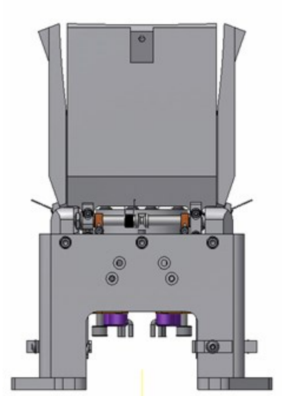
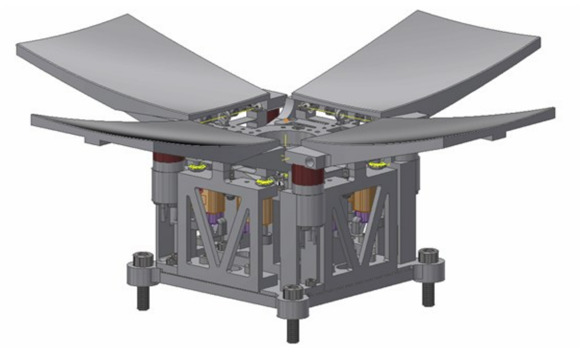
Science & Technology Facilities Council
UK Astronomy Technology Centre

HighRes: Laboratory Validation of a Deployable CubeSat Concept for High-Resolution EO





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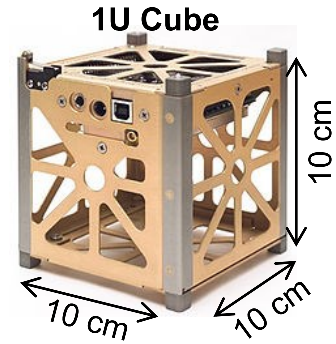
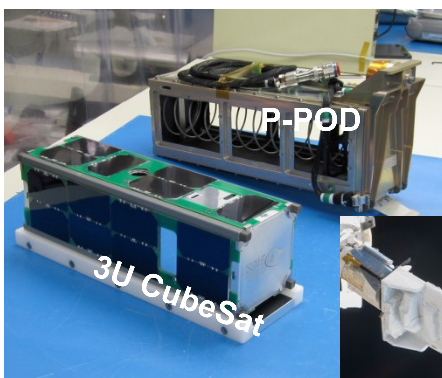
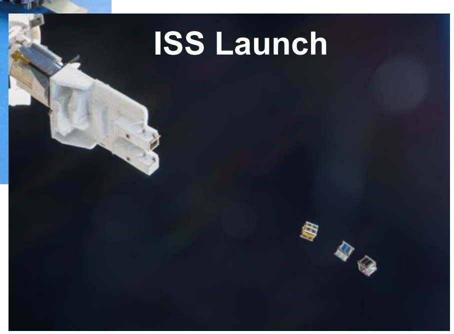
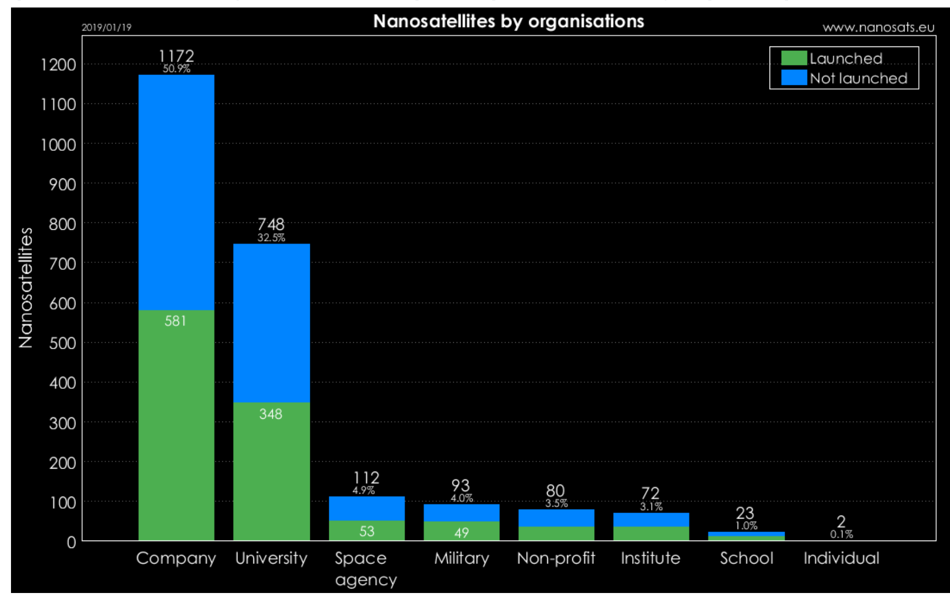
What is a CubeSat?

