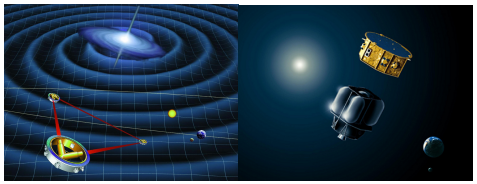
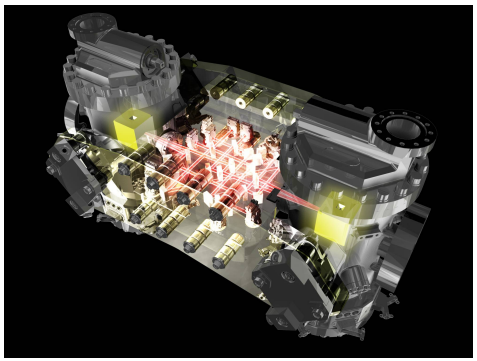
Space-based gravitational wave observatories

eLISA/NGO and LISA Pathfinder

Felipe Guzmán

Max Planck Institute for Gravitational Physics

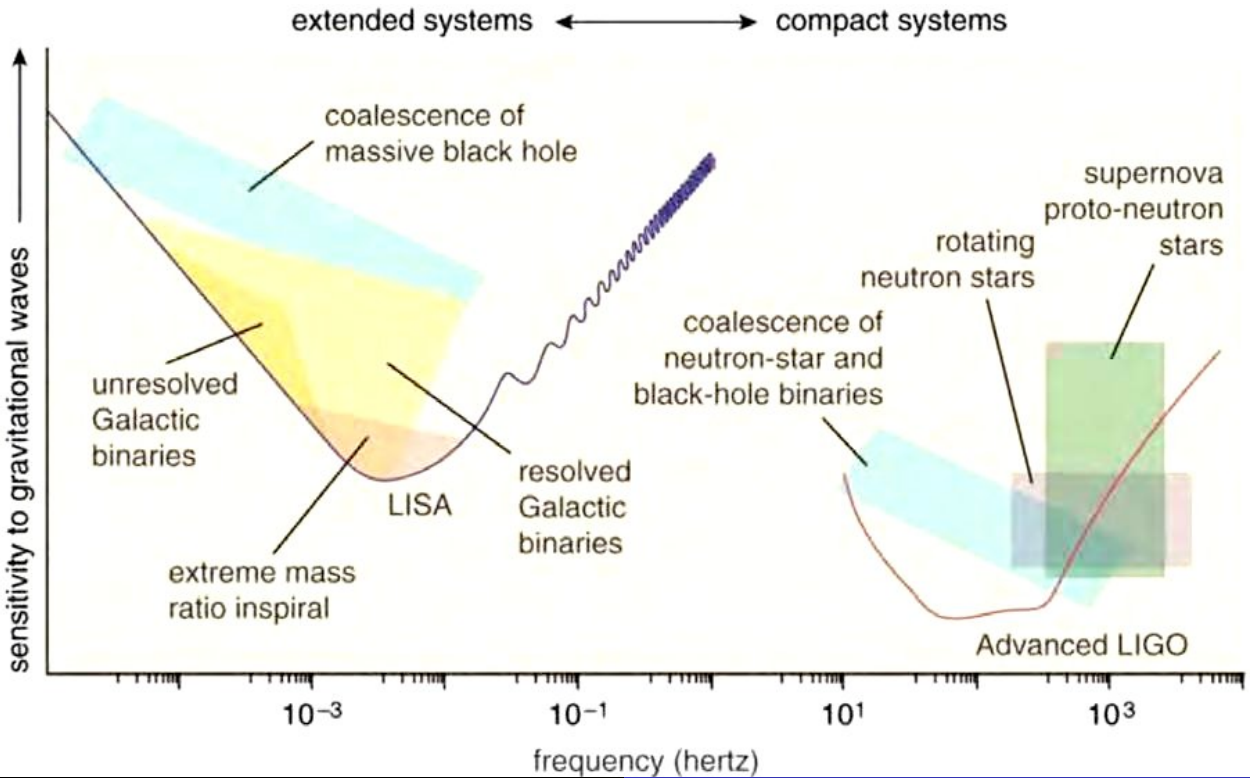




Astroteilchenphysik-Tagung
Zeuthen, 20.09.2012

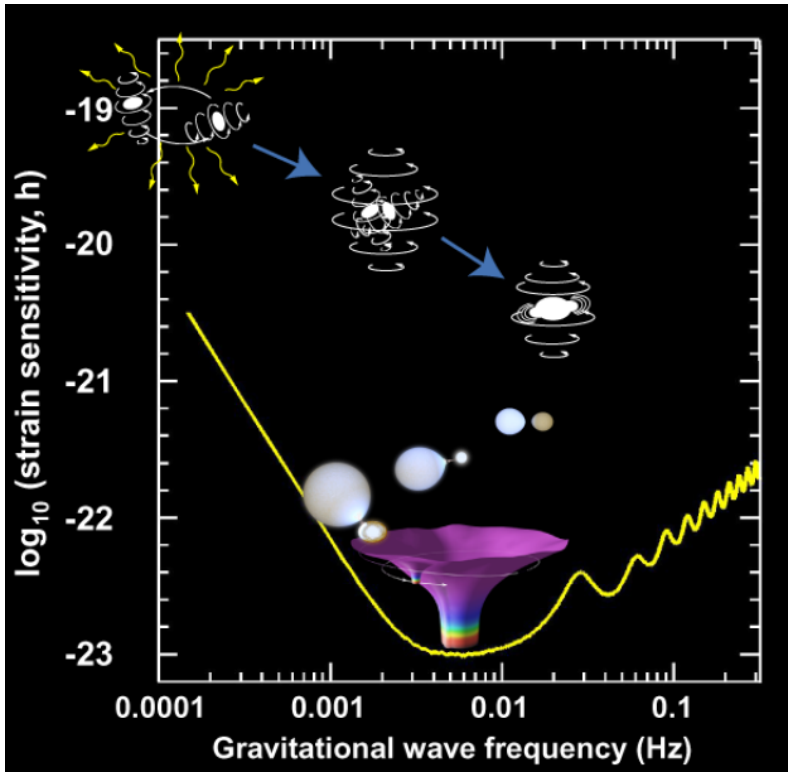
Sources of gravitational waves

- Binary systems
  - NS-NS, BH-BH, close WD
  - Massive black holes
  - Combined binaries
- Binary coalescence
- Supernovae
- Formation of massive black holes
- Unknown sources

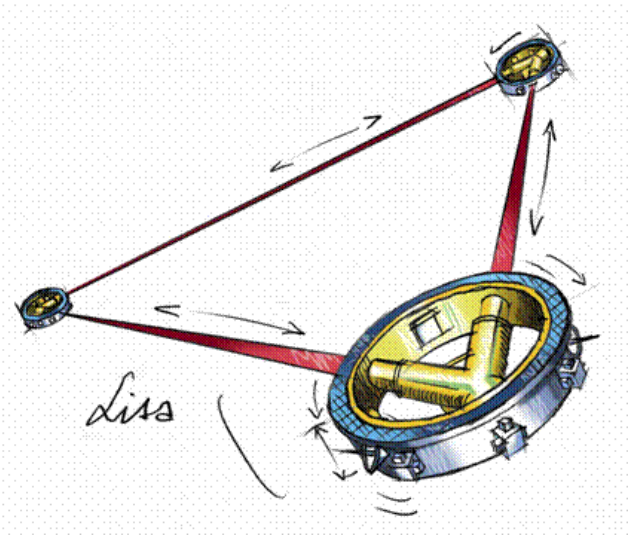


Why going into space?

- Frequencies below 1 Hz innacesible for ground-based detectors:
  $\rightarrow$ thermal noise
  $\rightarrow$ seismic noise
- More continuous sources an other interesting sources in LF band
- Detection at low frequencies
  $\Rightarrow$ Enlargement of the armlength



LISA: a space-based observatory concept



- LISA / NGO / eLISA ...
- Sensitivity at low frequencies: $10^{-4}\,\text{Hz} \cdots 0.1\,\text{Hz}$
  - Inaccessible for ground-based detectors (seismic noise predominance)
- three-spacecraft constellation in a heliocentric orbit trailing the Earth
- Interferometer arm: 10^9 m $\rightarrow$ $h = 2\dfrac{\delta L}{L}$
- Guaranteed sources of gravitational waves

Constellation of LISA missions

- Three spacecraft in equilateral triangle: million km arm lengths.
- Heliocentric orbits
- Arm-length mismatch
- Relative spacecraft velocity (Doppler)
- Angle variations

Optical bench and Drag-Free Test Mass

- Beam at emitter:
  $\sim 40\,\text{cm}$ diameter,
  1-2 W.

- Beam at receiver:
  $\sim 20\,\text{km}$ diameter,
  100 pW.

Politics trumps Science?

US and NASA

- LISA 2nd large missions recommendation of Astro Decadal 2010
- Budget crisis in US and NASA slows down progress on LISA for this decade
- Budget constrains incompatible with ESA's Cosmic Vision programatics

Europe and ESA

- ESA decides to maintain and rescope Cosmic Vision: 3 L-class candidates
- Cost cap: ESA 850 MEuro plus Member States contributions - 200 MEuro for eLISA
- LISA evolves $\Rightarrow$ mission redefinition in Europe
  eLISA/NGO
- Decision chain in ESA:
  SSAC $\Rightarrow$ SPC $\Rightarrow$ ESA

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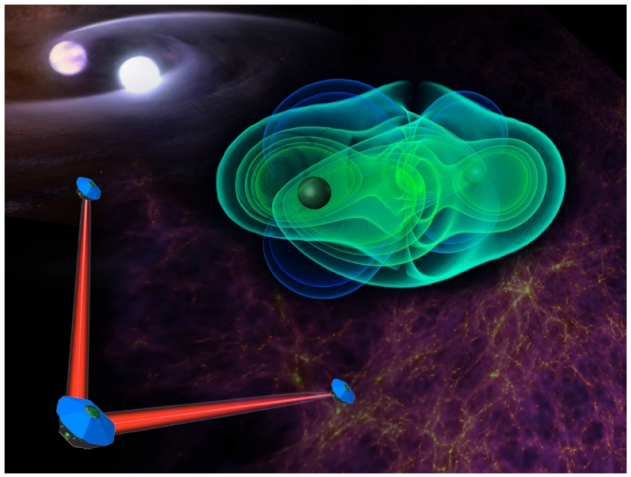
Answer to title question: **NO!!!**

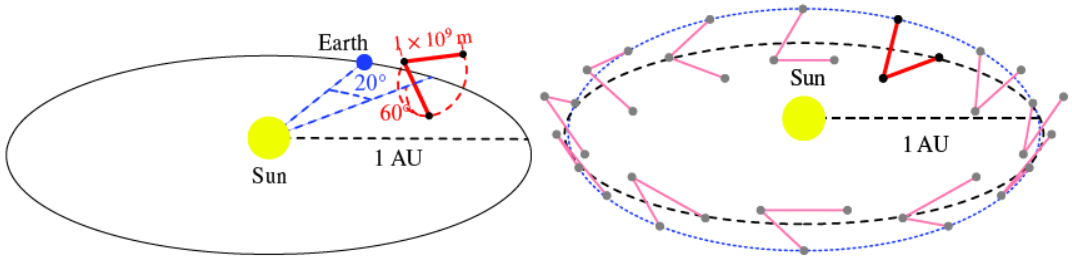
We go on! $\Rightarrow$ eLISA European Consortium has been created!
continuation funding being under discussion.

