LISA and LISA Pathfinder

space-based laser interferometry towards gravitational wave astronomy

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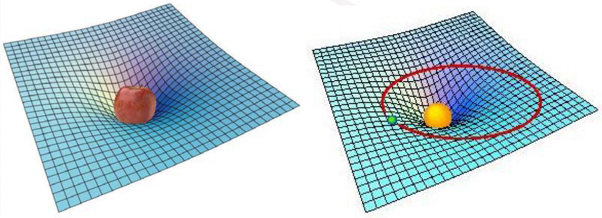
Historical Background: theoretical formulation

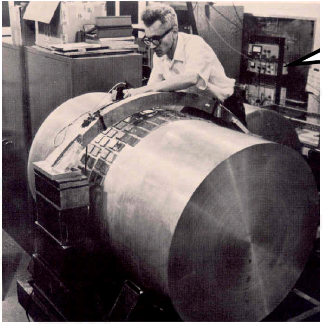
- 1916. Albert Einstein proposed a new model for Gravitation: General Theory of Relativity.



  - Mass determines space curvature.
  - Space curvature determines the movement of the masses.
- Accelerated masses $\Rightarrow$ Gravitational Waves.

Historical Background: experimental pioneers

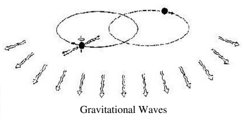
- 1960s. Joseph Weber gives first steps for possible experiments: Resonant Bar Detectors sensitivity limited to bar mechanic resonance active follow-on projects (EXPLORER, AURIGA, MINIGRAIL...)

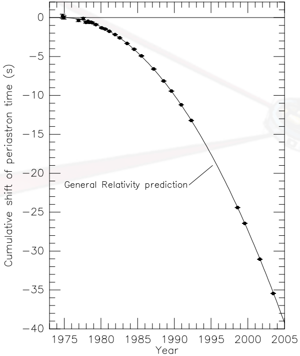


- 1970s. First laser interferometers as gravitational-wave detectors

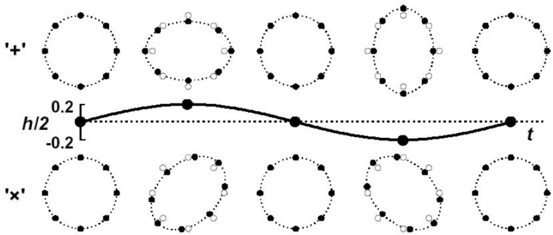
Historical Background: nobel prize

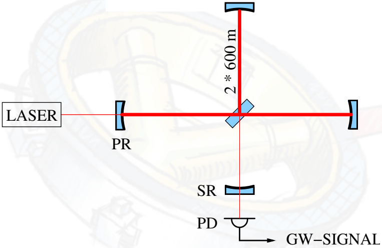
- 1974. *PSR1913+16* discovered by Russel Hulse and Joseph Taylor:
  First indirect evidence of the existence of gravitational waves
- 1993. Hulse and Taylor were awarded the Nobel Prize in Physics





Direct measurement of gravitational waves...

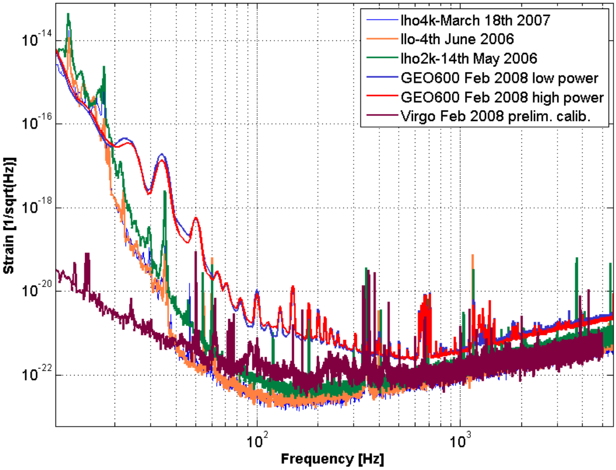




- Gravitational waves change distances between floating test-masses as they propagate.
- **Interferometers** monitor the distance between test masses $\Rightarrow$ ideal GW detectors.

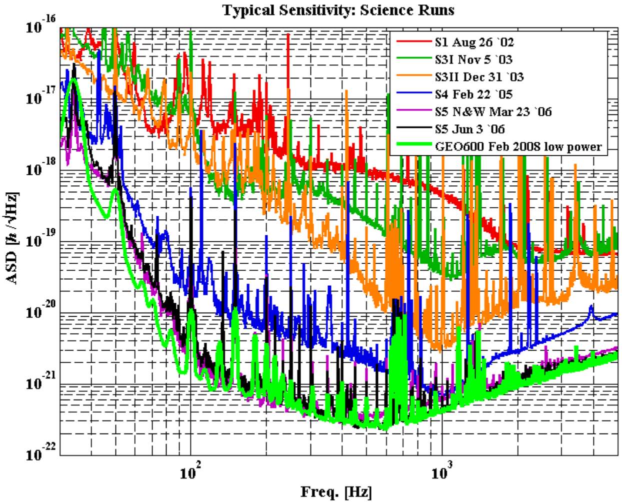
Ground based GW detector network

Ground based interferometer detectors sensitivity



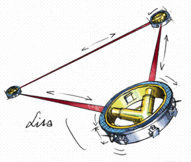
- Sensitivity of interferometric GW detectors

GW detector at AEI Hannover: GEO600



- Sensitivity evolution of GEO600: improvement of factor 3000 in 4 years!

LISA: Laser Interferometer Space Antenna



- Gravitational wave detector in **space** (ESA and NASA collaboration)
- Sensitivity at low frequencies: $10^{-4}\,\mathrm{Hz} \cdots 0.1\,\mathrm{Hz}$
  - Inaccessible for ground-based detectors (local disturbances...)
- Interferometer arm: 5 Million km $\pm$ 1 % $\;\rightarrow\; h = 2\dfrac{\delta L}{L}$
- **Guaranteed** sources of gravitational waves
- Launch: 2018

The LISA orbit

Three satellites in equilateral triangle formation, following the earth around the sun at a distance of 50 million kilometers.

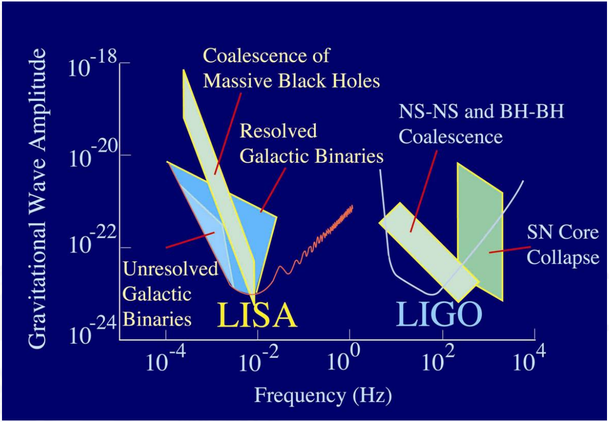
One LISA satellite

Each satellite is equipped with two free-floating test masses and two telescopes aligned (in 60 °) towards the other two satellites.

