Mechanised alignment for component positioning and Bonding: From academic origin to industrial application

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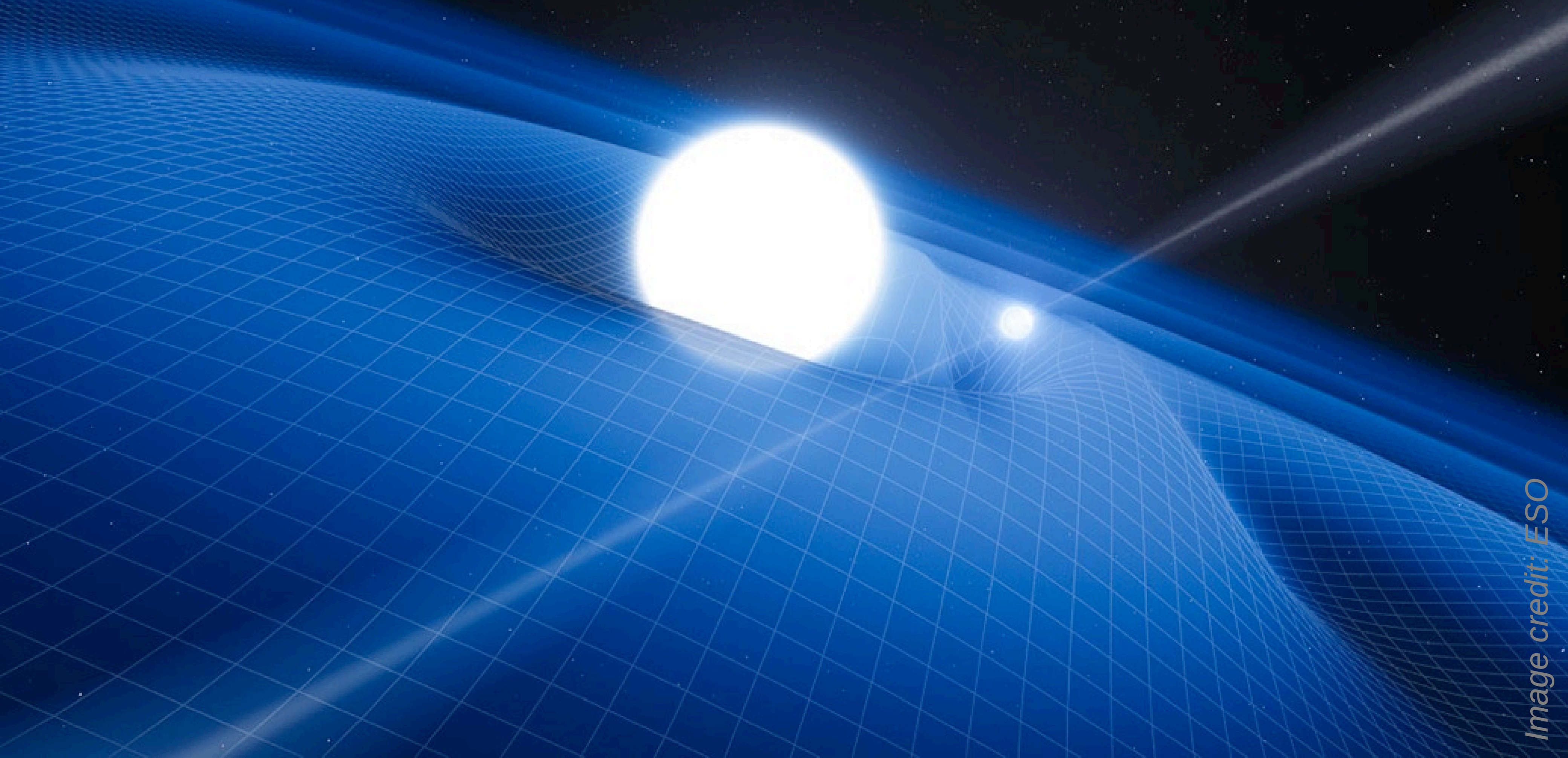