eLISA/NGO: rescoping of European-only mission

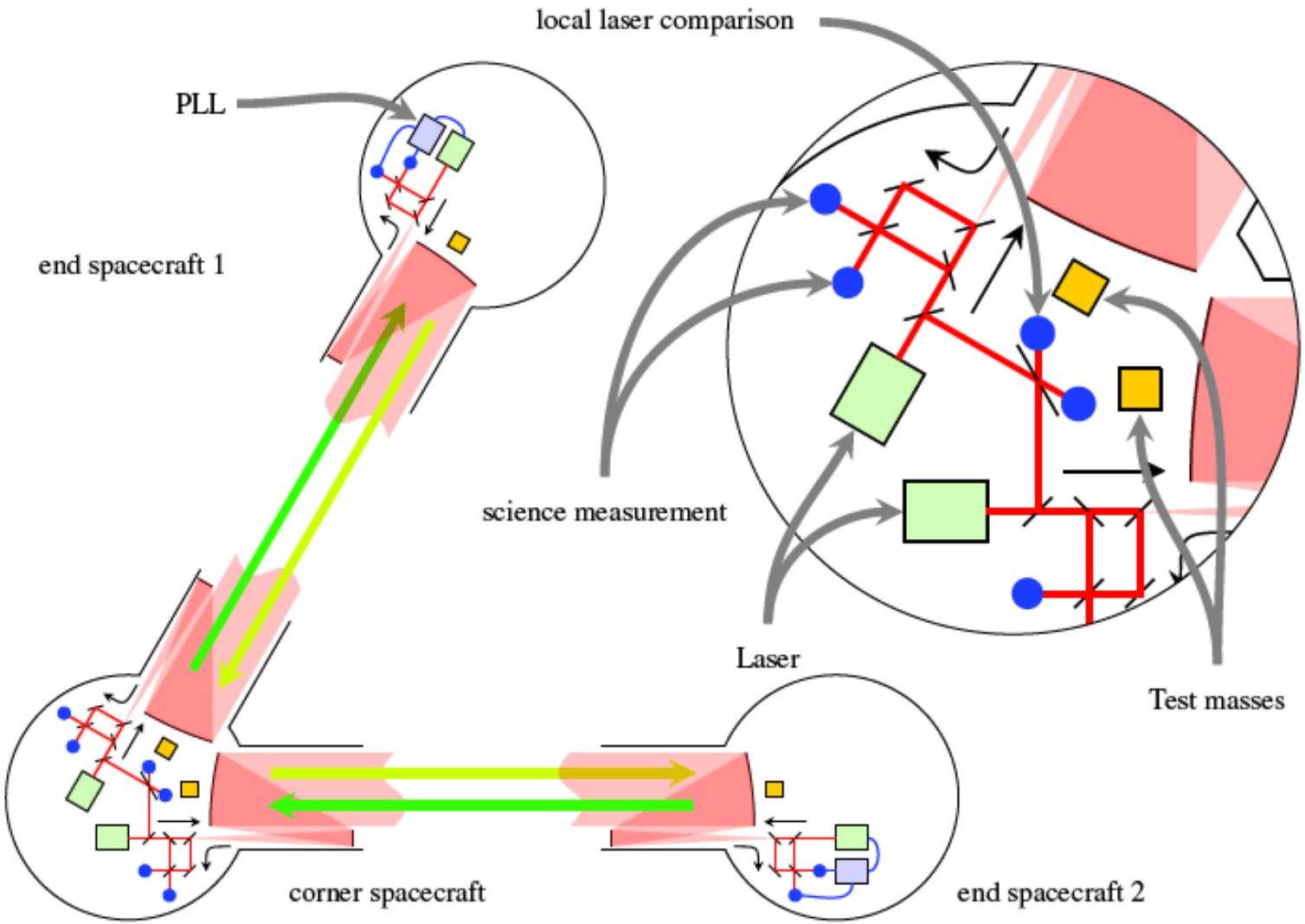
- Three spacecraft in V-formation:
  1 million km.
- two bi-directional laser links (instead of six)



- heliocentric orbit behind Earth
  drift-away orbit: 10°-25°



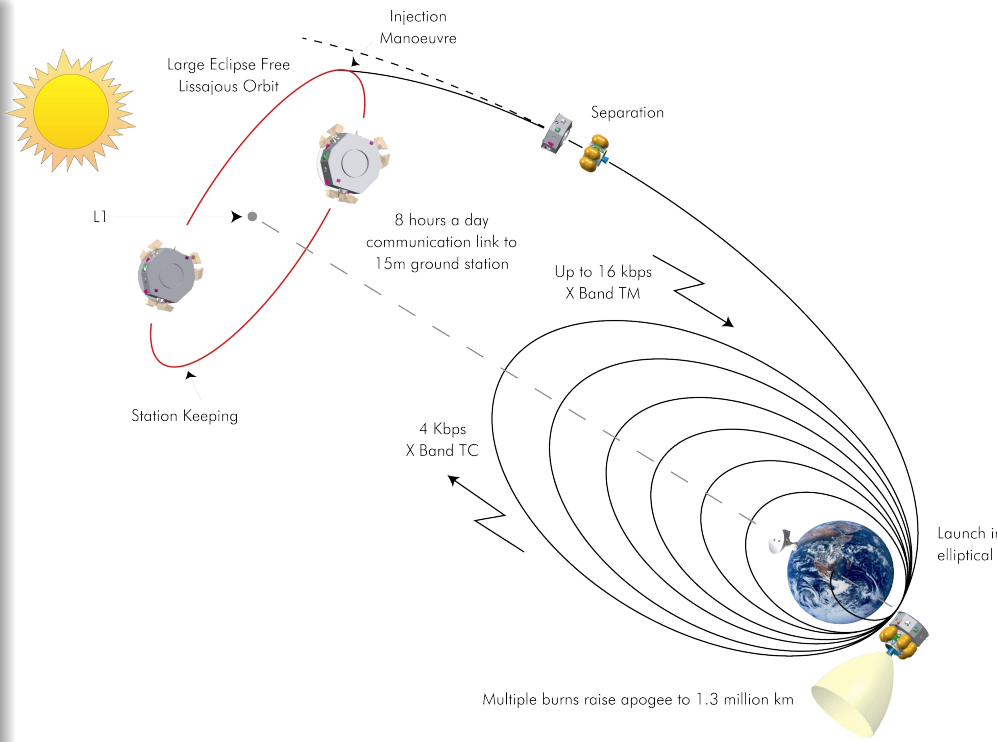
eLISA/NGO: spacecraft constellation



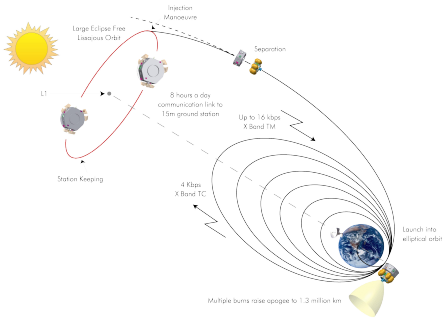
LISA Pathfinder (LPF)

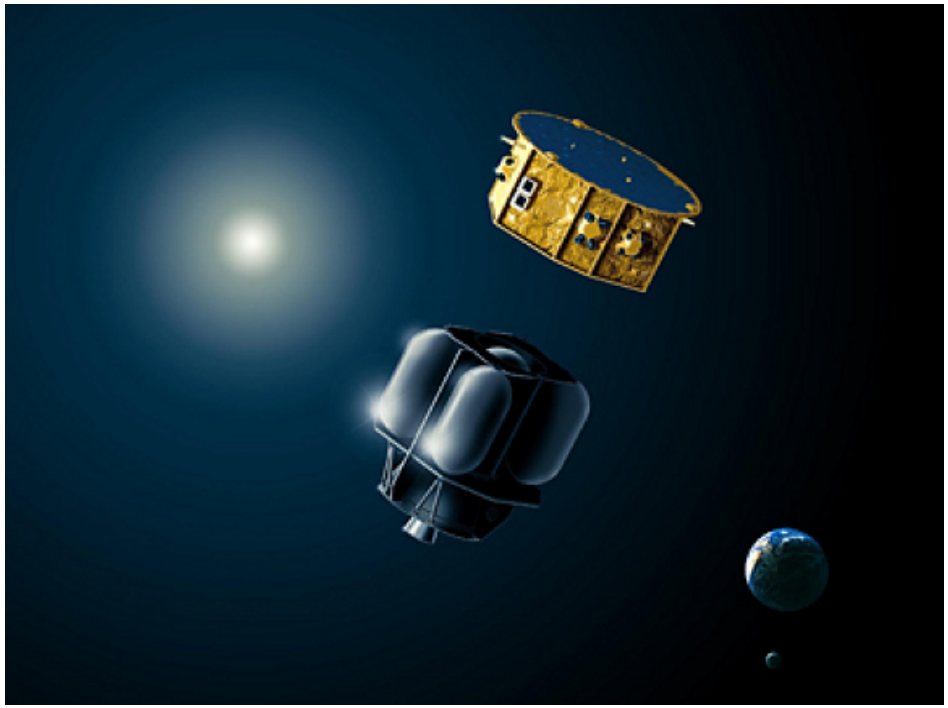
Demonstration of LISA technologies in space

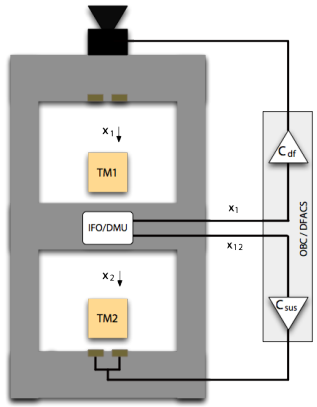
- Two LISA-like TMs inside one satellite $\Rightarrow$ one small "LISA-arm".
- **Interferometry** between Test-Masses with **picometer** precision.
- **Drag Free** System for Test Masses with **femtonewton** stability.
- Micronewton thrusters for drag free control of the satellite.
- LISA Technology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



The LISA technology package (LTP) core assembly







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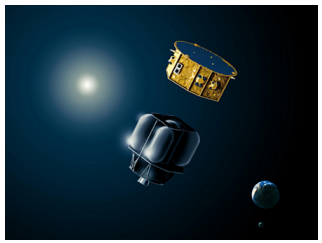

