A High Sensitivity Heterodyne Interferometer as Optical Readout for the LISA Inertial Sensor

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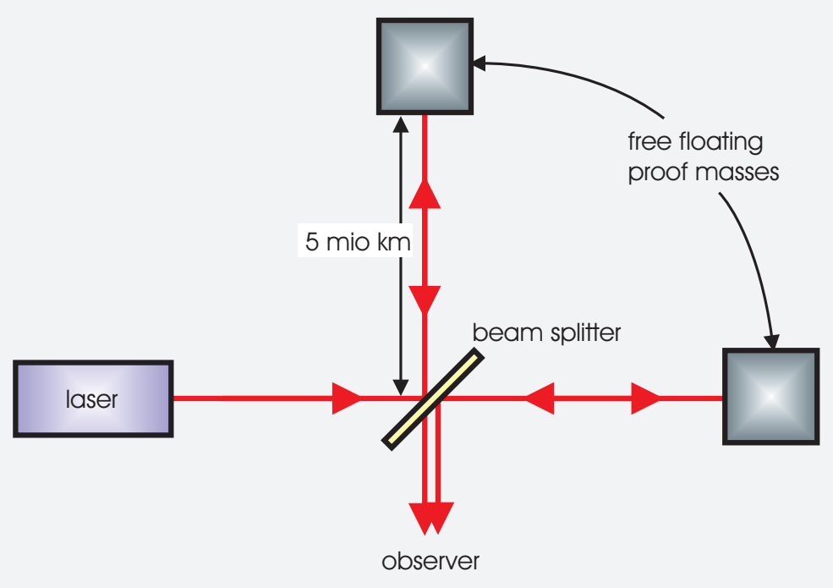
Abstract

LISA (Laser Interferometer Space Antenna) utilizes a high performance position sensor in order to measure the translation and tilt of the free flying proof mass with respect to the optical bench. Depending on the LISA optical bench design, this position sensor must have up to pm/√Hz sensitivity for the translation measurement and up to nrad/√Hz sensitivity for the tilt measurement. For this purpose, EADS Astrium GmbH – in collaboration with the Humboldt-University Berlin and the University of Applied Sciences Konstanz (HTWG) – develops a heterodyne interferometer. Differential wavefront sensing is implemeted in order to measure a tilt of the proof mass. The interferometer design exhibits maximum symmetry where measurement and reference arm have the same frequency, polarization and optical pathlengths. It is therefore, in principle, free of frequency and polarization mixing. The interferometer can be set up free of polarizing optical components preventing possible problems with thermal dependencies not suitable for space environment.

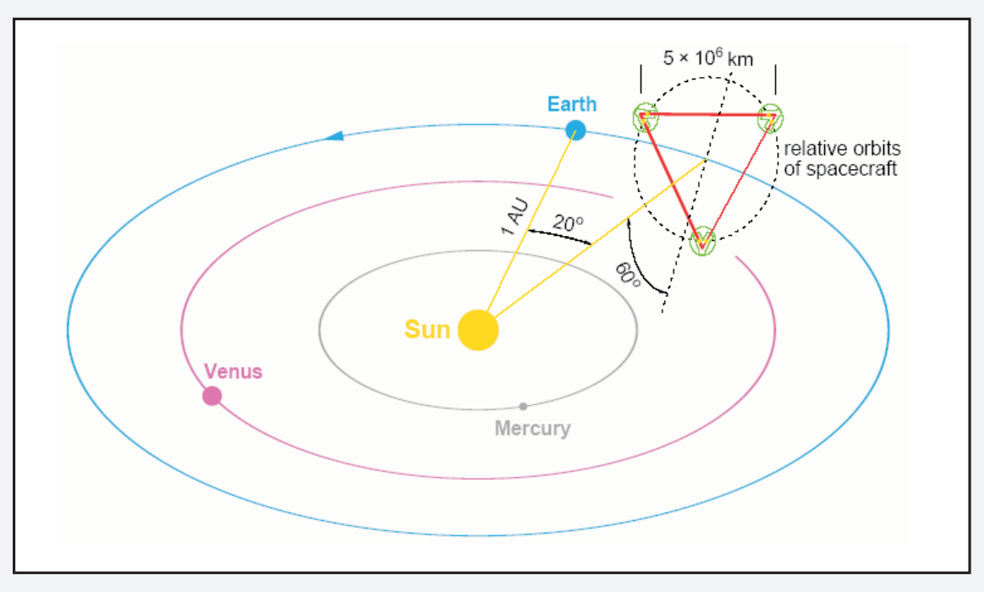
As a first demonstrator, we developed a mechanically highly stable and compact setup which is located in a temperature stabilized vacuum chamber. First measurements show noise levels below 1 nm/√Hz (longitudinal measurement) and 1 μrad/√Hz (tilt measurement) for frequencies above 10^{-3} Hz.

