# Optical Design of the LISA Interferometric Metrology System

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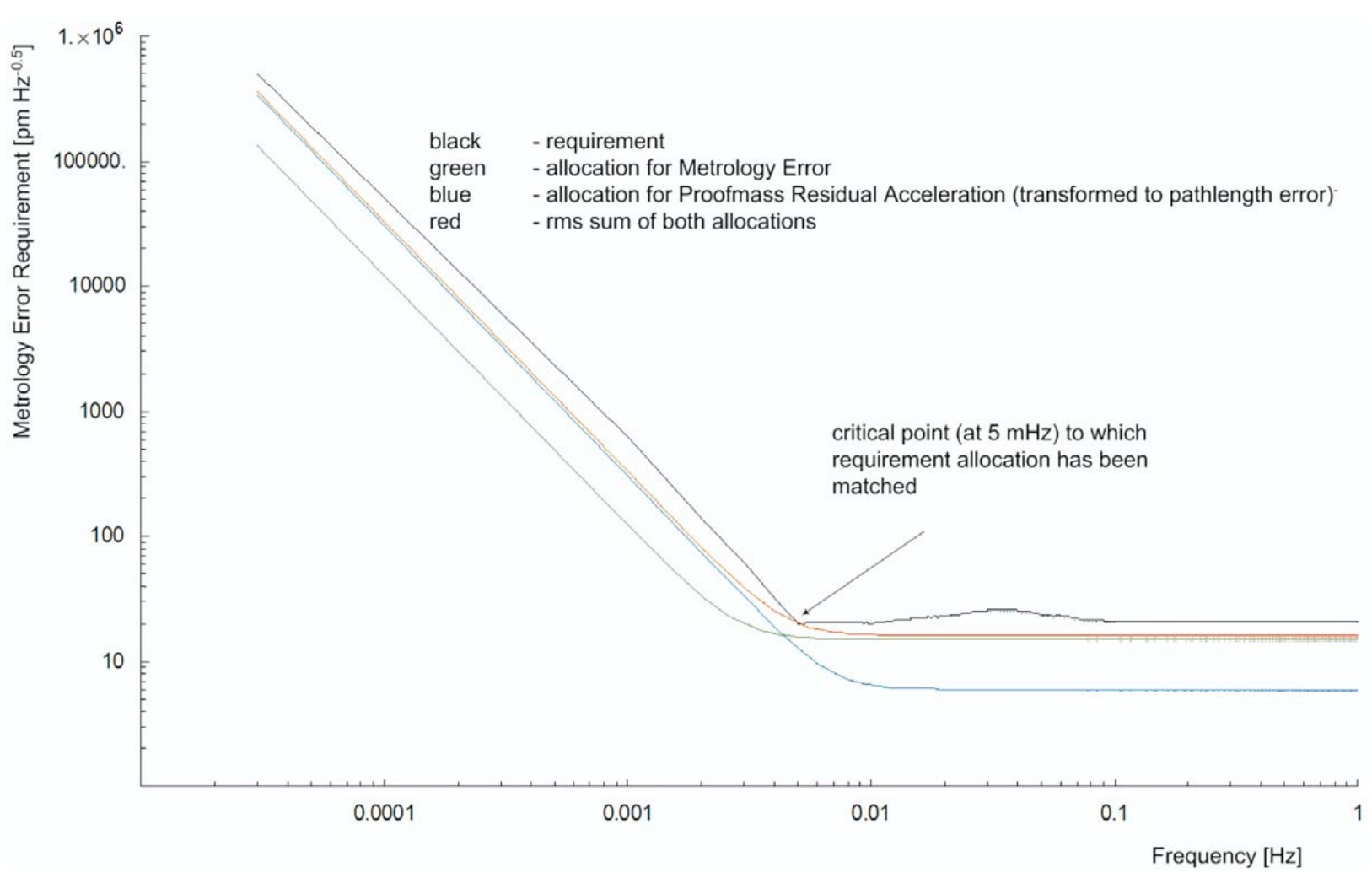
## Abstract

Within the context of the LISA Mission Formulation Study, we have developed a detailed concept for the optical layout of the LISA payload, which consists of two movable assemblies per spacecraft, each pointing to its respective remote spacecraft to form a constellation triangle of 5 million kilometer arm length. The movable assemblies comprise a Cassegrain telescope, an optical bench, and a gravity reference sensor with a free floating proof mass, which delimits the respective arm.