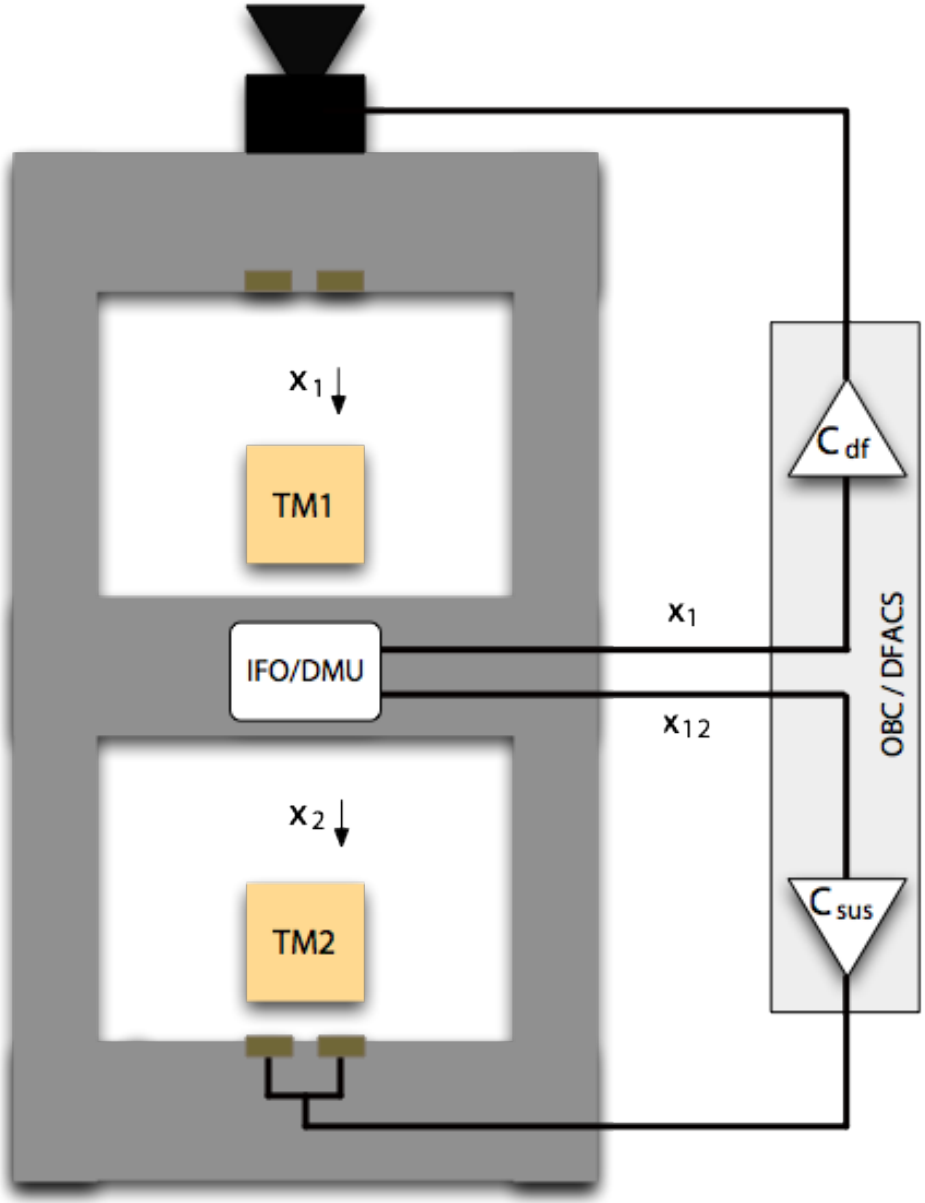

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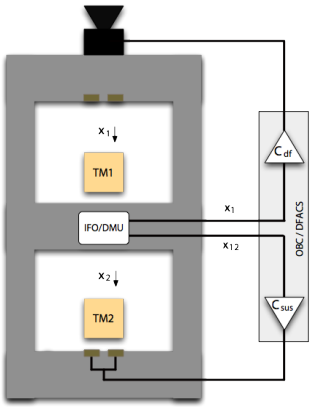

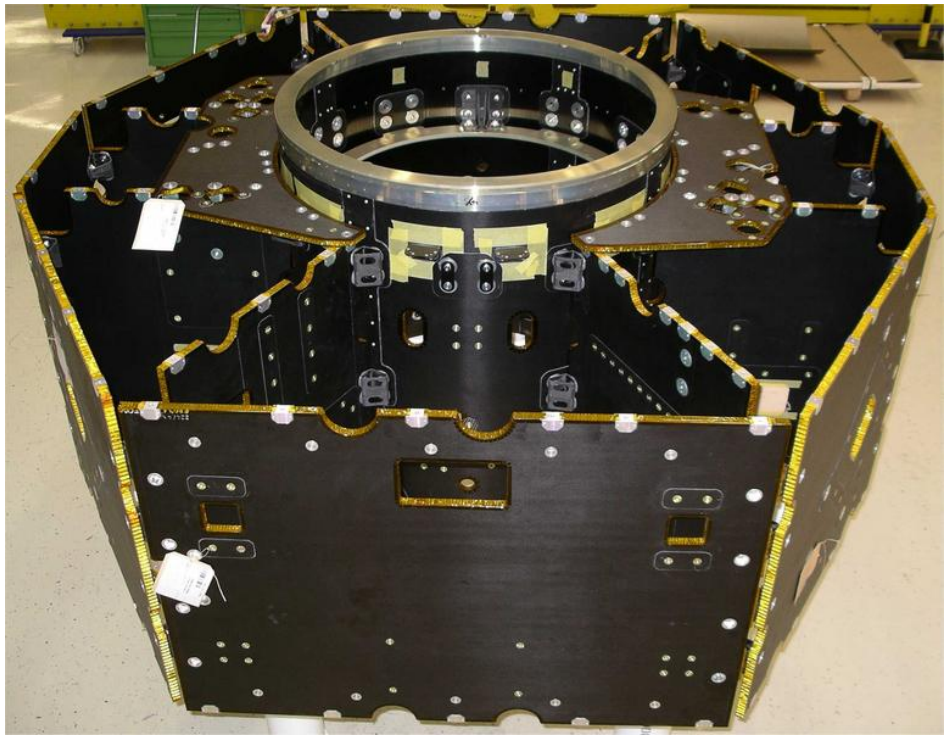

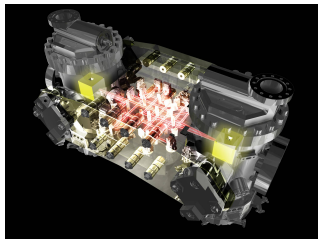

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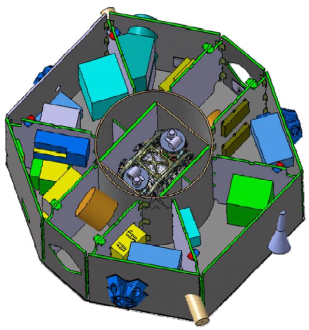
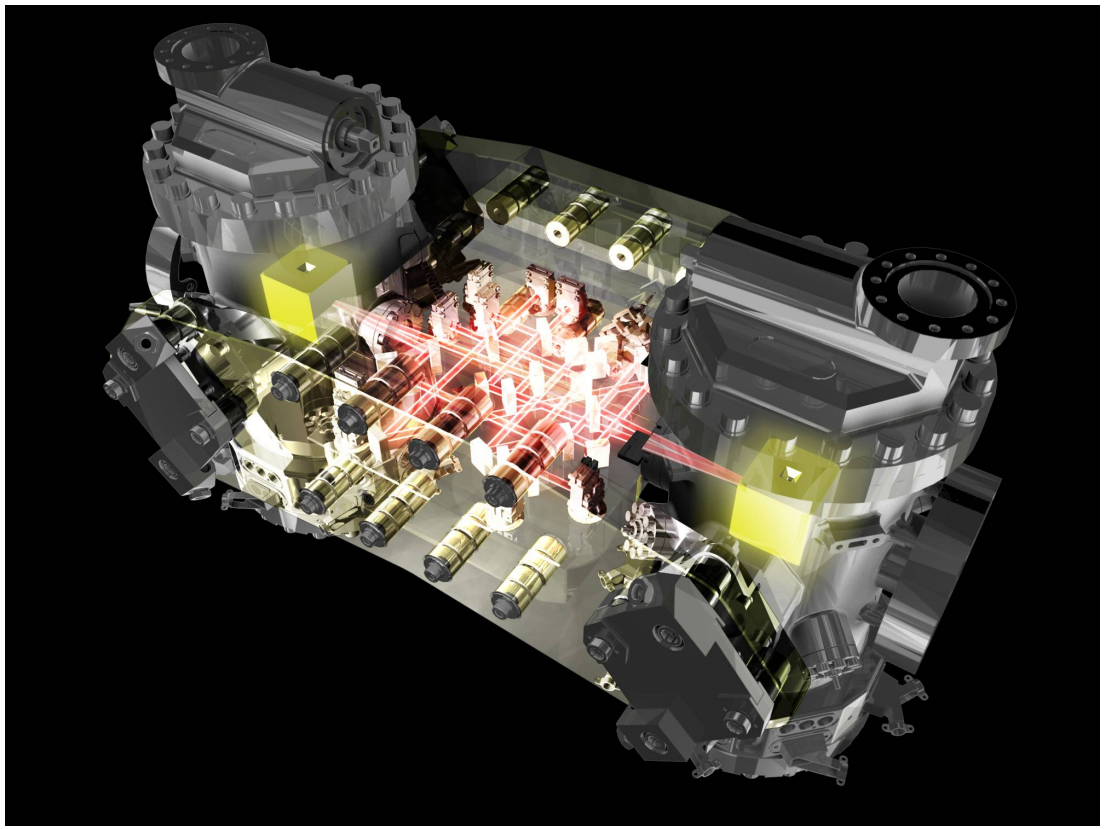
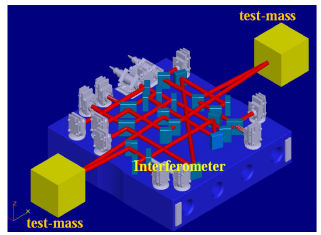


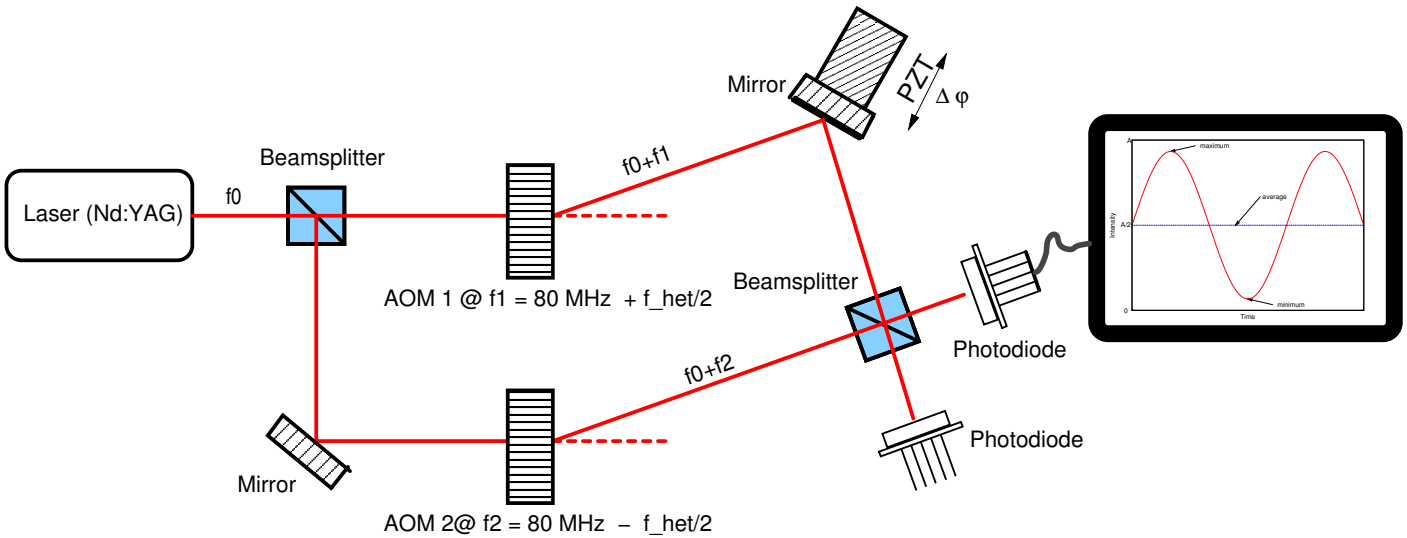




Two test masses inside their vacuum enclosures and interferometer between them.

