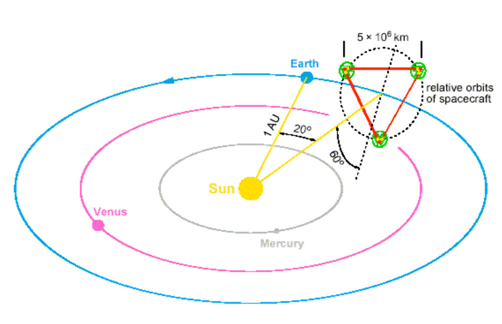
Preliminary Investigations of an Optical Assembly Tracking Mechanism for LISA

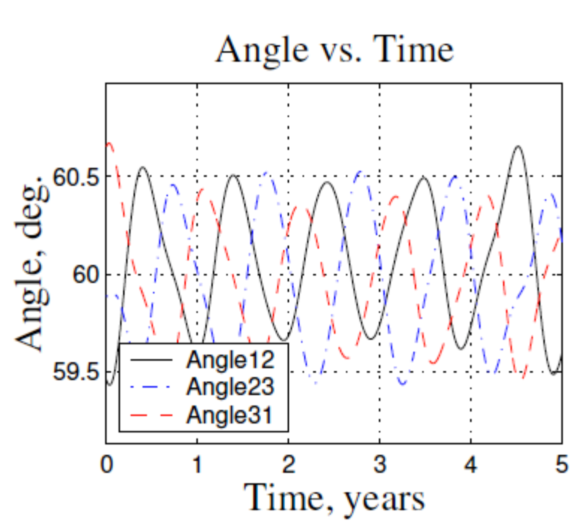
J.I. Thorpe[1], R. Stebbins[1], S. Schlamminger[2], J. Gundlach[2]
[1]NASA/GSFC, [2]U. Washington

Abstract

After injection into their specific orbits, the position of the LISA spacecraft (SC) are not actively controlled. Rather the SC are allowed to passively follow their trajectories and the roughly equilateral triangular constellation is preserved. Slight variations in the orbits cause the constellation to experience both periodic and secular variations, one consequence of which is a variation in the interior angles of the constellation on the order of 1°. This variation is larger than the field of view of the LISA telescope, requiring a mechanism for each spacecraft to maintain pointing to its two companions. This Optical Assembly Tracking Mechanism (OATM) will be used to accommodate these variations while maintaining pointing at the 8nrad/rtHz level to the far SC. Here we report on a possible design for the OATM as well as initial results from a test campaign of a piezo-inchworm actuator used to drive the mechanism.

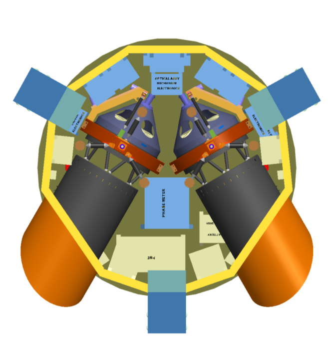


LISA orbital configuration and variations of the constellation's interior angles

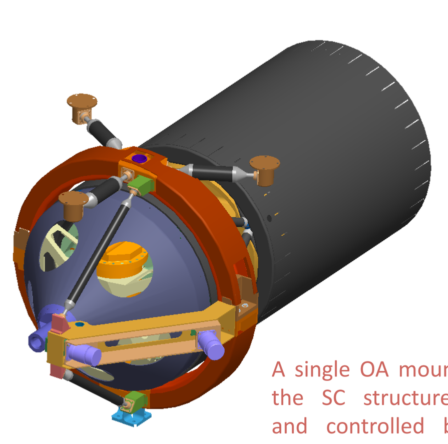


Requirements

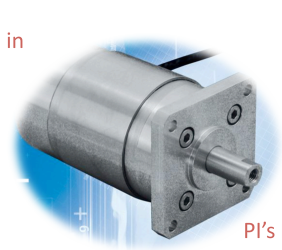
Range: The dynamic range of the OATM is set by the variation in the interior angles of the LISA constellation. The magnitude of these variations depends on the precise details of the orbit, but can safely be assumed to be less than 2° peak-to-peak.
Stability: Pointing jitter of the optical assembly will couple into the primary pathlength measurement at a level determined by geometrical tolerances. The current LISA error budget allows angular variations of 8nrad/Hz$^{1/2}$ or less in the LISA band from 0.1mHz to 0.1Hz.