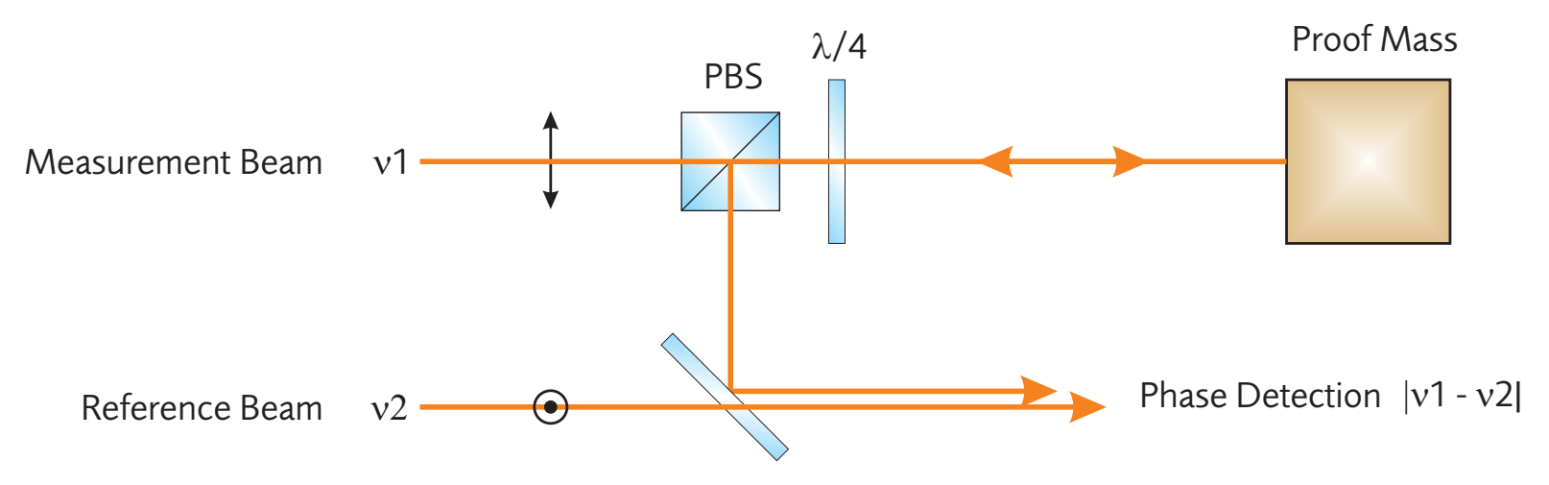
Differential changes in the distances between the two proof masses of each arm, caused by the passage of a gravitational wave, are detected by a combination of heterodyne interferometry and differential wavefront sensing. The optical metrology is characterized by a "strap-down" approach, in which an optical readout provides position as well as attitude information of each test mass with respect to its local optical bench. This information is combined with a second interferometric measurement of the distance between the local and the remote optical bench to yield the science signal for one interferometer arm. A "frequency swap" between transmitted and local reference beam is introduced to minimize the impact of straylight from each high power transmit beam on the local heterodyne detection.