Optical Measurement

- Baseline: Heterodyne Mach-Zehnder Interferometer

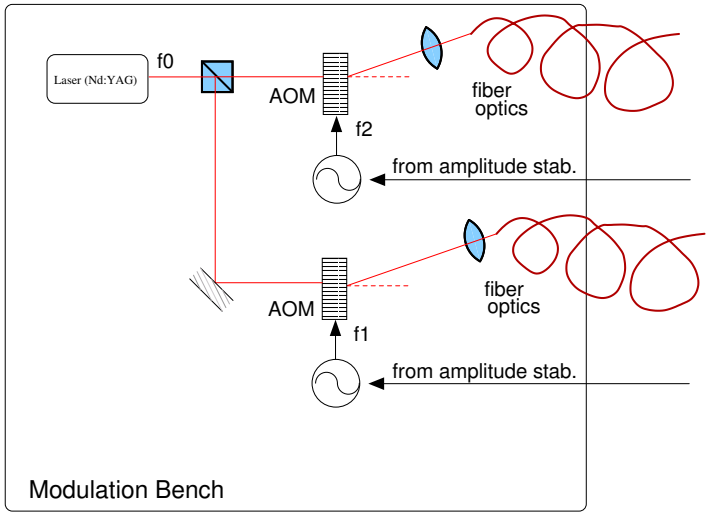


$$I(\varphi) = A\,(1 + \gamma \cdot \cos\,(2\pi \cdot f_{\mathrm{het}} \cdot t + \Delta\varphi))$$

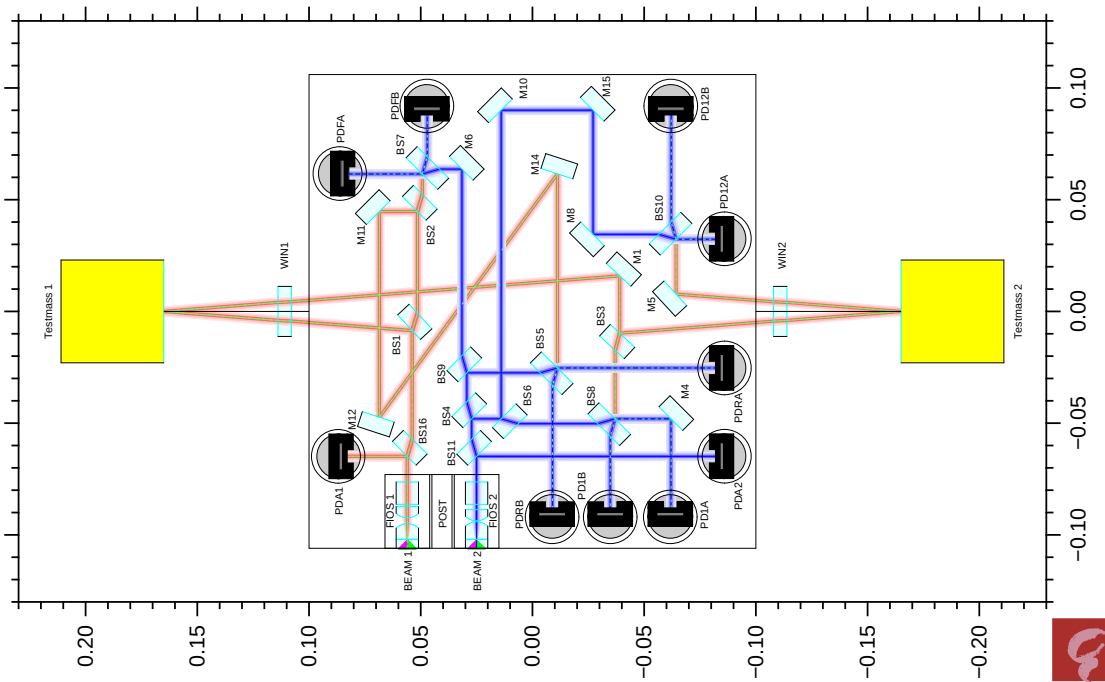
- Requirement: 6.4 $\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$, between 3 mHz and 30 mHz
- Two main stabilization loops required: laser frequency noise, optical pathlength difference.

LTP interferometer setup - **two separate modules**

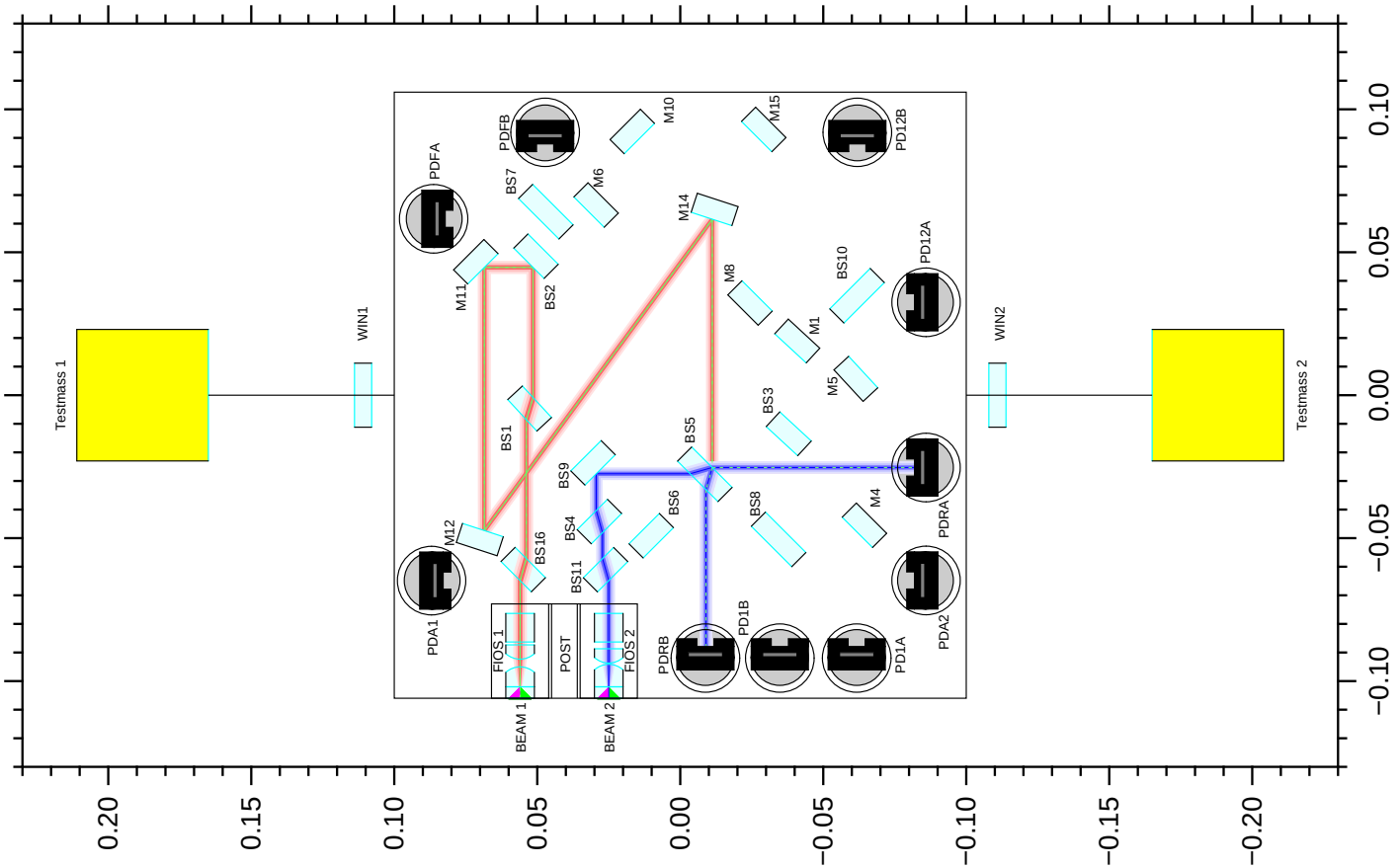
- Modulation bench:
  1 Nd:YAG laser and
  2 AOMs.



- Optical bench engineering model:
  Zerodur baseplate with 4 non-polarizing Mach-Zehnder interferometers