Optical bench and Drag-Free Test Mass

- Basic measurement: fluctuations of **one LISA arm**.
  - LISA arm: 5 million km (line of sight) between two test masses.
- Two arms combined → Michelson interferometer → GW detector.

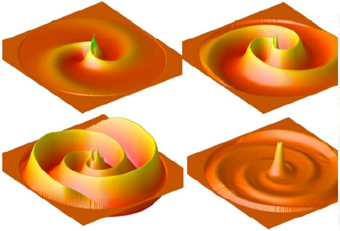
LISA strain sensitivity $\mathbf{h} = 10^{-23}$ at 1 mHz

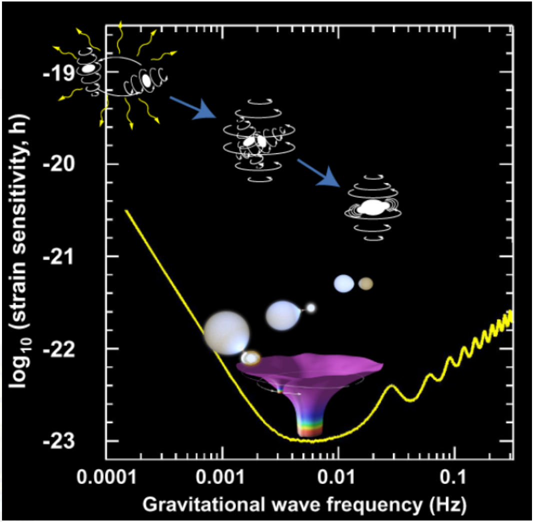


- One year integration time and SNR $= 5 \Rightarrow \mathrm{h} = 10^{-23}$
- Comparable to ground based detectors at high frequencies

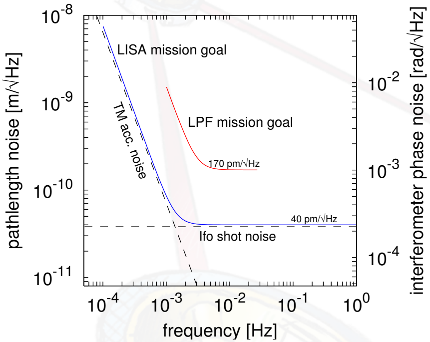
LISA main sources

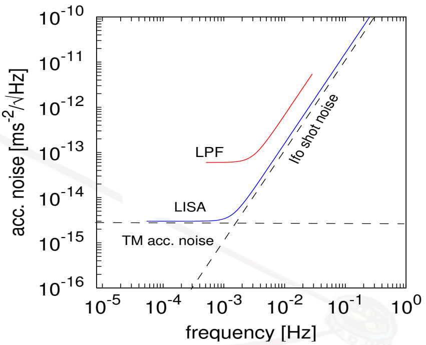
- Binary systems (from SMBH to white dwarfs)
- Coalescence and mergers
- EMRI extreme mass ratio inspirals
- Backgrounds





LISA main technologies





Interferometry

Optical pathlength sensitivity:

$\widetilde{\delta s} = 40\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 mHz.

Acceleration noise

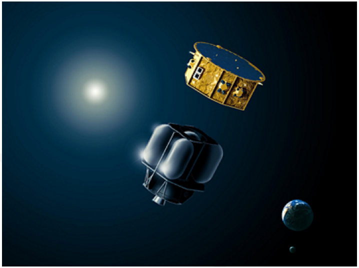
Test masses drag-free level:

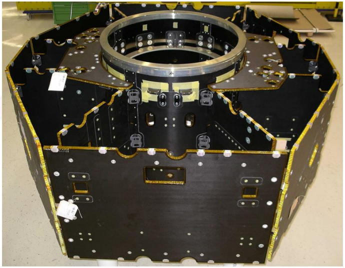
$\widetilde{\delta a} = 3\times 10^{-15}\,\mathrm{m}\cdot\mathrm{s}^{-2}/\sqrt{\mathrm{Hz}}$ at 1 mHz.

LISA pathfinder mission (LPF)

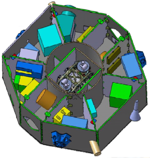
Demonstration of LISA technologies in space

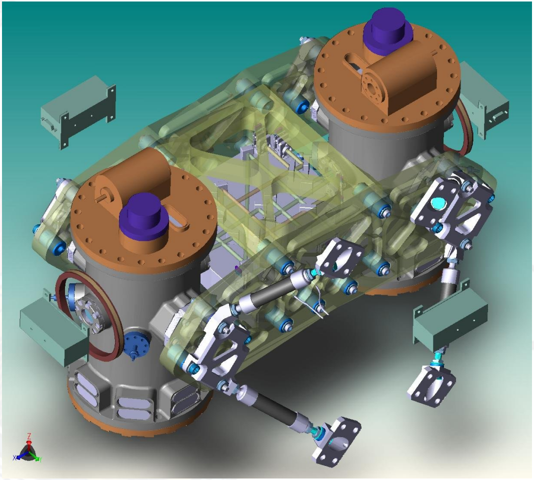
- Two LISA-like TMs inside one satellite ⇒ one small "LISA-arm".
- **Interferometry** between Test-Masses with **picometer** precision.
- **Drag Free** System for Test Masses with **femtonewton** stability.
- Micronewton thrusters for drag free control of the satellite.
- LISA Technology Package (LTP): European experiment (this talk).

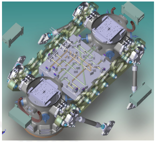




The LISA technology package (LTP) core assembly

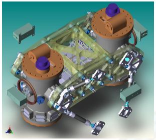


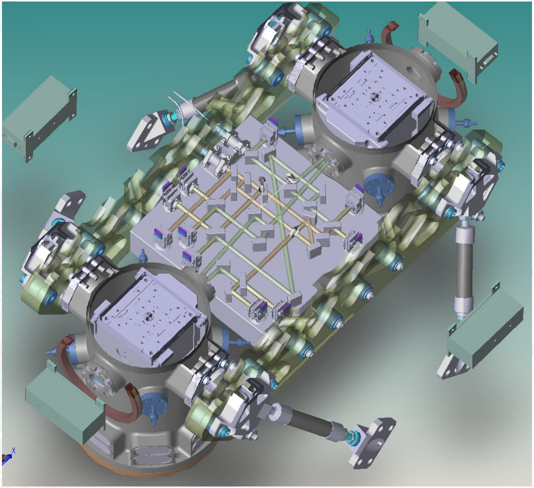


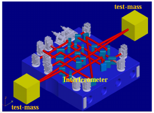


Two test masses inside their vacuum enclosures and interferometer between them.