Two Optical Assemblies (OA) in a LISA spacecraft (SC)



A single OA mounted to the SC structure (red) and controlled by the OATM (orange lever)



PI's NEXLINE actuator

Mechanism Design

Each LISA SC contains two identical payload subassemblies for making displacement measurements along the two arms for which the SC serves as a vertex. The assemblies, referred to here as Optical Assemblies (OAs) consist of a gravitational reference sensor, optical bench, telescope, and associated hardware. The OAs are mechanically connected to the SC structure via rotational flex pivots, which allow rotation within the required dynamic range.

We have identified a piezo-electric "inch-worm" actuator, the NEXLINE series by Physik Instrumente, which may have the required range and precision to drive the OATM. Through a series of shearing and clamping piezo motions, the NEXLINE actuator is able to deliver 30pm positioning resolution with a 2cm stroke. This fractional precision (~7x10^8) exceeds the angular precision requirement (2° / 8 nrad ~ 4x10^6) but there are no measurements on positional stability in the LISA band. A space-qualified version of the NEXLINE actuator is used in the caging mechanism for LISA Pathfinder, an ESA-led technology demonstrator mission for LISA.

The NEXLINE actuator provides a linear displacement, which can be converted to an angular displacement using a lever as shown in the Figure above. Appropriate design of the lever can be used to match the available dynamic range of the actuator with the required dynamic range of the OATM.

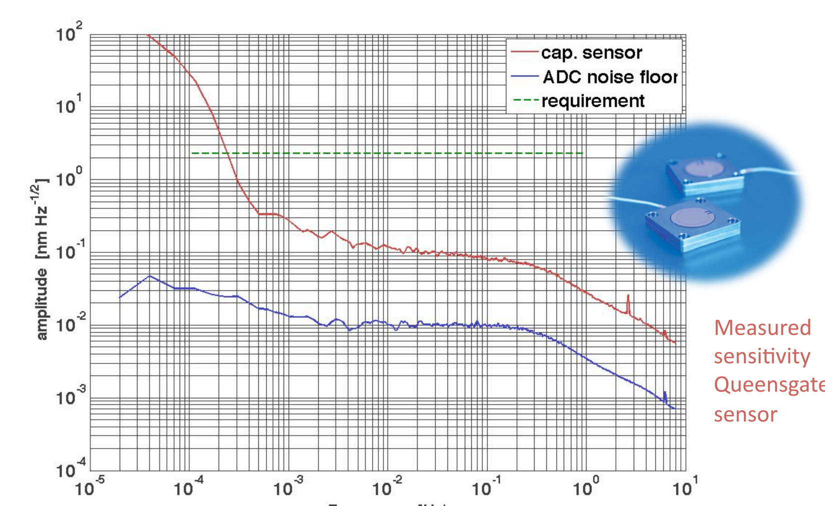
Experimental Plan

Phase I: Design and test a metrology system capable of evaluating the actuator stability.
Phase II: Measure the position noise performance, linearity, and other characteristics of the NEXLINE actuator.
Phase III: Implement a candidate mechanism design and measure the angular stability.

Phase I – Actuator Metrology System

Building a metrology system with the required range and precision is a challenging task in and of itself. For convenience, we elected to split the task between two commercial displacement sensors. The long-range sensor, able to cover the entire actuator range with a precision of ~3nm is a Zygo Z1000 compact interferometer. The high-precision sensor is a Queensgate NX series capacitive sensor, capable of 0.1nm resolution over a 150um range.

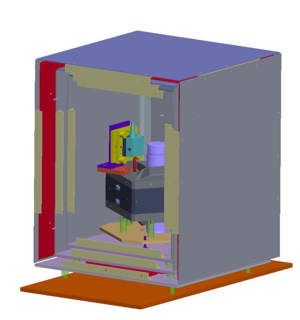
To verify the measurement precision of the capacitive sensor, we placed the device in an approximately athermal structure which was then placed in a passive thermal enclosure (i.e. styrofoam). We also developed a data acquisition system consisting of analog and digital anti-aliasing filters. The plot below shows the measured position stability. The sensor is shown to meet the requirements except at the low end of the LISA band. The rise at low frequencies is expected to be driven by temperature coupling through the uncompensated material. It is expected that a better thermal environment (vacuum chamber) will improve the low-frequency performance.



