a fit to the data (red). A quadratic contribution associated with a longitudinal pupil offset of the QPDs is still present.

In Fig. 2, an early alignment iteration is shown. There is still a significant quadratic contribution, which is associated with a longitudinal displacement of the QPDs with respect to their nominal position in the pupil plane.

The linear TTL assumes a value of 1.53 ± 0.13 mm/rad, which is smaller than the total allocation for LISA (2.68 mm/rad). However, from the TTL measurements and sensitivity studies, it is possible to infer a displacement of the lenses of the refractive telescope stage that can be used to compensate the linear TTL measured without compromising the wavefront error of the telescope.

In a well aligned setup, only a shallow linear slope remains. In Fig. 3, one can see the average of 100 measurements, with the mechanism moving back and forth in order to be insensitive to systematic errors due to slow thermal drifts. The value obtained for the TTL-coupling is -0.45 ± 0.01 mm/rad, where the error is three times the standard deviation of the mean. The TTL coupling thus assumes a value well within the budget for LISA. Moreover, the precision of the measurement allows for further improvement of the alignment, should the need arise.

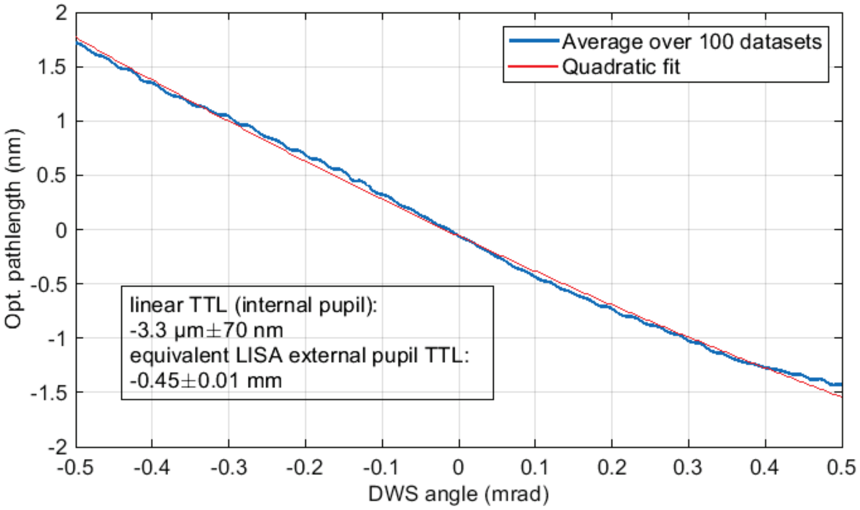

Figure 3: TTL-coupling of the setup for small angles. A quadratic function (red) is fitted to the data (blue) in order to determine the contribution of the different effects.

In order to demonstrate active breathing angle compensation using the IFPM mechanism for pointing, a simple PI controller using the DWS signal of the interferometer as feedback is implemented. Control of the angle of the IFPM such that the beam is back reflected in itself, if an angle is introduced by tilting the SCS in the entry pupil of the telescope, results in a first demonstration of active on-sky pointing for LISA in the lab.

In Fig. 4, one can see the time domain data of the motions of SCS, as measured with an optical encoder and the commanded position of the piezo drive of the IFPM. As the SCS is tilted at a speed of roughly 4 nrad/s (which is representative for the LISA orbit), the PI controller continuously repositions the IFPM accordingly, keeping the DWS signal close to zero. That demonstrates the key functionality of the active laser pointing of LISA, which is also supposed to operate in the DWS-zero-regime, controlled by the drag-free attitude control system of the spacecraft.

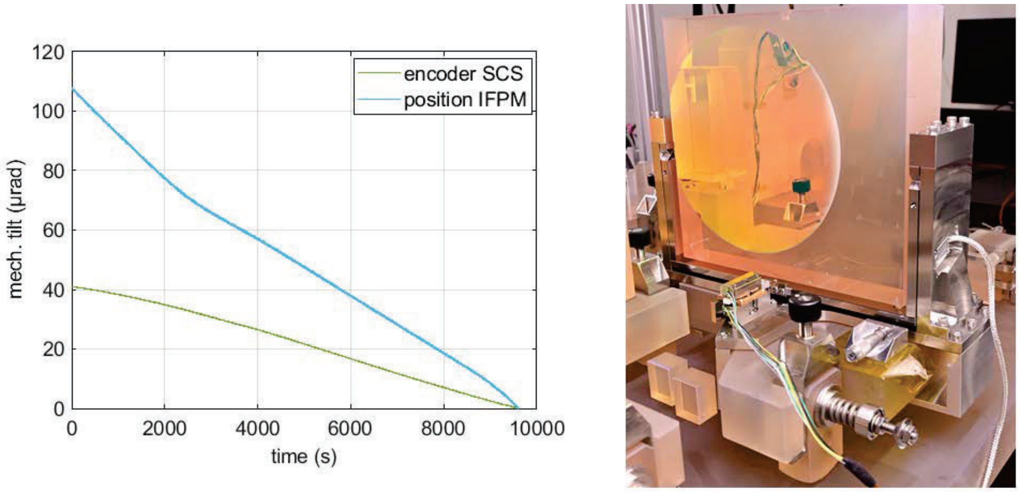

Figure 4: Left: Time domain data recorded during the active pointing demonstration. As the SCS is tilted (green curve), the actuator phase controlling the IFPM tilt (blue curve) accumulates accordingly, while the DWS angle is kept at values close to zero. Right: Photo of the SCS.