- CubeSat
  - ➢ Affordable satellites using standardised parts
  - ➢ Made of multiple cubic units "U"
    - ▪ 1U = $10 \times 10 \times 10\ cm^3$ & 1U < 1.33 kg
- Ideal solution to develop new space technologies
  - ➢ Cost effective & short development cycle
  - ➢ Experiment, technology demonstrators, derisking missions…
  - ➢ Launches by companies (>50%), space agencies (5%), military (4%)





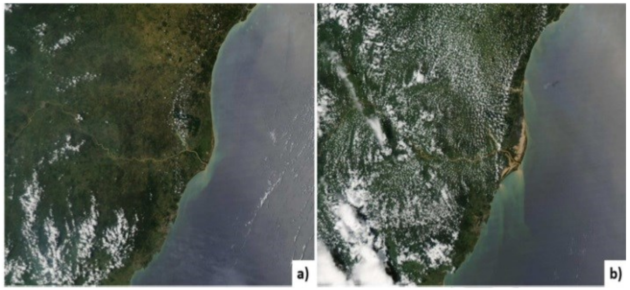




High Resolution

High-level specifications for HighRes

- ~1m resolution imaging platform
- 3U satellite (2U optical payload)
- Panchromatic imaging system: approx. 450-800 nm
- Diffraction limited imaging with D ≈ 300 mm



a) Normal conditions **b) Floods**

Targeted Applications

- EO applications
  - Security (e.g. border, humanitarian)
  - Disaster monitoring (e.g. earthquakes)
  - Constellations for global coverage for very low cost
    - High resolution and high temporal imagery complementary to Copernicus
- Astronomy
  - "Under-explored" spectral windows by avoiding the strong atmospheric absorption bands
  - Observation for long continuous period of time (e.g. >1yr)
- Potential applications
  - Space situational awareness, Free-Space optics, solar system science

Why do we want a deployable CubeSat?

- Optical aperture size determines
  - Light collecting area
  - Diffraction limited resolution

$$\Delta\theta = \frac{\lambda}{D}$$

Angular resolution ($\Delta\theta$); wavelength (λ); Diameter of aperture (D)

- 3U CubeSat
  - Limited to 9-10 cm apertures
  - ➔ Deploy optics to increase resolution

10 cm aperture at 350 km

2.1 m resolution

30 cm aperture at 350 km

0.7 m resolution

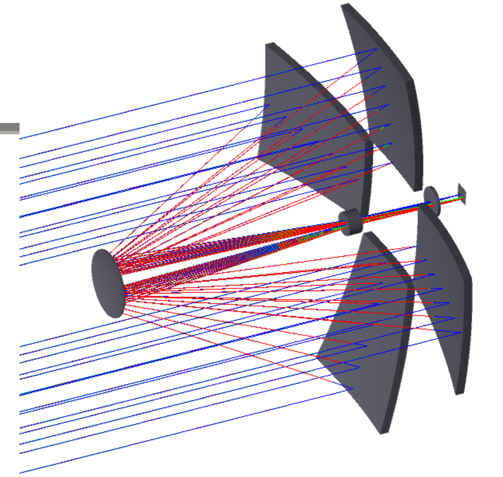
Deployable CubeSat concept

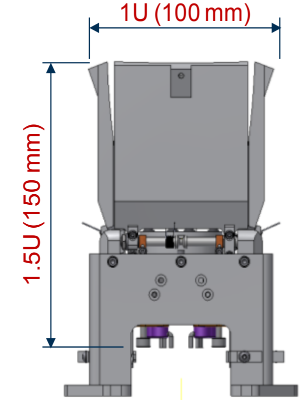
- Deployable telescope
  - Not new concept (James Webb Space Telescope)
  - Not yet fully validated in space
  - Deployable telescope on small is an innovation of HighRes

- **Mirror segment co-phasing:** Need tens of nm accuracy for diffraction limited imaging
  - Accurate deployment
  - Active alignment control mechanisms
  - Algorithms to monitor and control alignment

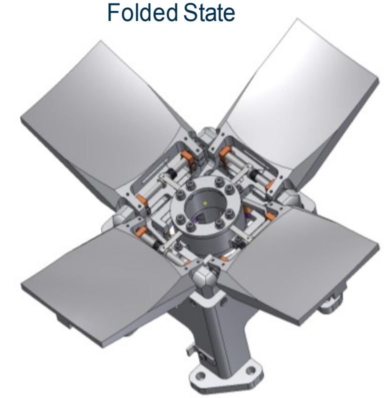
- Can we achieve ~300mm aperture (i.e. ~1m ground resolution) in a 3U CubeSat?

