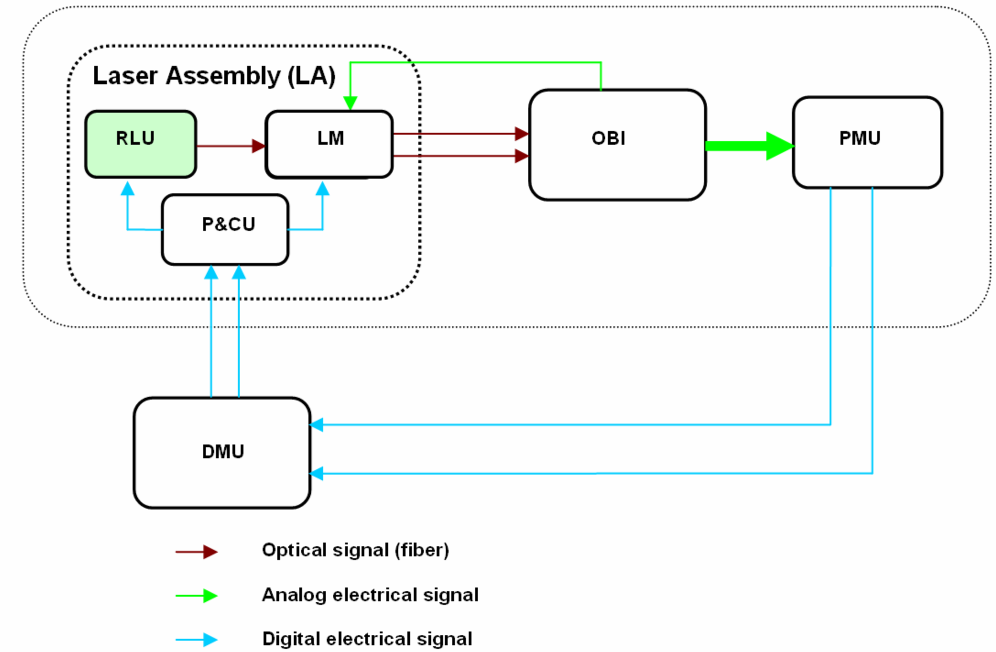
University of Glasgow

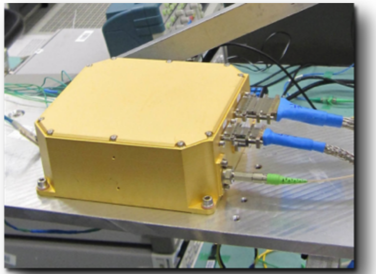
Outline

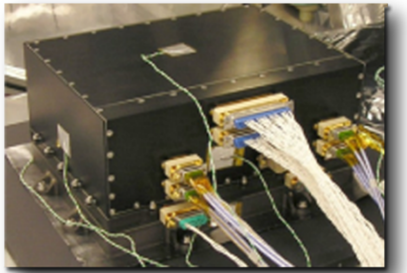
- LTP Optical Metrology System
  - Component parts
  - Main functions
- Requirements and constraints on its performance
  - Source of requirements
  - How they are met
    - Experimental results where possible
    - Modelling where direct ground testing impossible
    - Unexpected features and their solutions
- Summary of how well it performs

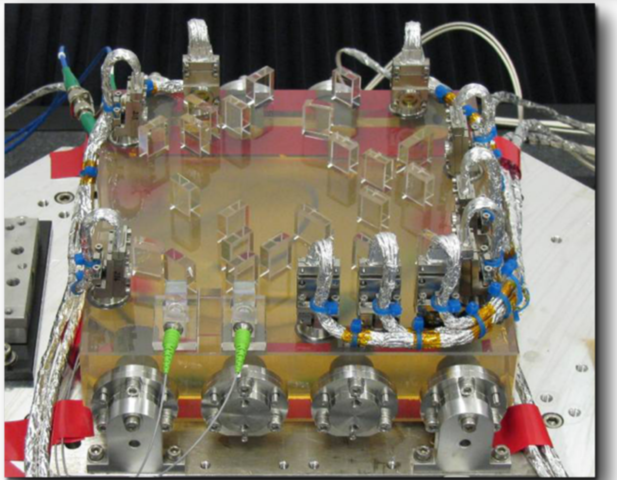
Optical Metrology System (OMS)

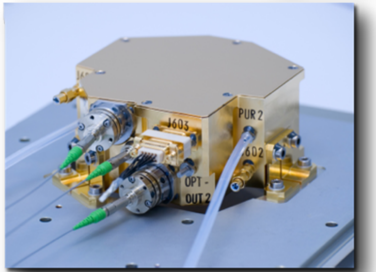
- Reference Laser Unit (RLU)
- Laser Modulator Unit (LM)
- Optical Bench Interferometer (OBI)
- PhaseMeter Unit (PMU)
- Data Management Unit (DMU)

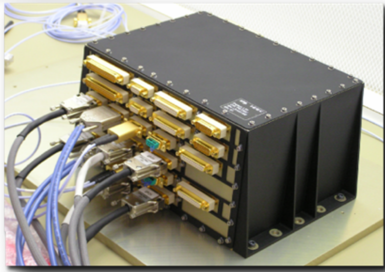



Reference Laser Unit


Phasemeter

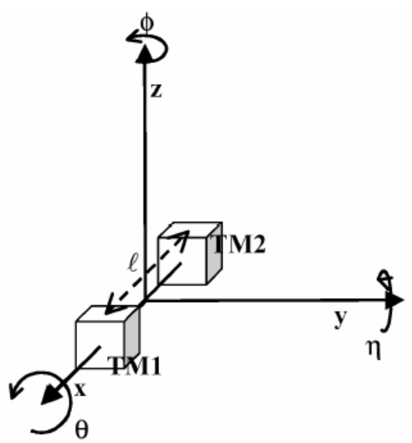

Optical Bench Interferometer

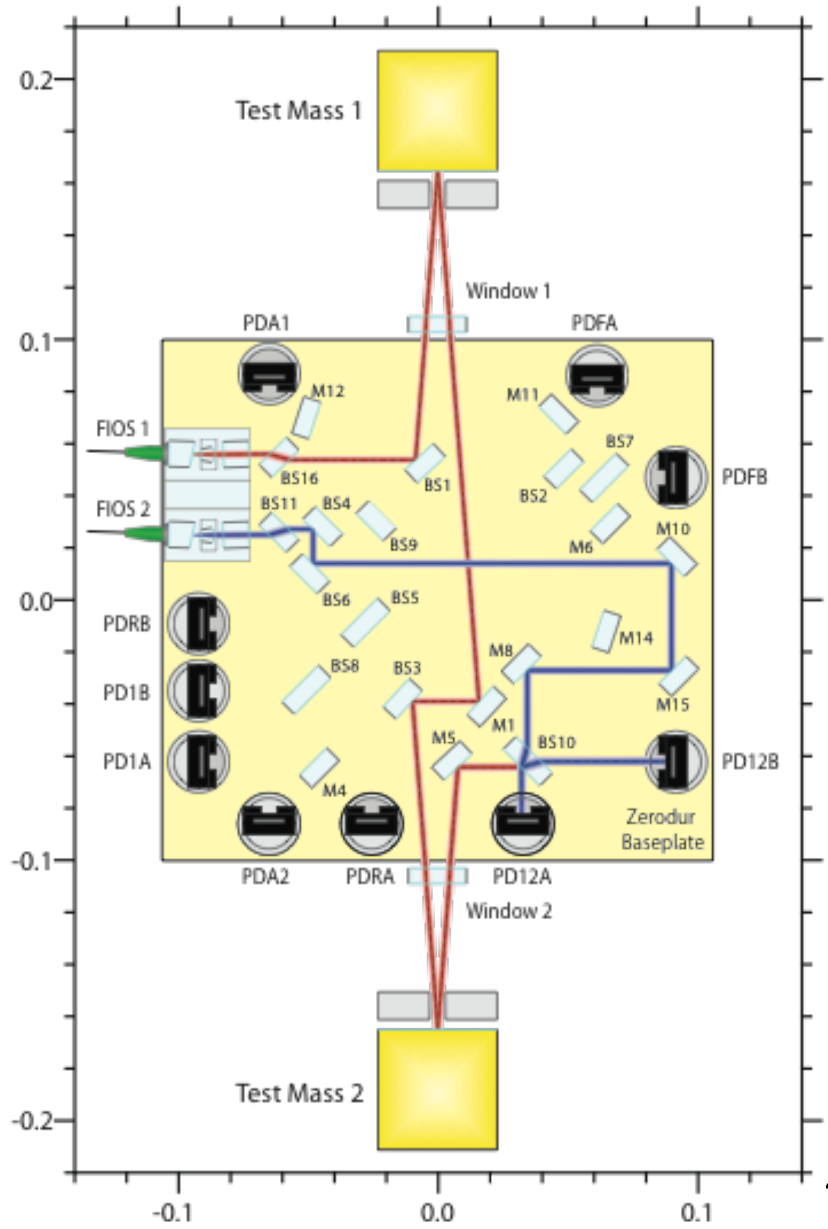

Laser Modulator


Data Management Unit

X12 interferometer

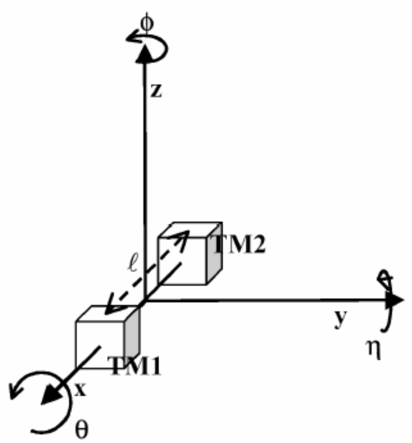
- Relative displacement between test mass 1 and test mass 2
  - x_{12}
- Relative angles between test mass 1 and test mass 2
  - Differential Wavefront Sensing (DWS)
  - η_{12}, ϕ_{12}