The LTP core assembly

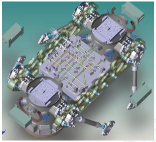


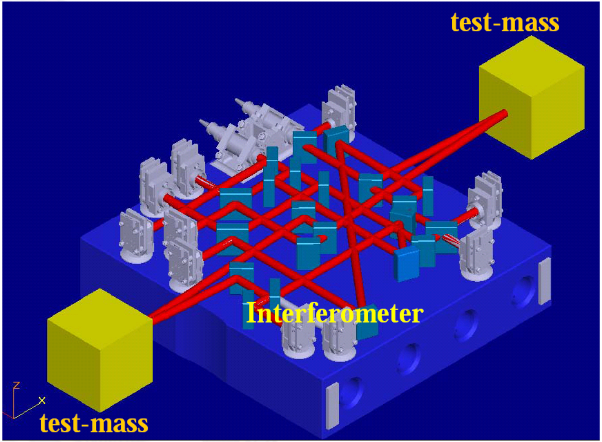


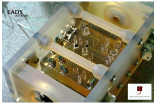


Two test masses inside their vacuum enclosures and interferometer between them.

LTP interferometric concept

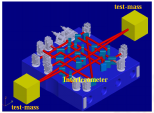


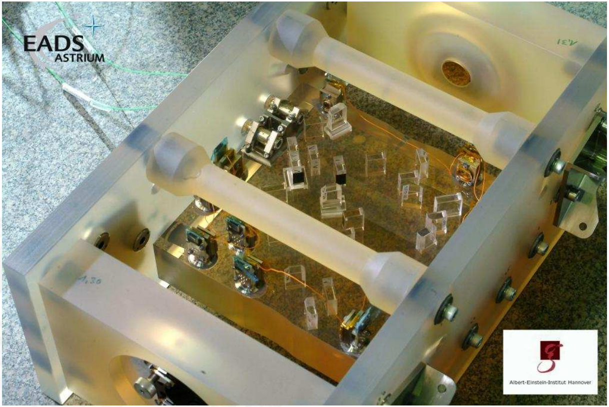




The LTP interferometer monitors test masses position fluctuations and alignment.

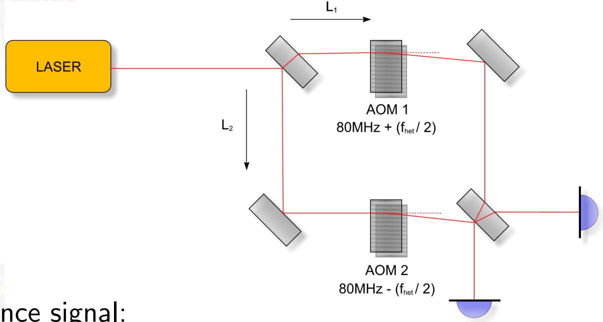
LTP optical bench engineering model (EM)





Space qualification of the EM optical bench

LPF interferometry concept: heterodyne Mach-Zehnder

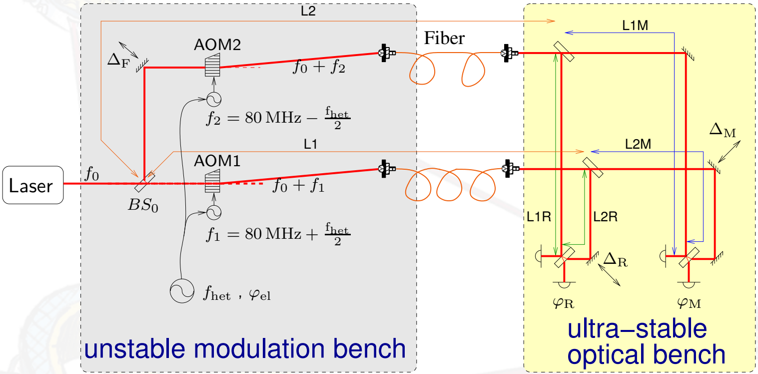


Interference signal:

$$I(\varphi) = A(1 - c\cos(2\pi\ \mathrm{f_{het}}\ t + \varphi_{\mathrm{int}}))$$

$$\varphi = \frac{2\pi(L_1 - L_2)}{\lambda} = \frac{2\pi s}{\lambda} = \varphi_{\mathrm{R}}$$

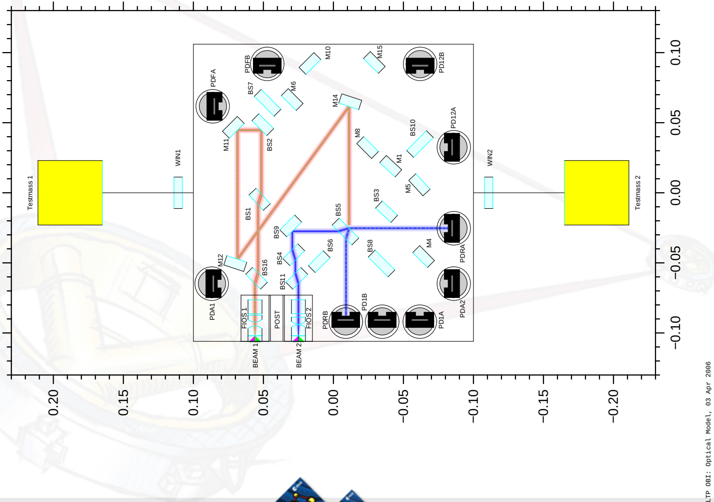
LPF interferometry concept: "reference - measurement"



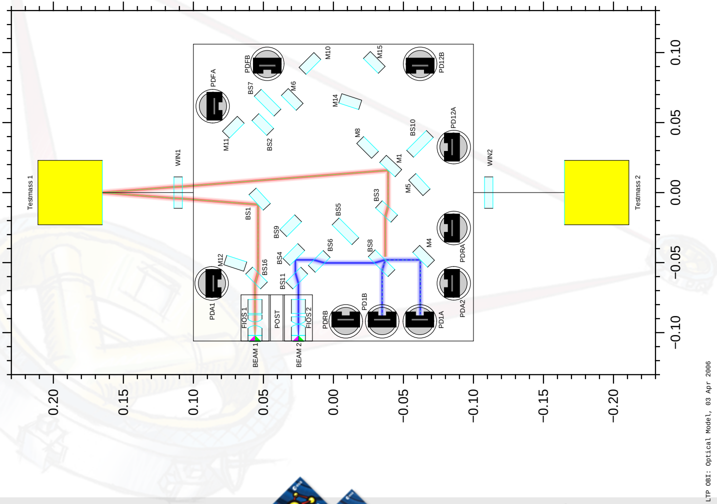
Common-mode noise subtraction

- Pathlength fluctuations from modulation bench present in both interferometers (Reference (R) and Measurement (M)).
- LTP Main output: $\varphi_R - \varphi_M \Rightarrow$ fluctuations cancel.