➔Technology Demonstrator = HighRes





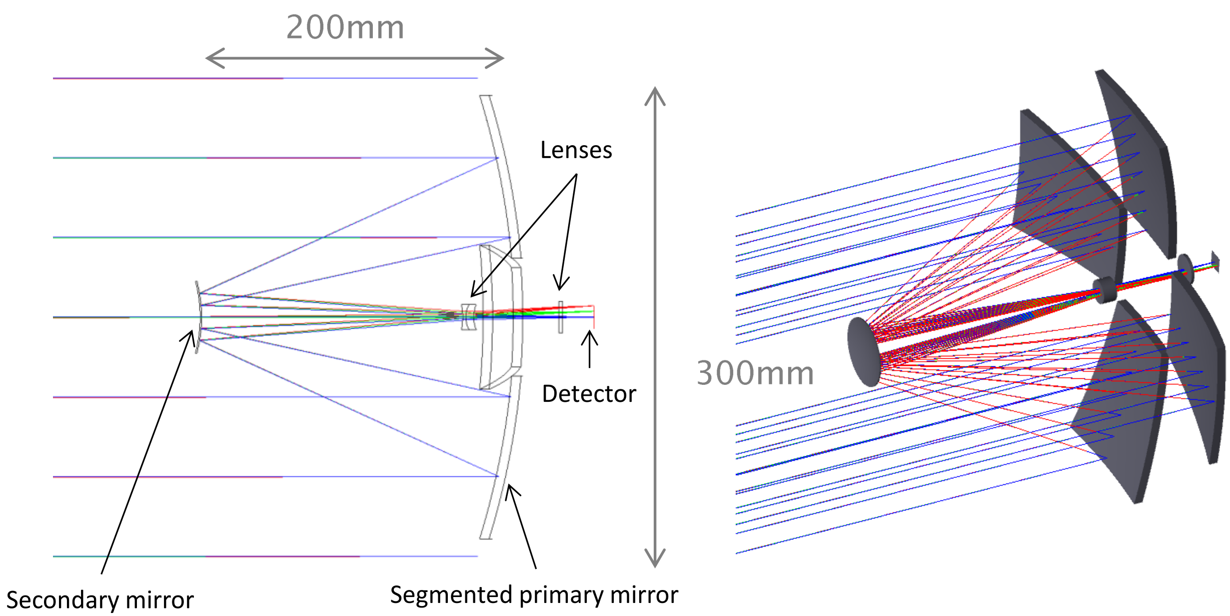
Folded State

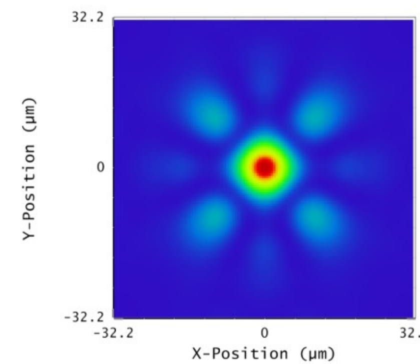


Deployed State

Optical Design Concept

Two mirror telescope with refractive field corrector
M1–M2 separation constrained to 200mm
Exact design depends on pixel size of sensor and ground sampling distance.