The LISA mission

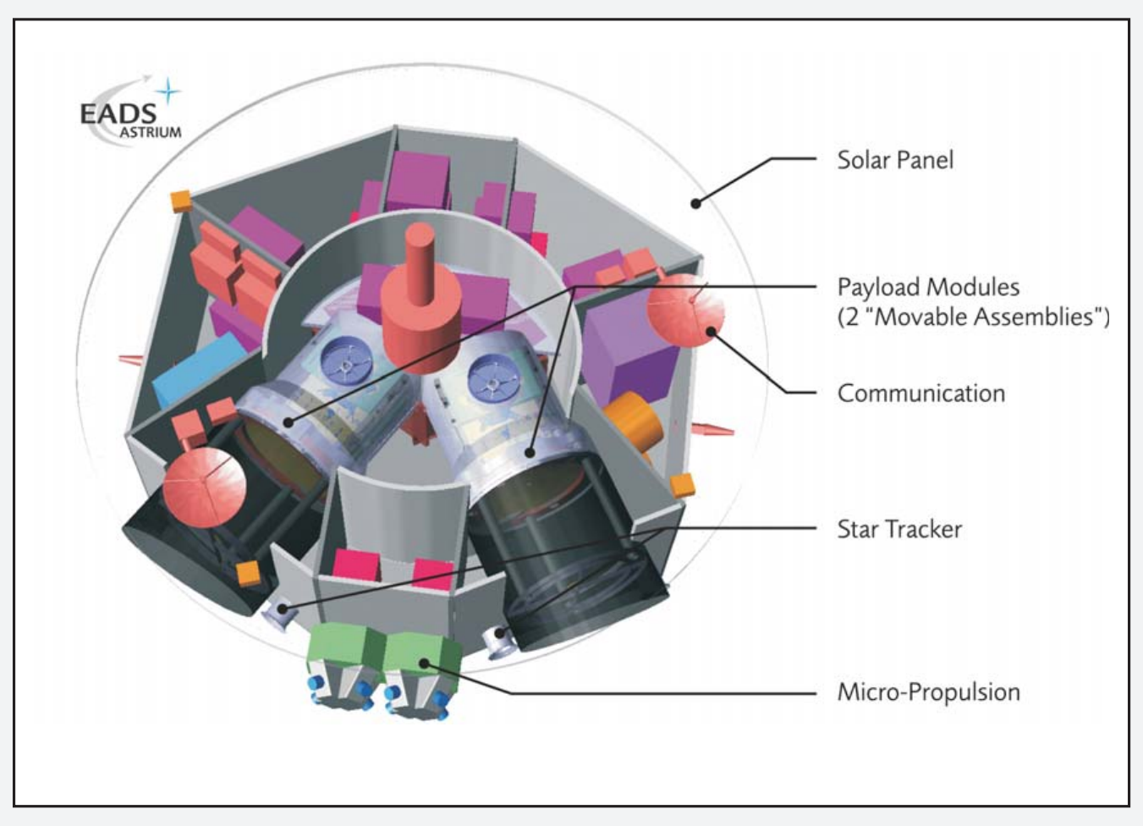
LISA as Michelson interferometer



The LISA orbit



The LISA spacecraft



Requirements for the proof mass (PM) position measurement

LISA Optical Bench design option 1:

"strap-down" architecture: PM position measurement is part of the inter-spacecraft interferometry

- ✻ Translation < 10 pm/√Hz
  (for frequencies above 2.8 mHz with an f^{-2} relaxation down to 30 μHz)
- ✻ Tilt < 10 nrad/√Hz
  (for frequencies above 0.1 mHz with an f^{-1} relaxation down to 30 μHz)