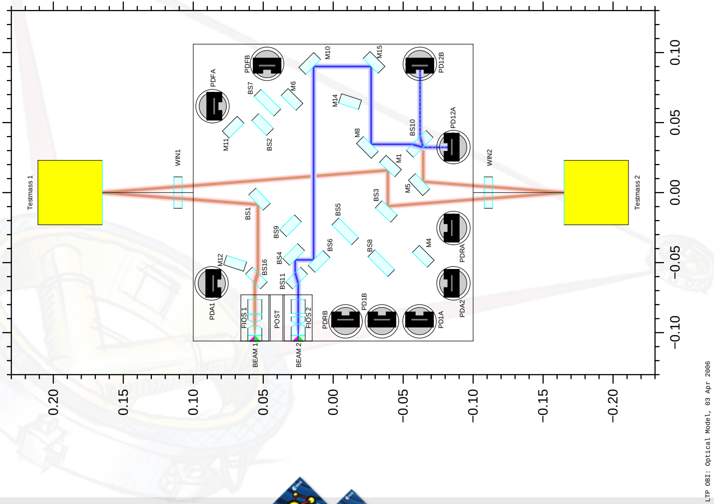
LTP Optical layout: reference interferometer



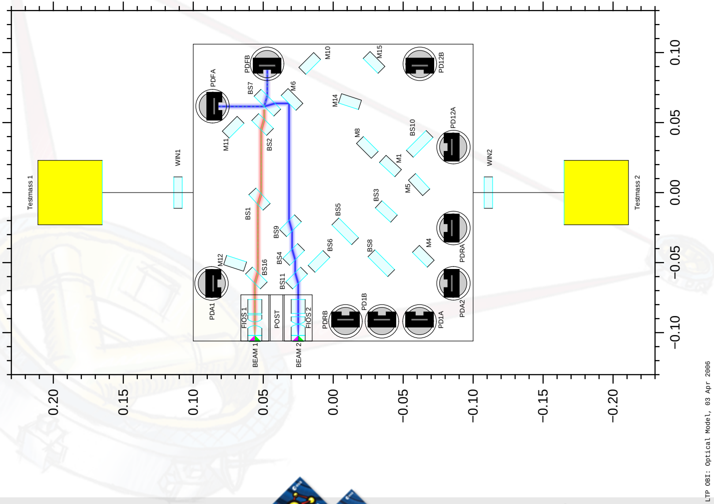
LTP Optical layout: X1 interferometer



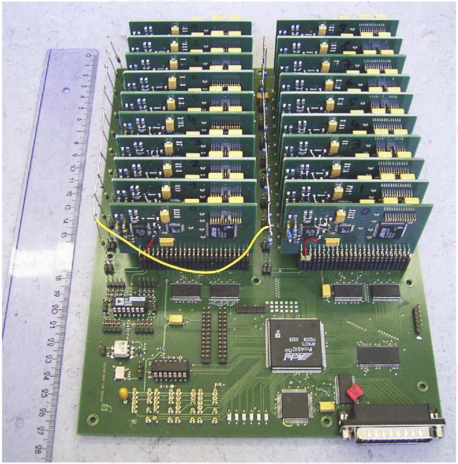
LTP Optical layout: X12 interferometer



LTP Optical layout: frequency interferometer



Phasemeter

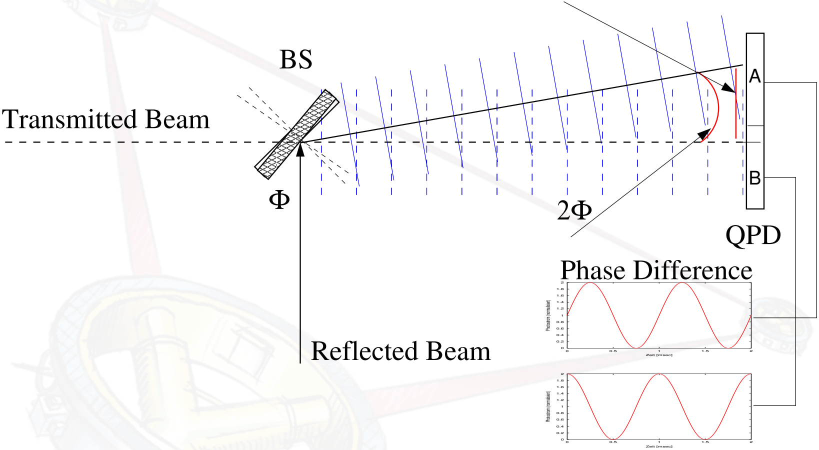


- FPGA based - 20 channel
- Output per quadrant: $dc_k,\ y_k,\ z_k$
- $c_k = z_k + iy_k$
- For each QPD:

$$DC_n = \sum_k dc_k,$$

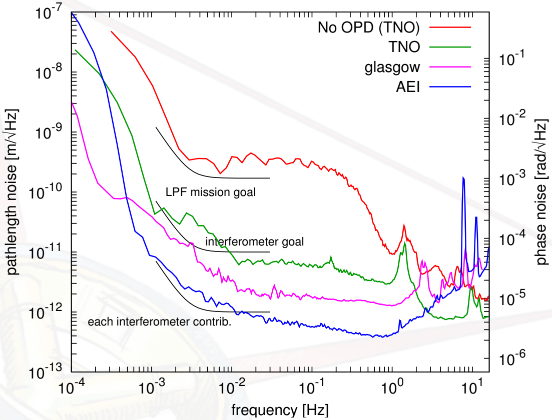
$$c_n = \sum_k c_k$$

Differential Wavefront Sensing



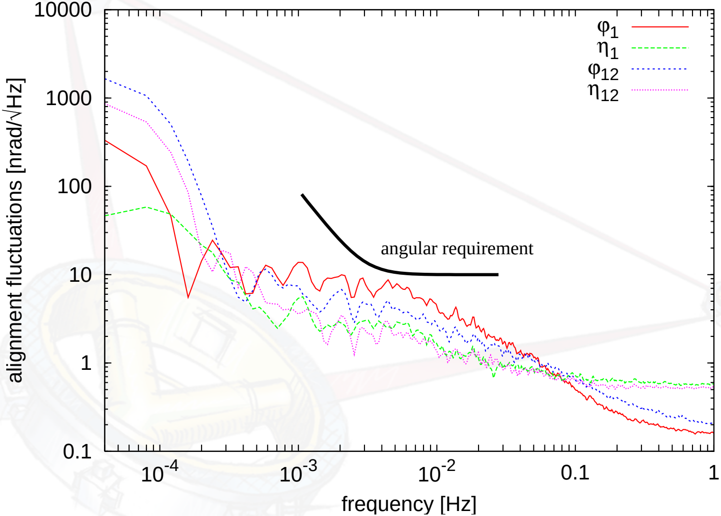
- Requirement: $10\,\frac{\mathrm{nrad}}{\sqrt{\mathrm{Hz}}}$, between 3 mHz and 30 mHz