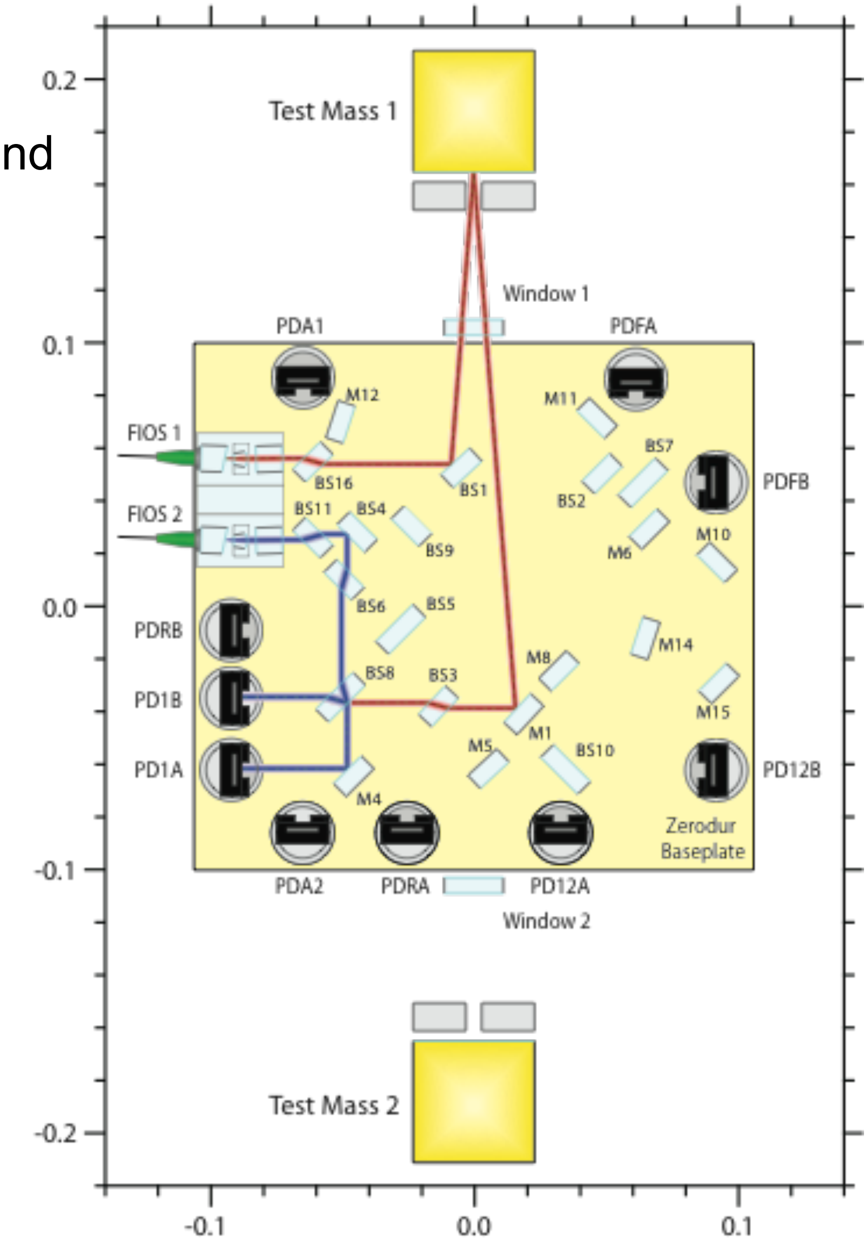




X1 interferometer

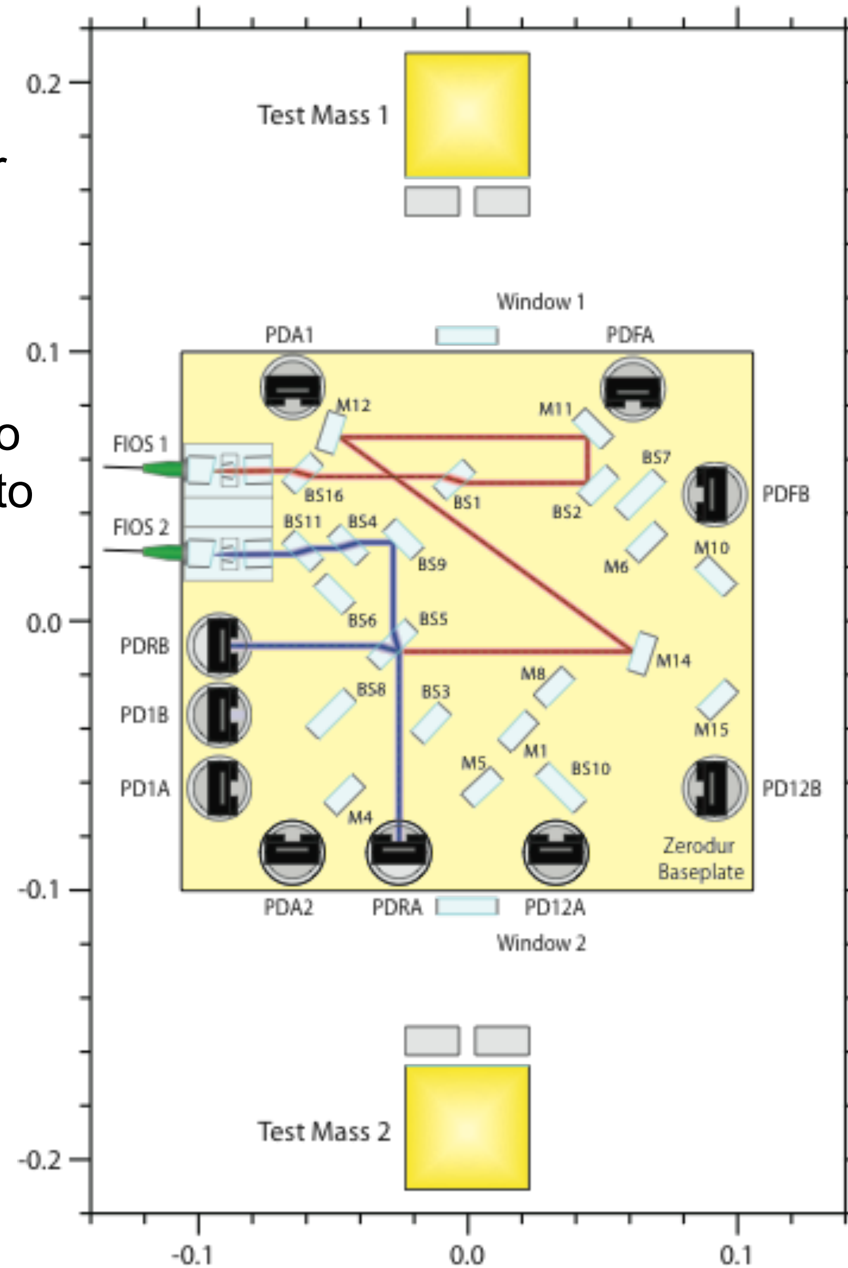
- Relative displacement between test mass 1 and the spacecraft
  - x_1
- Relative angles between test mass 1 and the spacecraft
  - η_1, ϕ_1





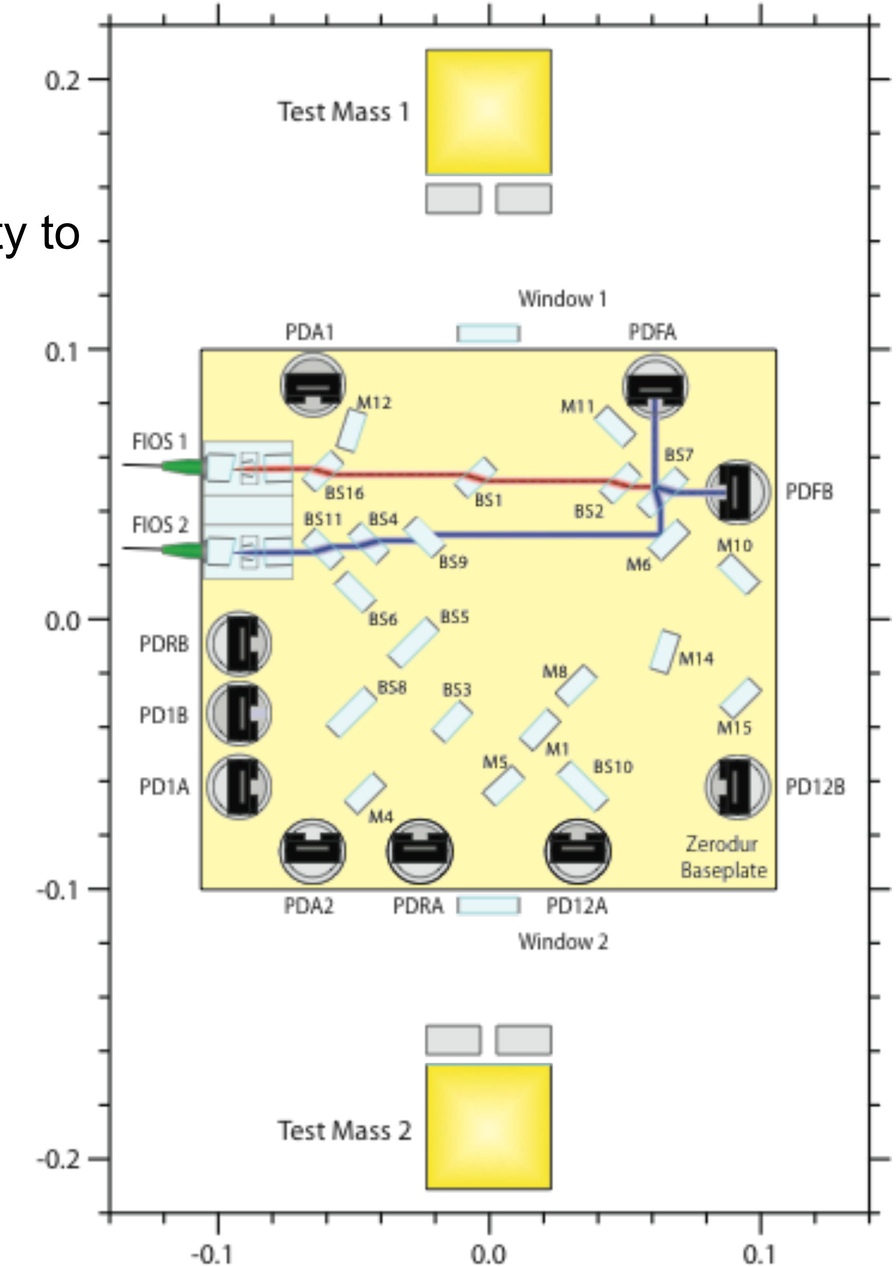
Reference interferometer

- Provides reference phase against which other signals are compared
- Allows optical path length noise before the optical bench to be monitored
  - Relative path length noise between the two feed fibres can be controlled by feedback to actuators in the modulator unit (LM)



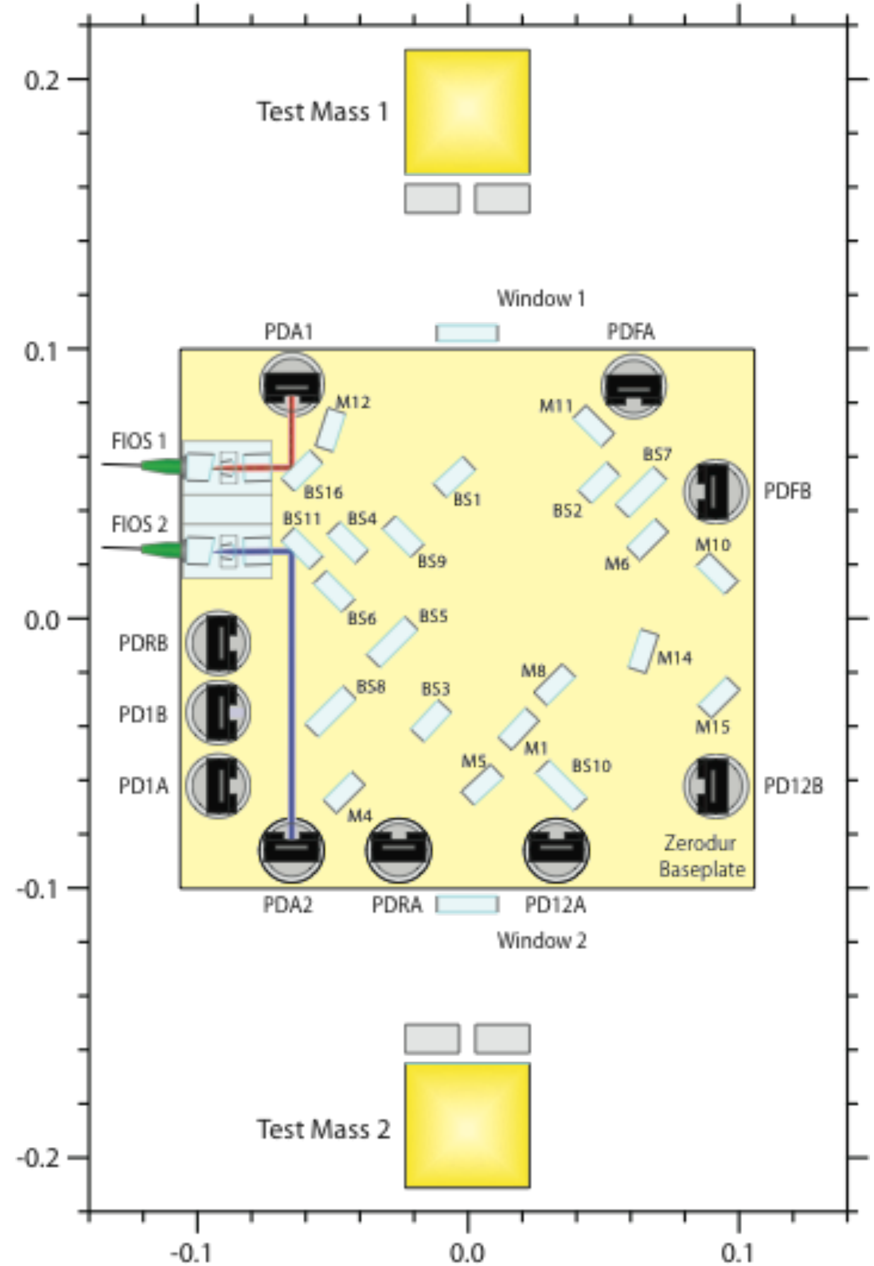
Frequency noise interferometer

- Measure laser frequency noise
- Optical path unbalance to enhance sensitivity to laser frequency noise