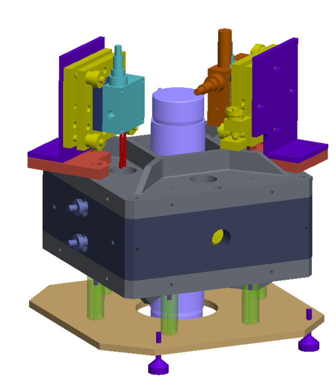
Measured displacement sensitivity of the Queensgate NX capacitive sensor

Phase II – Actuator Testing

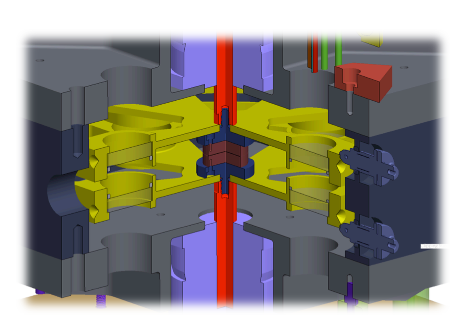
To test the NEXLINE actuator's stability, we have designed an assembly whereby two identical actuators move in opposition to maintain a nominal 100um gap. This ensures that the capacitive sensor can be used to measure the positional stability over the entire actuation range. The absolute position is tracked by two Zygo Z1000 interferometers as well as encoders internal to the actuators.

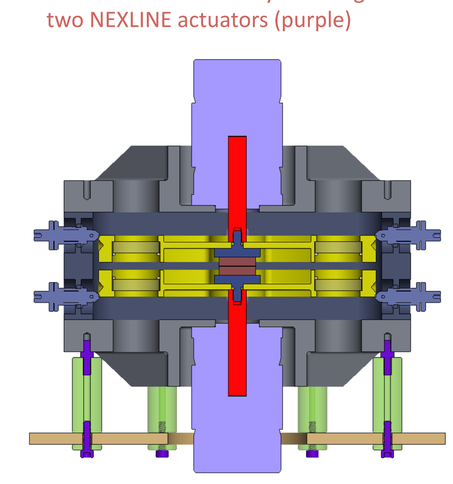


Actuator test assembly inside thermal shields



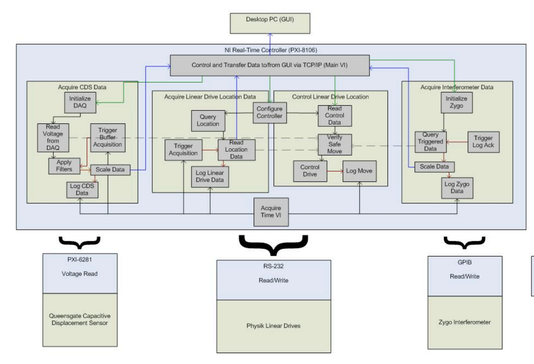
Actuator test assembly showing two NEXLINE actuators (purple)

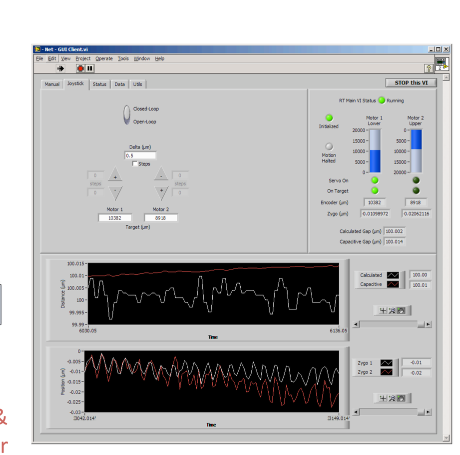




Cutaways showing actuator shafts (red), capacitive sensor (brown) and mirror holder (yellow)

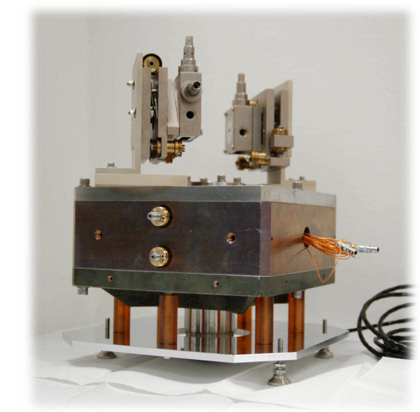
Mechanical/Thermal Design: Each actuator shaft drives a disk-shaped structure that is used for metrology. At the center of the disk is the capacitive sensor. Further out are four holes to accommodate target mirrors used in the interferometer system. The two actuators are mounted in a fixed structure that is designed to minimize the effective CTE of the measurement gap. The entire assembly is placed inside three nested thermal shields. The temperature of the outermost shield is actively controlled through a combination of a water manifold and thermoelectric elements.