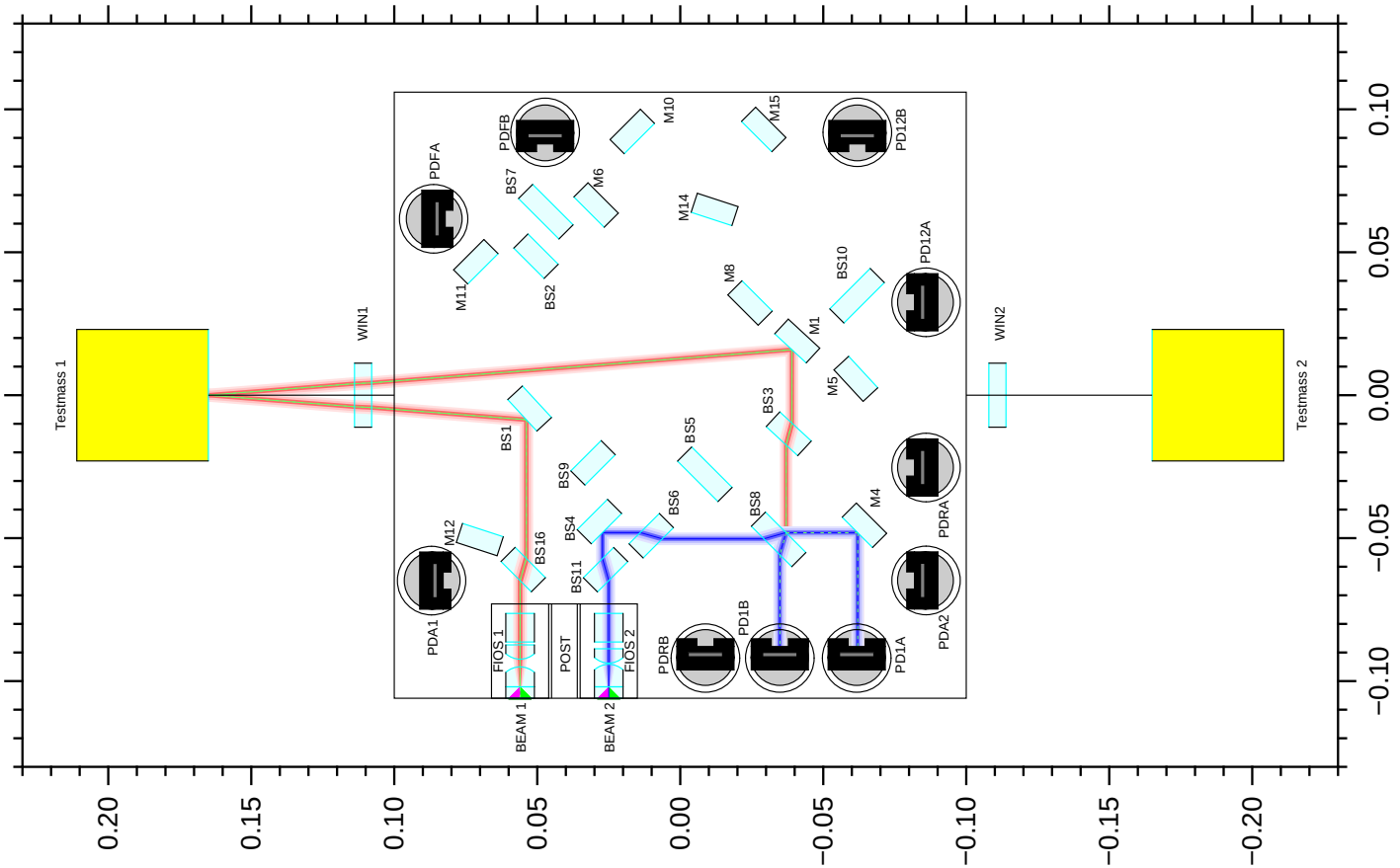


LTP Optical layout: reference interferometer



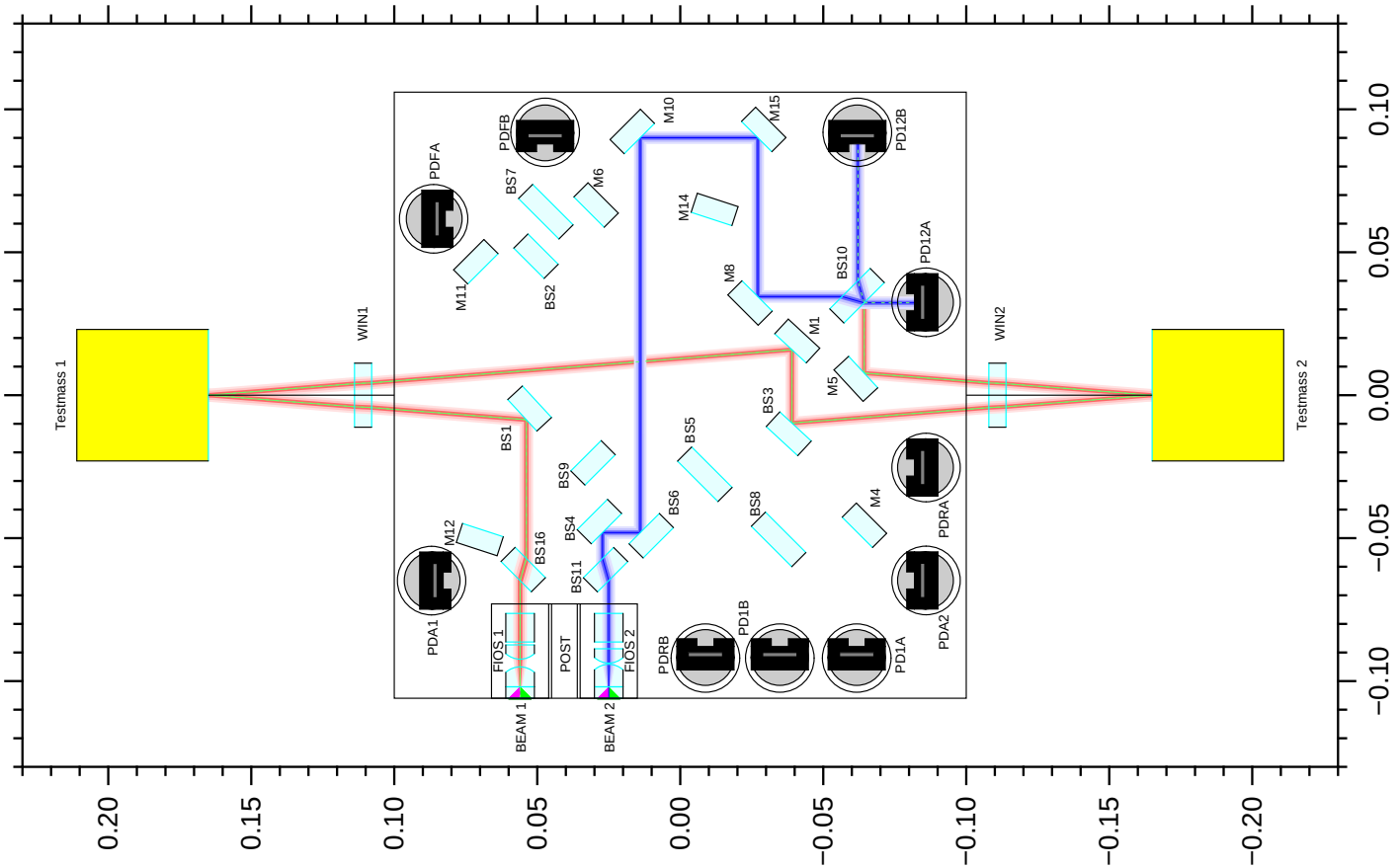
LTP OBI: Optical Model, 03 Apr 2006

LTP Optical layout: X1 interferometer



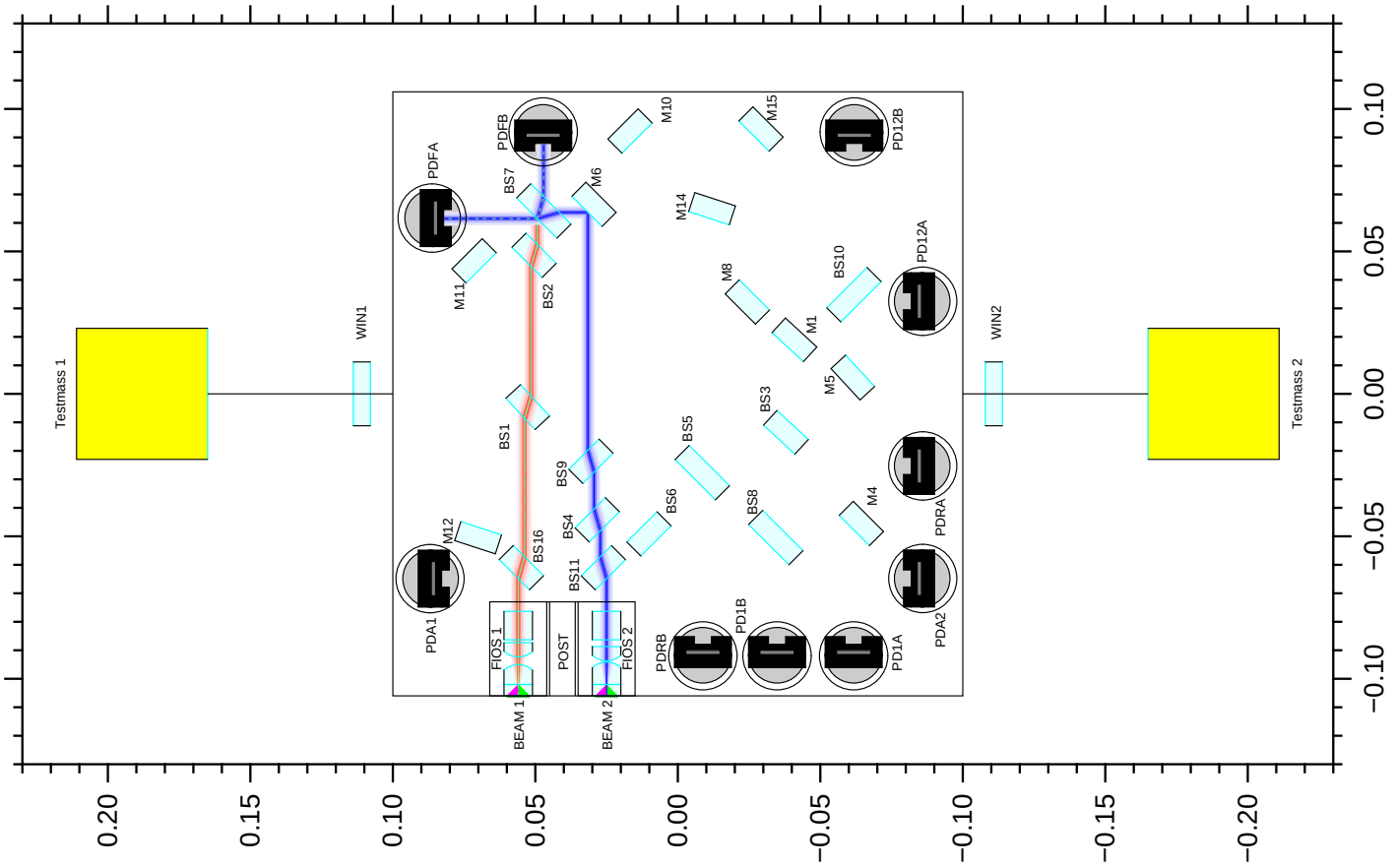
LTP OBI: Optical Model, 03 Apr 2006

LTP Optical layout: X12 interferometer



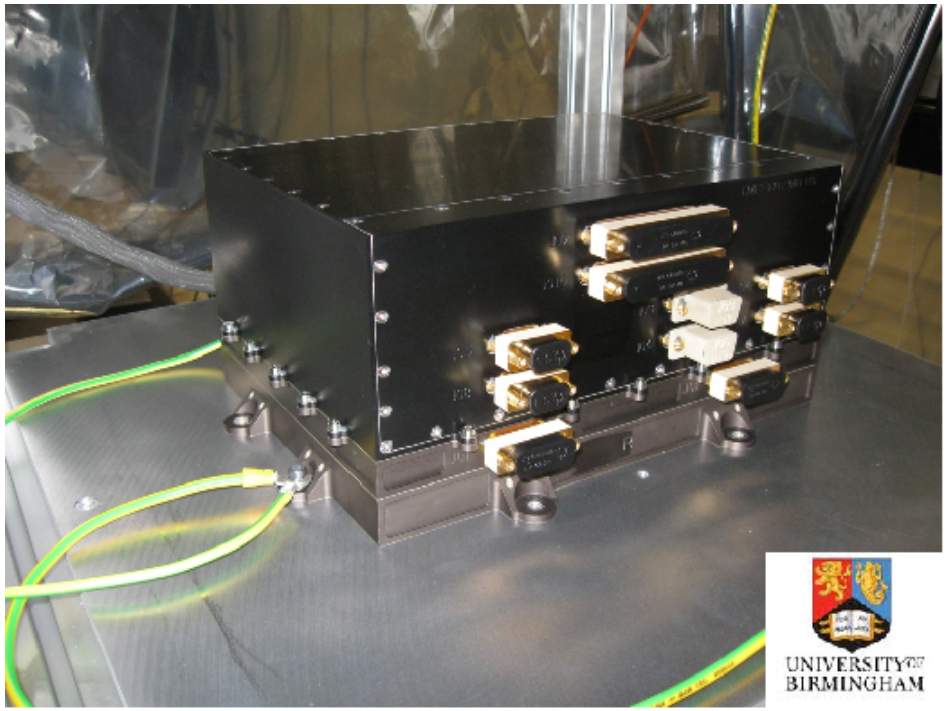
LTP OBI: Optical Model, 03 Apr 2006

LTP Optical layout: frequency interferometer



LTP OBI: Optical Model, 03 Apr 2006

Phasemeter

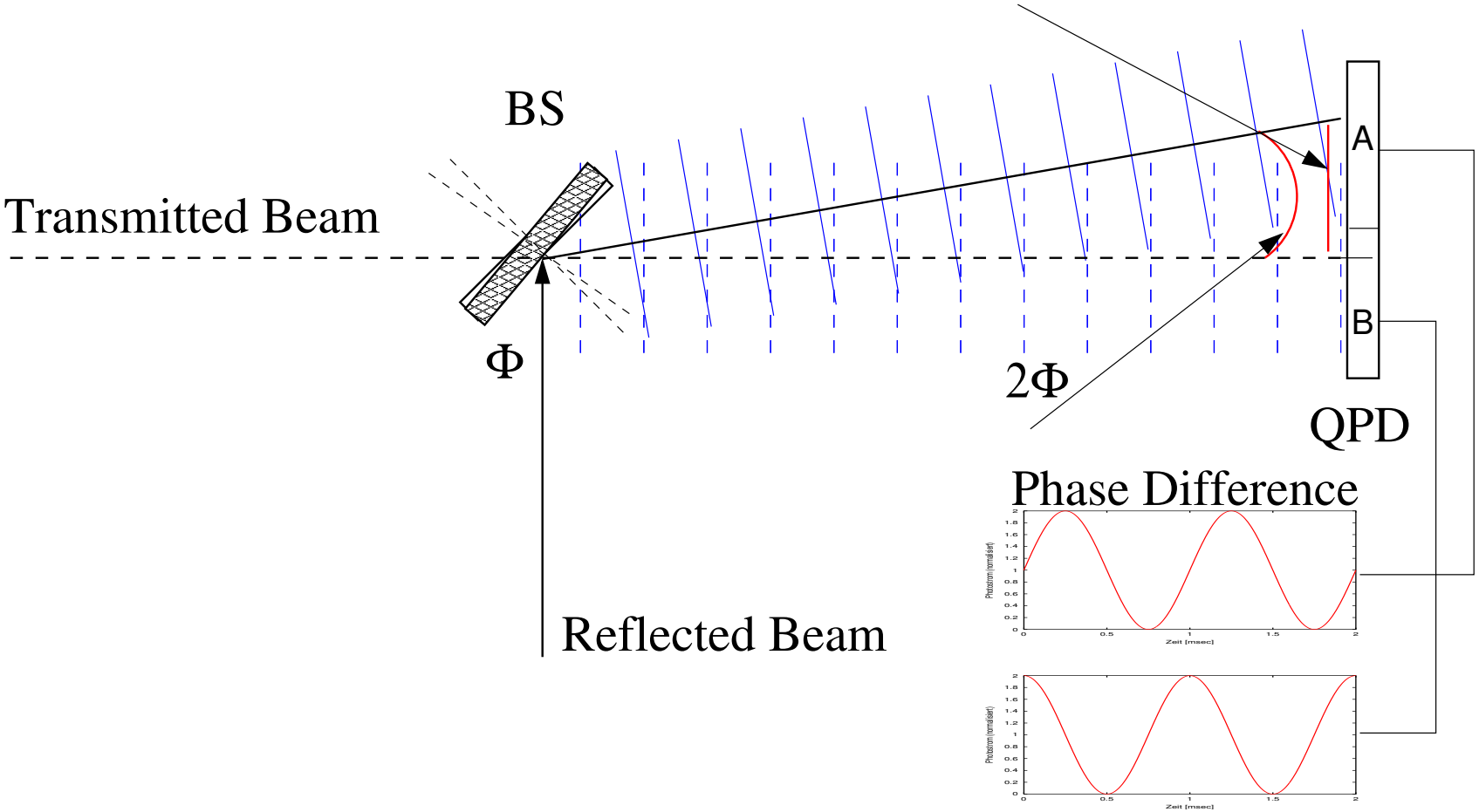


- FPGA based - 32 channel
- Output per quadrant:
  dc_k, y_k, z_k
- $c_k = z_k + iy_k$
- For each QPD:

$$DC_n = \sum_k dc_k,$$

$$c_n = \sum_k c_k$$

Differential Wavefront Sensing



- Requirement: $20\ \frac{\mathrm{nrad}}{\sqrt{\mathrm{Hz}}}$, between 3 mHz and 30 mHz

Phasemeter Data Processing

- longitunal phase Ψ_n:

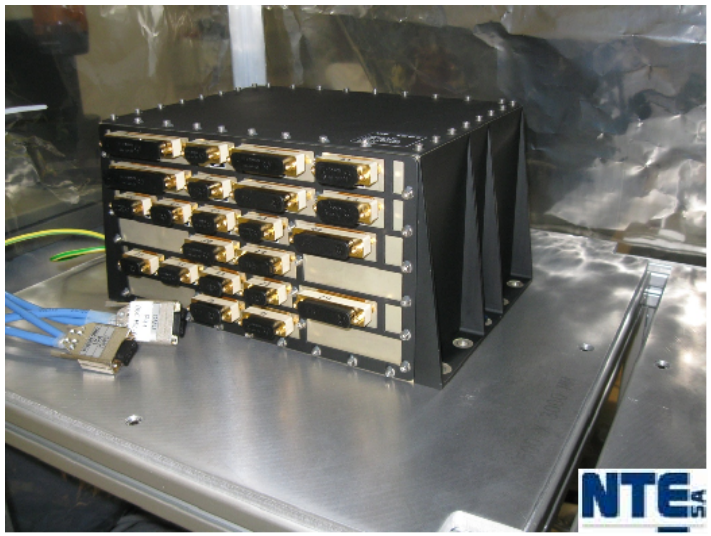
$$\Psi_n = PT\left(\arg\left(c_n\right) - \arg\left(c_{\text{ref}}\right)\right)$$

- alignment signals:
  - DC signals:

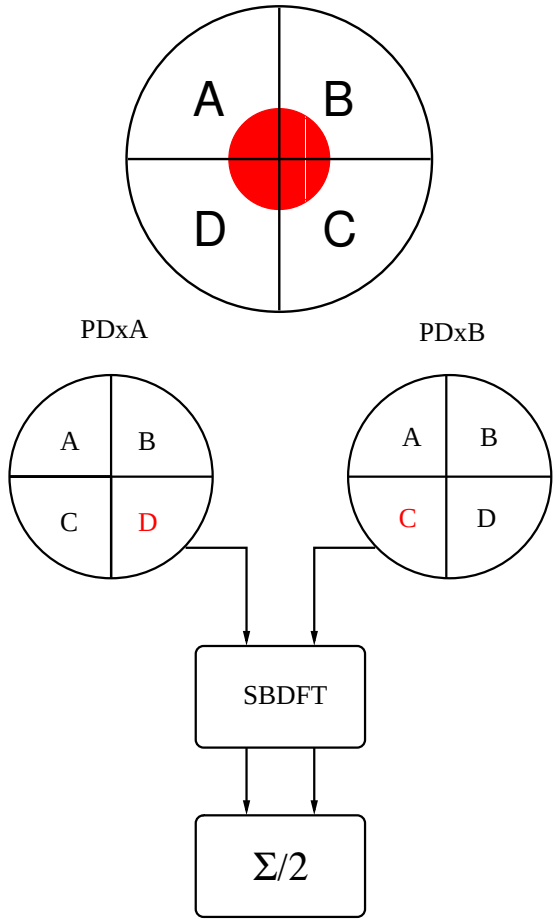
$$DC_n^{\varphi,\eta} = \frac{DC_{\text{left,up}} - DC_{\text{right,down}}}{DC_n}$$

  - DWS signals:

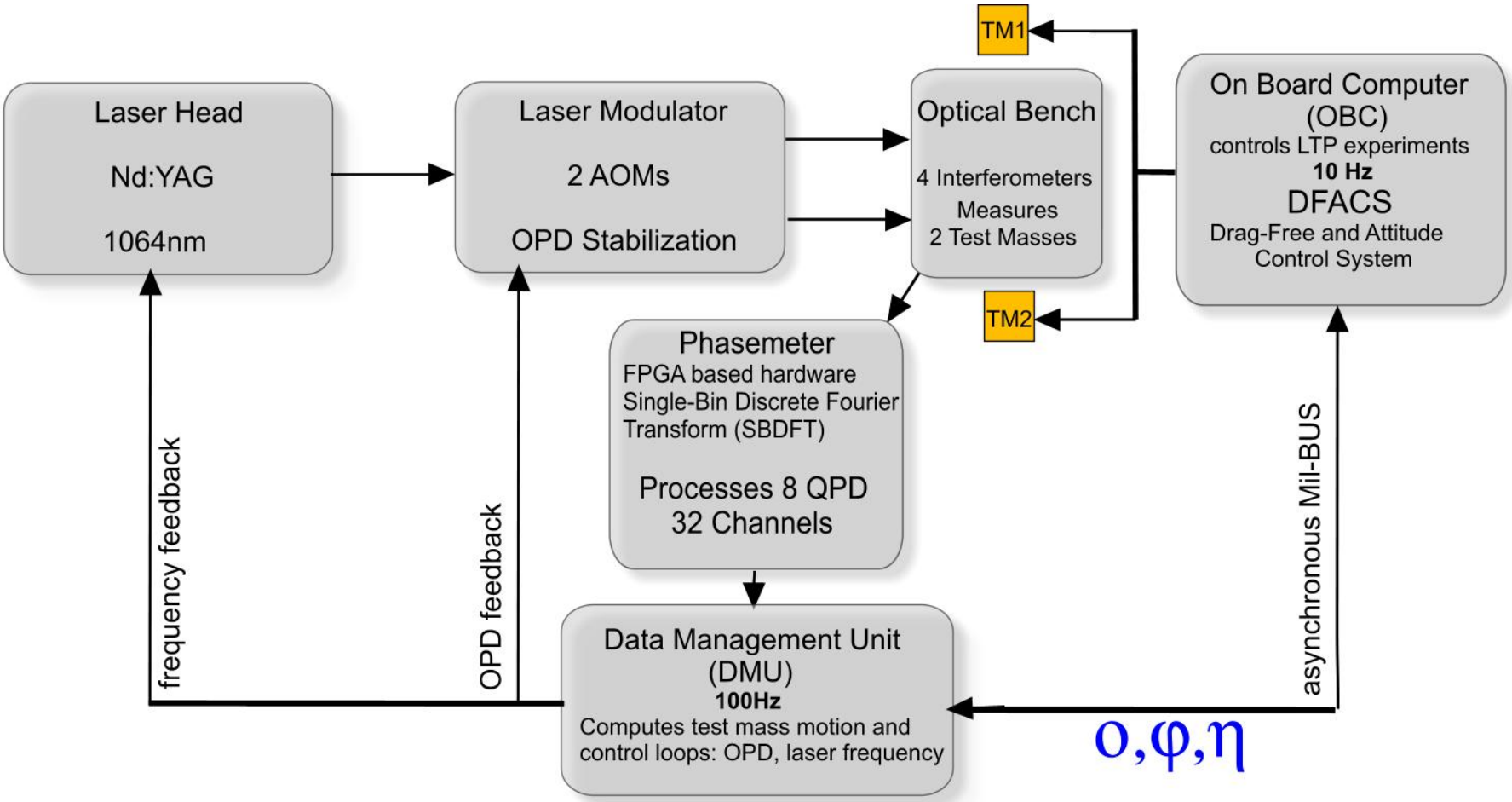
$$DWS_n^{\varphi,\eta} = \arg\left(\frac{c_{\text{left,up}}}{c_{\text{right,down}}}\right)$$



Data Management Unit (DMU)



LPF optical metrology system - major German contribution



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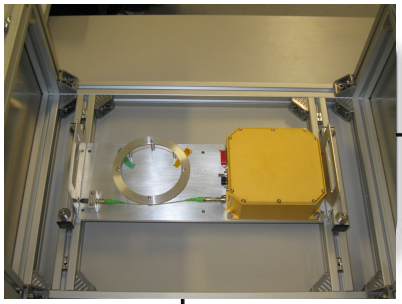

Laser Modulator

2 AOMs

OPD Stabilization

TM1

Optical Bench

4 Interferometers
Measures
2 Test Masses

TM2

On Board Computer (OBC)
controls LTP experiments
10 Hz
DFACS
Drag-Free and Attitude Control System

Phasemeter
FPGA based hardware
Single-Bin Discrete Fourier Transform (SBDFT)

Processes 8 QPD
32 Channels

Data Management Unit (DMU)
100Hz
Computes test mass motion and control loops: OPD, laser frequency

frequency feedback

OPD feedback

asynchronous Mil-BUS

o, φ, η

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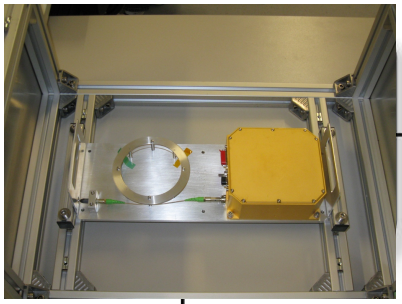