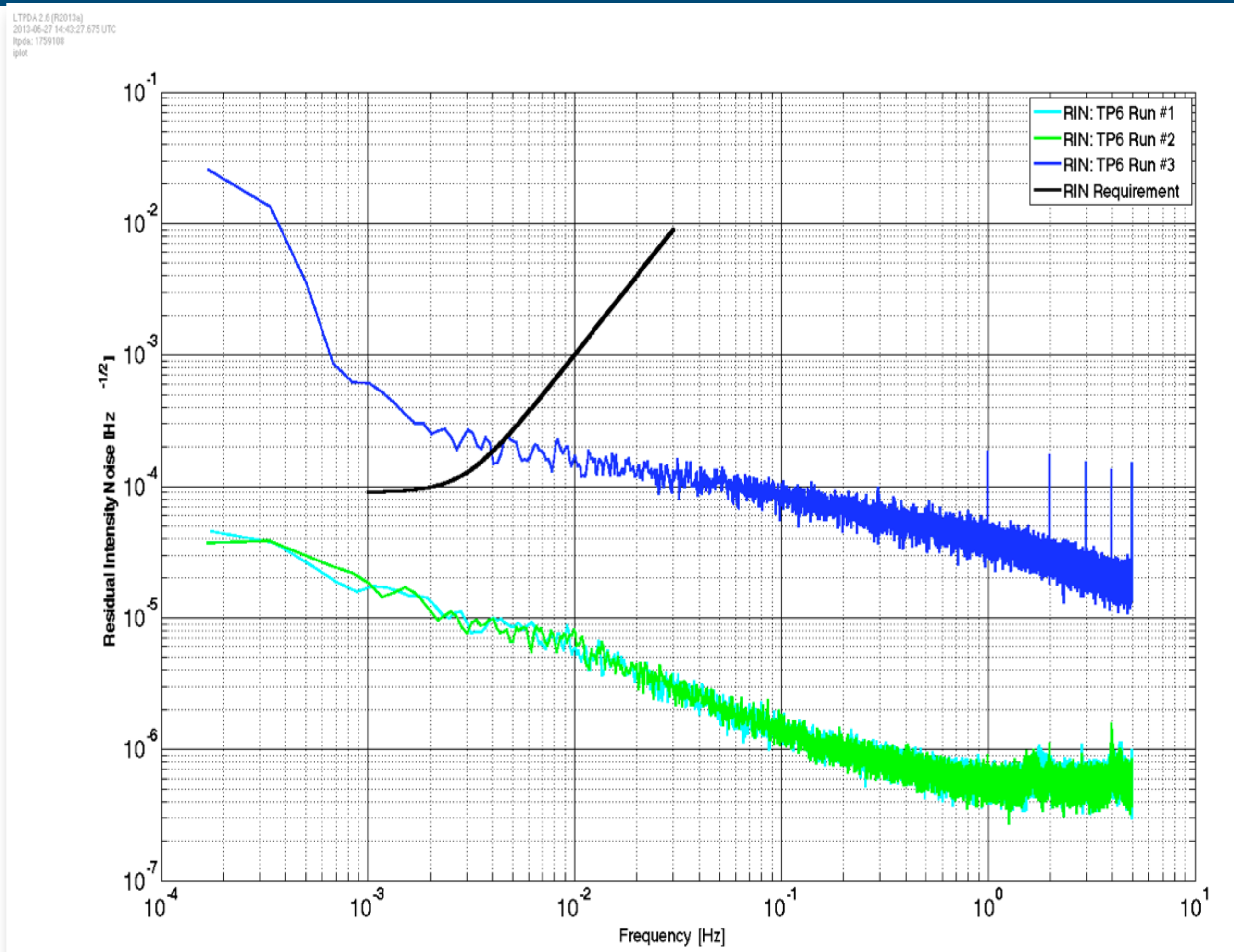
Power monitor

- Monitor the optical power from each fibre feed

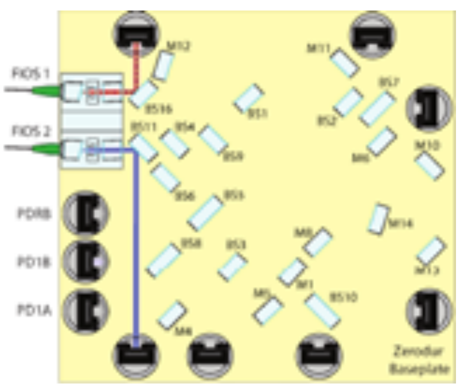


Beam power noise

- Light beam onto test masses
- Direct force on test masses
- How to control laser power
  - Measure the noise
    - Allows subtraction from the data (OK)
    - Allows closed loop control (better)
  - Low noise laser (best)



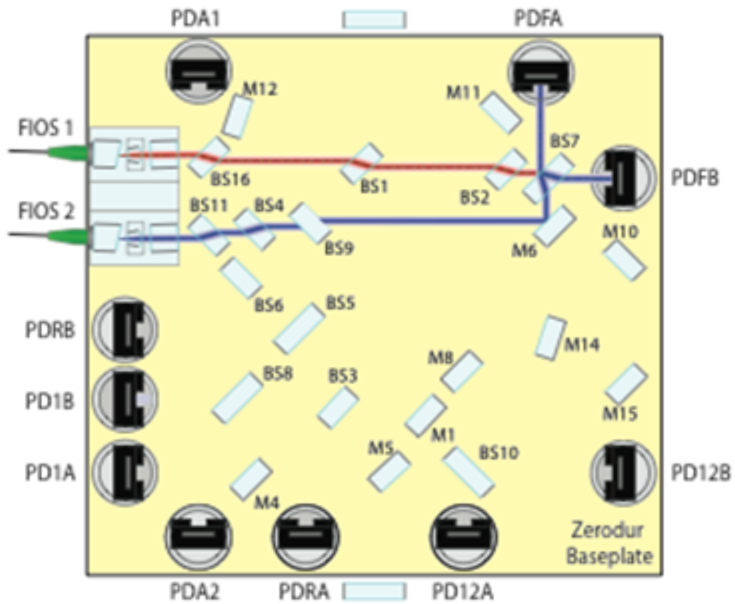
Residual laser power noise against frequency with the requirement in **black**– In the **blue** curve the control system is switched off



Laser frequency noise

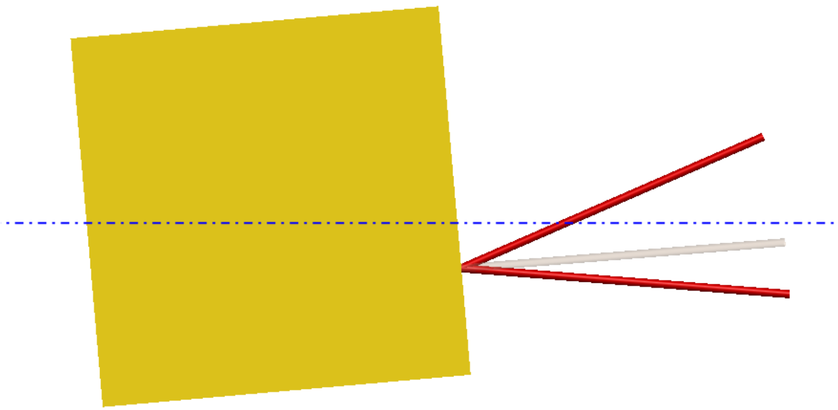
- Laser frequency noise $\delta\nu$ can cause apparent test mass displacement noise δx
  - Couples through path length mis-match ΔL
- Minimise effect by:
  - Well matched optical path lengths
    - Tracked during build matching which modelled the path length differences to be better than 10μm
    - Independent measurement gave upper limit of <100μm with a requirement of <1mm
  - Measure f-noise with frequency noise interferometer
    - Path length mismatch 382mm
    - Control laser frequency or subtract
  - Low noise laser
- Results extremely good – see second last slide

$$\delta x = \Delta L \left[\frac{\delta\nu}{\nu} \right]$$



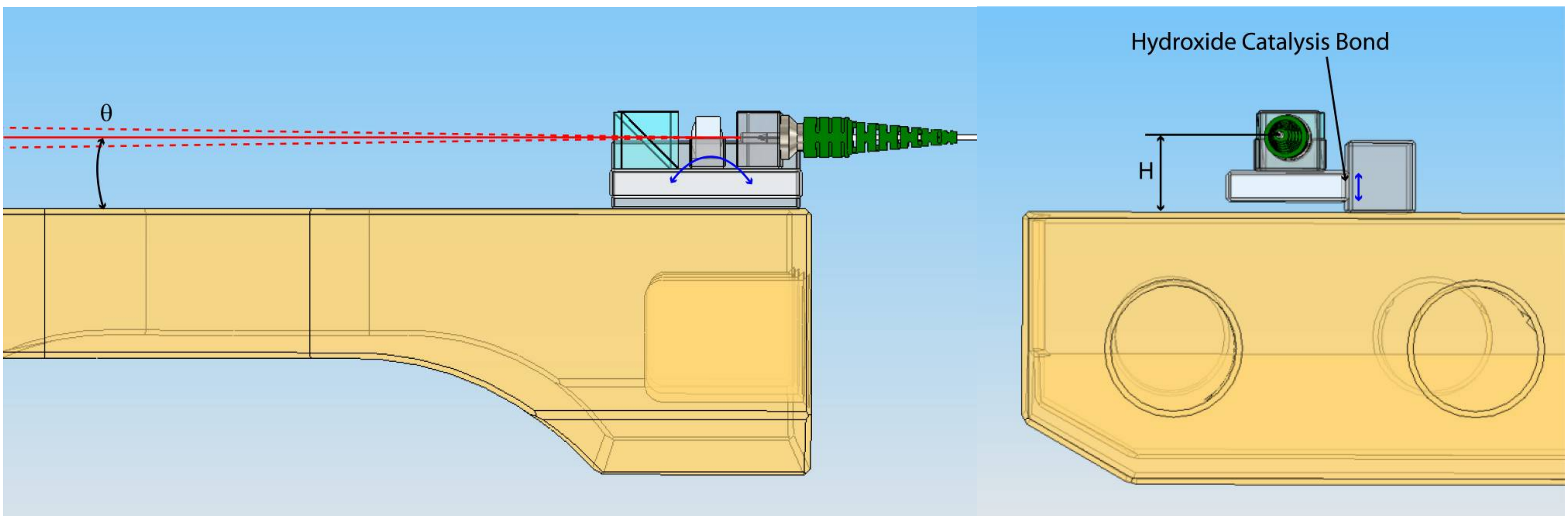
Beam alignment onto test masses

- Why it matters
  - Geometrical piston effect
- OBI allowance is beam aligned to nominal point on test mass surface to better than +/-25μm
- How it is achieved
- Maintain alignment over thermal range
- Maintain alignment over launch and into operations
- Results



Beam Alignment – out of plane

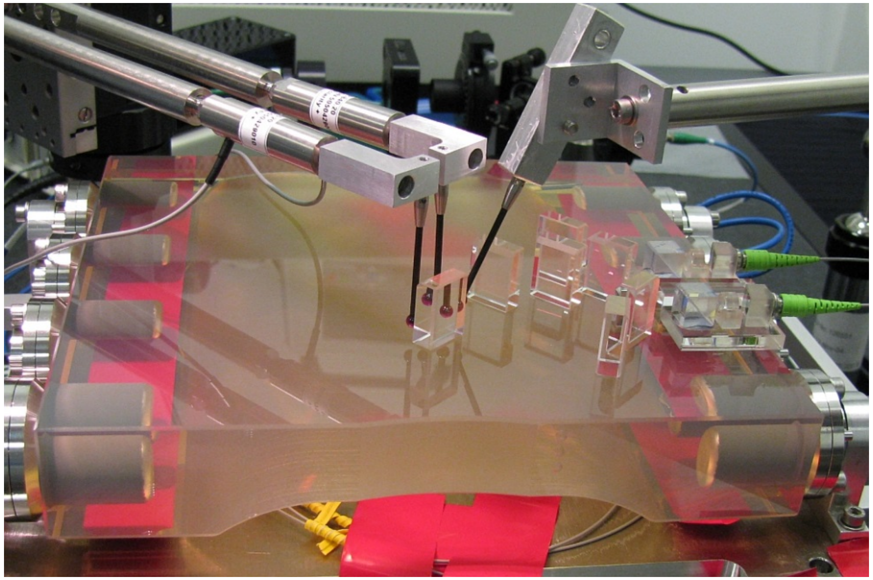
- Control the launch angle and height of beam launcher (FIOS)
- Target height at both test mass positions
  - Target error in H <15μm (achieved 10μm)
  - Target error in θ<30μrad (achieved 24μrad)
- Subsequent components must be extremely perpendicular
  - 90 degrees to 1 arc second