LTP interferometry test-bed: performance milestones

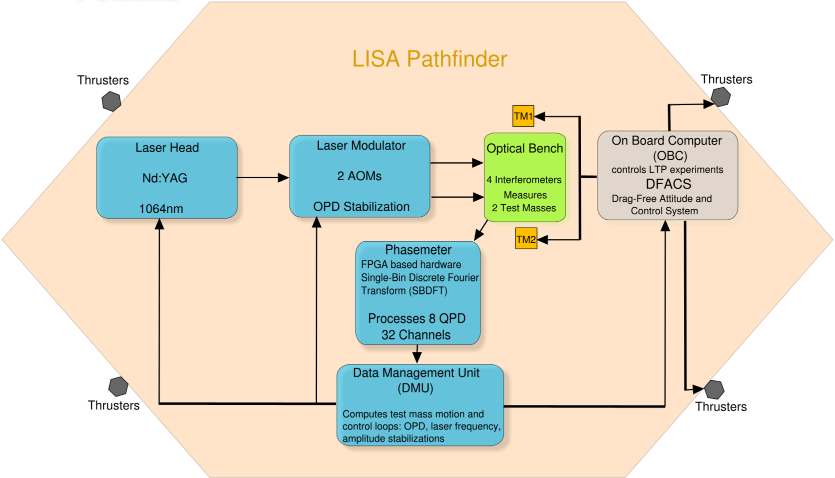


Current performance with AEI phasemeter and EM optical bench.

DWS alignment sensitivity



Testing engineering and flight hardware at AEI



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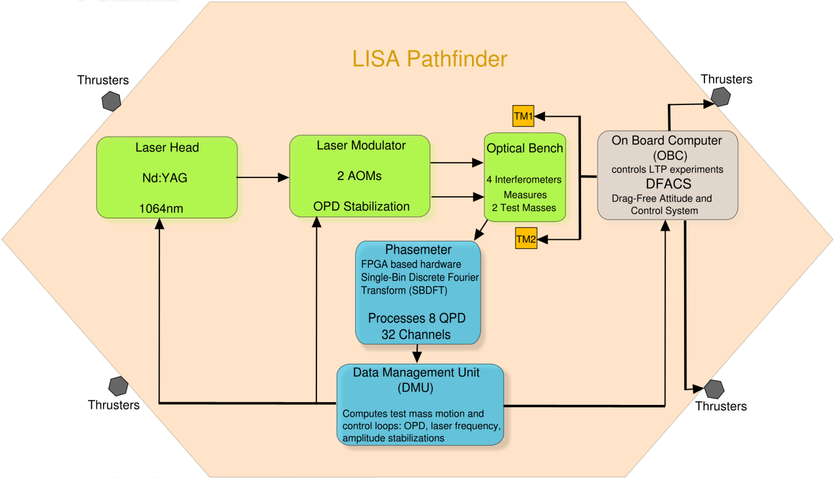

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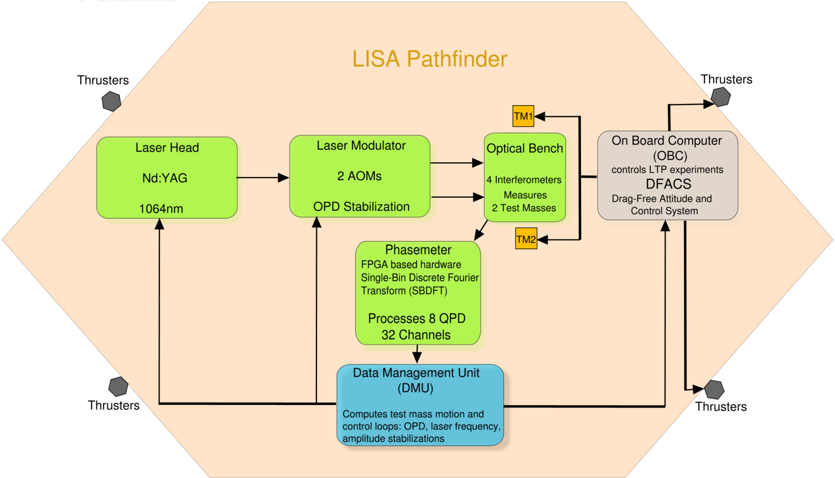

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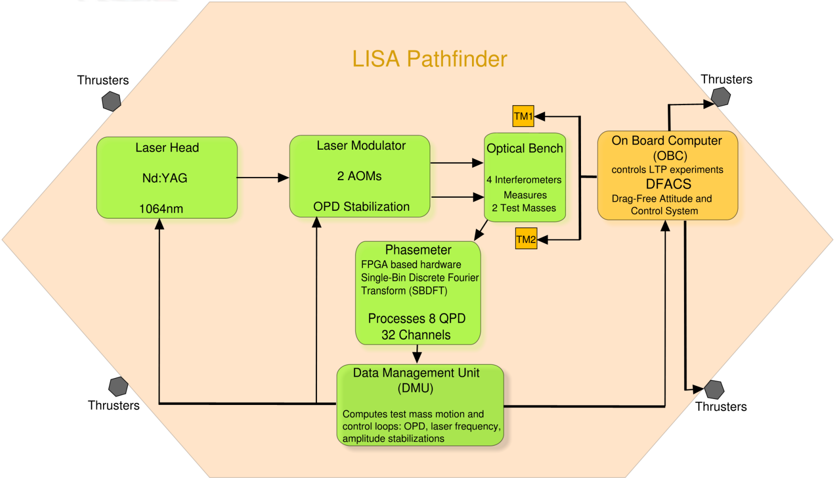
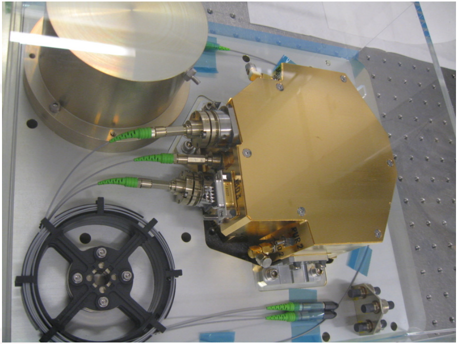


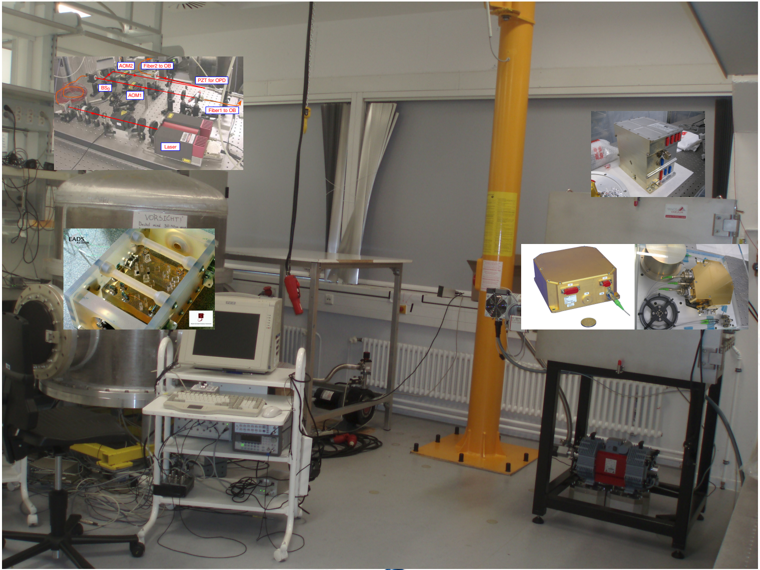
LPF Engineering model of the Laser and Modulation Bench



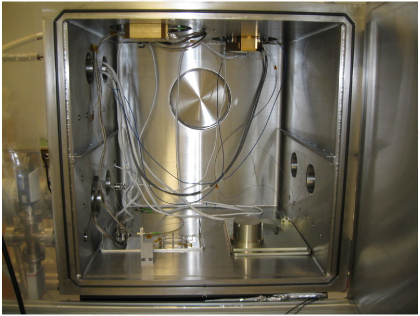
Starting with...