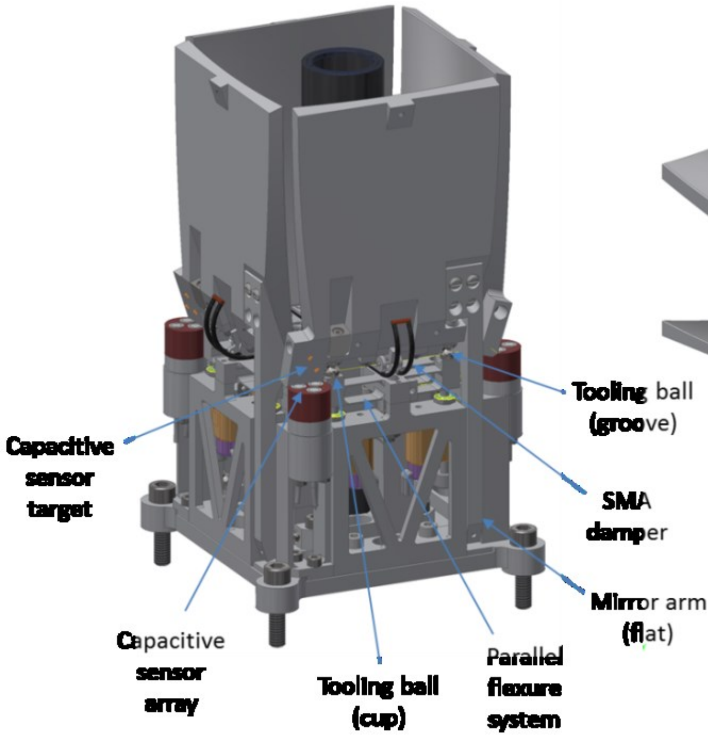


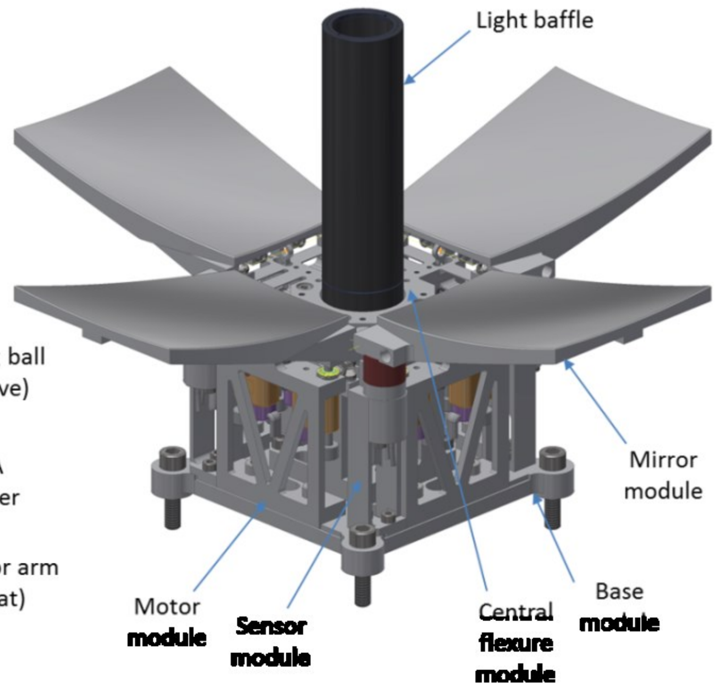


The diffraction limited point–spread function.

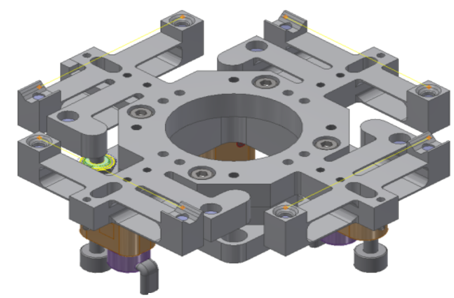
NB: For bench demonstrator we place detector further back, allowing lenses to be omitted

Mechanical Design Concept





Deployment controlled by shape memory alloy

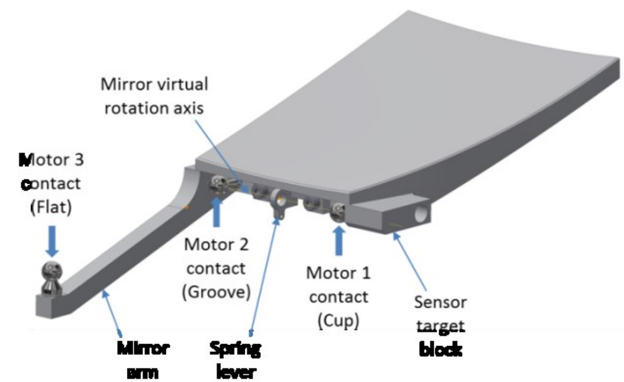


Central flexure assembly

Three motors and sensors on each mirror segment for tip/tilt/piston control

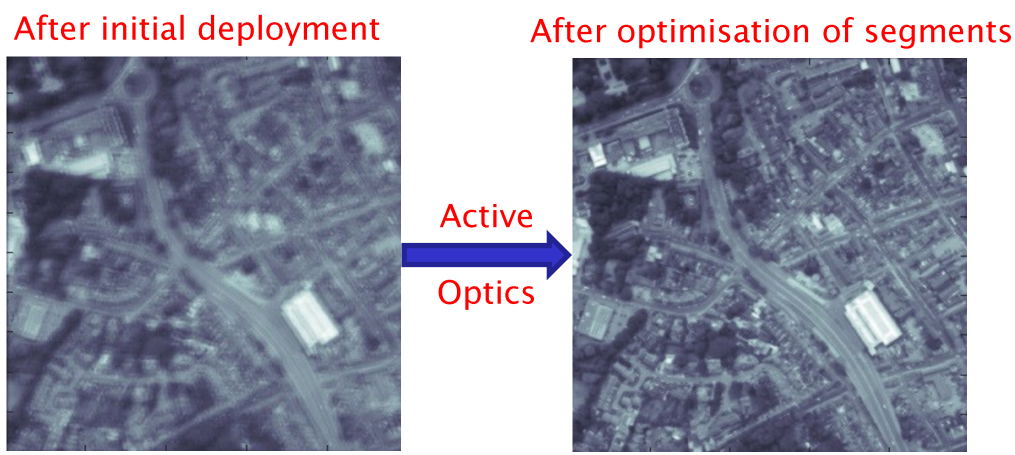
Floating hinges on parallel flexures

Kinematic location with tooling balls



Active Optics Correction

- Control position of Primary Mirror segments
  - On point-source and extended objects
  - Large measurement/control range: ~10 μm
  - High measurement/control resolution: ~10-20 nm
  - Temporal bandwidth: < a few Hz