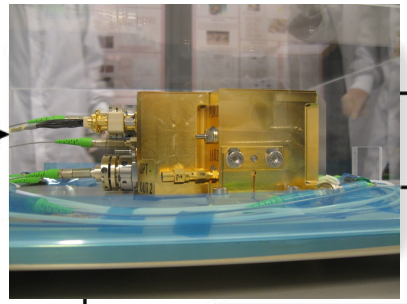

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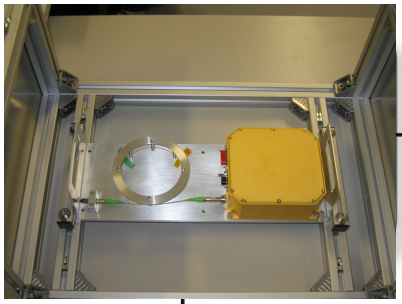

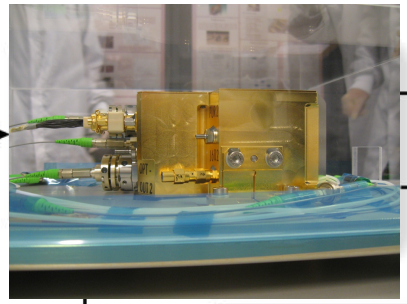

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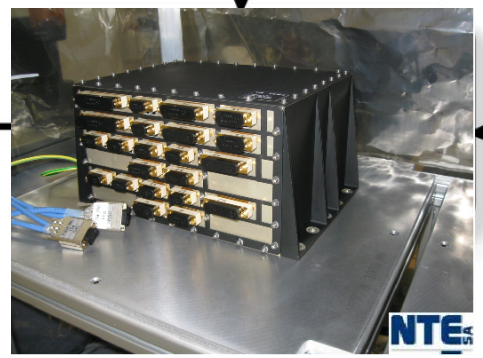

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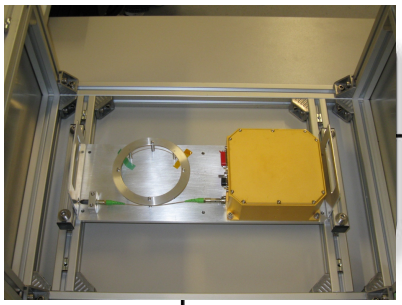

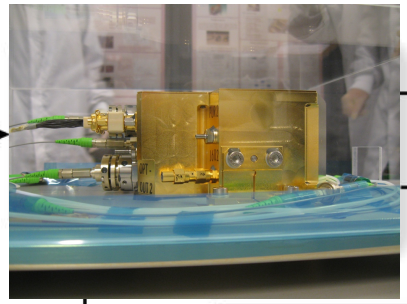

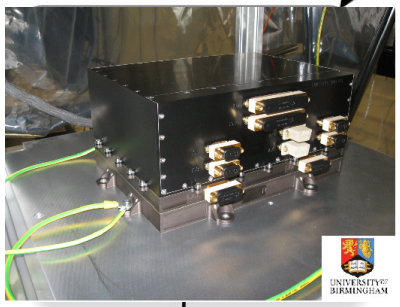

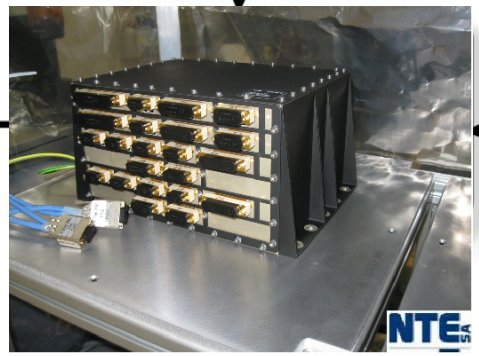

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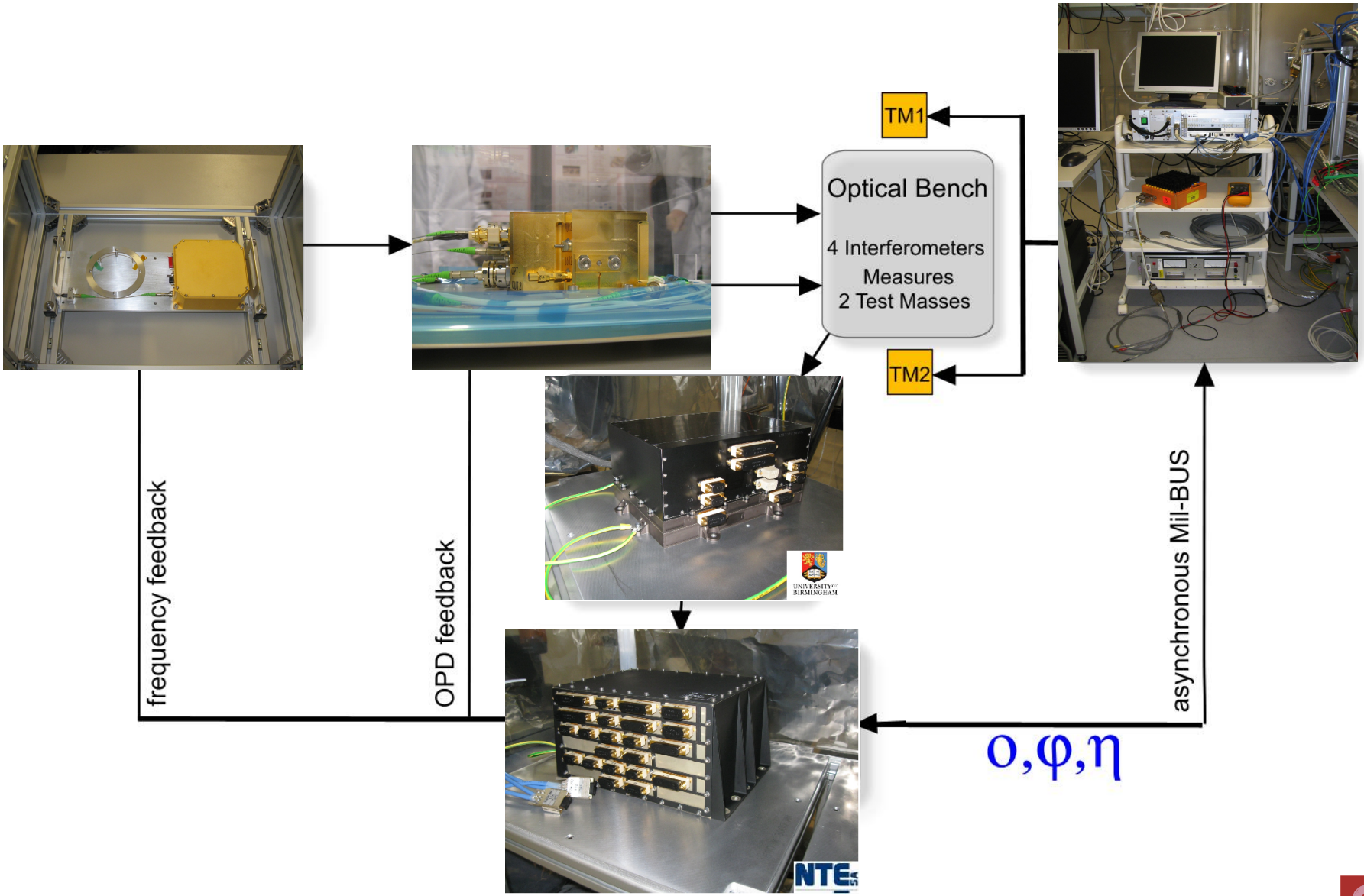

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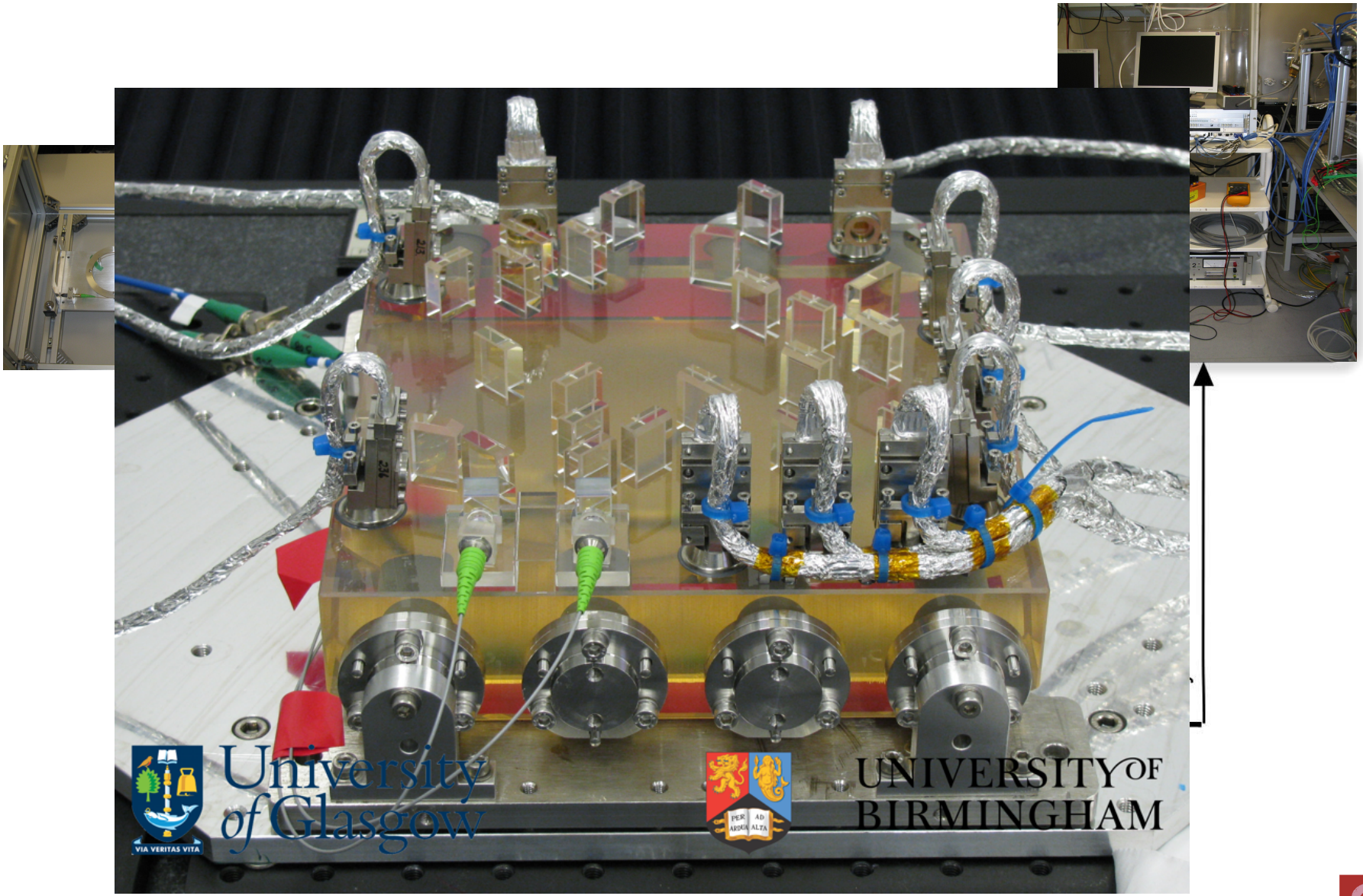