Starting with...

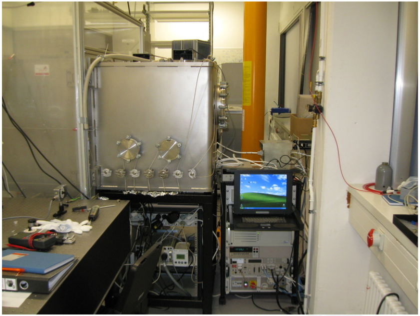
Starting with...



Support equipment



Engineering Models inside Vacuum chamber



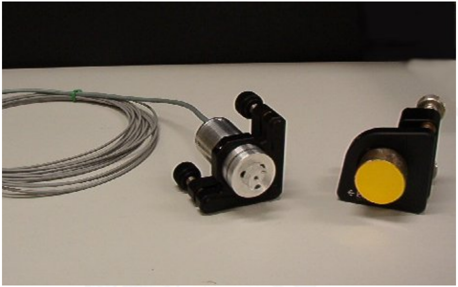
Ground support equipment for Laser Assembly

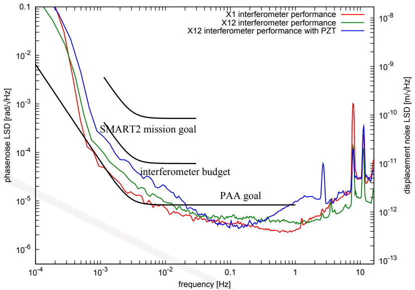
- Cubic chamber for Engineering and Flight Models
- Two stage clean room tent for unpacking

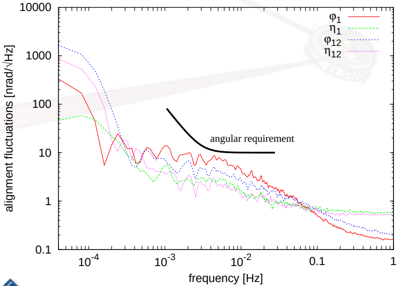
Current research activities

- LISA Pathfinder:
  - Prepartion of test-bed for engineering and flight hardware testing.
  - Testing of experiment procedures and optical components.
  - LTPDA: Development of software tool for mission's data analysis.
- LISA:
  - EOM phase fidelity.
  - Fiber reciprocity.
  - Weak-light phase-offset lock.
  - Point-ahead angle mechanism (PAAM).
  - LISA TM optical readout.
  - Phasemeter.

LTP interferometer performance

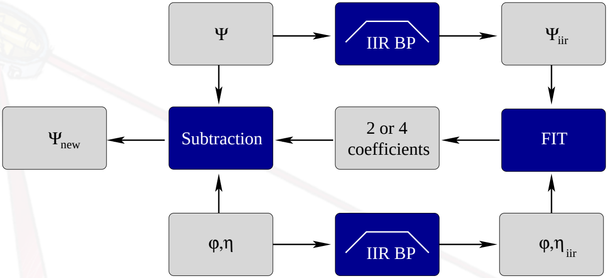


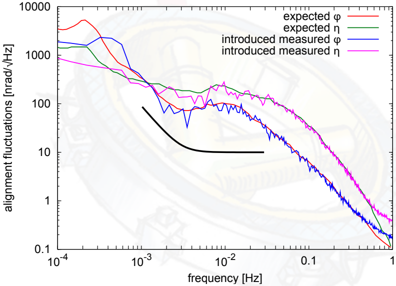


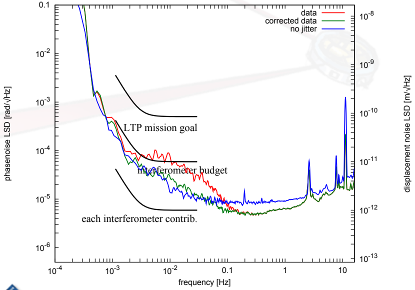


- 3-axis PZT actuated mirrors
- wide range
- long-term stability

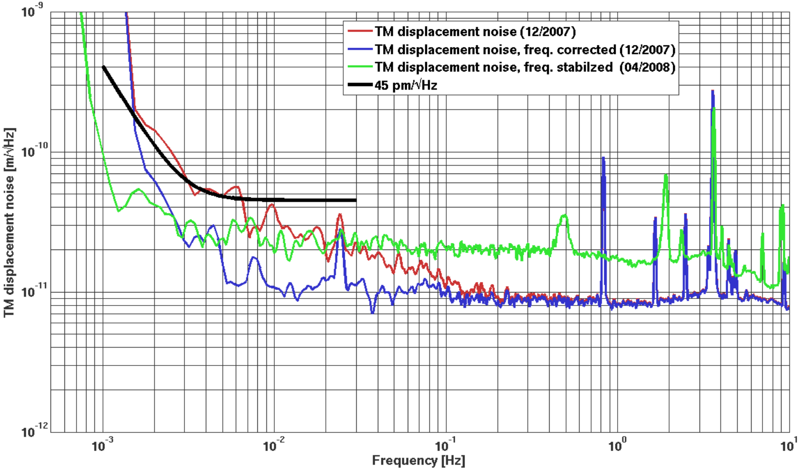
Angular noise subtraction



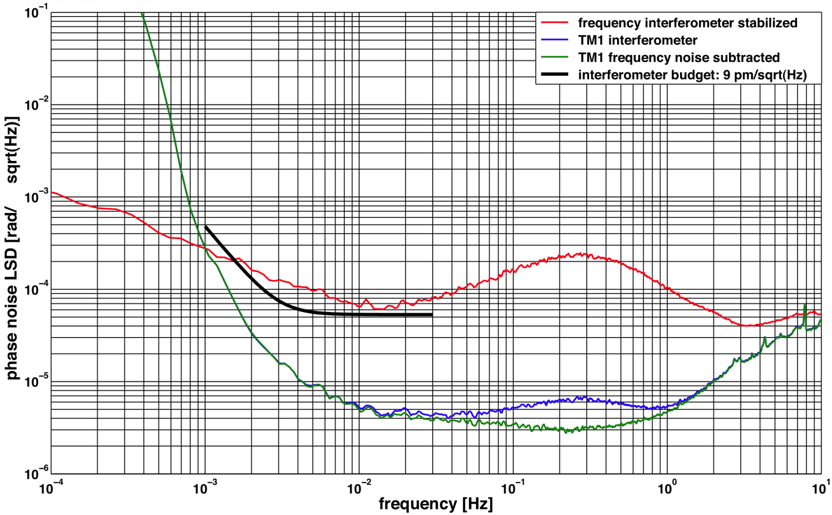




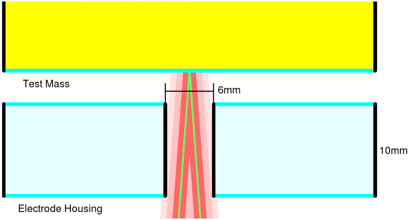
Laser frequency noise subtraction: free-running laser