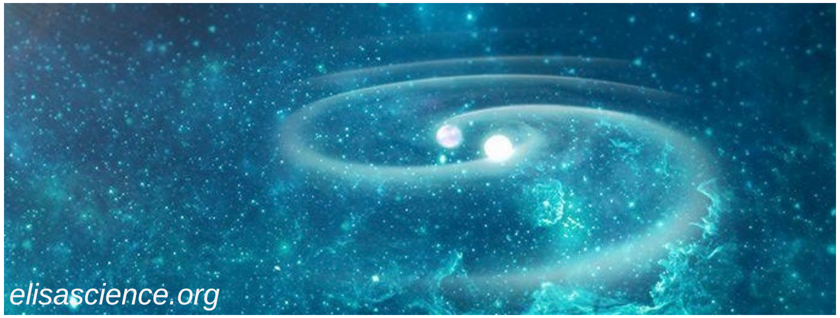
Image credit: ESO

Overview

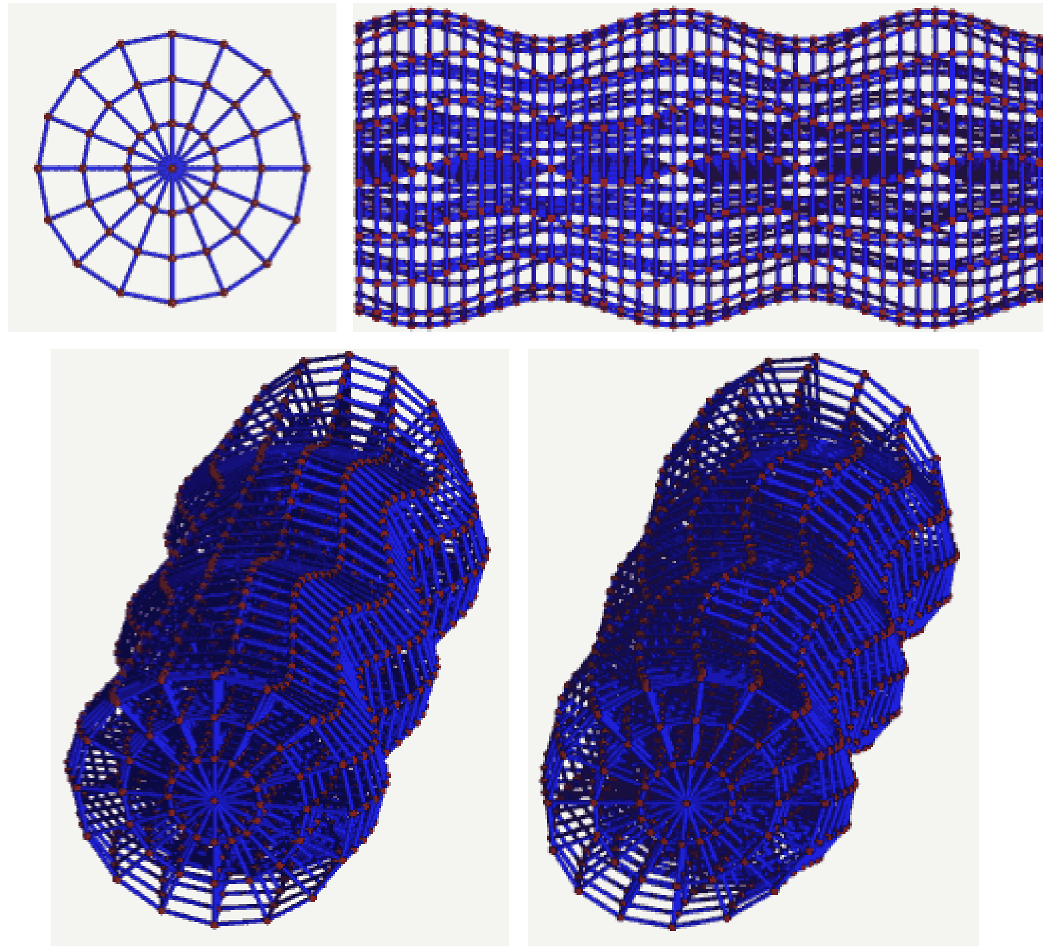
Developing capability in precision optical hardware for ground- and space-based activities

Gravitational Waves

- What are they?
  - Ripples in the curvature of spacetime
  - Predicted by Einstein's General Relativity
  - Awaiting first direct detection
  - Carriers of astronomical information not visible to electromagnetic energy



- What effect do they have?
  - Stretch and squeeze spacetime
    - This makes it possible to detect them…



Effect of a gravitational wave passing through an arrangement of test particles.
Courtesy of M. Pössel/Einstein Online [http://www.einstein-online.info]

Gravitational Wave Detectors

- The best way we have to build gravitational wave detectors is to isolate 'test masses' from local disturbances and measure their separation as gravitational waves pass through the system
  - We use laser interferometry as the 'ruler' as high precision is needed

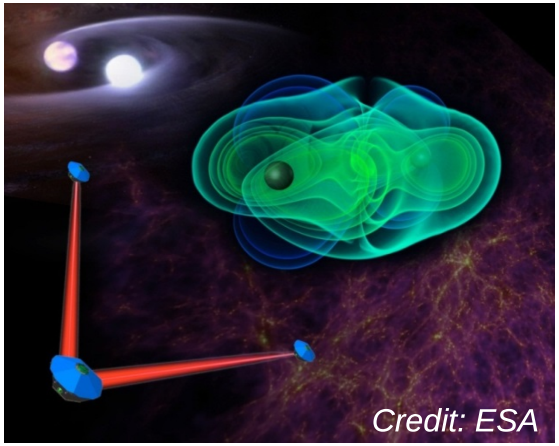
The 4 km arm length LIGO gravitational wave observatory in Louisiana, part of the world-wide effort to detect gravitational waves

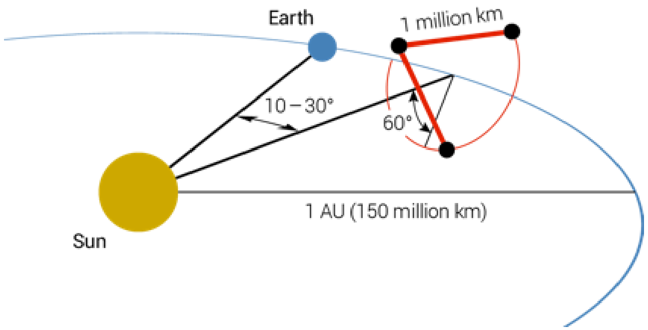
$$h = \frac{\Delta L}{L} \sim 10^{-20}$$

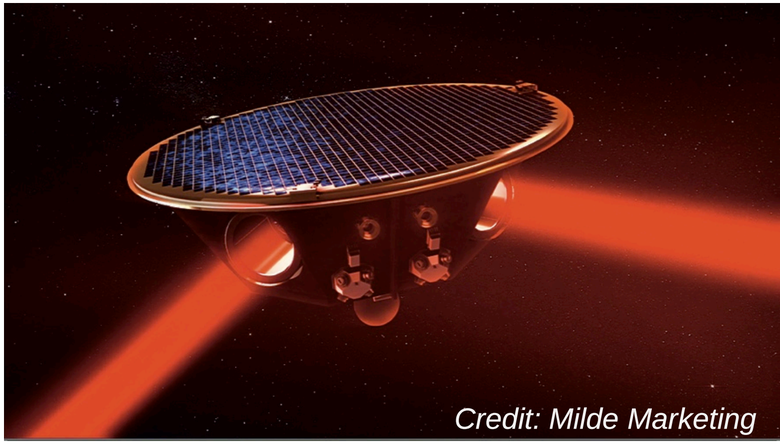
- This leads to long arm lengths and very precise position measurements

A problem and a solution

- Changes in local mass distribution – even clouds passing – cause a variation of the forces acting on the test masses
  - This is a problem if the mass distribution changes in the band you want to measure
- We need to go to a gravitationally quiet environment: space
  - Added benefit that we can have very long armlengths
- eLISA is a proposed spaceborne gravitational wave detector