## Metrology Principles

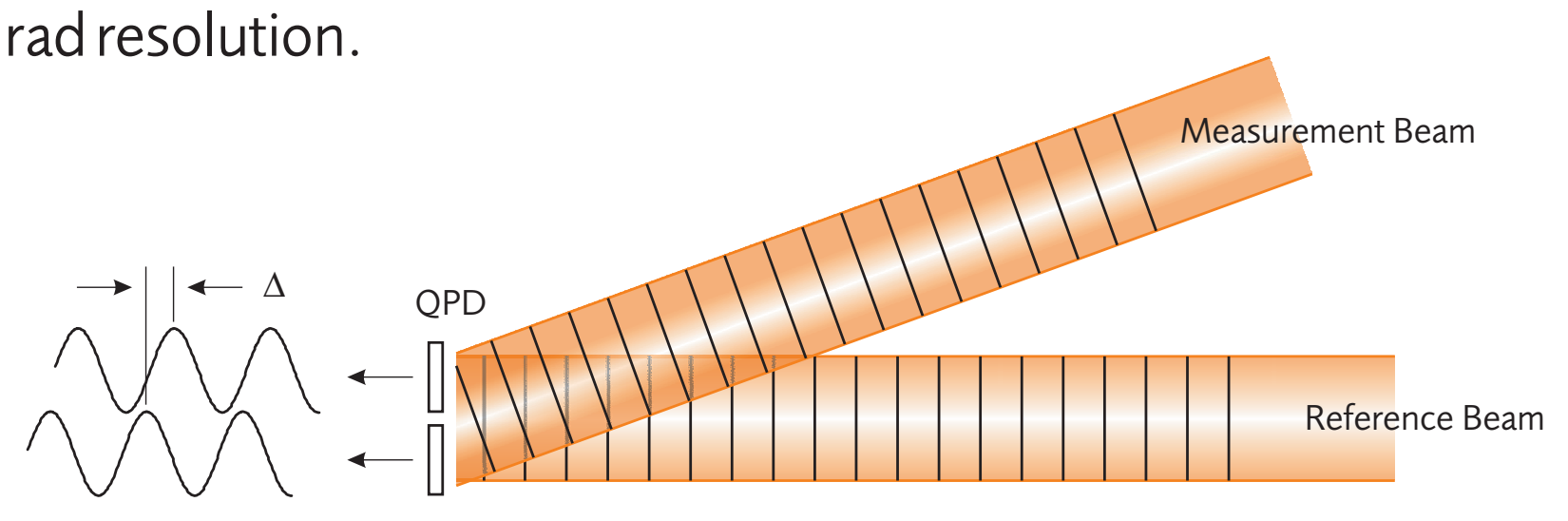
The allowable "single link" metrology error is **12 pm/ Hz** at high frequencies, with a relaxation below 2.8 mHz.



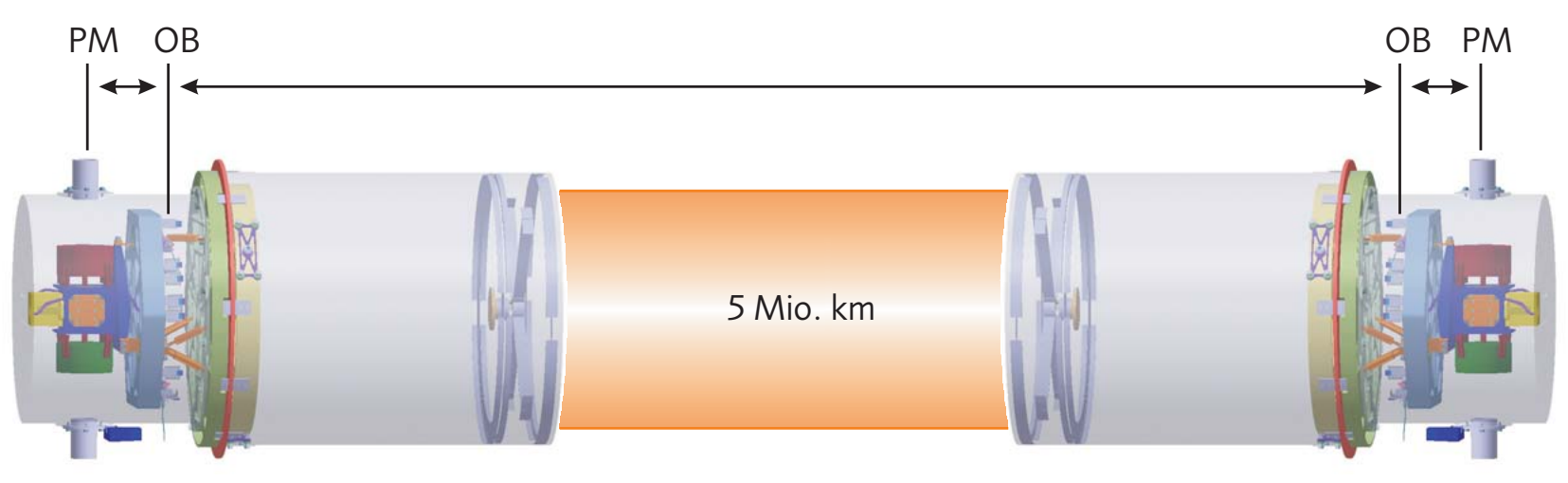
**Polarizing heterodyne interferometry** is applied as main metrology principle to achieve the required level of accuracy.