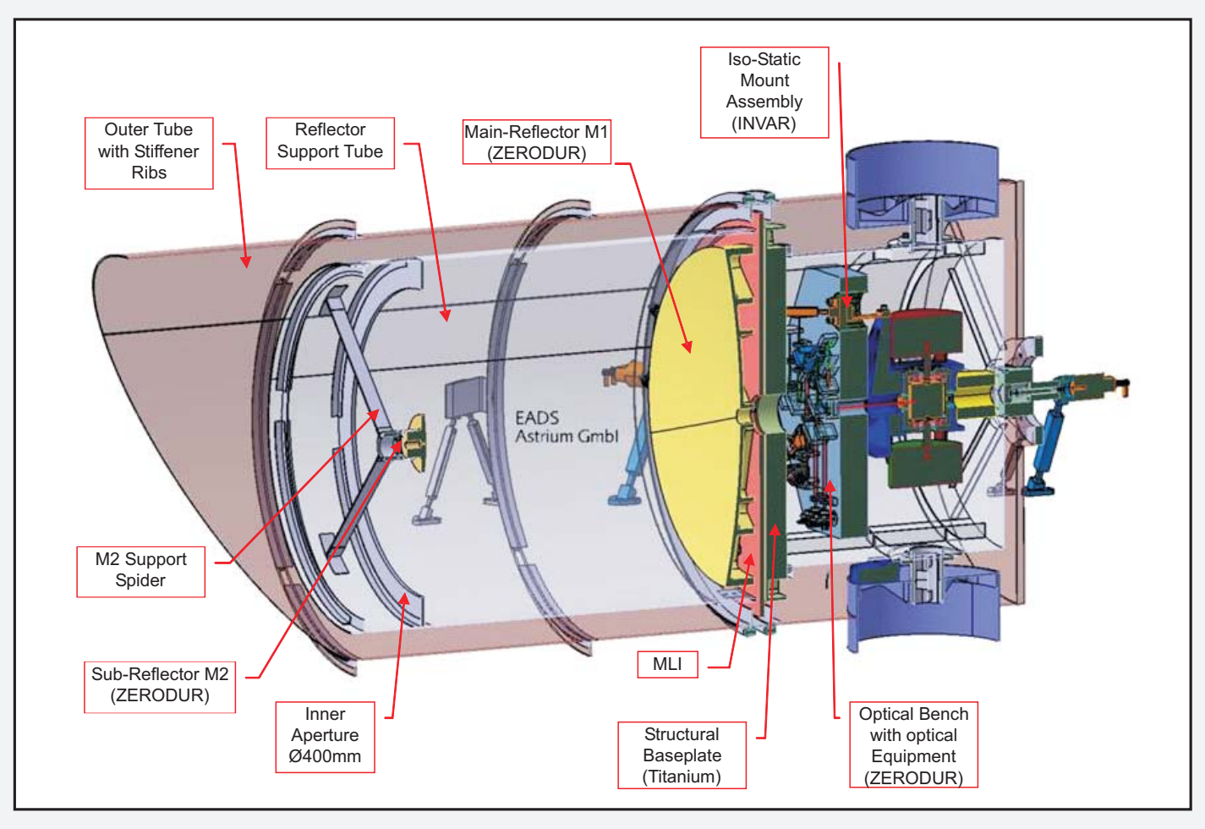
LISA Optical Bench design option 2:

PM position measurement as part of the drag-free attitude control system (DFACS)

- ✻ Translation < 1 nm/√Hz
- ✻ Tilt < 20 nrad/√Hz

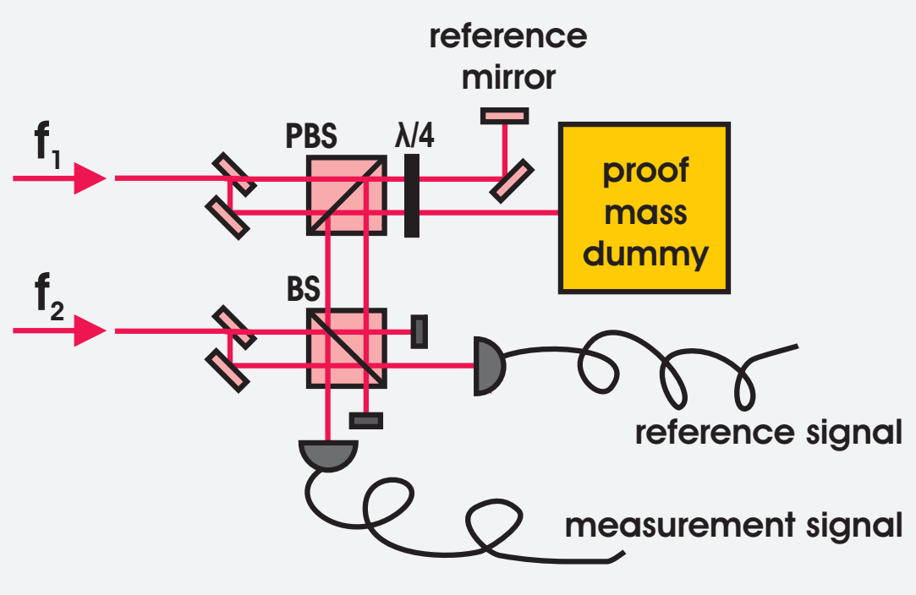
(for frequencies down to 0.1 mHz)

Overview of the LISA payload design



Heterodyne interferometer as optical readout

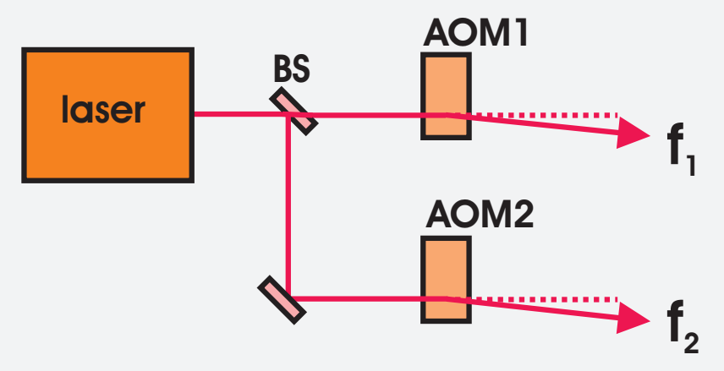
Schematic of the interferometer



cf. C.-M. Wu et al.
Opt. Quant. Electron. **34**: 1267-1276 (2002)