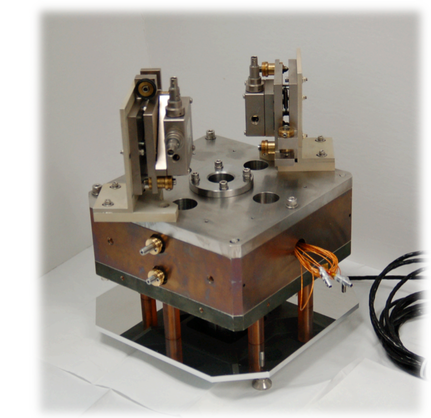




Functional block diagram of the data acquisition & control system (top) and front panel of the controller (right)

Data Acquisition: A custom data acquisition and control system has been developed to operate the actuator test-bed. This system, running on a National Instruments real-time processor, allows the user to control the position of each actuator and record position information from the capacitive sensor, interferometer, and internal actuator encoders. Temperature data is recorded separately by the thermal control system.

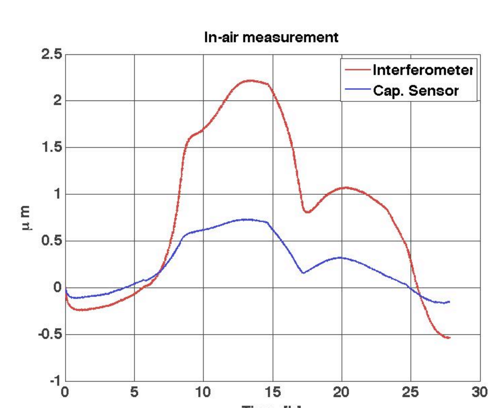


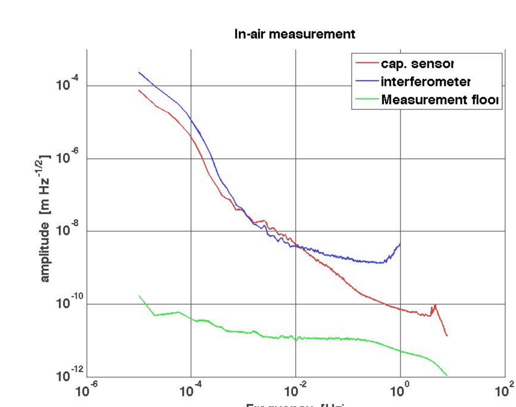


Completed actuator assembly with dummy actuator installed in upper position. The polished plate and brown legs are part of the thermal isolation system.

Single-Actuator Test: During testing one of the actuators was determined to have a problem with its internal position encoder. While the actuator was being serviced, we proceeded with a single-actuator test where one actuator was replaced by a fixed shaft. This prevents the full range from being measured with the capacitive sensor but allows short-range, high-precision measurements as well as lower-precision measurements over the full stroke.

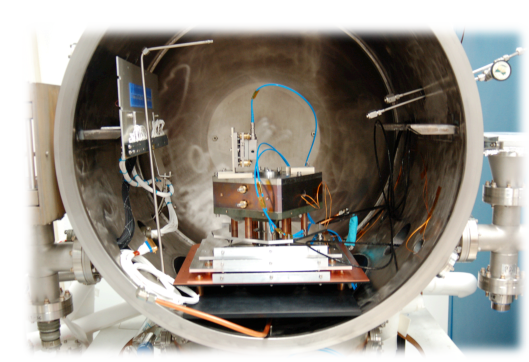
Preliminary Results: Prior to integrating the system in vacuum, the actuator test-bed was tested in air to verify operation. The plots below show capacitive and interferometric displacement measurements for a case where the actuator was asked to hold position. The displacement measured by the interferometer over long time scales was consistent with that measured by the capacitive sensor except with a ~4x greater amplitude. This is consistent with the ratio of effective CTEs for the two measurements, calculated to be ~3:1. The thermal response of the assembly will be further characterized once the system is in vacuum and the temperature diagnostics are operational.