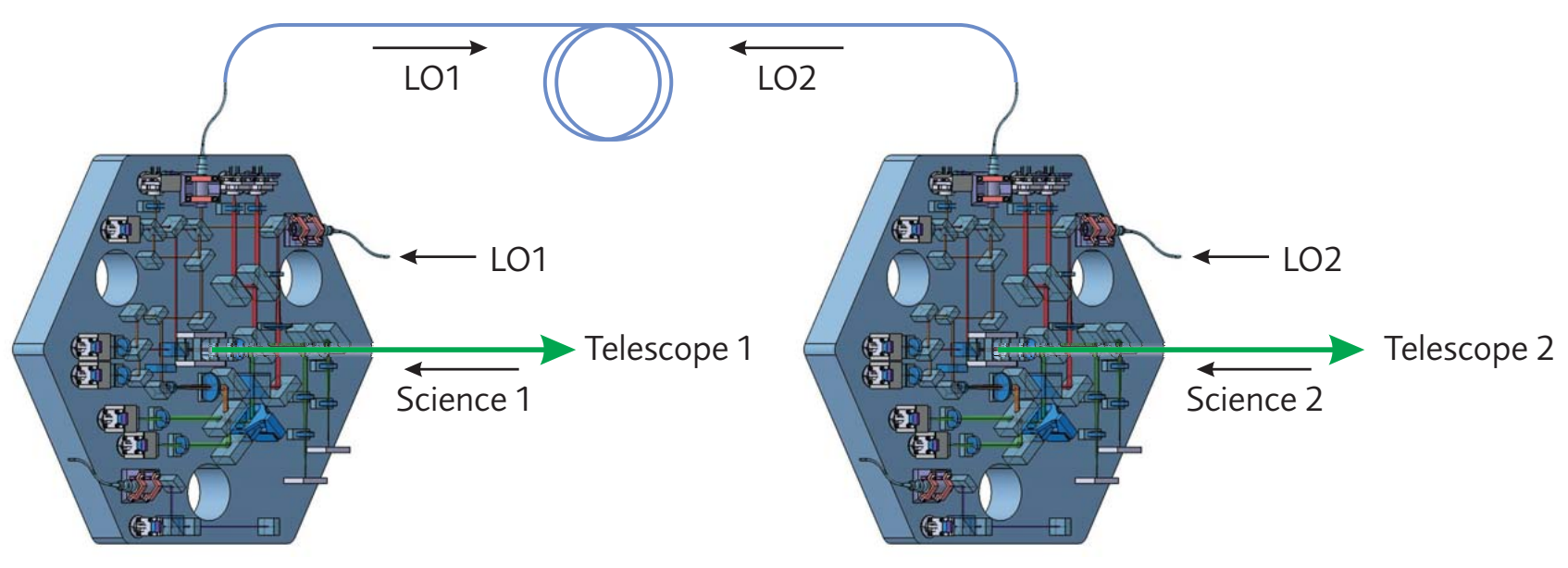
By performing a spatially resolved phase measurement (**Differential Wavefront Sensing**), the tilt of the incoming wavefront as well as the test mass attitude can be aquired with nrad resolution.



The distance measurement between the two proof masses of a single arm is separated into two steps, where one set of interferometers measures path length changes from optical bench to remote optical bench, and a second set of interferometers measures the movement of each proof mass with respect to the local optical bench. This **"strap-down" architecture** offers the advantage of a technical and functional decoupling of the proof mass assembly from the intra-spacecraft interferoemtry.



A **"frequency swap"** between transmit and local oscillator beam reduces the impact of stray light from the high power transmit beam to a tolerable level.