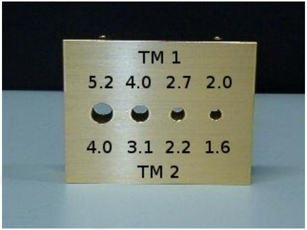


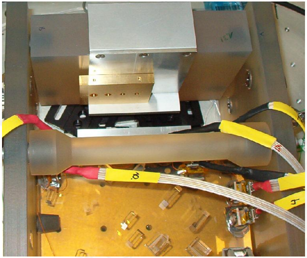
Laser frequency noise subtraction: rest noise

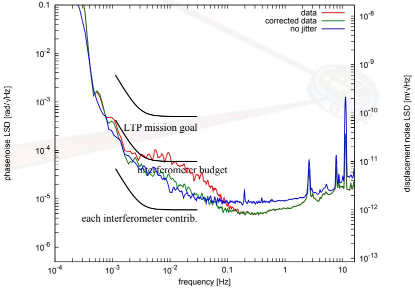


Inertial Sensor beam clipping

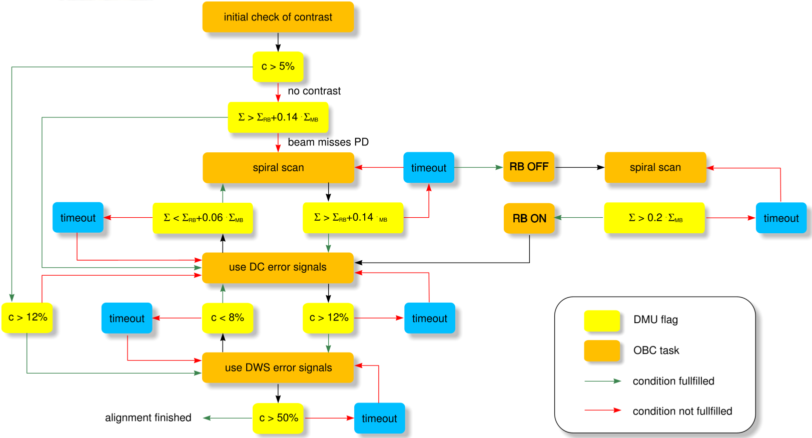






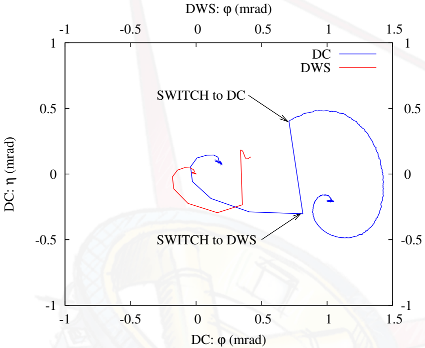


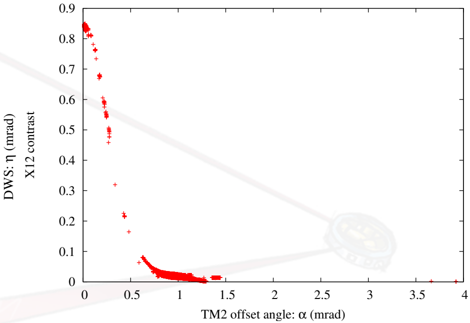
Initial TM alignment



- DMU/OBC tasks separated
- asynchronous data link
- averaged alignment signals
- alignment loop closed

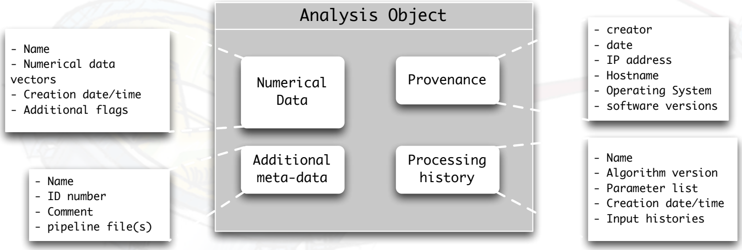
Experimental Demonstration





LISA Technology Package data analysis: LTPDA

- Development of software tool for mission data analysis.
- ESA verification procedure starting now.
- Based on the concept of analysis objects:
    - structure containing data, history, information on provenance of the object.
    - ease data analysis handling: reproducibility and traceability of results.

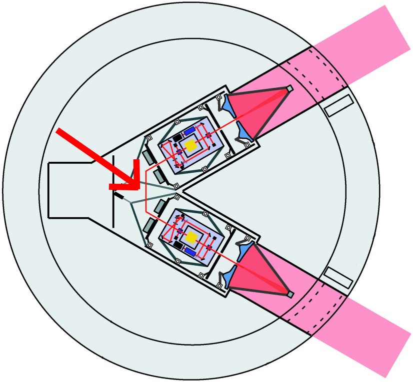


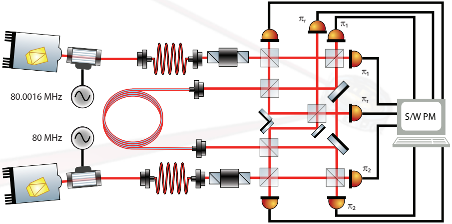
LTPDA

- Developed as MATLAB toolbox using object-oriented programming.
- Collection of many very useful and smart algorithms for data analysis.
- **Free** software for data anylisis for download: http://www.lisa.aei-hannover.de/ltpda

Fiber reciprocity

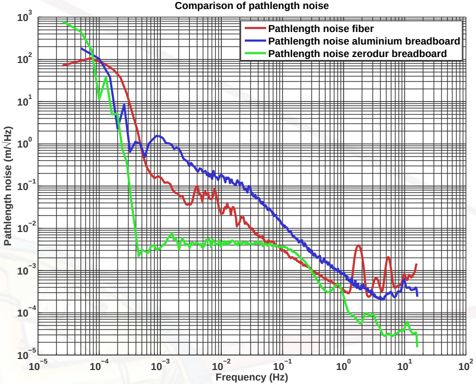
- Fiber link is current baseline for LISA
- Aim is to investigate non-reciprocal pathlenght noise





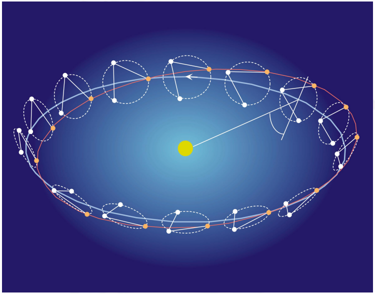
Fiber reciprocity

- Sensitivity of the setup



- Length measurement and fiber reciprocity reach comparable level
- Sensitivity limited by mechanical stability of setup ⇒ next step: Bonding!