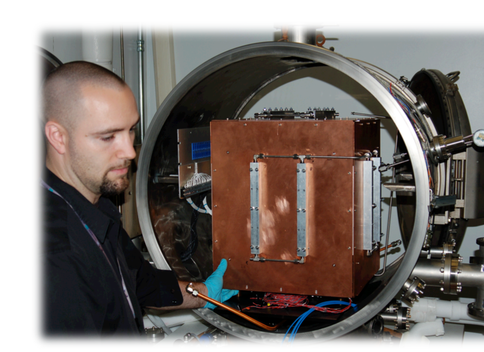


Timeseries (left) and spectrum (right) of the initial in-air functional test of the test assembly.

Current Status: The system is currently being integrated into a vacuum chamber with both active and passive thermal shielding. This should provide adequate environmental stability to reach the required measurement precision across the LISA band.



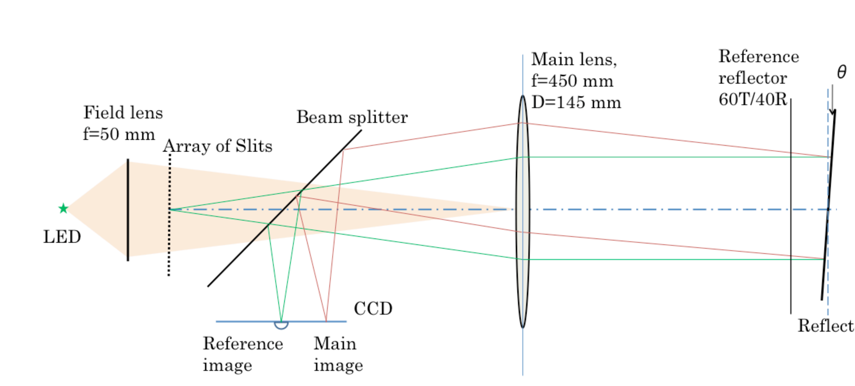
Actuator assembly being installed in vacuum chamber.



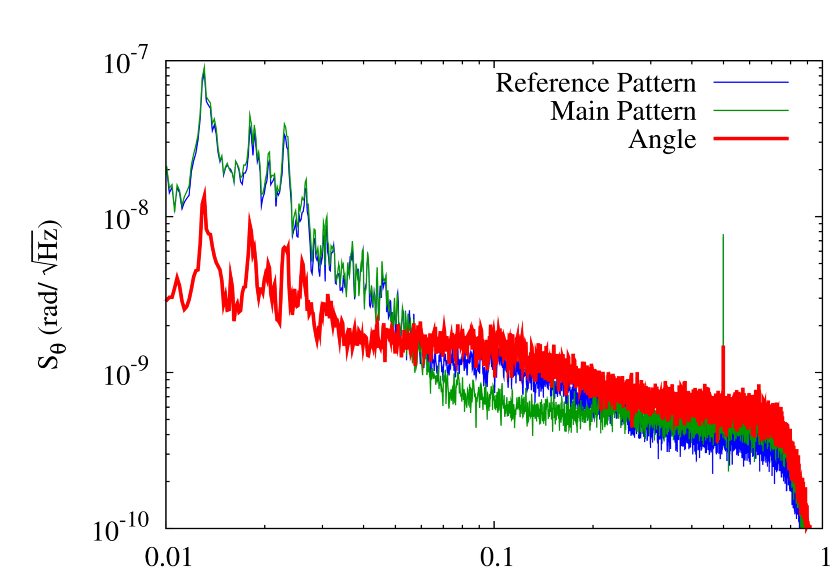
Thermal shields during installation. The outer copper shield is actively controlled using a water manifold.

Phase III – Mechanism Testing

The design of the mechanism and the test apparatus is still in its early stages. Progress has been made, however, on an angular position sensor that will meet the precision and range requirements. Developed at U. Washington and based on a classic autocollimator, the new device uses a series of slits and a CCD to improve angular precision. The system is capable of measuring over a 3° range with preliminary noise of a few nrad/Hz$^{1/2}$.



Schematic design of the autocollimator developed at UW.



Angular noise performance of UW autocollimator.