Frequency generation

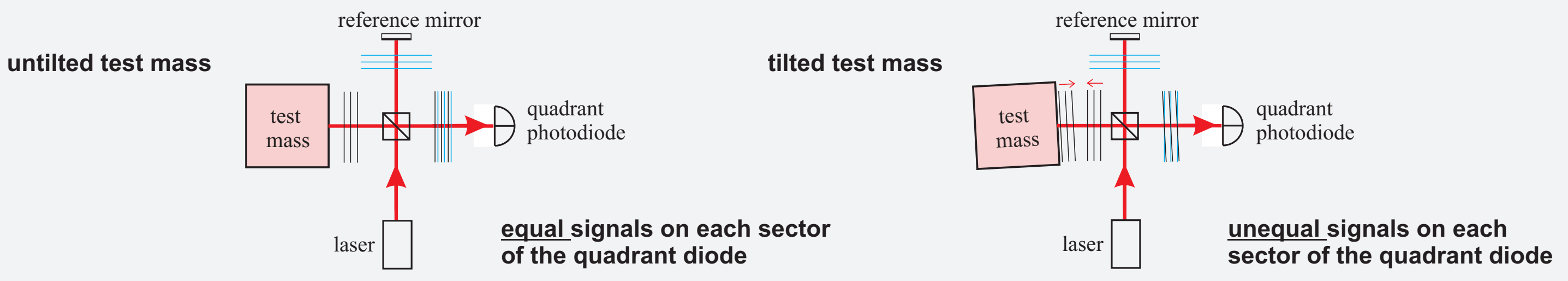
2 acousto-optical modulators (AOMs)...



... or 2 phase locked lasers

Tilt measurement: differential wavefront sensing

replace single-element photodiode in the measurement arm by quadrant diode



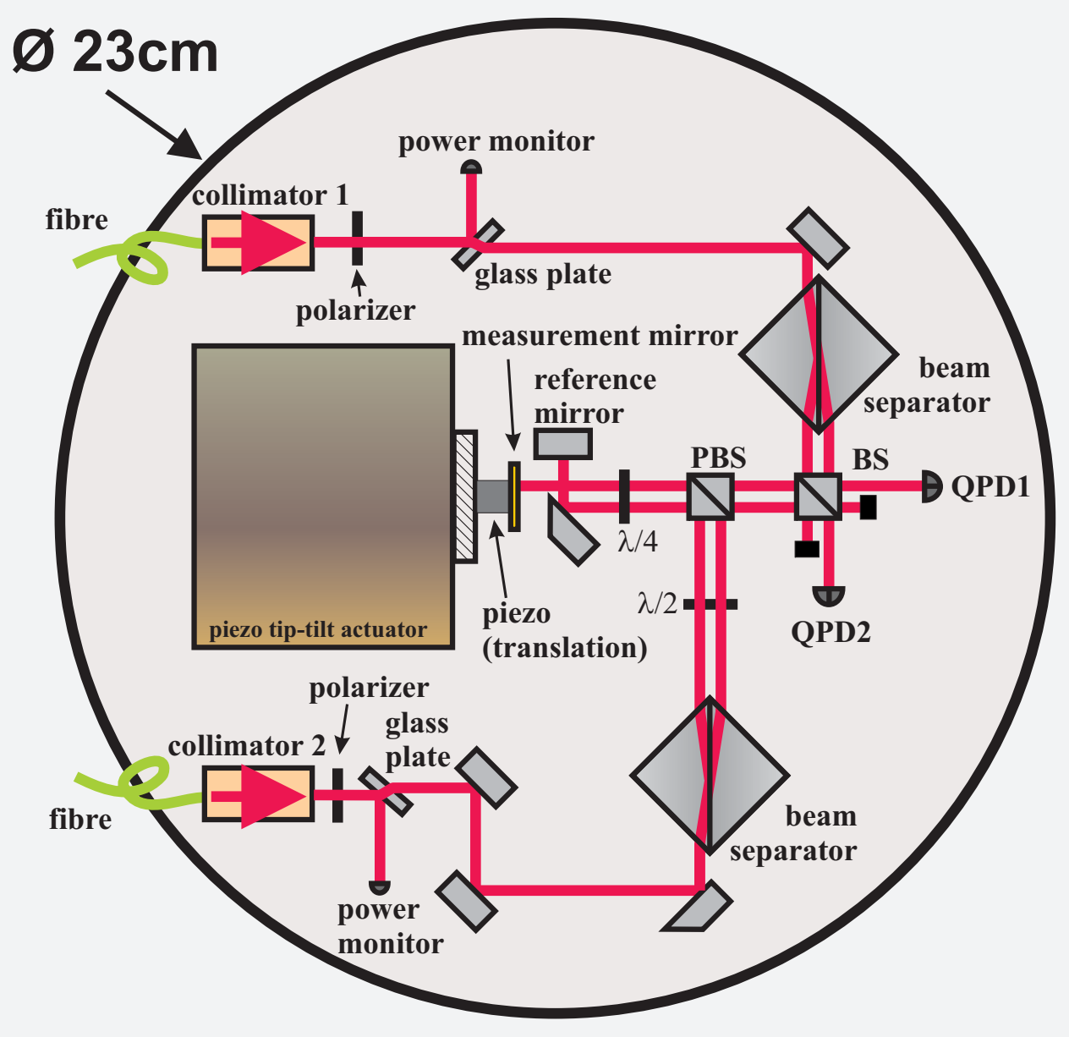
equal signals on each sector of the quadrant diode