In Fig. 5, the DWS-data recorded by the interferometer is plotted in the frequency domain. For comparison, the angular noise in case of both mirrors being static is shown (grey curve). The in-loop signal during active control of the IFPM while the SCS is actuated (red curve) shows the expected behavior for a controller of the PI type (the controlled axis is shown in the plot on the right hand side), with a gain proportional to the frequency for frequencies within the control bandwidth. In addition, the DWS measurements for two auxiliary interferometers are shown (yellow and blue curves) that are quasi monolithic and do not suffer from structural-mechanical instabilities associated with the mounting of the reflective telescope optics. Those measurements are limited by electrical noise (partly due to thermal drifts of the electronics exposed to ambient conditions).

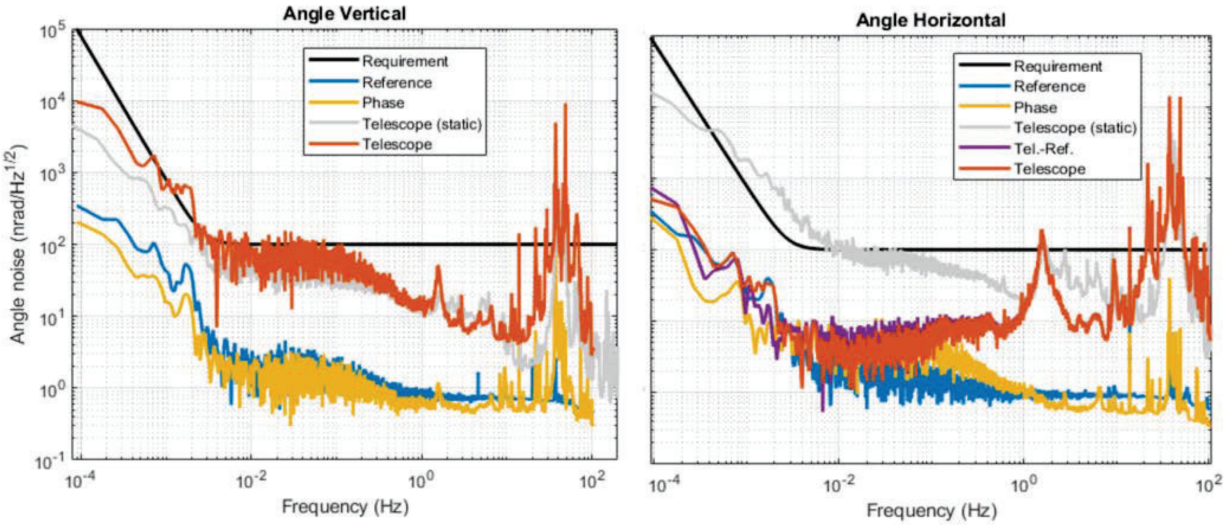

Figure 5: Interferometrically recorded angular noise spectra. See text for details. Left: The noise of the unactuated axis remains nearly unaltered during active pointing. Right: The angular noise of the actively controlled axis is well below the requirement, whereas the angular noise with static IFPM is slightly violating the requirement.

As the in-loop signal already is on the same noise level as those of the auxiliary interferometers, a further increase in controller gain would not yield further improvements. The axis orthogonal to the nominal actuated axis of rotation experiences a slight increase in noise while actively steering the IFPM due to cross coupling, but is still within the requirement.
While out-of-loop measurements have yet to be performed, the auxiliary interferometer performance indicates, that the electronics and phasemeter should allow for an angular noise during active pointing that is well below the requirement, as is suggested by the in-loop-measurements shown here. The out-of-loop measurement will be performed once the relay optics in front of the 2nd QPD are integrated, also allowing for balanced detection in the telescope measurement path. So far, the second stage was left out in order to enable precise measurements of the longitudinal pupil positions.

Conclusion

The tilt-to-pathlength alignment of a LISA-representative telescope featuring a mechanism for a beam pointing as well as an interferometer for optical read out by using TTL measurements was demonstrated to a level compatible with the LISA performance budget. Note that the LISA baseline architecture features 3 pupil planes while our alignment was done for a total of 4 planes. In combination with previously demonstrated wavefront errors [6], far field TTL as well as linear TTL coupling are well within requirements.
In a next step, we will determine the end-to-end TTL over the telescopes' entire field angle range.

Furthermore, a first demonstration of active beam pointing based on DWS-measurements was performed. The in-loop angular noise was significantly reduced by enabling active pointing. In the frequency domain, the data exhibited the expected behavior considering the PI control scheme applied. A noise floor due to the photodetector electronics was observed, but situated well below the requirement and thus not a limitation. For very low frequencies, an improved control scheme might produce slightly better results, as the performance is limited by thermos-elastic effects. Detailed investigations including out-of-loop measurements are planned for once the relay stage in front of second QPD of the telescope measurement path is integrated.

Acknowledgements

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