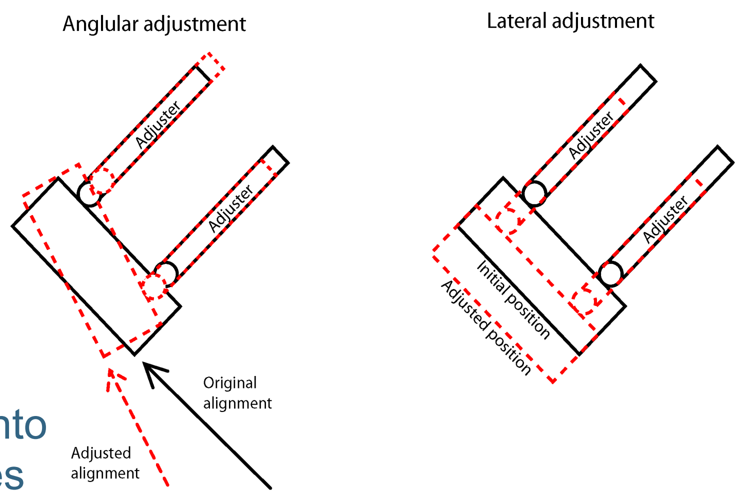


Beam Alignment – in plane

- Control position and angle of critical components when bonding
  - Repeatability of positioning ~10nm
  - Accuracy ~2μm
- Critical components
  - Alignment onto test masses
  - Recombination beamsplitters
  - Optical path length matching

Flight Model	Y deviation (μm)	Z deviation (μm)
Test Mass1	-6	-15
Test Mass 2	-16	-7
Flight Spare	**Y deviation (μm)**	**Z deviation (μm)**
Test Mass1	15	-4
Test Mass 2	9	-1



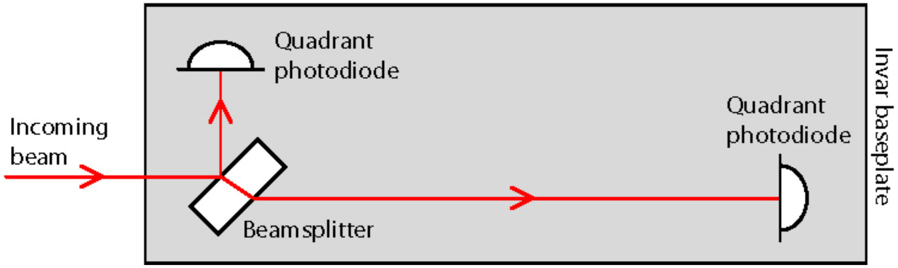


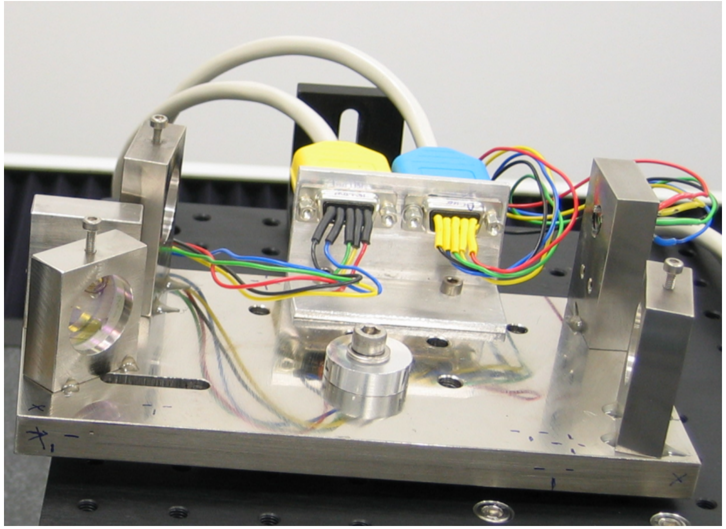
Alignment onto test masses

Target was <25μm

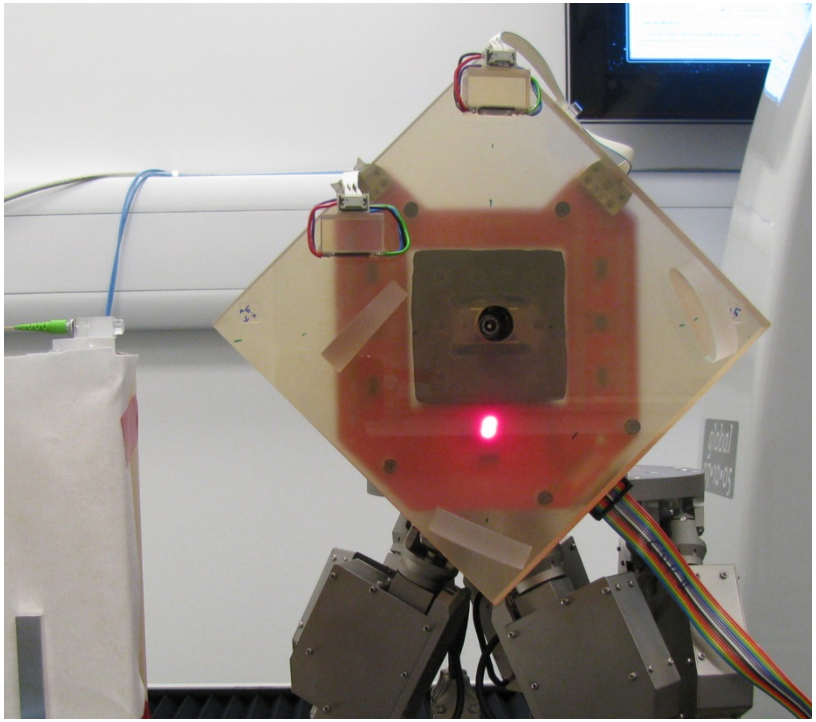
Calibrated quadrant photodiode assembly (CQP)

- Absolute measurement of beam position
  - Combined with a Coordinate Measuring Machine
    - Physical measurement with accuracy <2μm
    - Overall accuracy 4μm and 20μrad





LPF CQP

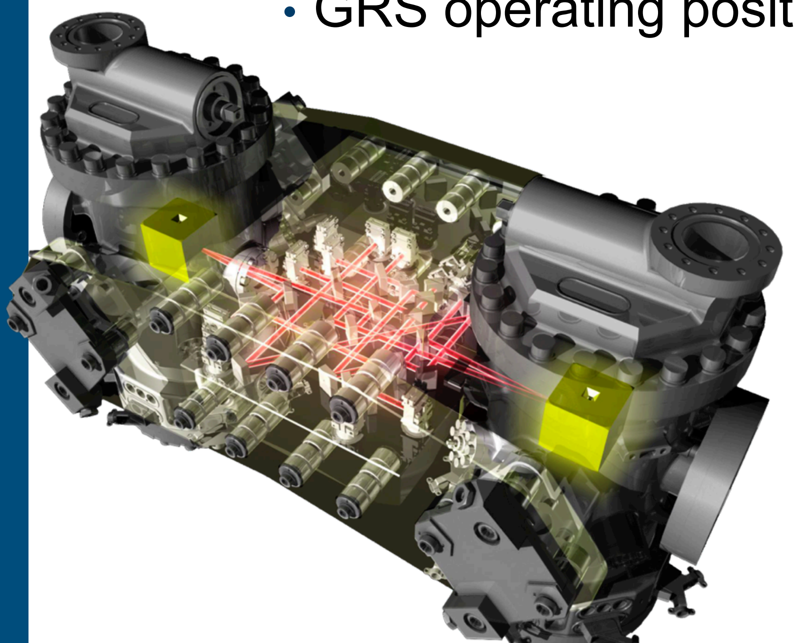


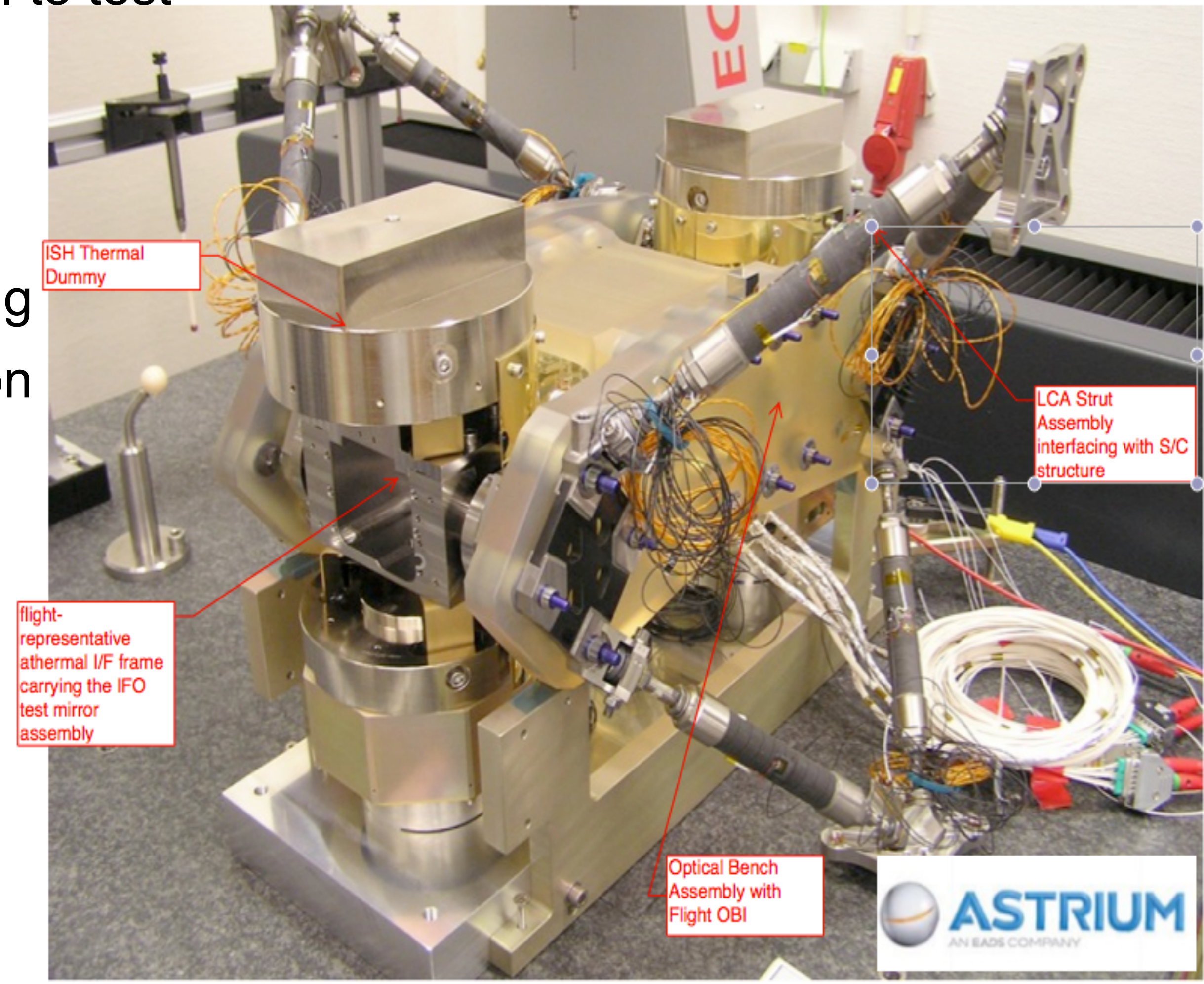
Improved CQP

OMS to test mass alignment

OBI alignment is only part of the story

- Maintain alignment form OBI to test masses – alignment chain:
  - Side slabs
  - Vacuum can
  - GRS electrode housing
  - GRS operating position