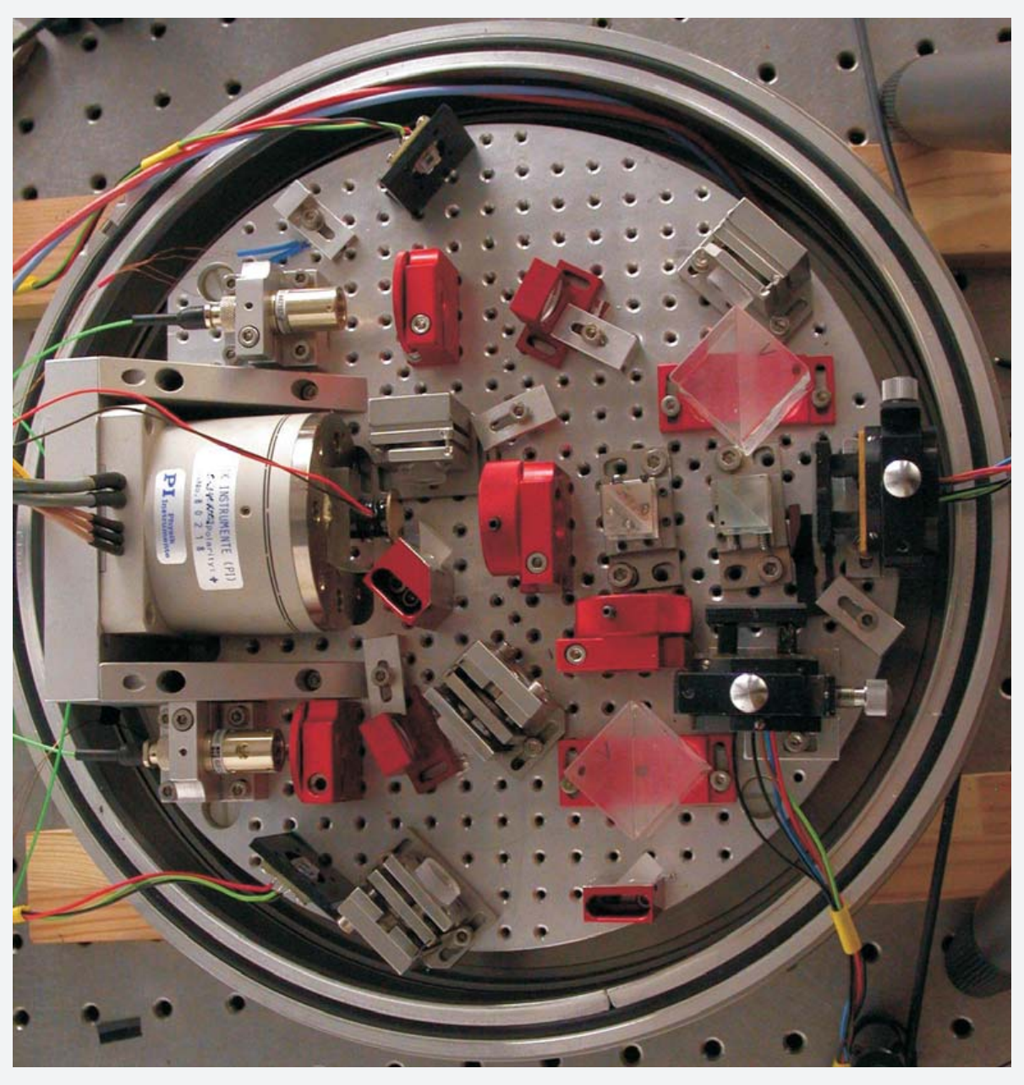
unequal signals on each sector of the quadrant diode

