Martin Staab - Time-delay interferometric ranging for LISA

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Time-delay interferometric ranging for LISA

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The Laser Interferometer Space Antenna (LISA) is a future ESA-led space-based observatory to explore the gravitational universe in the frequency band between 10^{-4} Hz and 1 Hz. LISA implements picometer-precise inter-satellite ranging to measure tiny ripples in spacetime induced by gravitational waves (GWs). However, the single-link measurements are dominated by laser frequency noise, which is about nine orders of magnitude larger than the GW signals. Therefore, in post-processing, the Time-delay Interferometry (TDI) algorithm is used to synthesize virtual equal-arm interferometers to suppress laser frequency noise.

In this presentation we identify several laser frequency noise coupling channels that limit the performance of TDI. First, the on-board processing, which is used to decimate the sampling rate from tens of megahertz down to the telemetry rate of a few hertz, gives rise to laser noise residuals and thus requires careful design. Second, the post-processing delays applied in TDI are subject to interpolation and ranging errors. We study these laser and timing noise residuals analytically and perform simulations to validate the models numerically. Our findings have direct implications for the design of the LISA instrument as we identify the instrumental parameters that are essential for successful laser noise suppression and provide methods for designing appropriate filters for the on-board processing.

In addition, we discuss Time-delay Interferometric Ranging (TDIR) that serves as a third ranging sensor to estimate bias-free ranges that can be used to calibrate the biases in the primary absolute ranging measurements. We present a thorough statistical study of TDIR to evaluate its performance. Therefore, we formulate the likelihood function of the interferometric data and use the Fisher information formalism to find a lower bound on the estimation variance of the inter-satellite ranges. We find that the ranging uncertainty is proportional to the inverse of the integration time and the ratio of secondary noise power, that limits the interferometric readout, to the laser noise power. To validate our findings we implement prototype TDIR pipelines and perform numerical simulations. We show that we are able to formulate optimal estimators of the unbiased range that reach the Cramér-Rao lower bound previously expressed analytically. The developed TDIR pipeline will be integrated into the ranging processing pipeline to perform consistency checks and ensure well-calibrated inter-satellite ranges.

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