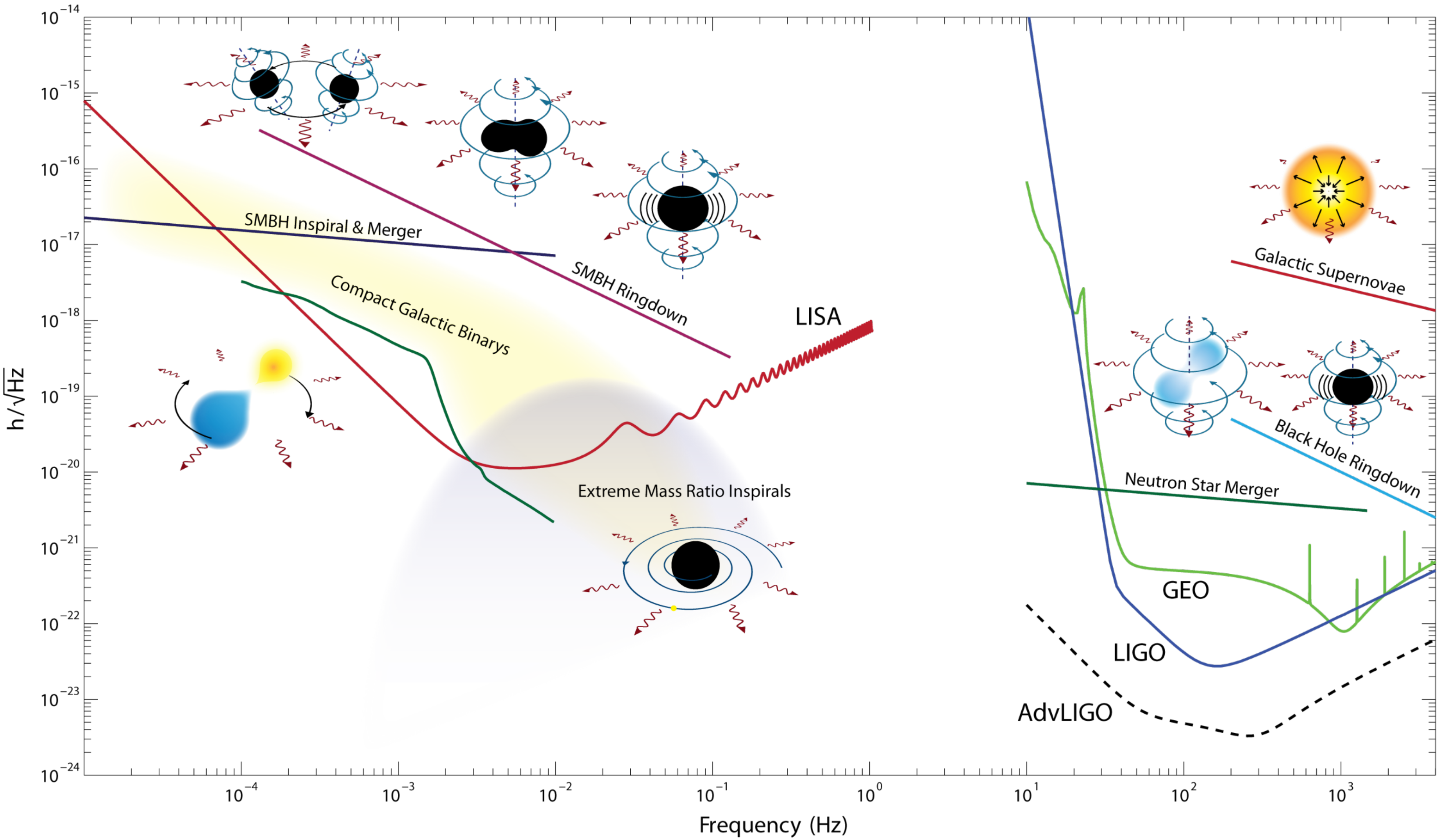






- Similar detection principles as ground-based detectors: monitor separation of inertially free masses using interferometry
- With gigametre armlengths and requiring picometre test mass monitoring at milliHertz
  - A demonstrator mission – LISA Pathfinder – is being flown to retire technological risks

Astronomy with Gravitational Waves



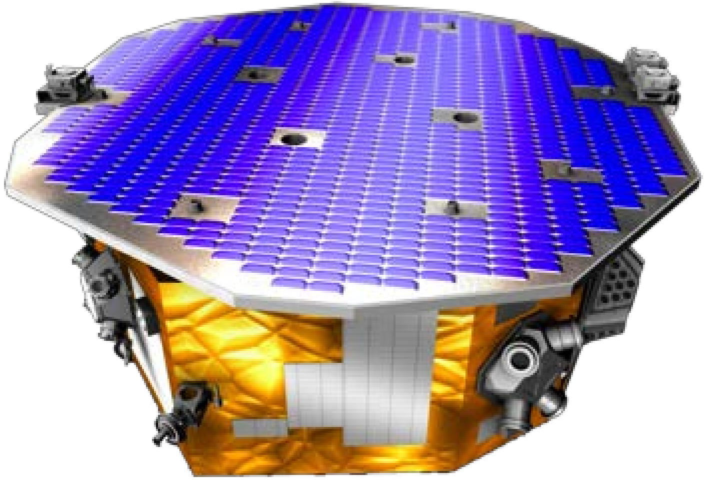
Slides courtesy of Ewan Fitzsimons

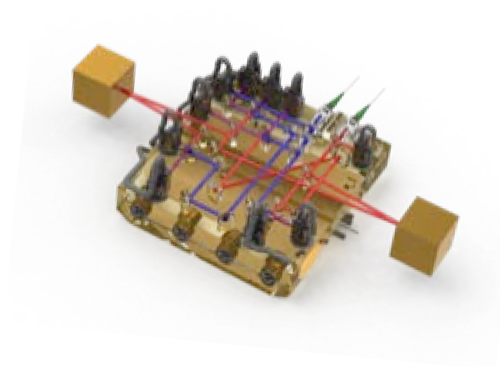
LISA Pathfinder

- We can verify many aspects of eLISA on ground, but not all
- The aim of LISA Pathfinder is to verify technology for future spaceborne gravitational wave detectors
  - It will effectively demonstrate the 'short-arm' interferometry for eLISA
- Fly two test masses and measure the purity of their freefall
  - Experiment in micro-gravity at L1
- European Space Agency mission due for launch in **2015**
- Significant technological development in many areas is required for this mission
  - I will only mention aspects of the optical test mass position measurement

LISA Pathfinder structural model (courtesy Airbus DS UK)