## Optical Modeling (Defocusing)

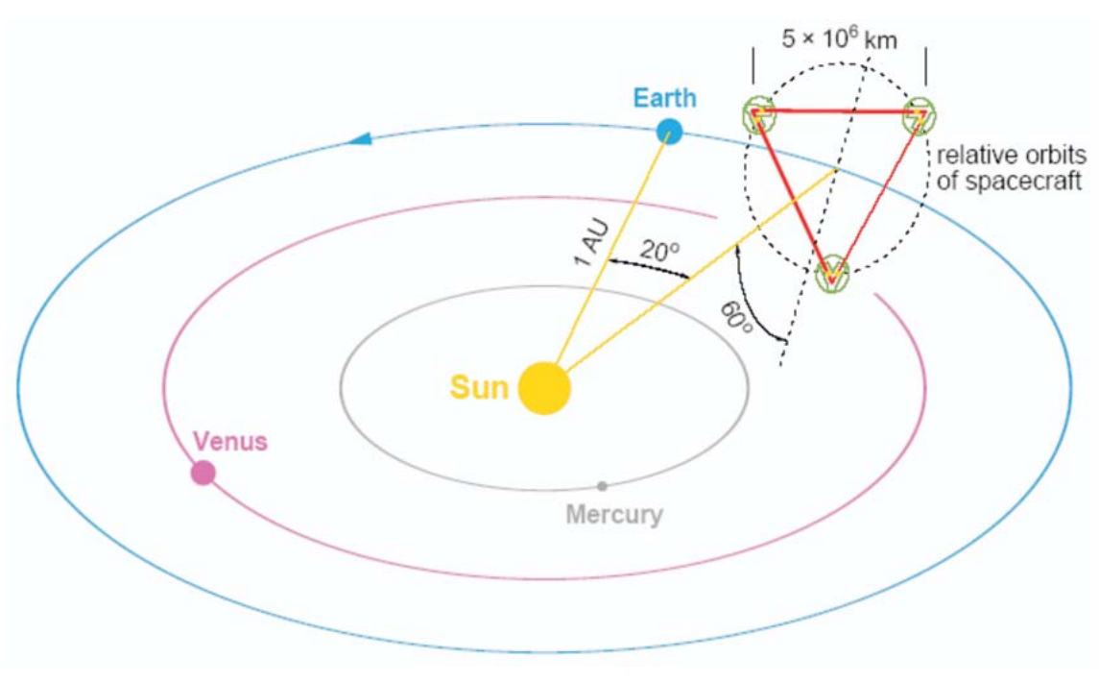
Far field shaping is possible by an active adjustment of the first beam expander lens in the transmit beam.

A large lens shift can be used to expand the far field cone, as shown on the left. This might ease initial beam acquisition.

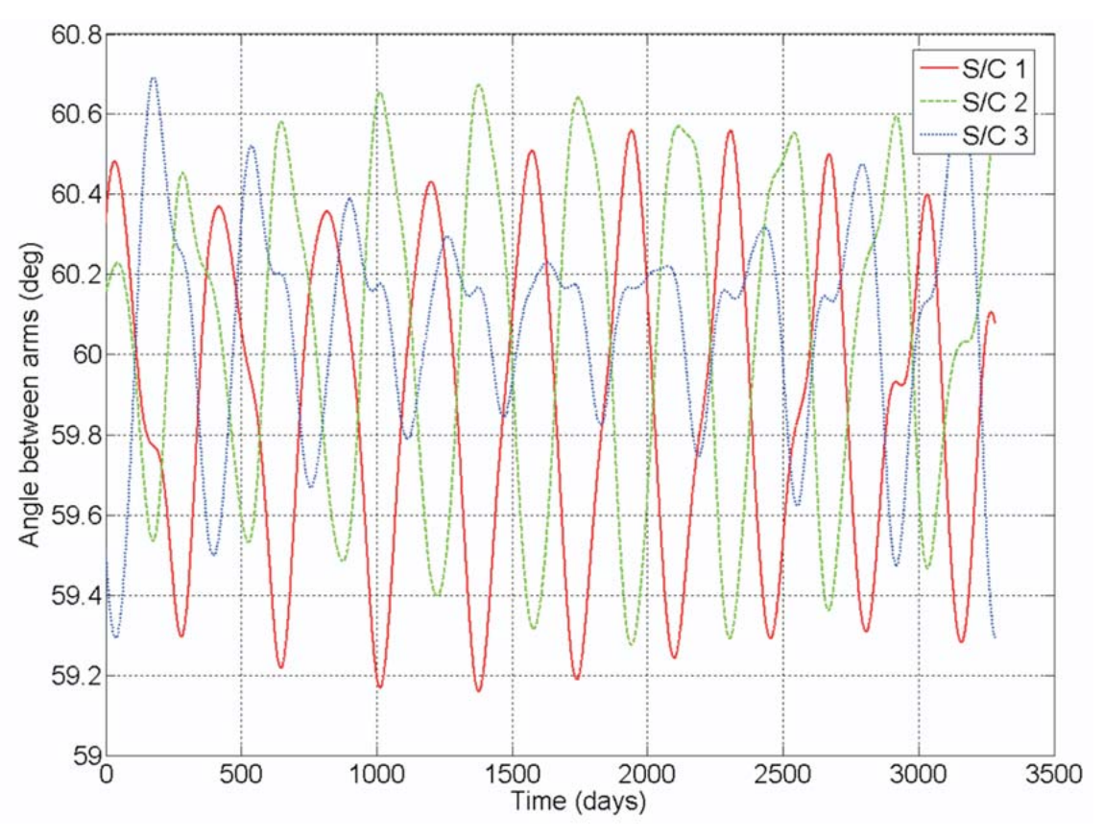
Smaller lens shifts may help to correct the shape of the far field wavefront in flight, e.g. in order to adjust the phase center position.