Experimental setup

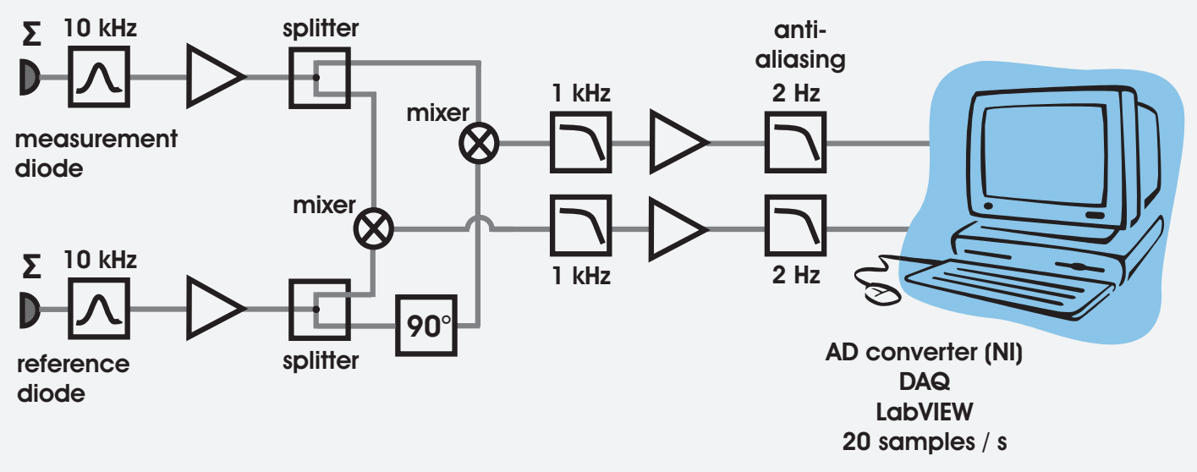
- ✻ NPRO Nd:YAG laser @ 1064 nm
- ✻ 2 AOMs (phase locked) working @ 80 MHz and 79.99 Mhz: f_{het} = 10 kHz
- ✻ interferometer set up in a temperature stabilized vacuum chamber in order to minimize environmental path length variations
- ✻ utilizing compact and robust optical mounts with a beam height of 2 cm
- ✻ proof mass dummy (measurement mirror): piezo tip tilt with additional piezo for translation or fixed mirror
- ✻ ~ 100 μW optical power at test mass dummy
  ~ 200 μW at the quadrant diodes

Ø 23cm



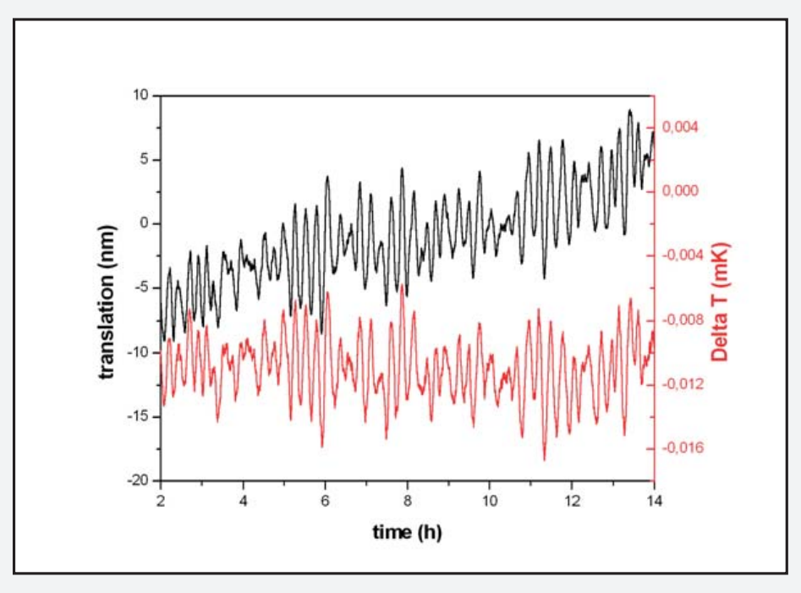


Analog phase measurement

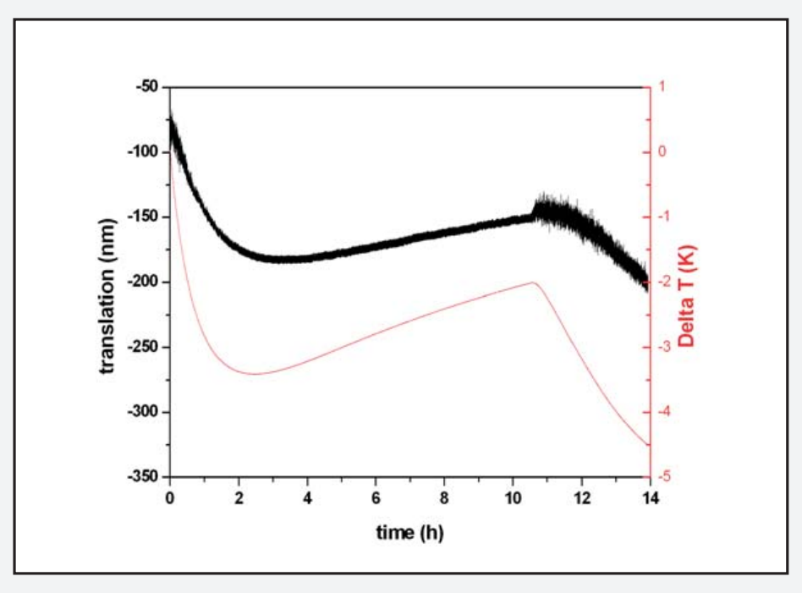


- ✻ in-quadrature measurement in order to overcome λ/2 constraint in the dynamical range
- ✻ data acquisition via National Instruments computer board
- ✻ LabVIEW program for phase computation