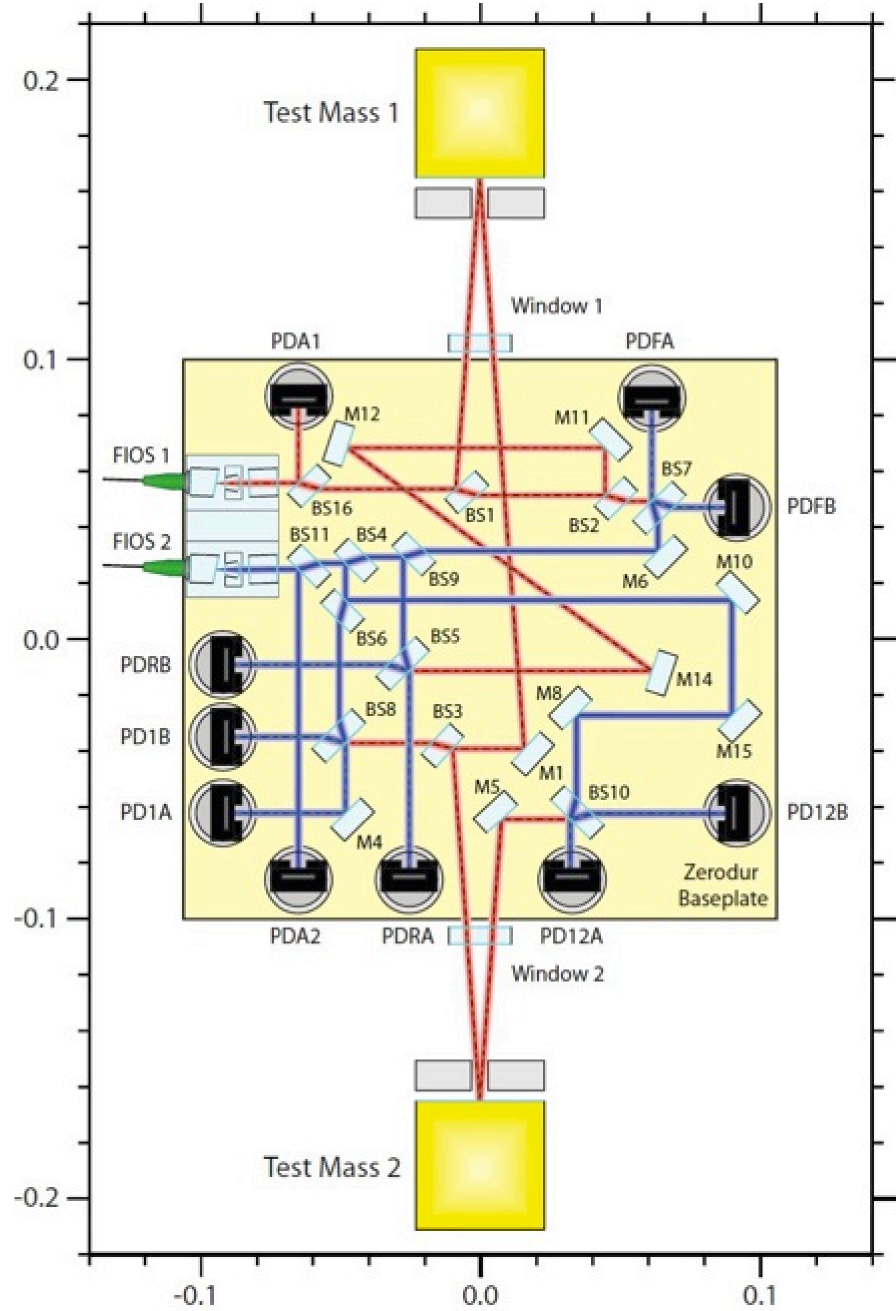
LISA Pathfinder optical bench

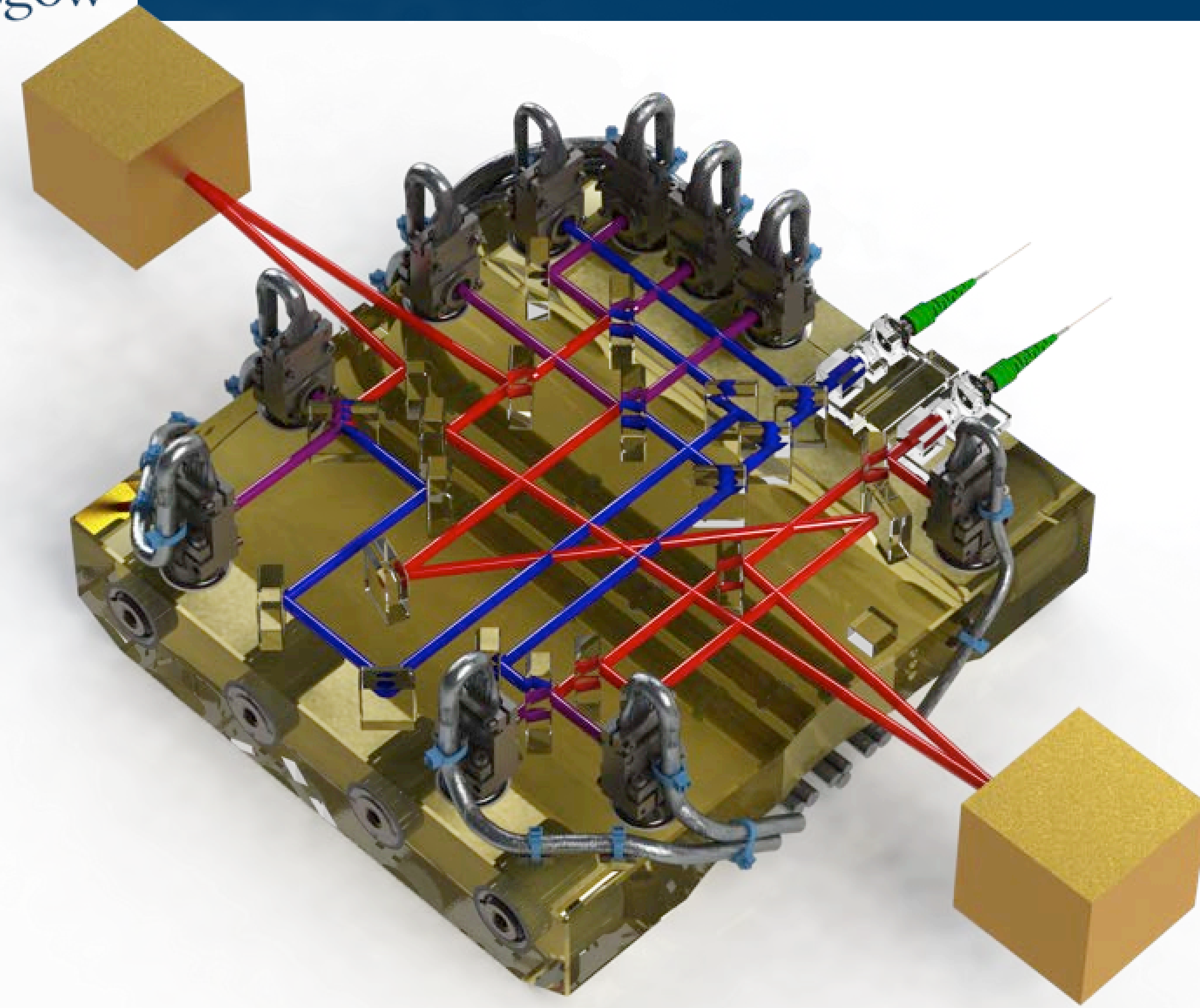




Design from first principles

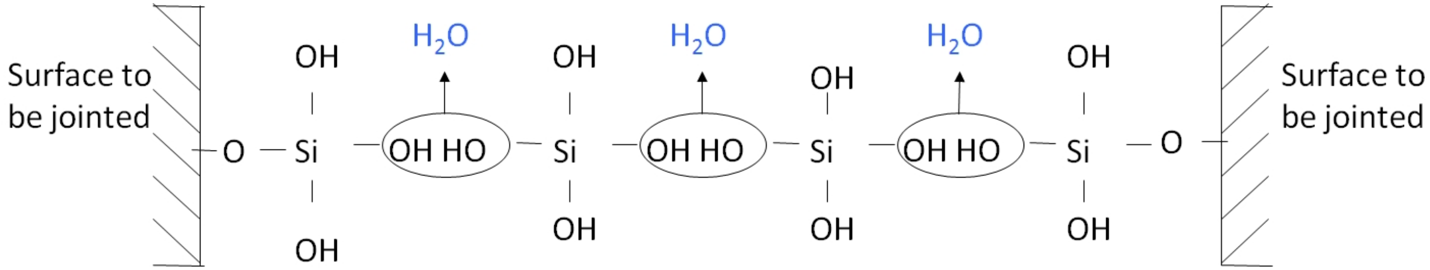
- The Optical Bench Interferometer
  - Has to physically fit into the space available
  - Plays a structural role
  - Has to survive launch and radiation environment
  - Be non-magnetic
  - Measure 10 picometre longitudinal variations and 20 nanorad angular beam motion (in band) in milliHertz regime
  - Beams have to hit the Test Masses within 25 μm of absolute nominal
- This leads to a lot of derived requirements
  - And a lot of paperwork

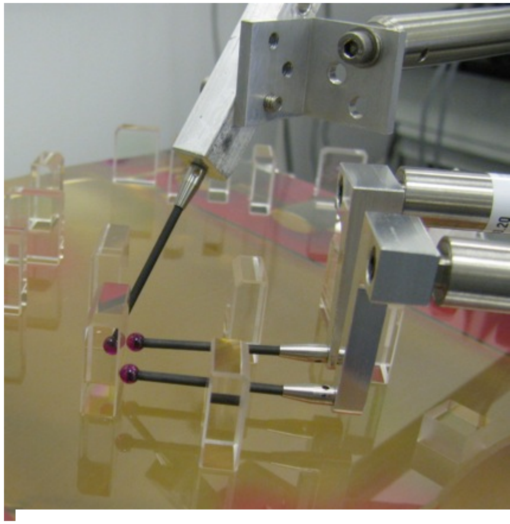




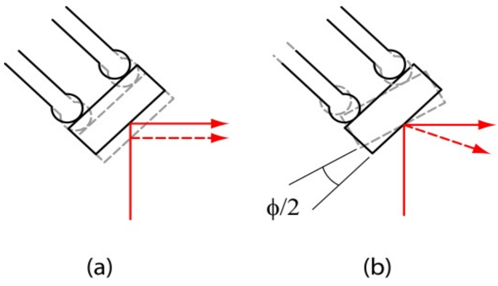
Enabling technology

- A technology was identified as being useful in gravitational wave detectors: hydroxide-catalysis bonding
  - First space-science use in Gravity Probe B
  - An adhesive free method of joining substrates that, in general, form oxides
  - Forms very strong, thin bonds that are UHV compatible





- We have developed the technique to precision locate components and bond them in place
  - Once built the assembly is permanently aligned
  - Demonstrated picometre stability
  - Component placement at the μm and 20 μrad level
  - Measure reflected beam with absolute accuracy 4μm and 20 μrad
  - Killow *et al.* Applied Optics, Vol. 52, Issue 2, pp. 177-181 (2013)