## Mission Overview

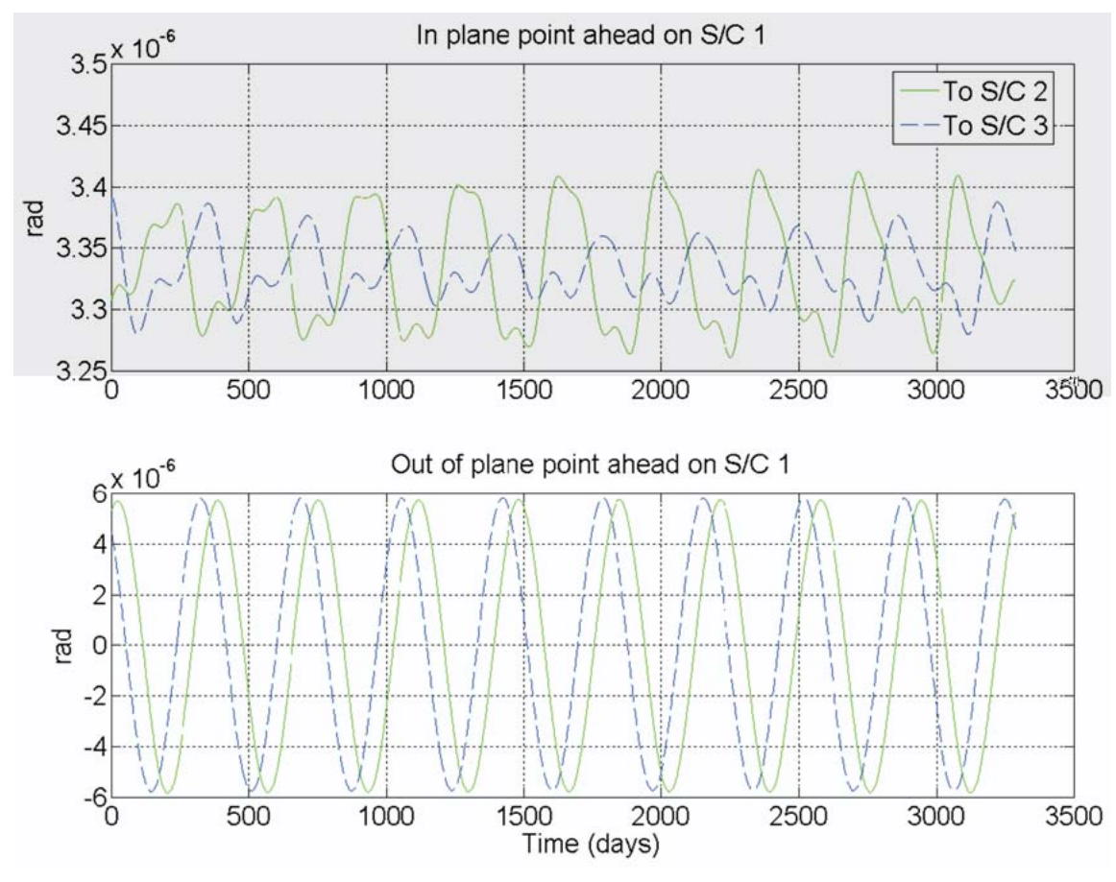
LISA consists of a constellation of three identical spacecraft forming an equilateral triangle with a side length of 5 Mio. km, which is trailing earth in a heliocentric orbit.



