Enhanced laser noise suppression for LISA using arm and cavity locking

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Gravitational waves (GWs) can be described as disturbances in the spacetime curvature by the motion of masses, propagating in the speed of light. It was first predicted by Einstein in his general theory of relativity and the first detection was made in 14th September 2015 using the ground-based laser interferometer, LIGO. Due to the sensitivity of LIGO to seismic noises on Earth, a space-based interferometer, LISA, was proposed to see the universe through a broader window.

The Laser Interferometer Space Antenna, or LISA, consists of three spacecrafts in a triangular formation, separated by 2.5 million kilometers. The interferometer will be sensitive to GWs coming in the 0.1 mHz - 1 Hz and aims to reach a displacement sensitivity of 10 pm/$\sqrt{\text{Hz}}$ [1]. To measure displacement, stabilization of laser frequency noise is a critical part of GW detectors. In the current LISA baseline, Pound-Drever-Hall (PDH) locking and Time-Delay-Interferometry (TDI) are utilised to reach the sensitivity goal. PDH locking uses a phase modulation scheme and locks the laser to a stable optical cavity. TDI is a post-processing technique that synthesizes an equal-arm Michelson response by algebraic combinations of time-delayed link displacement measurements.

This research proposes a novel laser stabilization for the LISA mission by locking the primary laser to two references concurrently – the on-board optical cavity and the arms of the interferometer (which is the most stable reference in the LISA mission). The locking scheme can be implemented using digital controllers with minimal or no hardware changes to the LISA baseline structures. The preliminary results indicate that the technique can lower the residual laser frequency noise in the LISA science band by over 3 orders of magnitude: from 30 Hz/$\sqrt{\text{Hz}}$ to to as low as 7 mHz/$\sqrt{\text{Hz}}$ at 10 mHz, potentially allowing the requirements on TDI to be relaxed [2]. The main challenge with this dual sensor (cavity + arm) approach is the undesirable slow laser frequency pulling which couples into the control system due to imperfect knowledge of the Doppler shift of the light in the LISA arms. To maintain the laser lock on the cavity, we have outlined the requirements on the Doppler shift knowledge and potential schemes to realise these requirements using on-board measurements – the inter-spacecraft ranging information using Pseudo Random Noise (PRN) codes and, the interferometer response with pre-stabilized laser.

[1] K. Danzmann et al. *LISA: A Proposal in Response to the ESA Call for L3 Mission Concepts* (2017)

[2] J.T. Valliyakalayil et al. *Phys. Rev. D* 105 062005 (2022)