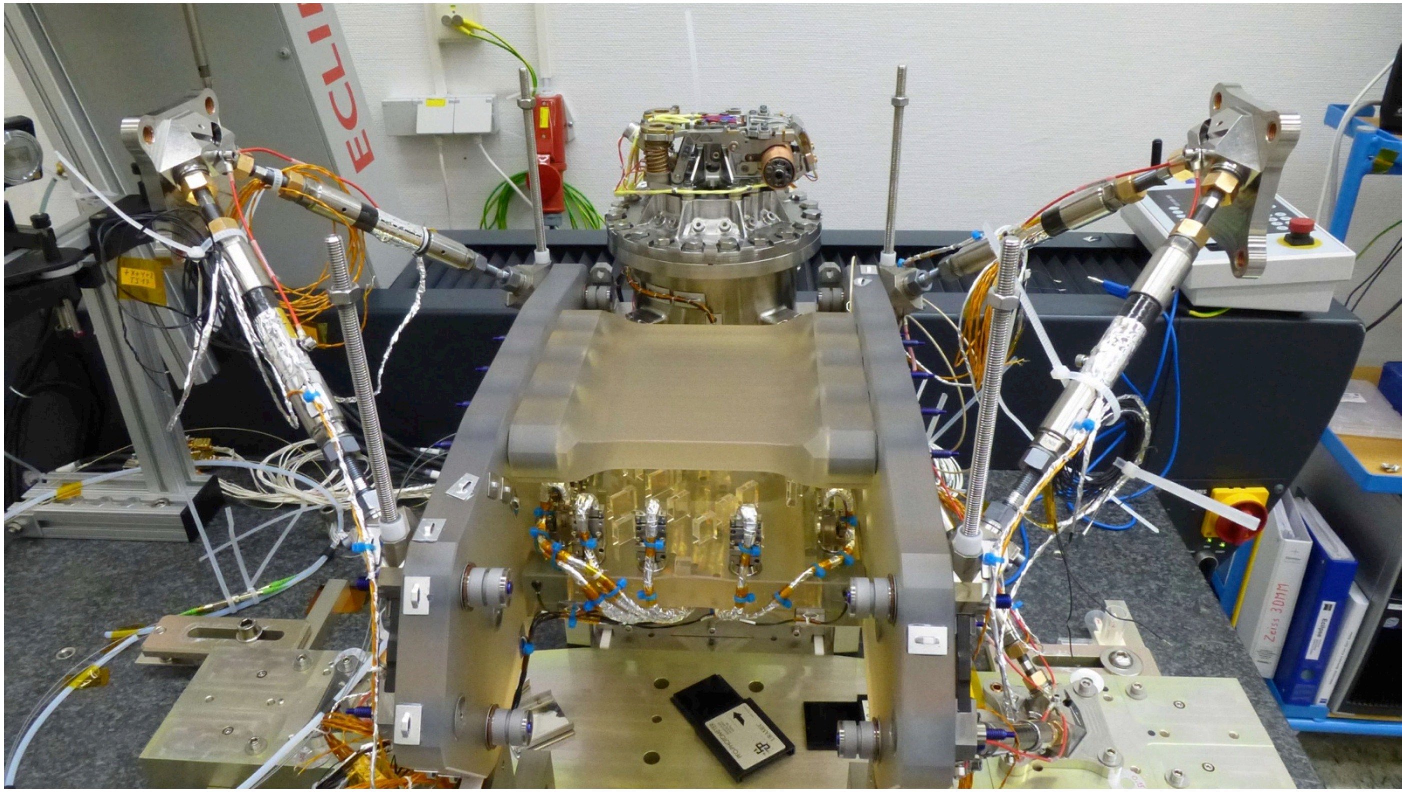
Space worthiness of current alignment process

- The flight OBI underwent considerable testing (details in Robertson *et al*. Class. Quantum Grav. 30 (2013) 085006)
  - **Thermal Vacuum cycling**
  - **Vibration and shock**
  - Properties of the optical chain
    - Transmission efficiency
    - Photodiode responsivity
  - Alignment to the IAF Frames
  - Beam DC positions and scaling
  - DWS Calibration
    - Operating point
    - k-coefficients
  - Other Optical Properties
    - Interference contrast
    - Path length matching

Vibration testing of the qualification pair of LISA Pathfinder fibre injectors at Selex ES

Summary so far….

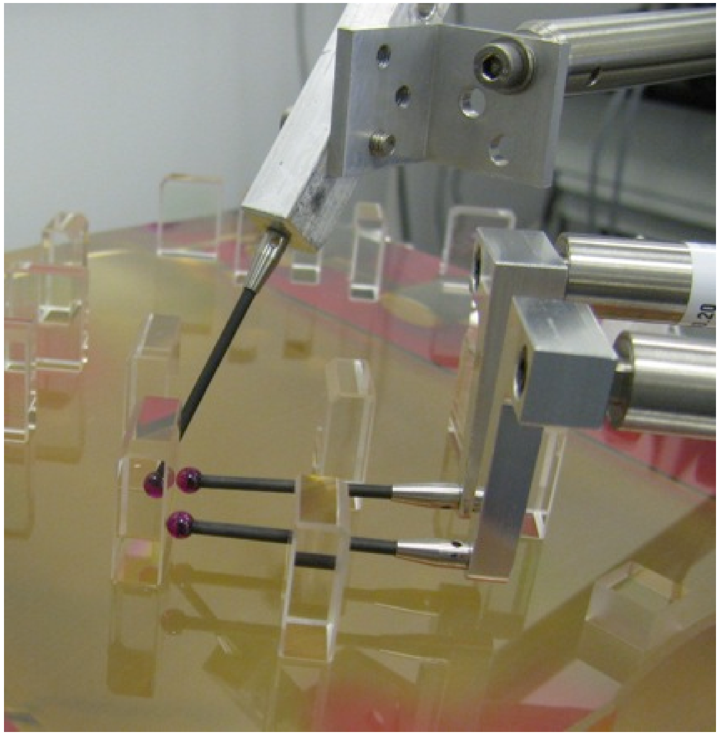
- We have developed the technique to precision locate components and bond them in place
  - Once built the assembly is permanently aligned
  - Demonstrated picometre stability
  - Component placement at the sub-μm and 20 μrad level
- Tested and qualified for space flight
- Built and delivered
- Launching this year

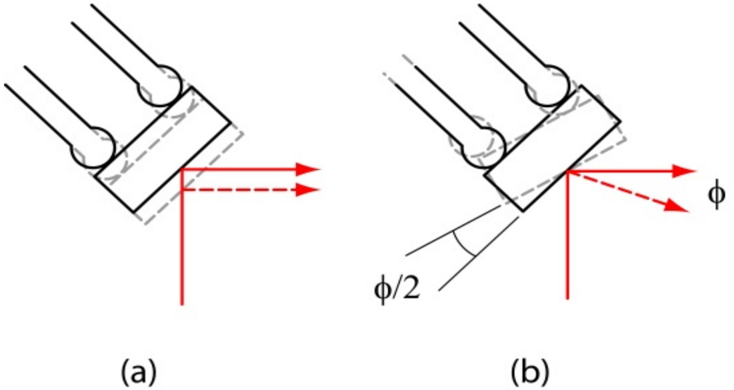


Optical bench being integrated into the LPF Core Assembly (Airbus, Friedrichshaven)

A bonding stage (*not real time*)