Due to orbital dynamics, the nominal 60° angle between the two lines of sight of each s/c varies with an amplitude of max. 1° over time.



Also the point-ahead angle, i.e. the angle between send and receive beam on a single arm, varies in the course of a year. Active compensation is required for the out-of-plane point-ahead variation of 6 μrad.



## Sciencecraft & Payload Design

The optical payload on board each LISA spacecraft consists of two "movable optical assemblies", which can be rotated individually to track the varying line of sight angle.

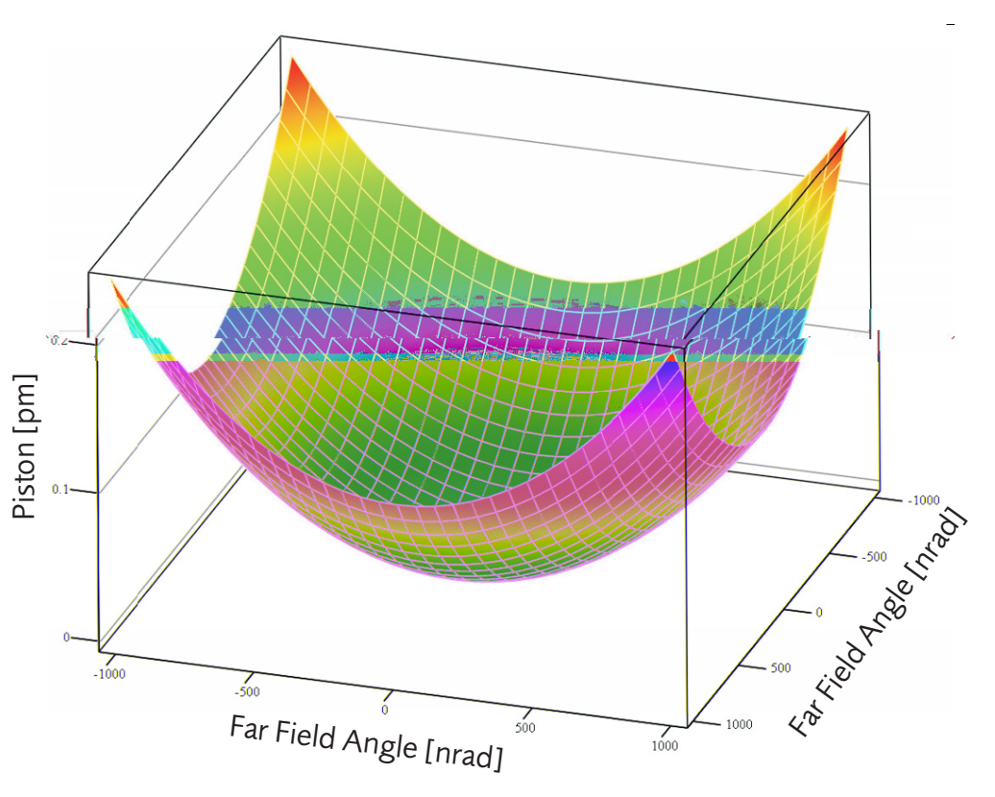
Each movable assembly comprises a Cassegrain telescope, an optical bench, and the proof mass assembly with the Au-Pt cube, surrounded by its electrode housing.

Mounting of these subsystems to a titanium structural baseplate is realized such that mechanical transfer functions are optimized and thermal fix points are provided on the optical axis.

The light-weighted optical bench is made from an ultra-low CTE material like Zerodur. Placed within a compartment of 10 K/ Hz thermal stability, it provides the dimensional stability required for correlating the various interferometric measurements. Optical

## Optical Modeling (Nominal Far Field)

Any deviation of the far field wavefront from a perfect sphere translates into piston noise from spacecraft jitter. Currently, a jitter of 8 nrad/ Hz is achieved.