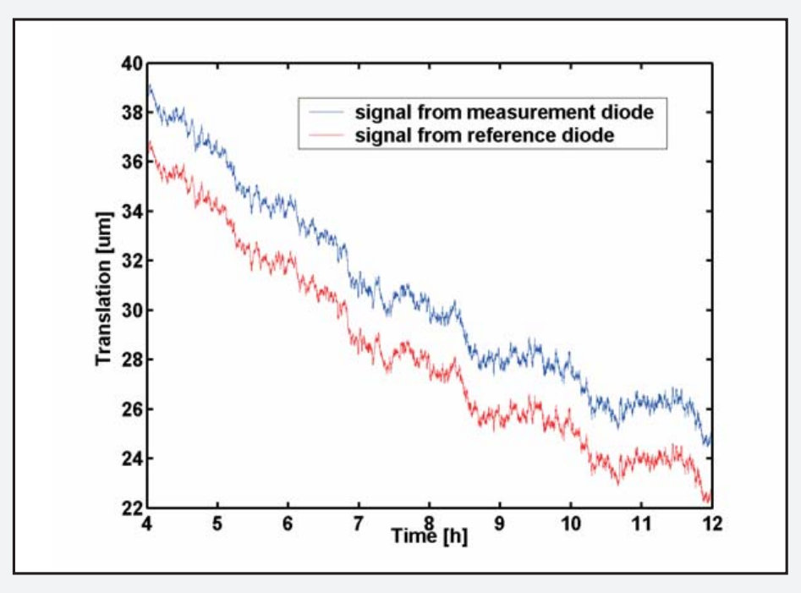
First measurements



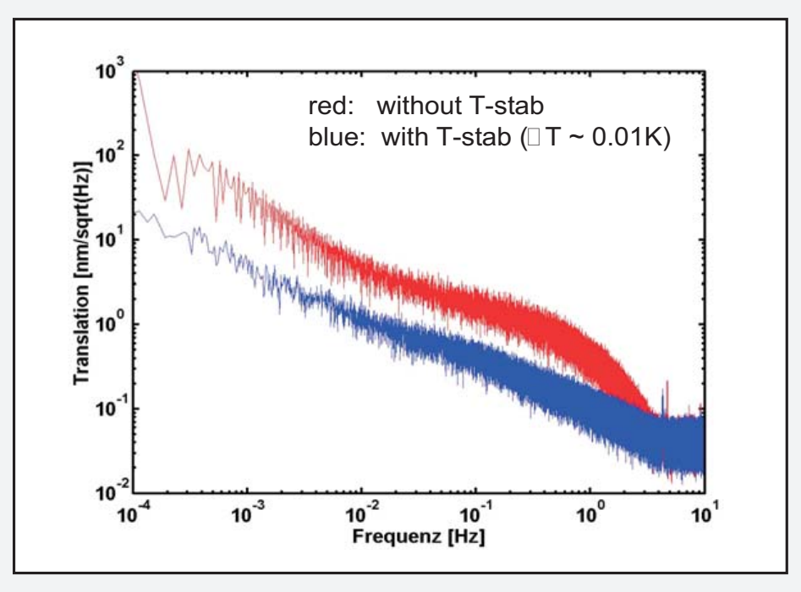
Measured translation signal with piezos in the measurement arm. The large temperature correlation (with a coefficient of ~ 1000 nm/K) is mainly caused by the piezos.



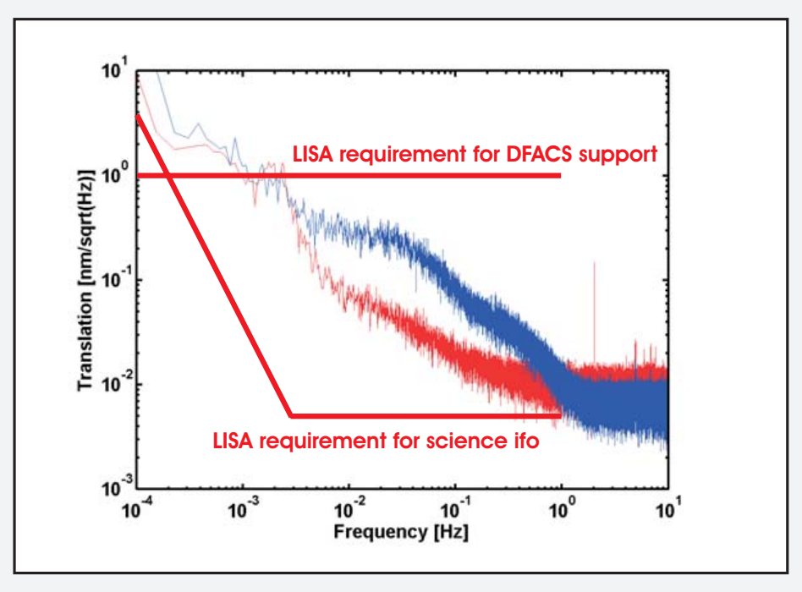
Translation measurement where measurement *and* reference beam are reflected by the piezo tip tilt: temperature correlation coefficient is reduced to ~ 25 nm/K.