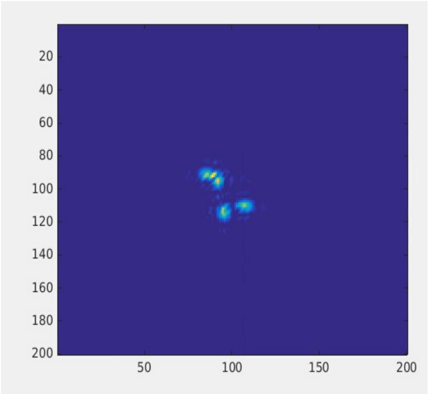


- Constraints – CubeSat
  - Very limited volume available
  - Limited electric & computing power

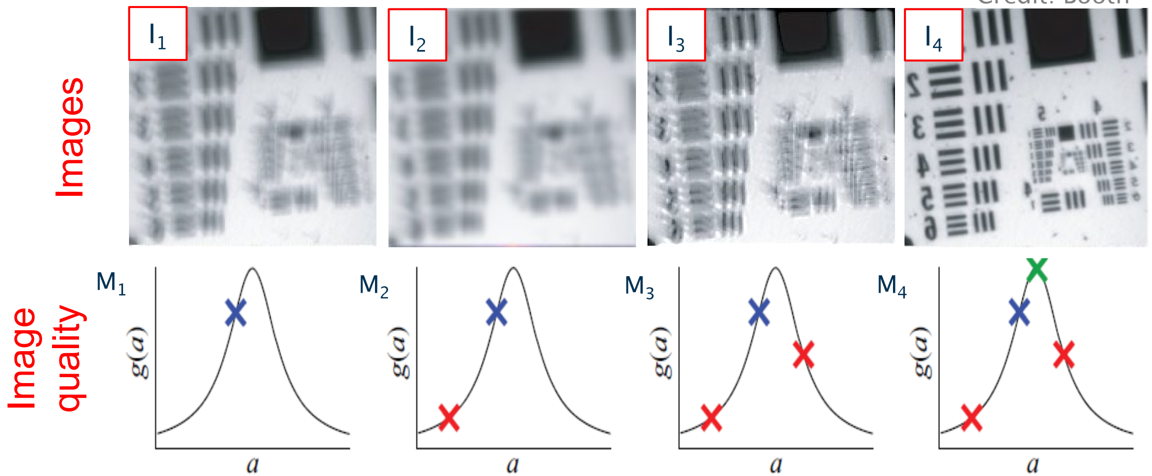
Active Optics Correction Concept

- <u>Direct wavefront sensing</u> ✗
  - e.g. Shack-Hartmann, Pyramid…
  - Requires additional hardware & volume
- <u>Displacement sensors</u> ✓
  - Measures the back surface or outside of M1
- <u>Focal plane (or image-based) sharpening</u> ✓
  - Direct use of image
  - Iterative process