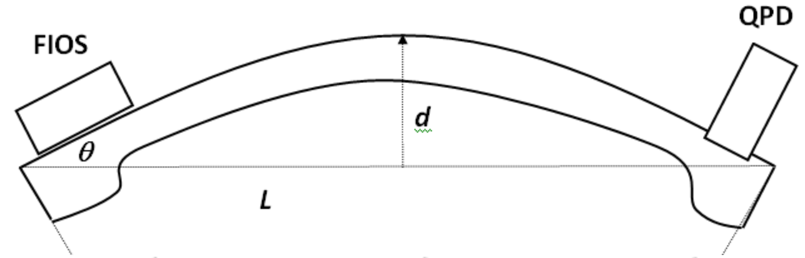


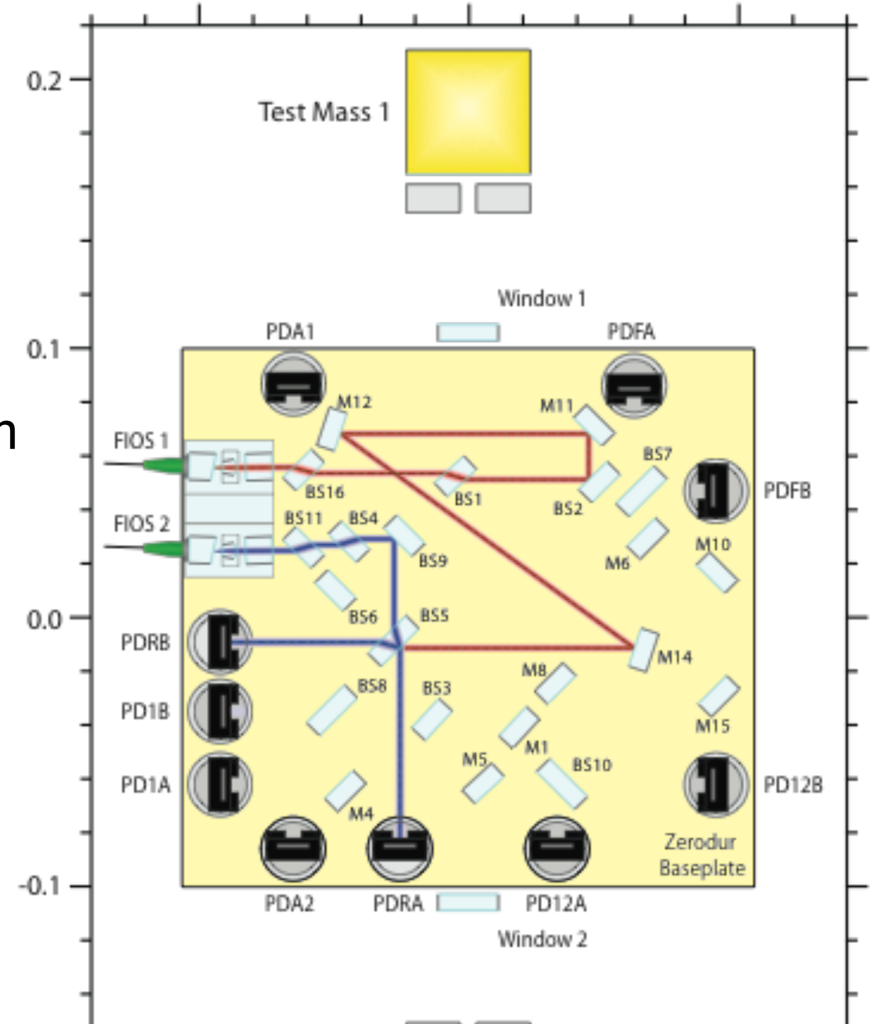


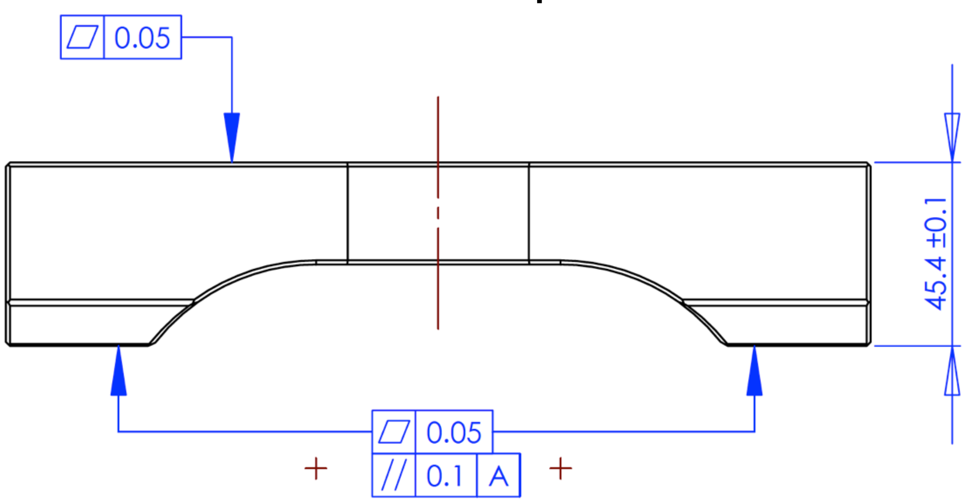
Maintaining OBI alignment

Mounting of the OBI must be stress free

- Minimise mechanical stress in Zerodur
  - Structural safety
  - Minimise misalignments caused by distortion of the Zerodur OBI baseplate
    - These could cause misaligment of the beams onto the test masses
    - 1.7μm distortion(*d*) gives 37μm beam movement on photodiode PDRB



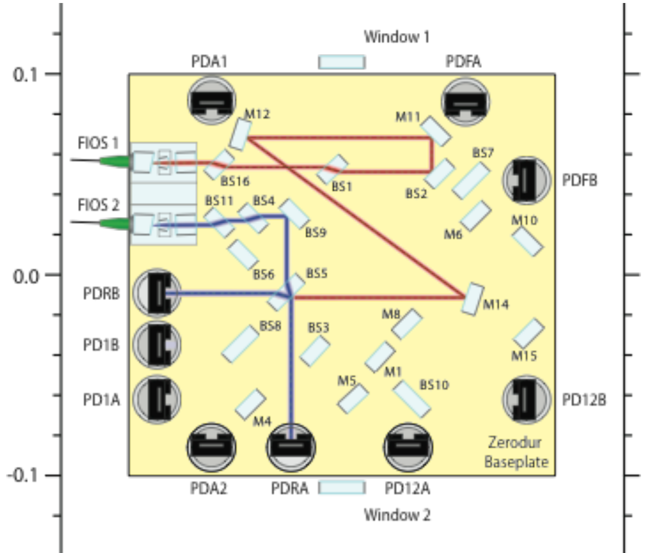


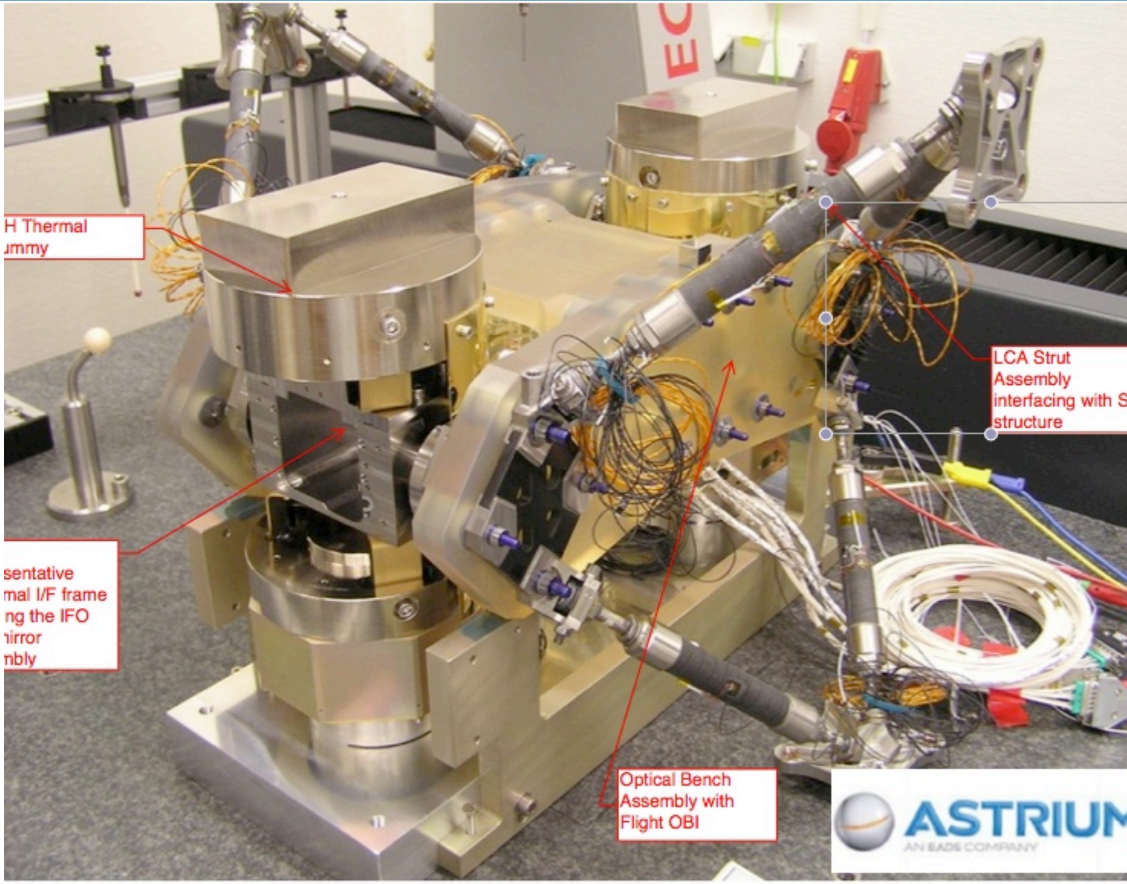


Monitoring OBI distortion

Monitor beam positions on photodiodes during critical parts of the integration

- Minimising beam movements minimises OBI distortion
- System used during assembly