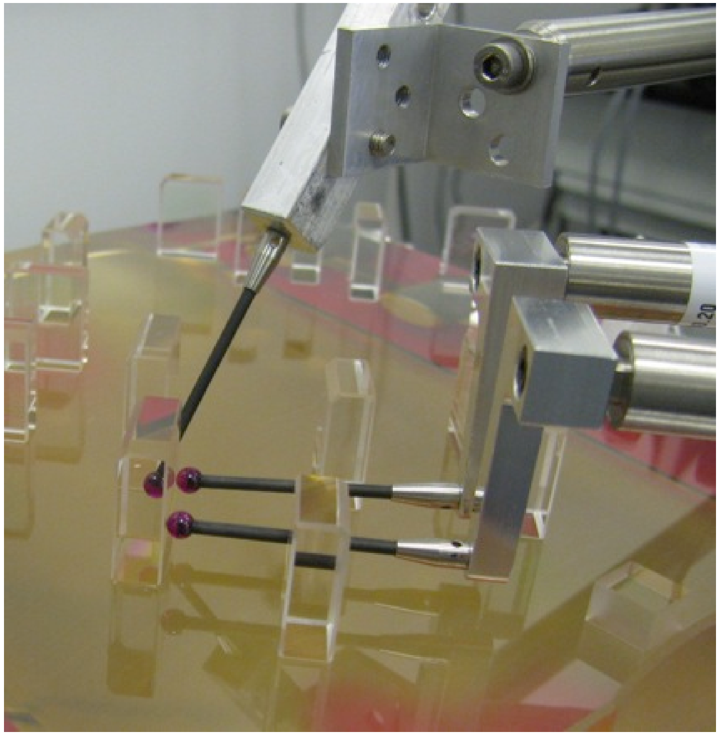
- Precision locating and bonding of components is currently a complex operation
- OK for small number, high-value work
- Reducing the complexity of the process will reduce cost, effort and required skill-set of operators
- Current CEOI-ST 7th Call project to replace several manual steps with mechanisation
  - Collaboration between the University of Glasgow



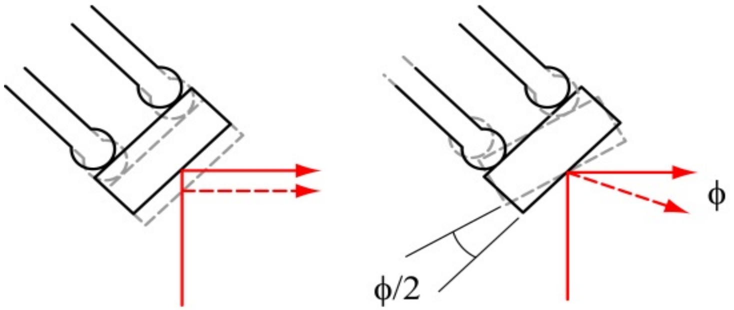


Requirements

- Hover component above surface of optical bench
  - No repeated placement of component
- Align component in x, y, ϕ as before
  - Accuracy at least as good as previous μm and 20 μrad level
- Align surfaces to be bonded
  - z, ψ, θ with accuracies of 10 μm and 10 μrad (2 arc seconds)

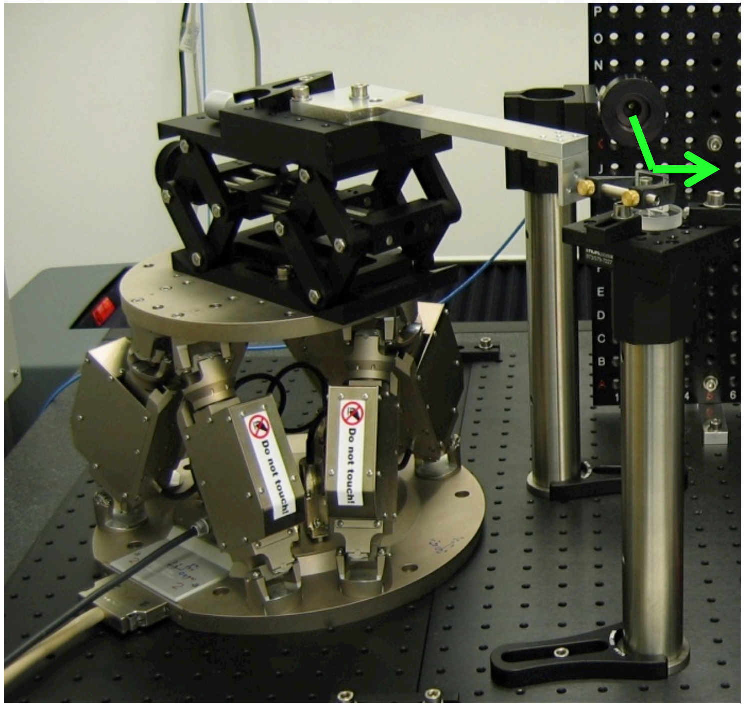


Manual alignment system



Solutions

- Mount component from a precision 6 DoF Hexapod
  - Mechanical movement
  - No sensing
- Align component in x, y, ϕ as before
  - Accuracy at least as good as previous μm and 20 μrad level
  - Use our existing beam measuring technology
- Align surfaces to be bonded
  - z, ψ, θ with accuracies of 10 μm and 10 μrad (2 arc seconds)
  - Develop sensing system to measure relative alignment of surfaces
  - Sensing system is the key enabler
  - CEOI Funded



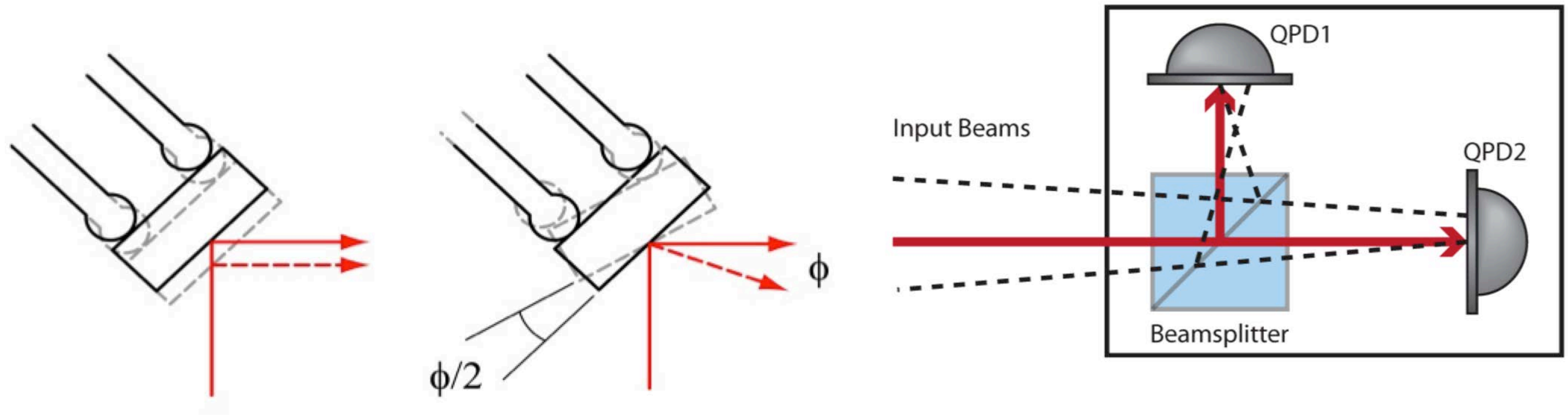
A 6-axis hexapod being used to make preliminary alignment tests. The green line denotes a laser beam which is being reflected off a mirror and directed towards a beam measurement target