Example of PSF after deployment

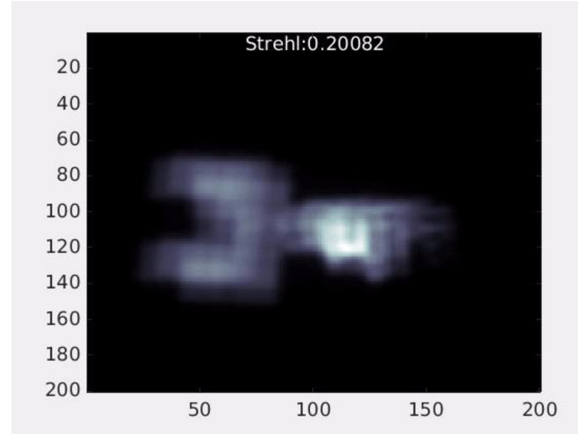


Credit: Booth



Focal Plane Sharpening

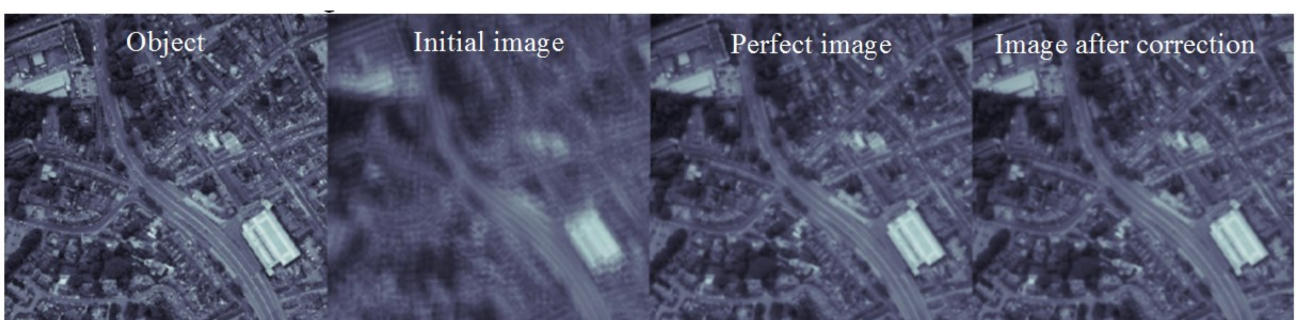
Use detector image as input
Calculate an image metric
Change segment tip/tilt/piston
Repeat with optimisation algorithm



Final correction quality

- Reach diffraction limit both on point-source & extended objects
- Image contrast is a very good indicator of final correction quality
- Limited impact of noise under realistic observation conditions

On-board computing possible with current technology



Laboratory Demonstrator

Key aims of demonstrator

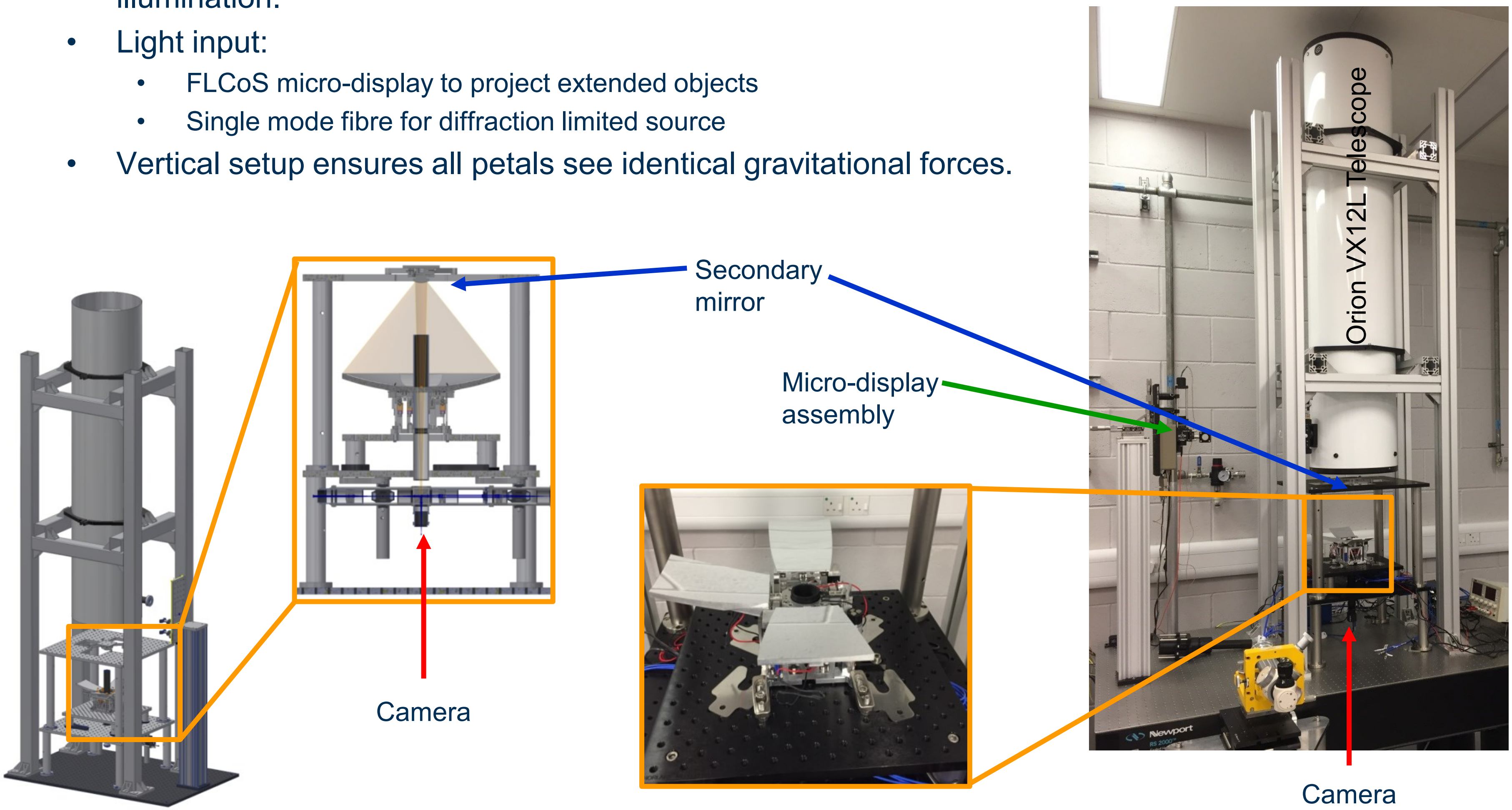
- deployment of primary mirror segments
- manipulation and metrology of mirror segments (characterise motors and sensors)
- control using focal plane sharpening algorithms