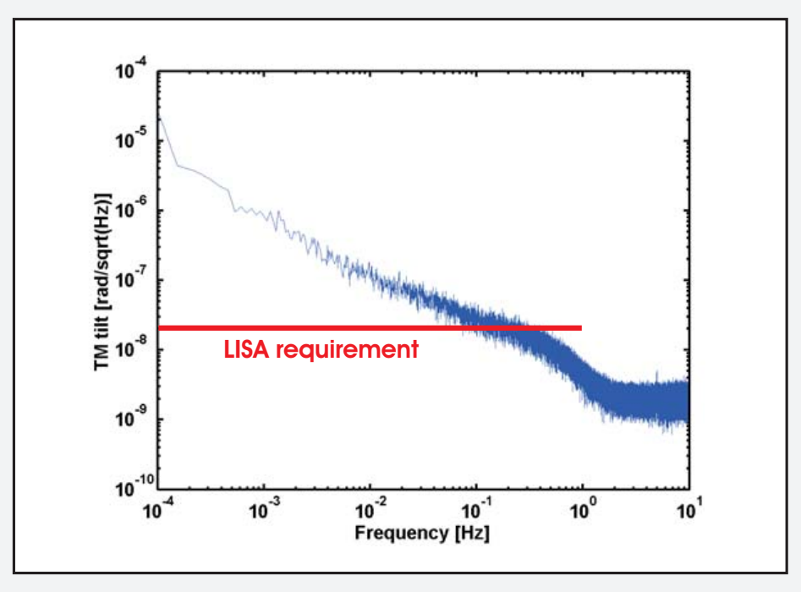
Measurement of the common mode effects. The two sum signals are separately phase compared to an external 10 kHz reference: 600 nm noise here compared to 4 nm noise in the differential interferometer, i.e. common mode rejection of ~ 150. The drift is mainly caused by the fibres and the AOMs.



Power spectral density of the measurement where *both* beams are reflected by the piezo tip tilt.



Power spectral density of the translation measurement where measurement *and* reference beam are reflected by the same *fixed* mirror.



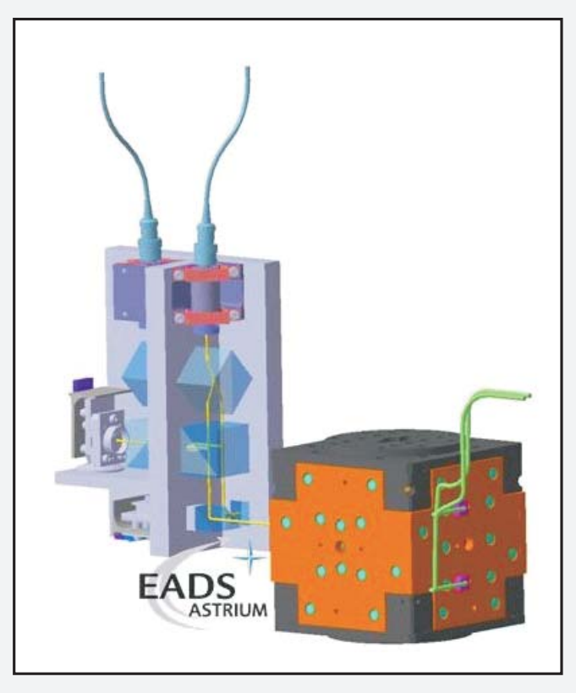
Power spectral density of the tilt measurement where measurement *and* reference beam are reflected by the same *fixed* mirror.

Planned improvements

- ✻ larger vacuum chamber (0.8 m x 1.1 m) with better temperature stability
- ✻ implement intensity stabilization of the two heterodyne frequencies
  (by feedback onto the AOM RF-amplitudes)
- ✻ implement frequency stabilization of the (frequency doubled) Nd:YAG laser to a hyperfine transition in molecular Iodine
- ✻ implement phase-lock of the two heterodyne frequencies at the fibre outputs in order to minimize effects caused by AOMs and fibres (i.e. minimize common mode signal)
- ✻ replace analog phasemeter by a digital one (National Instruments FPGA board)

Outlook

Quasi-monolithic setup using a mechanically and thermally stable glass ceramics (e.g. Zerodur with a thermal expansion coefficient of $2 \cdot 10^{-8}$/K) as baseplate where the optical components are made out of fused silica and connected to the baseplate via hydroxide-catalysis bonding. This leads to a very small, robust, fibre-coupled module.



Acknowledgements: The authors thank the Albert-Einstein Institute Hannover for their support and discussions.