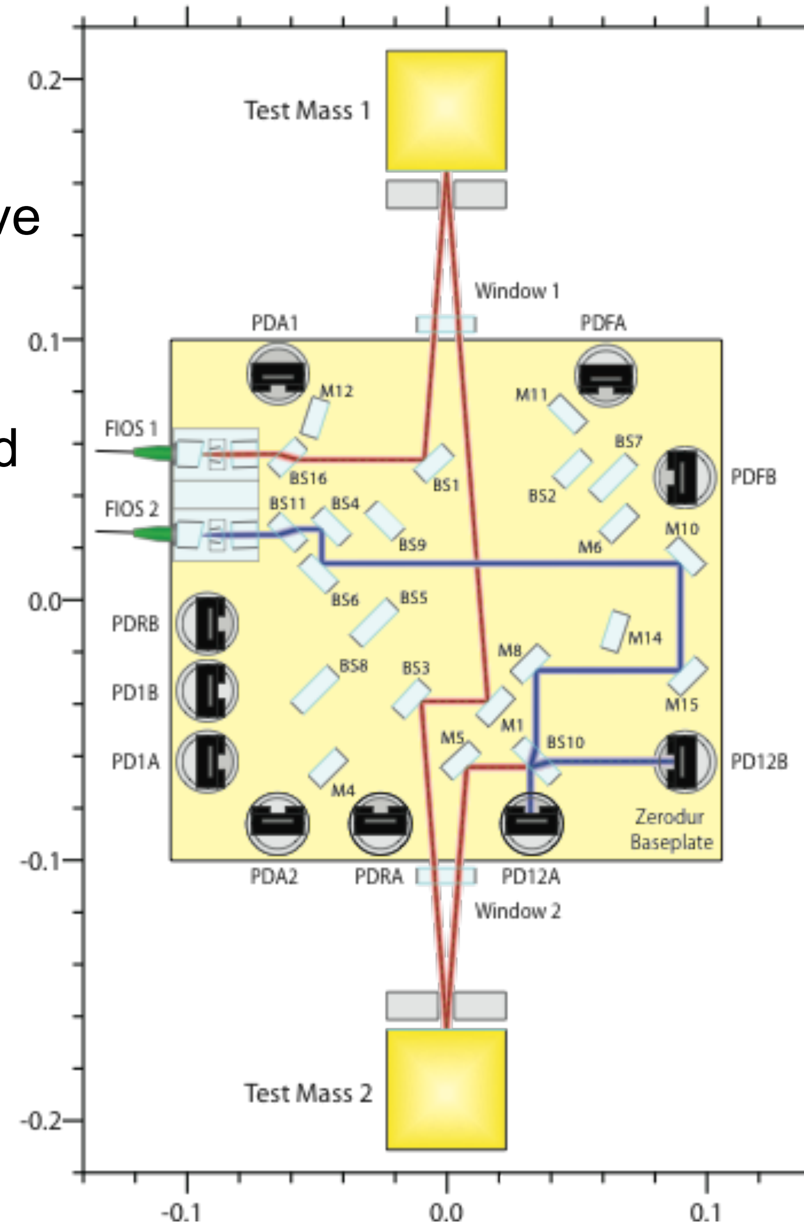




Moving test masses

OMS's main aim is to measure the freely floating test masses

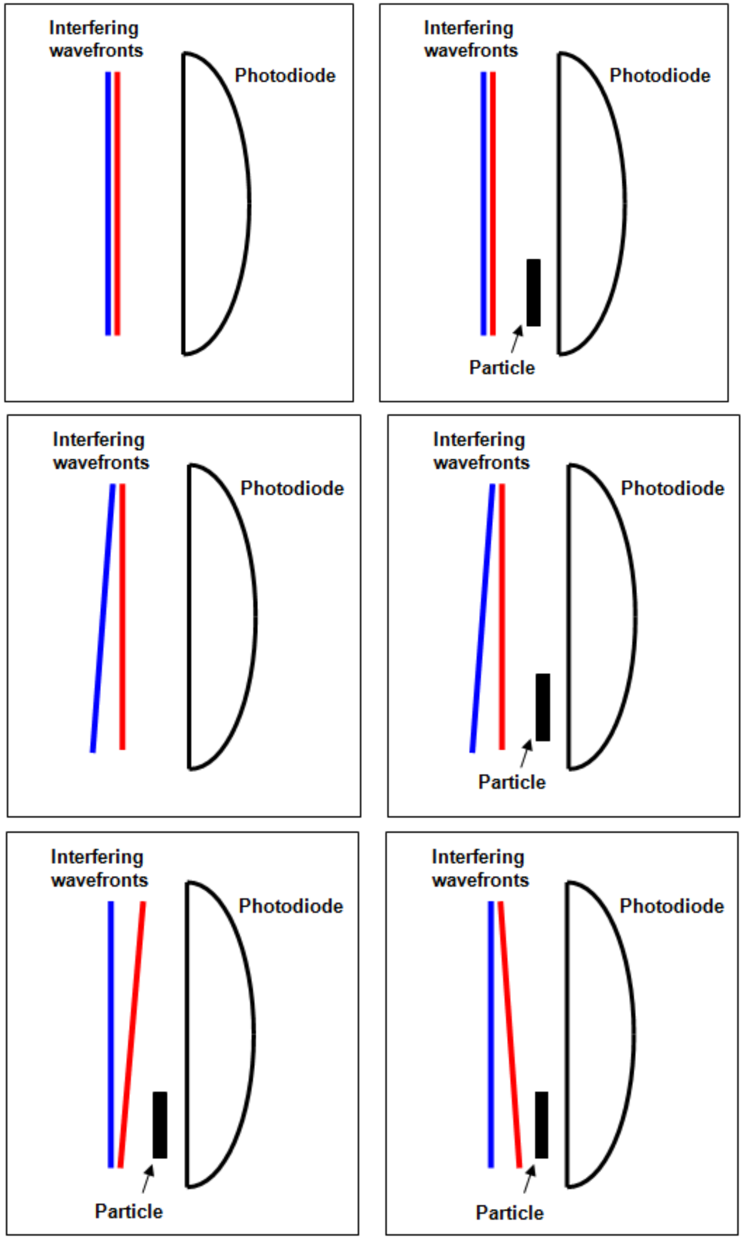
- Optical beams reflected from them will move with respect to the OBI
- Potential noise couplings
  - Not noise performance tested on ground
  - Check expected performance though modelling and characterisation



Beam obscuration and moving beams

Why beam obscuration matters

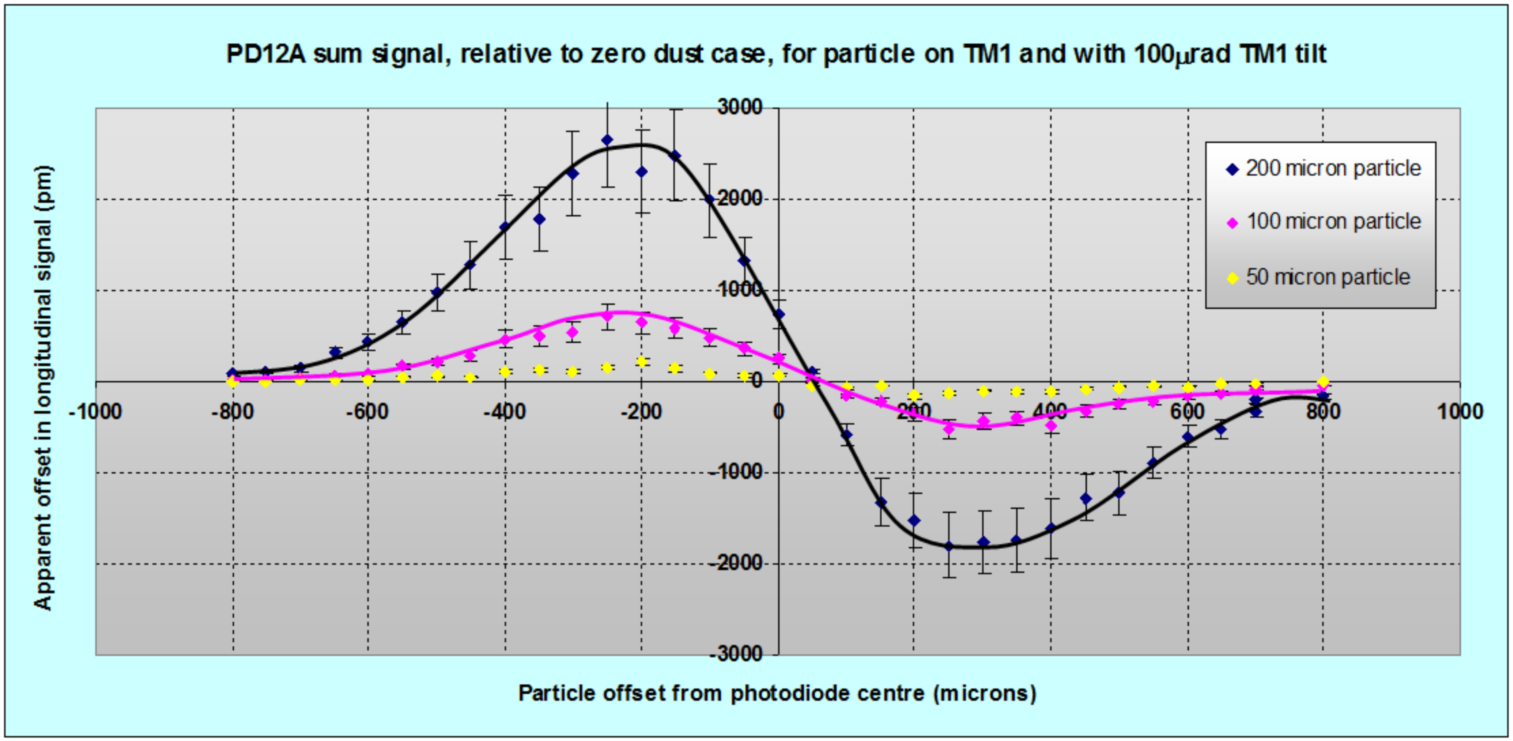
- Two interfering wavefronts
  - Diode detects the signal integrated over the whole beam
- 1) Parallel wavefronts with dust particle obscuring part of the beam
  - Signal amplitude reduced, no phase effect
- 2) Angled wavefronts
  - Signal amplitude reduced, static phase offset
- 3) Angled wavefronts
  - Signal amplitude reduced, phase offset varies with wavefront angle
  - Effectively a tilt to piston coupling due to the OMS

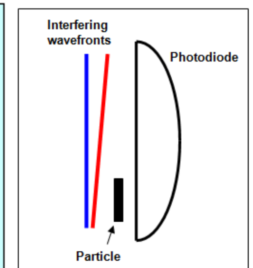


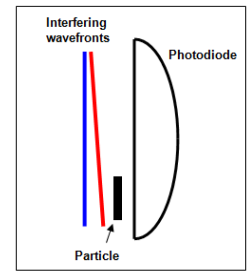
Beam obscuration and moving beams

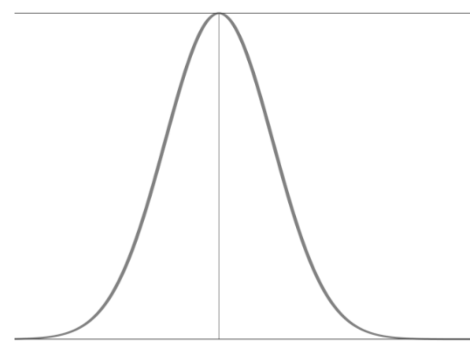
Modelling

- Effect is zero if the contamination is centred on the interfering beams
- Maximum effect at a little under half a beam radius from beam centre
  - Set allowable contamination size of < 60μm for a particle in optimally bad position
    - 1pm/√Hz noise allowance, TM angular noise 300nrad/√Hz



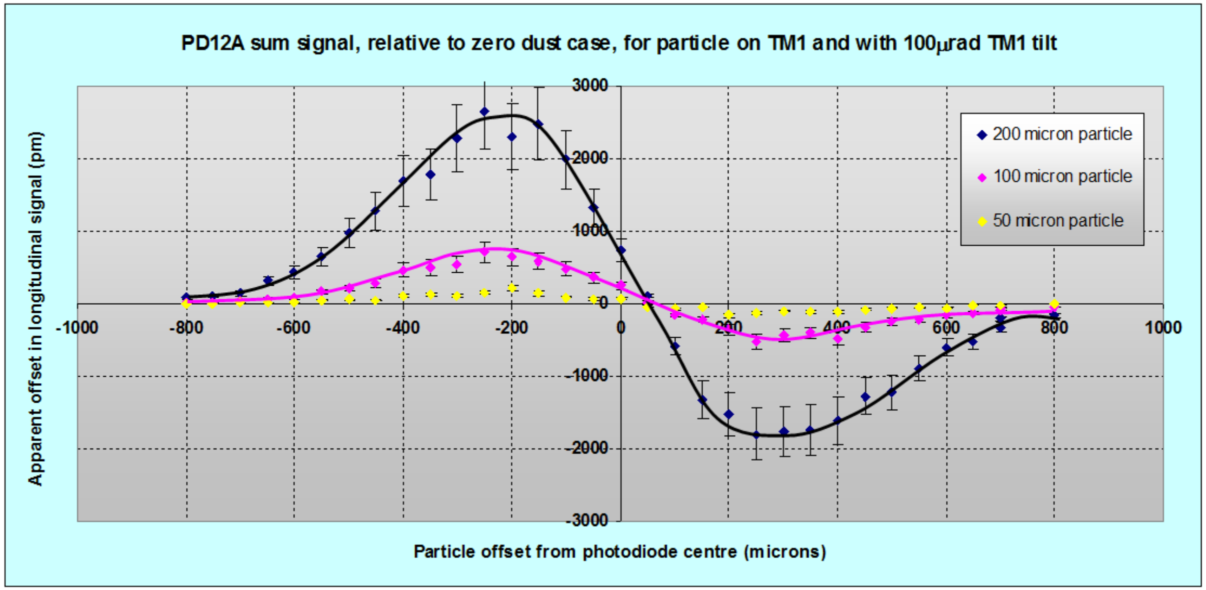


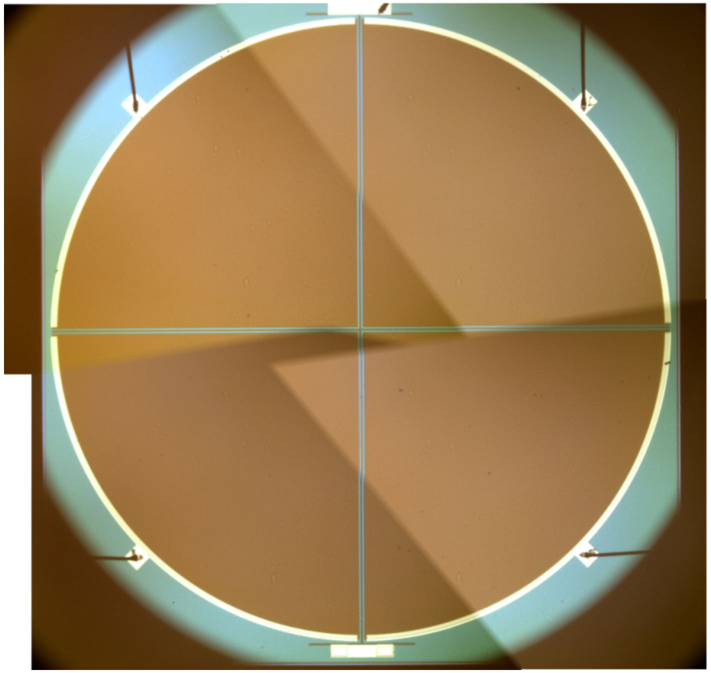




Photodiode alignment

- Diameter 5mm
- Inter-quadrant gap 45 μm
  - Acts like a linear dust particle
  - Photodiode must be centred on interfering beams to <33 μm
  - 1pm noise allowance, TM angular noise 300nrad/√Hz