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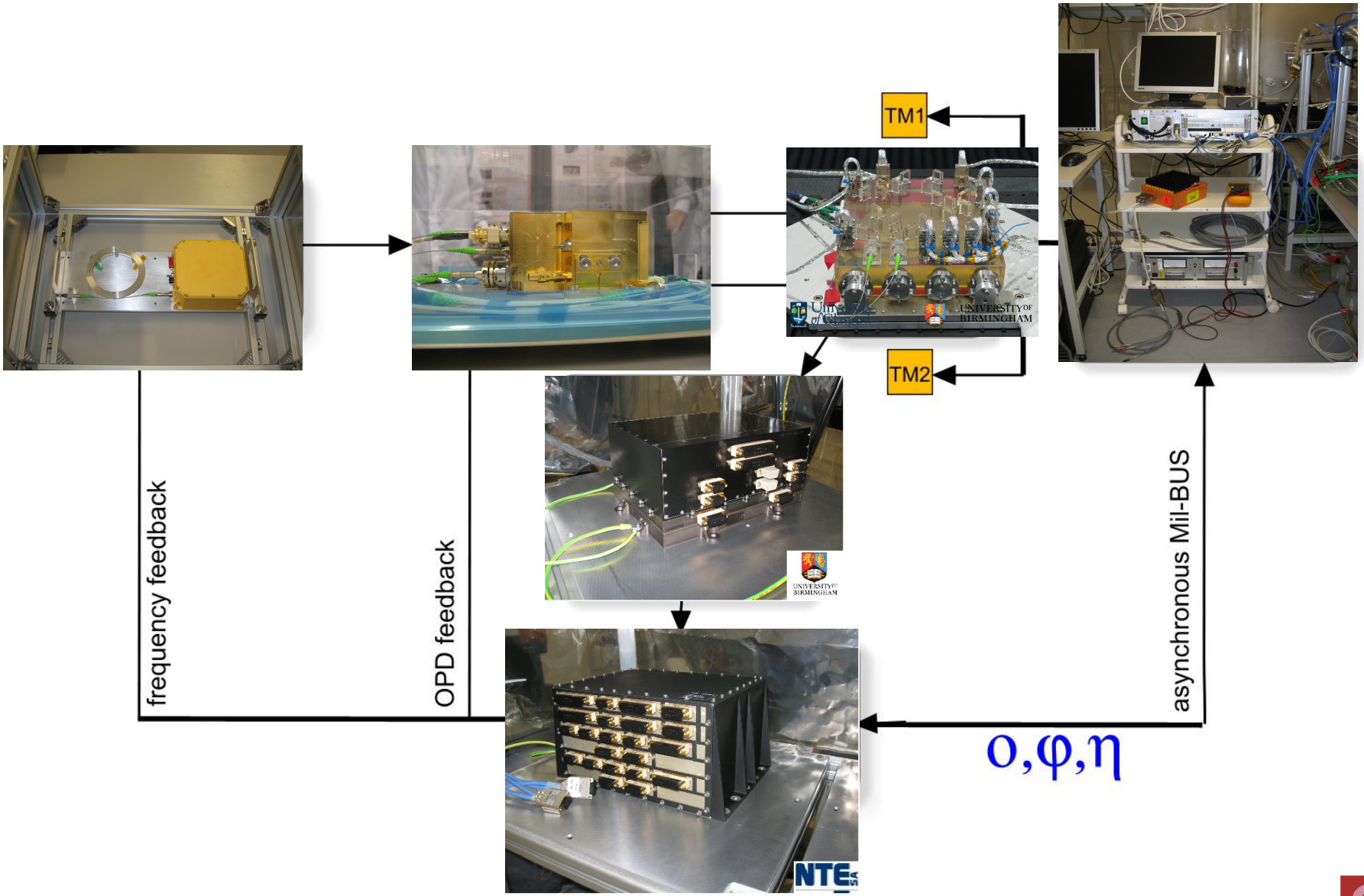
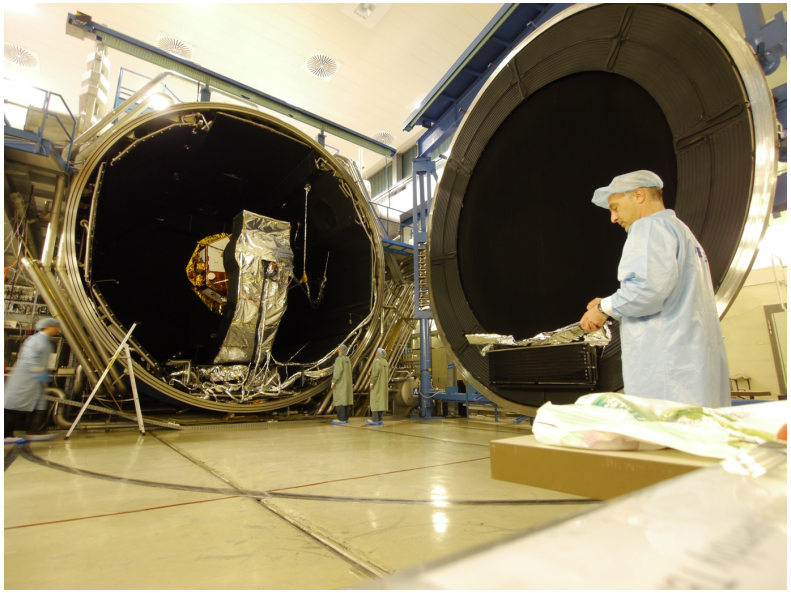
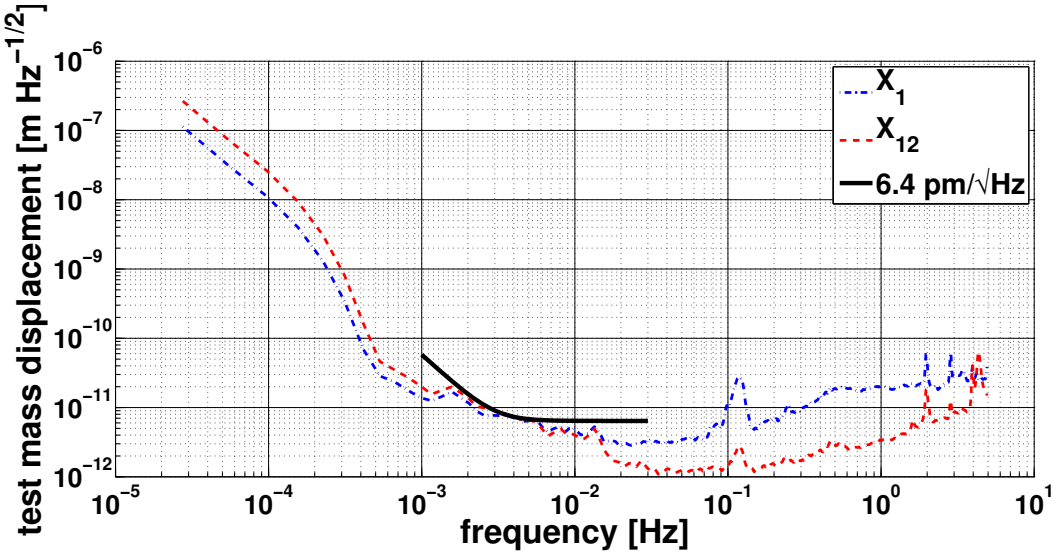
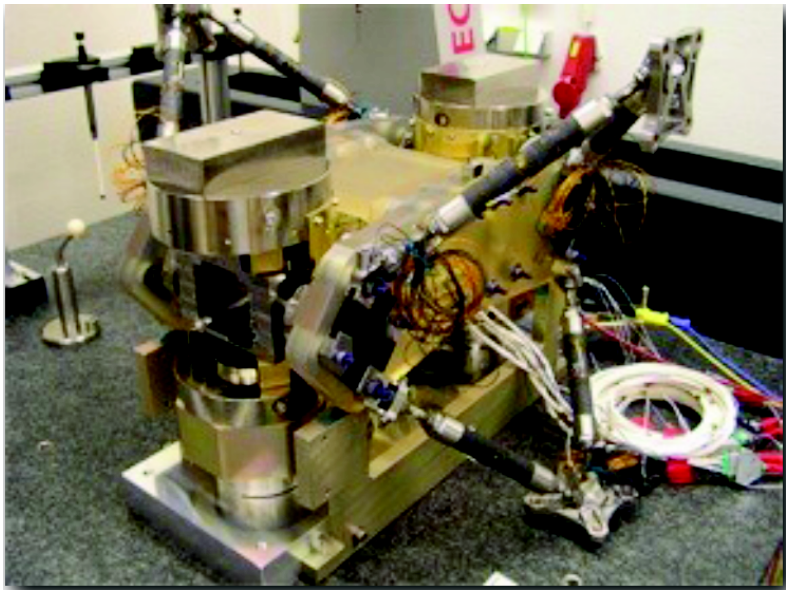
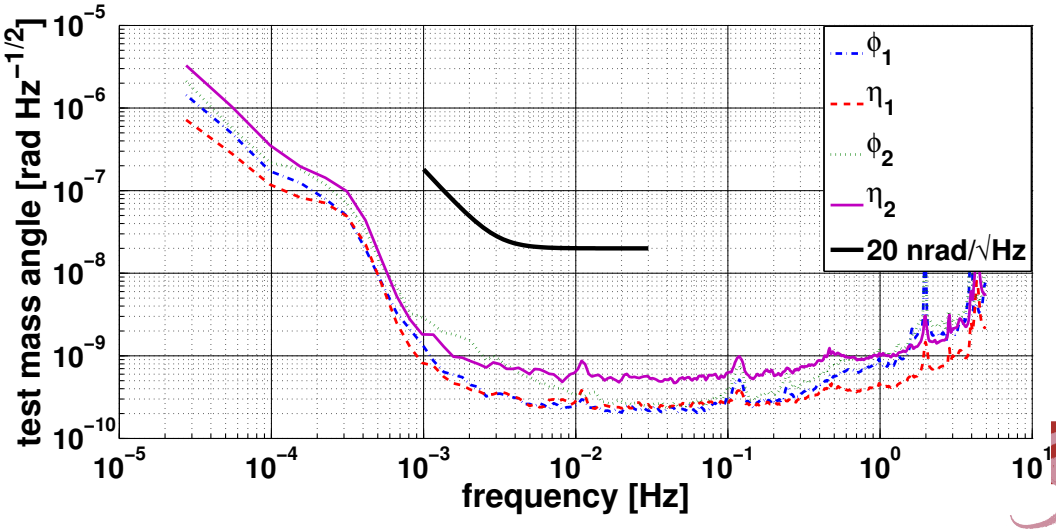


LISA Pathfinder Thermal-Vacuum Tests









Future concepts

Besides eLISA/NGO and LISA Pathfinder:

- Space-based GW observatories - US mission concept studies:
  - SGO: LISA-like space gravitational observatory
  - Non-drag-free concepts: Folkner and McKenzie (LAGRANGE)
  - OMEGA

    http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission-rfis.php
  - NASA Headquarters has appointed PhysPAG and GWSAG

    GWSAG: **http://pcos.gsfc.nasa.gov/sags/gwsag.php**
    Chair: Prof. Guido Müller- University of Florida, Gainesville.
- Ground-based GW observatories - future generations:
  - Upgrade of LIGO and VIRGO to second generation (Advanced detectors)
  - Third generation: **Einstein Telescope**

Summary

- We have a mature concept for space-based GW observatories: LISA class - eLISA.
- LISA Pathfinder is a great test facility for LISA technology.
- Flight models of LISA Pathfinder units have been delivered and have been tested.
- Future GW missions: high heritage from LISA Pathfinder.
- Setup of the LISA Pathfinder LabSat in 2012 - engineering models.
- eLISA Consortium currently very active.
- Likely change at ESA to Cornerstone missions favorable for eLISA: science is just too compelling!