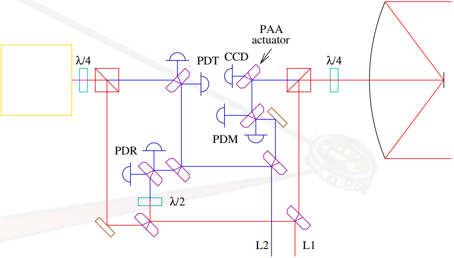
Point-ahead angle (PAA)



- Rotation axis 60 degrees inclined to the ecliptic plane
- Nutation of the rotation axis results in significant out-of-plane PAA requiring active compensation

Beam divergence with 30 cm – 40 cm telescope:

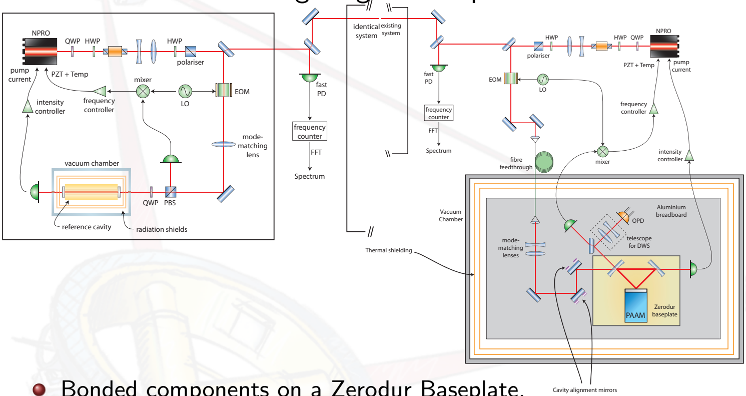
$$\approx 2\mu\text{rad}$$



"Strap–down" Optical Bench with former backside ifo as heterodyne optical readout and Karsten's frequency swapping drawn by G Heinzel AEI 2005/05/19

Point-ahead angle mechanism tests

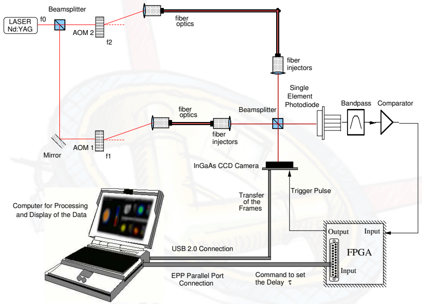
- Adapting the existing frequency stabilisation setup at AEI Hannover for testing longitudinal performance of PAAMs:

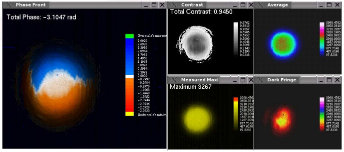


- Bonded components on a Zerodur Baseplate.
- Thermally stable vacuum system ($10^{-5}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ @ 3 mHz).
- Accuracy $<<$ 1 pm longitudinal resolution at 1 mHz.
- Angular jitter readout via differential wave front sensing.

Real-time wavefront measurement device

- Wavefront quality in LISA of great importance for sensitivity
- Magnification of wavefront distortions over 5 million km
- Device developed for LPF developments: based on heterodyne phase detection





Example of measured wavefronts

- Approximately 6-7 phasefront measurements per second
- Measured accuracy to 3 mrad $\approx \lambda/2000$
- Instrument is currently being used for manufacture flight models of LPF fiber injectors and optical bench

LPF Engineering Model

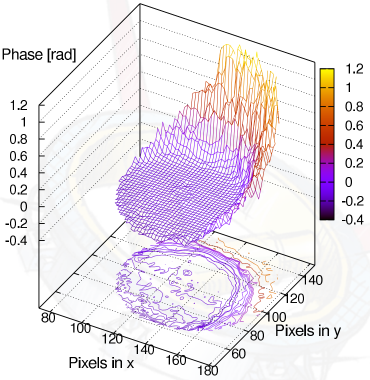
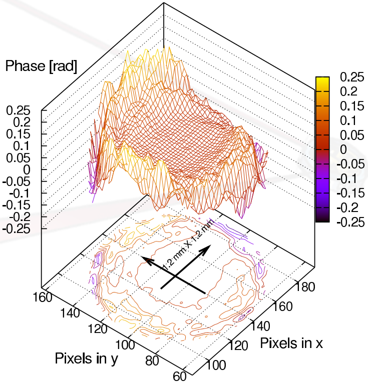
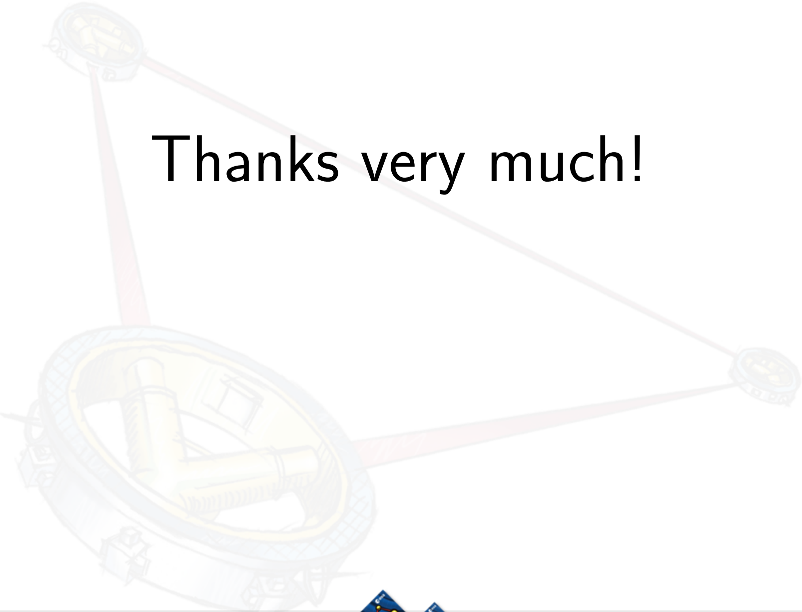


table-top interferometer



Summary

- LISA Pathfinder is a great test facility for LISA technology.
- Topics such as TM angular noise, on-orbit auto-alignment and LISA local interferometry can be tested.
- LISA interferometry is much more complex: point-ahead angle mechanism, laser frequency noise, wavefront distortions
- Still a long way to go but we're getting there...



Thanks very much!