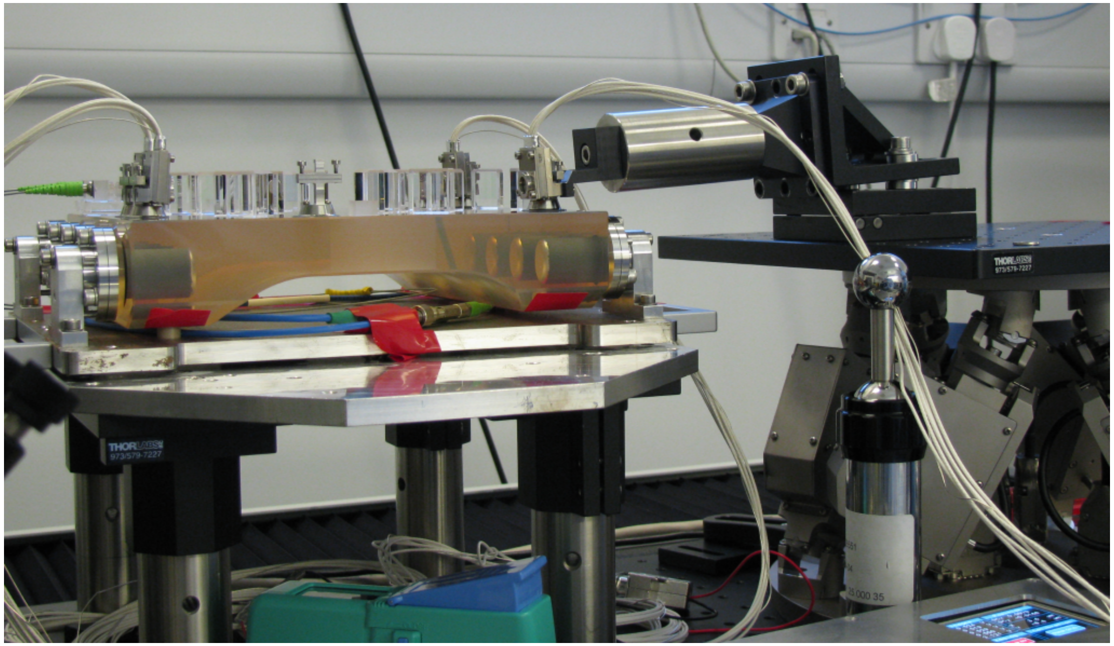




Composite image of an LTP InGaAs quadrant photodiode taken with an optical CMM

LPF photodiode alignment

- All just about within specification on the moving beam interferometers



Aligning photodiodes onto the Flight Spare optical bench

	X(mm)	Y(mm)
PD12A	8	0
PD12B	12	37
PD1A	12	3
PD1B	-5	-5
PDRA	-13	-6
PDRB	58	89
PDFA	21	-29
PDFB	8	-13

Moving beam interferometers (PD12A, PD12B, PD1A, PD1B)

Fixed beam interferometers (PDRA, PDRB, PDFA, PDFB)

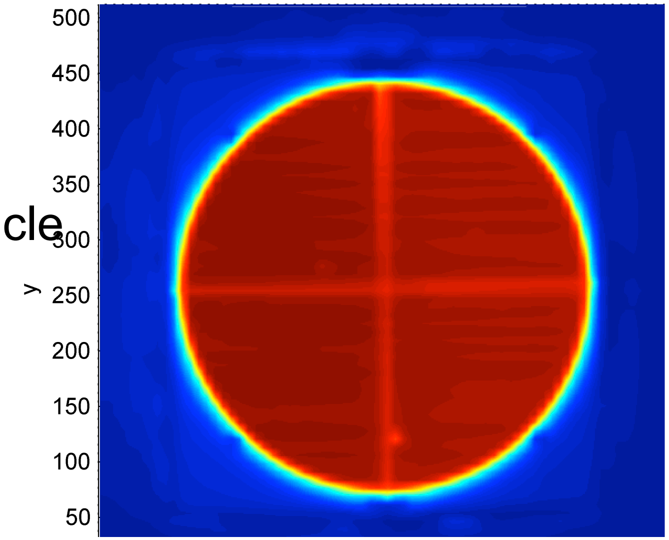
Photodiode	Angle (degrees)
PD12A	-0.17
PD12B	-0.08
PD1A	-0.26
PD1B	-0.19
PDRA	0.05
PDRB	-0.02
PDFA	-0.22
PDFB	0.05

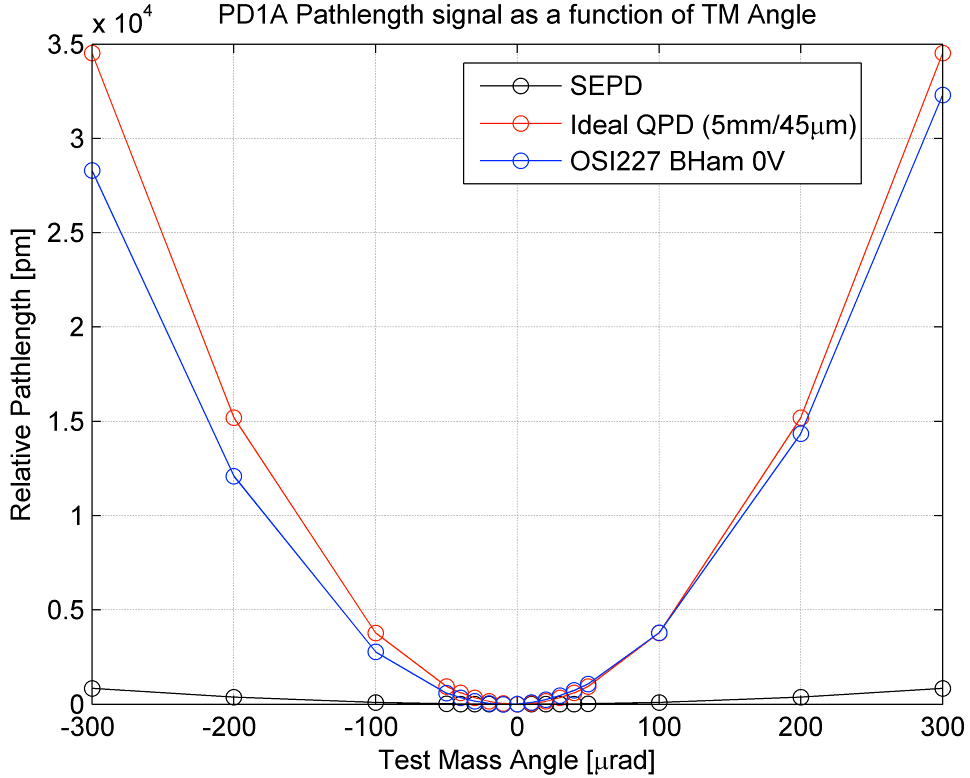
Photodiode angular rotation

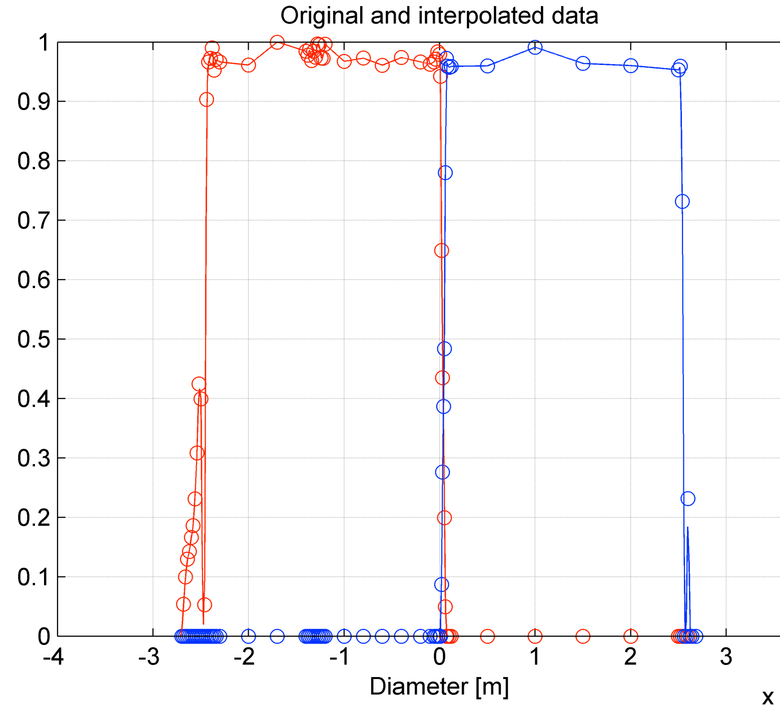
Target <0.5 degrees

Flight QPDs are InGaAs

- Uniformity of response measured by scanning beam
- Effect of non-uniformity is similar to a diffuse dust particle
- Flight model QPDs very uniform response
- Very sharp division between quadrants
- Tilt to piston marginally better than "ideal" QPD







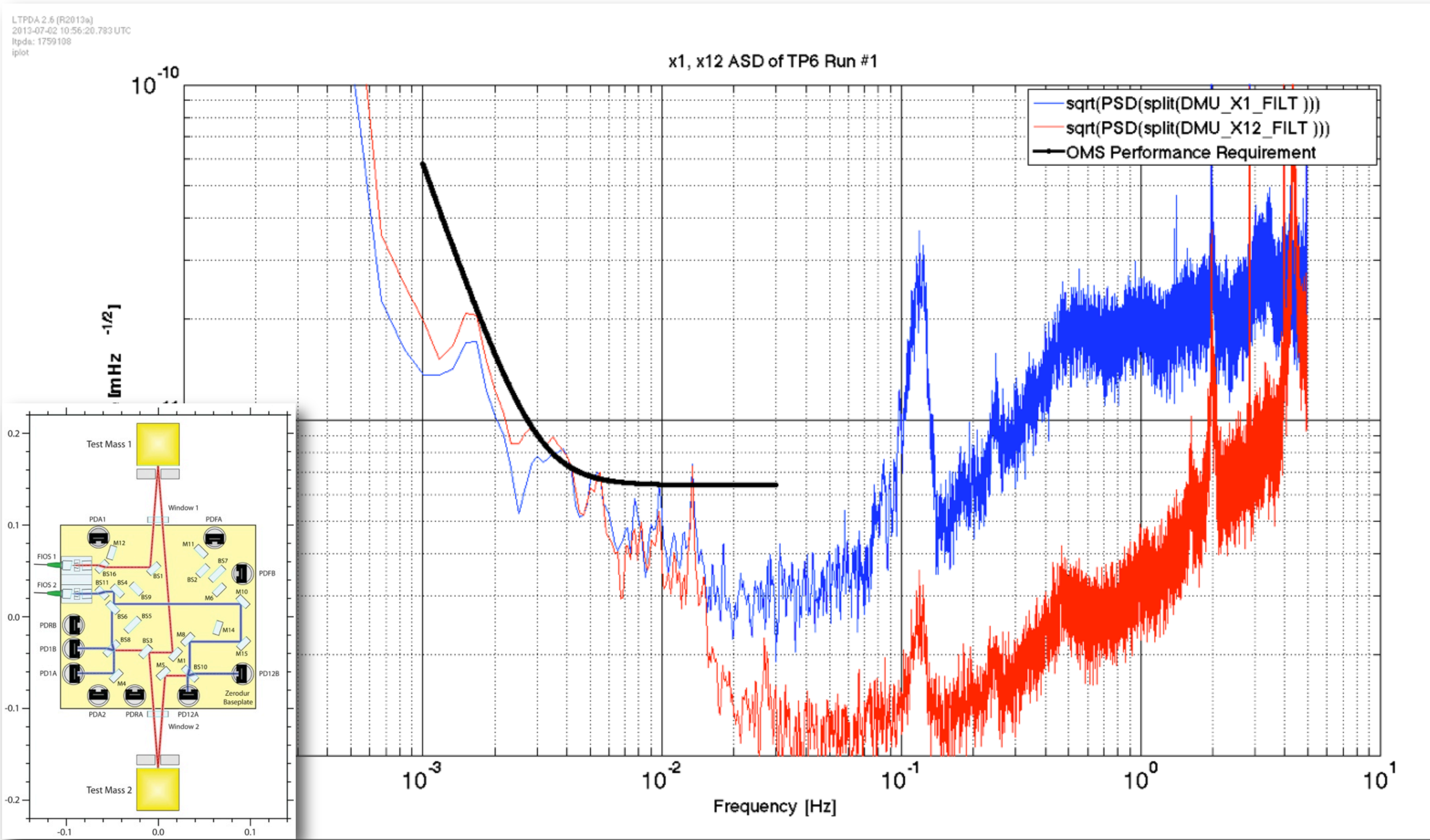
On Station Thermal Test Results

On Station Thermal Tests

- Full optical metrology system
- Static dummy mirrors in place of test masses
- Overall performance exceeded expectations