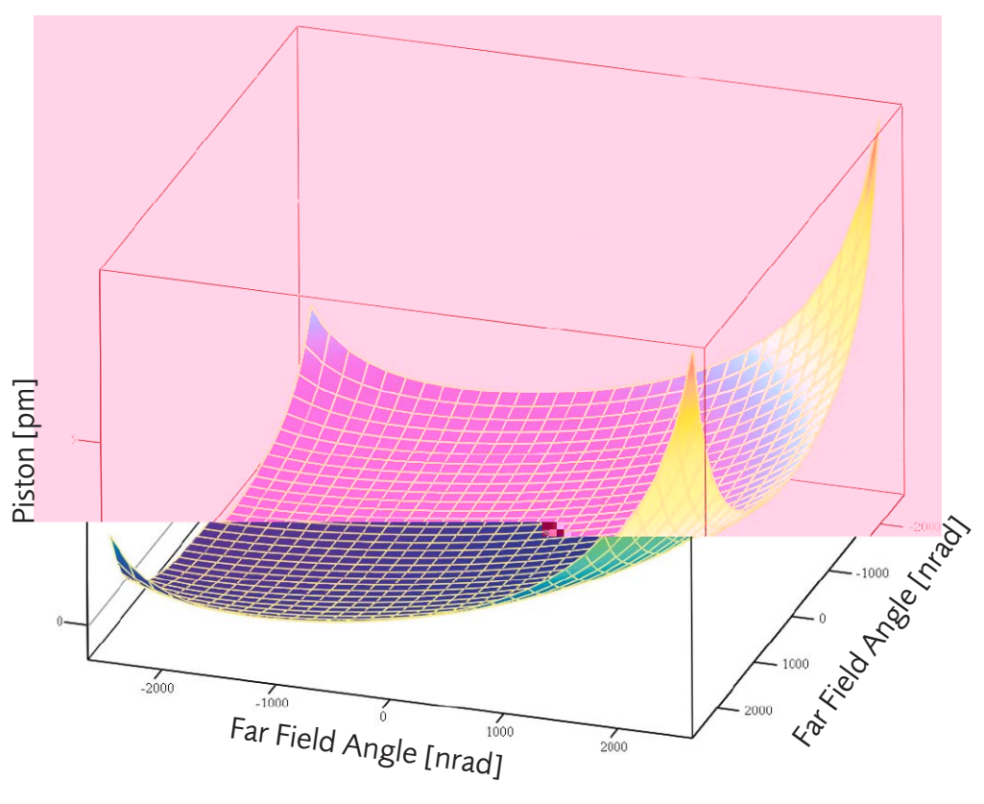


Fresnel propagation of an analytical (perfect), truncated Gaussian Beam. Shown is the deviation of the wavefront from a sphere at a distance of 5 Mio. km.

- Aperture radius: r = 200 mm
- Optimal clipping ratio: $w_0 = r/1.12$
- Aperture center coincides with focal point position (phase center)
- On axis intensity: $3.6 \times 10^{-9}$ W/m$^2$ for 1 W of launched power.
- Resulting piston gradient @ 1000 nrad offset from axis: $3 \times 10^{-4}$ pm/nrad

This is the best performance to be expected under all circumstances.

Results from a BeamWarrior model of the optical setup, starting at the fiber launcher on the optical bench:



The above plots have been obtained for an optimized position of the defocusing lens (shifted to +14.33 μm, see modeling of defocusing).

Apparently, there is a slight lateral offset between the assumed phase center (center of the far field sphere) and the actual phase center (focal point position of transmitted beam in the exit pupil).

A similar piston structure is reproduced by Fresnel propagation of a truncated Gaussian beam **shifted laterally by 1 μm** with respect to the center of the clipping aperture (see plot on the left).

## Payload Mechanisms

Out-of-plane point-ahead angle compensation is performed with a dedicated mechanism in a pupil plane of the receive path ("Point-Ahead Angle Mechanism"). As part of the science chain, it has to ensure minimal piston effects below **3 pm/ Hz**.

Fiber launchers on the optical bench will be equipped with a Fiber Positioning Unit for switching between redundant laser sources.