Not in scope

- deployment or active control of secondary mirror
- not fully representative of CubeSat system

Laboratory Test Bench

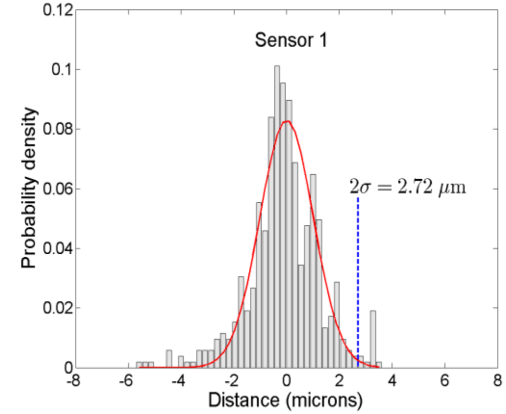
- Commercial Newtonian telescope used to provide 300 mm collimated illumination.
- Light input:
  - FLCoS micro-display to project extended objects
  - Single mode fibre for diffraction limited source
- Vertical setup ensures all petals see identical gravitational forces.

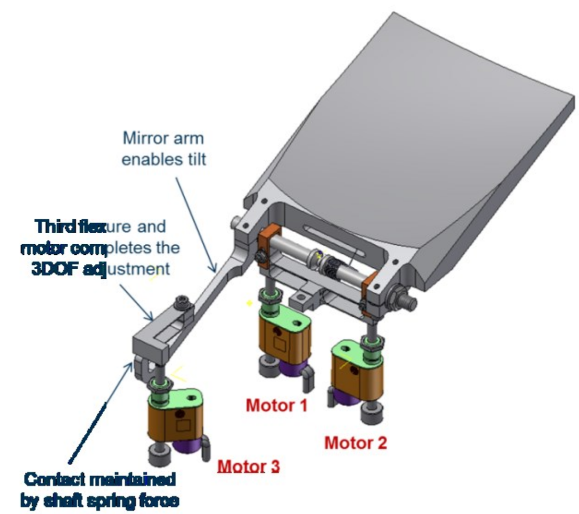


Performance

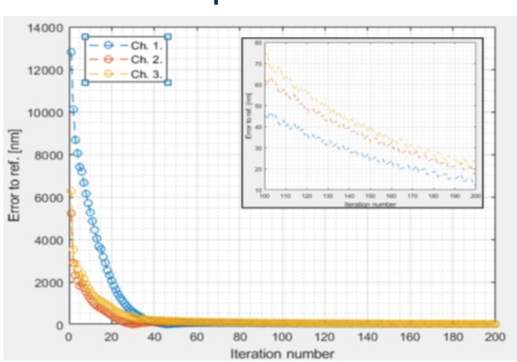
- Mirrors can be deployed accurately
- Mirror manipulated with sufficient precision to allow co-phasing
  - Large hysteresis and backlash
  - Load/displacement dependency
- Focal plane sharpening can be used to control co-phasing on realistic image scenes (static)
- Issue with mirror quality and vibration to fully validate demonstrator