Bonding surface sensing system

- Built and tested
- Angular accuracy better than 1μrad (1/5 arc second)
  - Significantly better than requirement
- Automated bonding surface alignment
  - Almost push button
- Subject of possible patent application
  - No details here on how it works

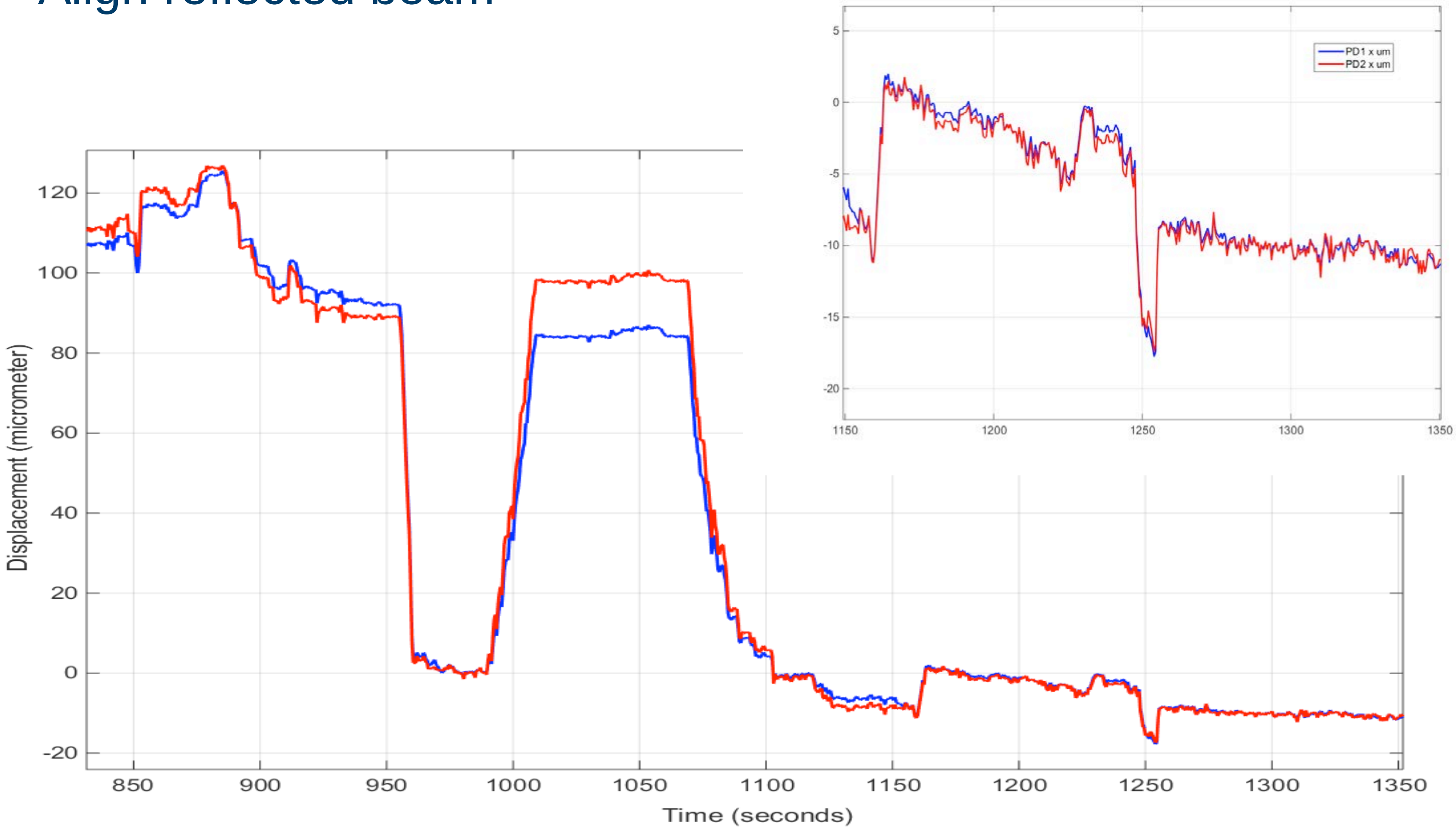
Test bond alignment

- Measurement of reflected beam to gauge precision of alignment
- First align bonding surfaces z, ψ, θ
- Second align reflected beam onto two separate quadrant photodiodes (QPDs)
  - Adjust x, y, ϕ



Early test bond results

- Bonding surfaces already aligned
- Align reflected beam



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Summary

- Hydroxide-catalysis bonding is a versatile tool that is proven for space science (TRL8, TRL9 by Christmas)
  - Precision aligned systems
  - High stability systems
  - Extremely robust
- Simplifying and improving the processes for adjustable positioning and permanent bonding of optical assemblies will open up more opportunities
  - We aim for this to be of benefit to Earth Observation instrumentation
  - Further development has opened up new industrial applications


Any
Questions
?

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References

- https://www.elisascience.org/whitepaper/
- Robertson *et al*. Class. Quantum Grav. 30 085006 (2013)
- Fitzsimons *et al*. Applied Optics, 52 (12). pp. 2527-2530 (2013)
- Killow *et al.* Applied Optics, Vol. 52, Issue 2, pp. 177-181 (2013)
- A. A. van Veggel and C. J. Killow, Adv. Opt. Techn. 2014; 3(3): 293–307
- Search ‘LISA Pathfinder’ on YouTube