LPF Spacecraft being prepared for OSTT campaign

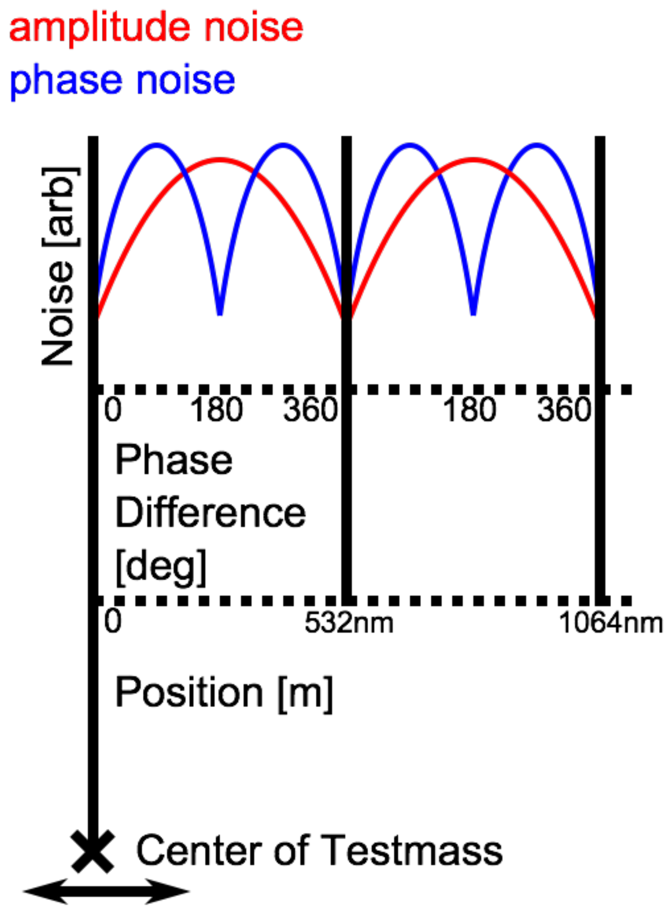
Longitudinal performance



Out of band noise can couple to OMS measurements

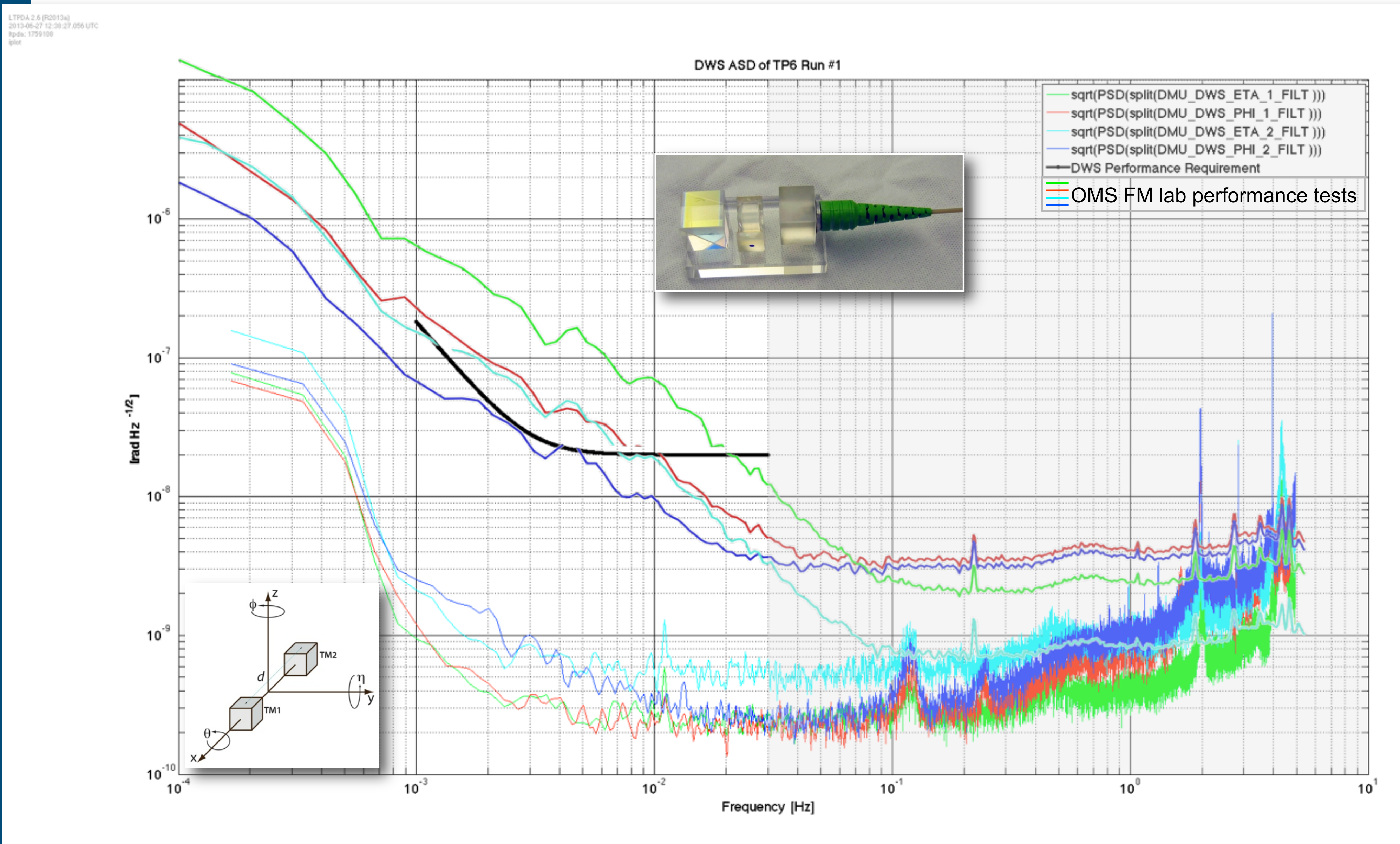
- Amplitude noise
- Phase noise
- Coupling can be minimised by moving test masses longitudinally to an optimum operating point
  - Test mass movements of <λ
- Effect seen in OSTT data

- See "**Optimising Test Mass Position for the LISA-Pathfinder Optical Metrology System**" by Andreas Wittchen on Thursday afternoon



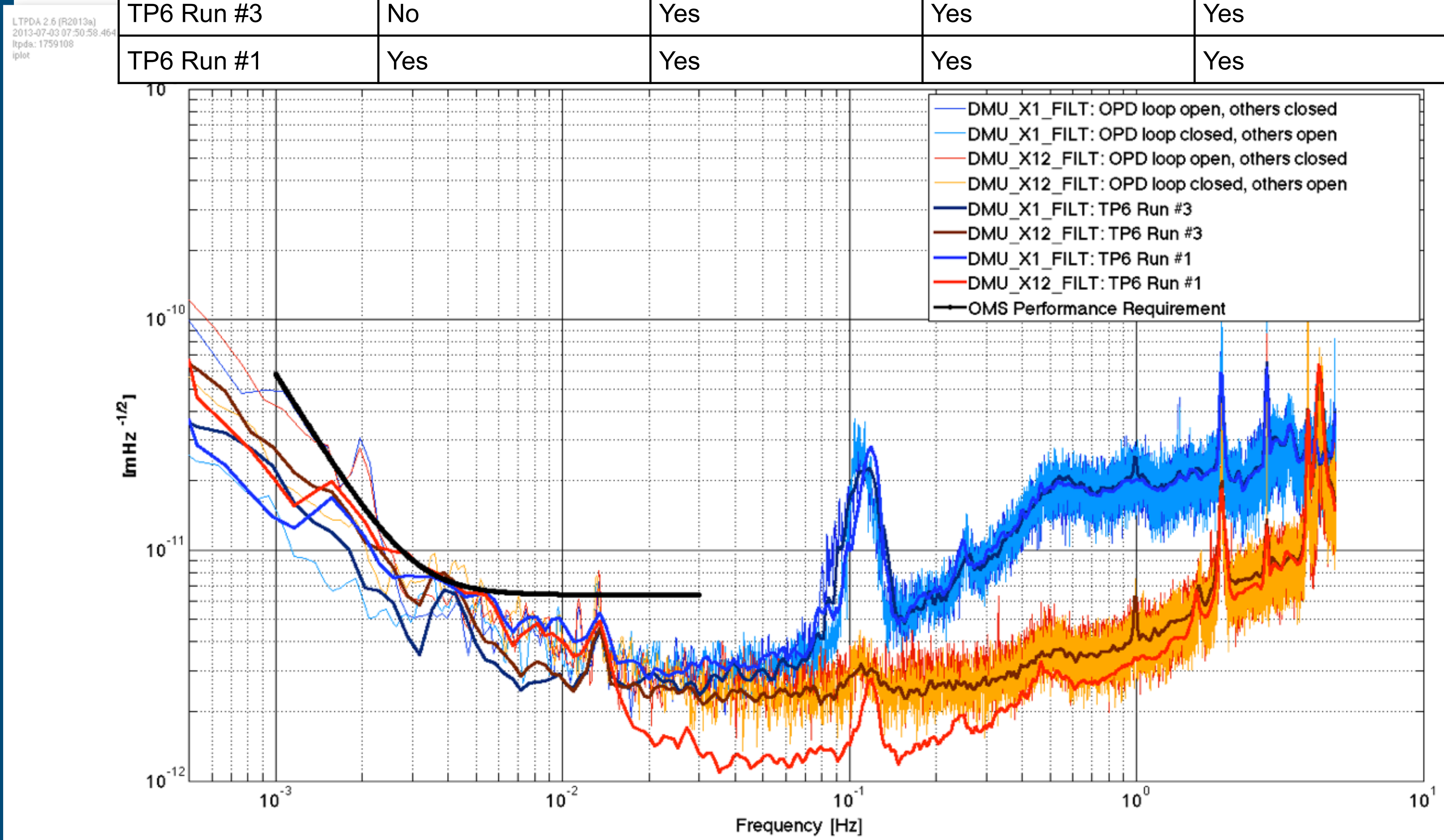
Noise coupling with test Mass position - See Andreas Wittchen's presentation for full details

Differential Wavefront Sensing



Longitudinal performance–control loops off

Run Number	Power Loop	Fast Frequency	Slow Frequency	OPD Loop
1	Yes	Yes	Yes	No
2	Yes	No	No	Yes
TP6 Run #3	No	Yes	Yes	Yes
TP6 Run #1	Yes	Yes	Yes	Yes



Conclusions

- LTP OMS technology fully integrated into LPT core assembly
- Building the LTP OMS has exercised many components, technologies and systems relevant to LISA local interferometry
- Testing at component and system level ~~very satisfactory~~ AWESOME!
  - Static noise performance
  - Noise coupling measurements
  - Performance meets or exceeds goals
  - Some interesting features
    - Strategies to deal with them in place
- Now needs tested on orbit!