Deployment repeatability

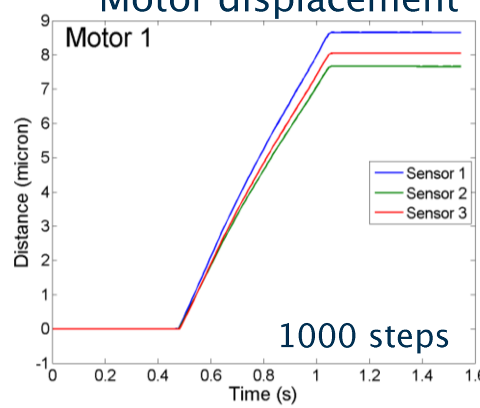




Close Loop Mirror Control

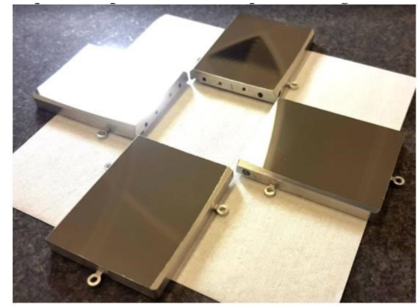


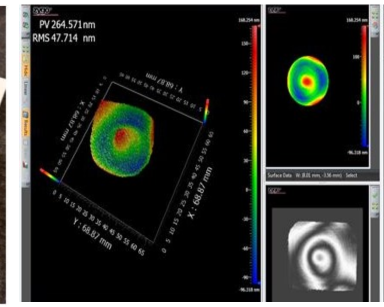
Motor displacement

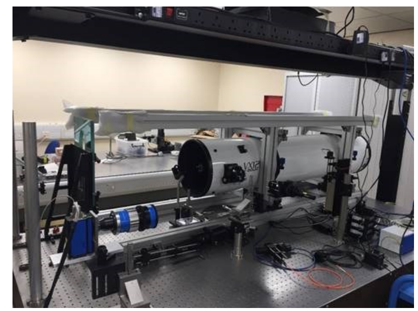


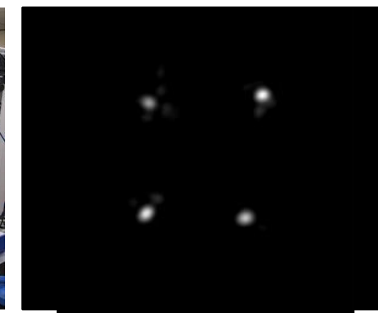
Current Issues and Future Improvements

- **Current Developments**
  - ✓ New mirrors with better optical quality
  - ✓ Changed setup to solve issues with vibrations and air currents
  - ➢ Validating co-phasing in laboratory









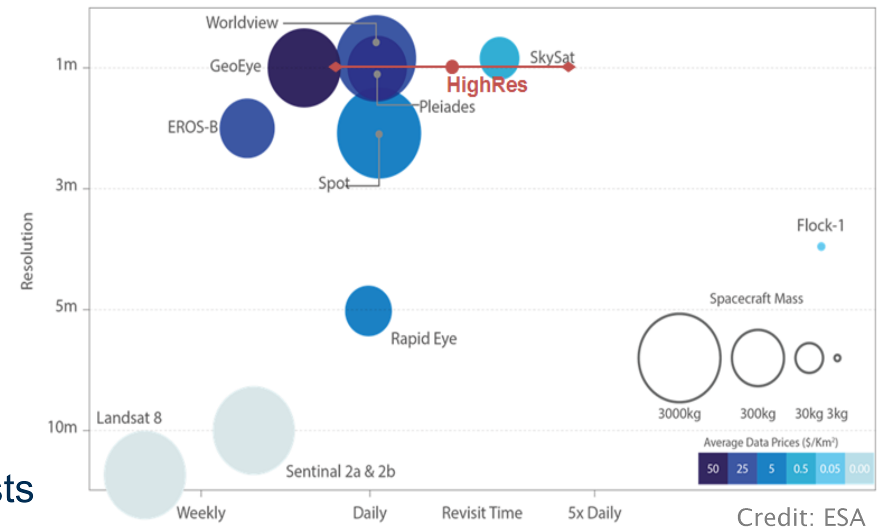
- **Further Improvements**
  - ➢ Develop mechanism for secondary deployment
  - ➢ Miniaturise electronics displacement sensors
  - ➢ New motors (Hysteresis / backlash)
  - ➢ Consider larger platforms (e.g. 6U)
  - ➢ On-board active optics control
  - ➢ Launch…

Summary

- Disruptive technology for EO & Astronomy
  1. Miniaturisation of the opto-mechanics (fold + deploy)
  2. Integrates active optics within a telescope
  3. Implements a fully automated onboard process to align & phase the telescope.

- Breakthrough in terms of performance
  - Miniaturisation
    - 30 cm deployable telescope
    - Fitting in a 3U to 6U CubeSat
  - Enhanced performance
    - Ground Sampling distance
    - Automation, power reduction…
  - Reduced cost
    - Use of COTS items
    - Reduction of 10 expected in EO data costs

Low-cost, rapid-revisit, high-resolution imaging



Credit: ESA

Impact

- Technology Development Roadmap
  - ➢ Time-to-market (depends on funding availability)
    - ▪ Integrate the high-value fast-growing CubeSat market within 5 years
  - ➢ Strengthening UK & Europe's position in EO
    - ▪ Alternative low-cost CubeSat technology
    - ▪ Achieving very high resolution in the optical wavelengths

- Commercialisation
  - ➢ CubeSat market
    - ▪ Fast growing with 500+ launches a year
  - ➢ Deployable optics as COTS
    - ▪ Will ultimately provide a solution that can be adapted to different industrial uses (production and cost-efficiency).

Number of launches per yr