Science & Technology Facilities Council
UK Astronomy Technology Centre

DEPLOYABLE OPTICS TECHNOLOGY AT UKATC

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Science and Technology Facilities Council

Outline

Objective

High-angular, high-temporal nanosats

Top-level requirements

1.5U prototype

Initial results

Issues and problems to be solved

4U telescope Payload

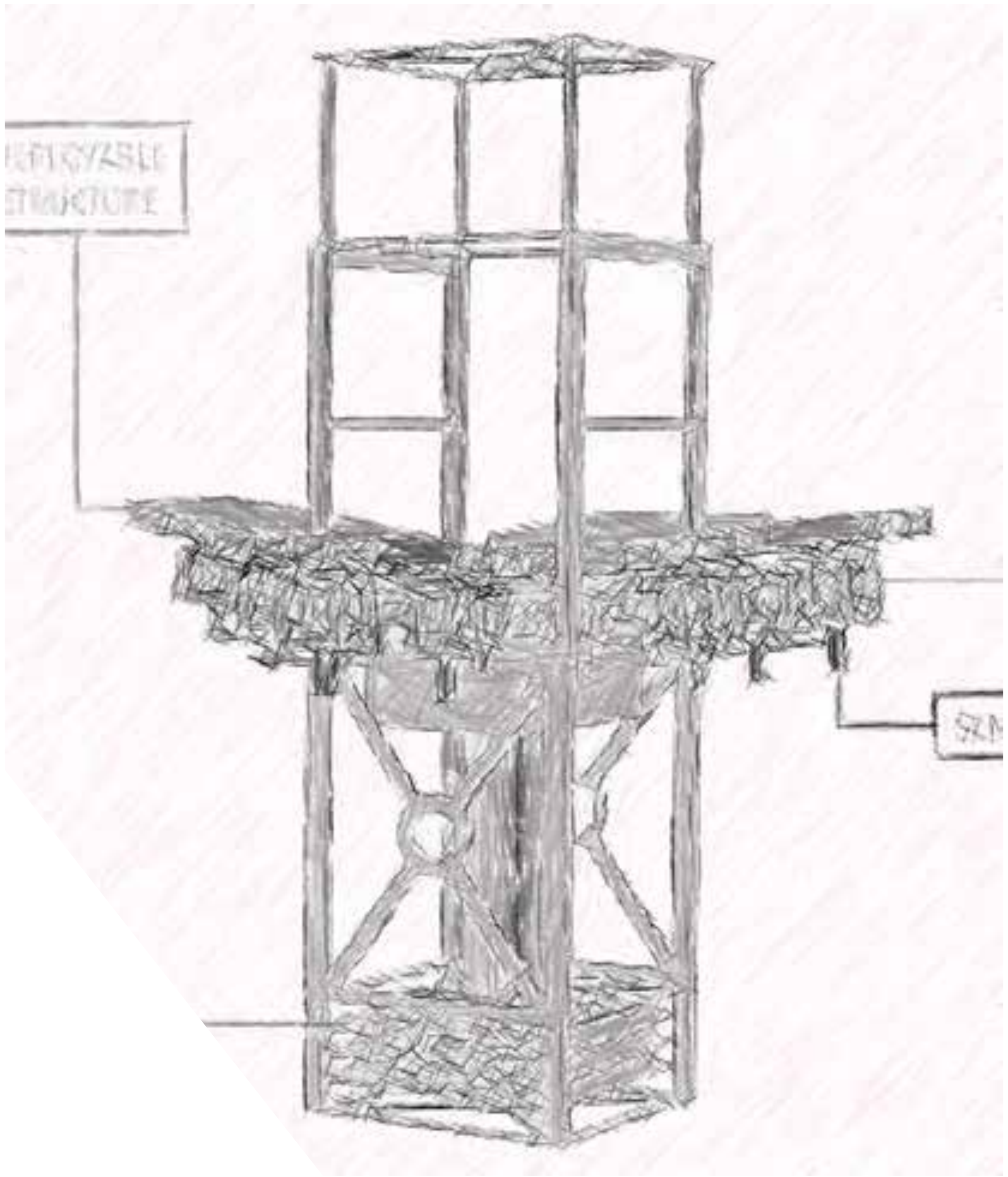
Improved packaging

Deployable M2

Wavefront sensing

Aspirations for the future

In-orbit demonstration



1m ground resolution

Aim of project

- Provide **high-resolution** EO data, at **lower costs,** and **high-revisit times**
  - ➢ 1 m Ground Sampling Distance (VHR)
  - ➢ CubeSat (standardisation)
  - ➢ Constellation

New space but old physics

- Spatial resolution limited by aperture size ($\theta \approx \lambda / D_{aperture}$)
- Ground speed & revisit time limited by orbit (Kepler's law)
  - ➢ High-resolution high-SNR images require large mirrors

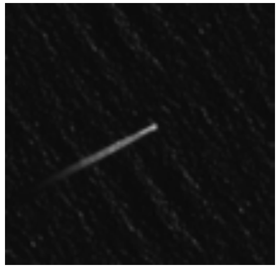
High-angular resolution

- Orbit: 500km   Swath: 5km   Wavelength: 450-800nm

►►► 30cm aperture diameter ◄◄◄

Primary mirror size largely driving by size of satellite, but…

Normal conditions **Floods**



Maritime security (GEO-HR)

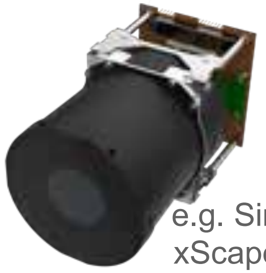
2.1 m resolution (10 cm at 350 km)

0.7 m resolution (30 cm at 350 km)

Large aperture in space

Large aperture on small platforms

- Typically limited to 9-10 cm apertures (e.g. 6U CubeSat)

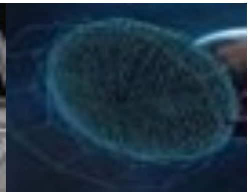


e.g. Simera xScape100

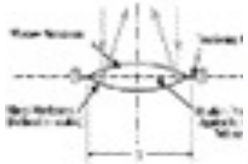
- How to increase optical aperture

Monolithic

Photon sieve



Membrane



Inflatable

Docking

Free-flying

Deployable

Deployable optics

- Trade-off: aperture size versus the maturity of technology
- Not a new concept, but the only precedent is JWST (launch 2021)

JWST @NASA

►►► Use of deployable optics to increase aperture diameter ◄◄◄

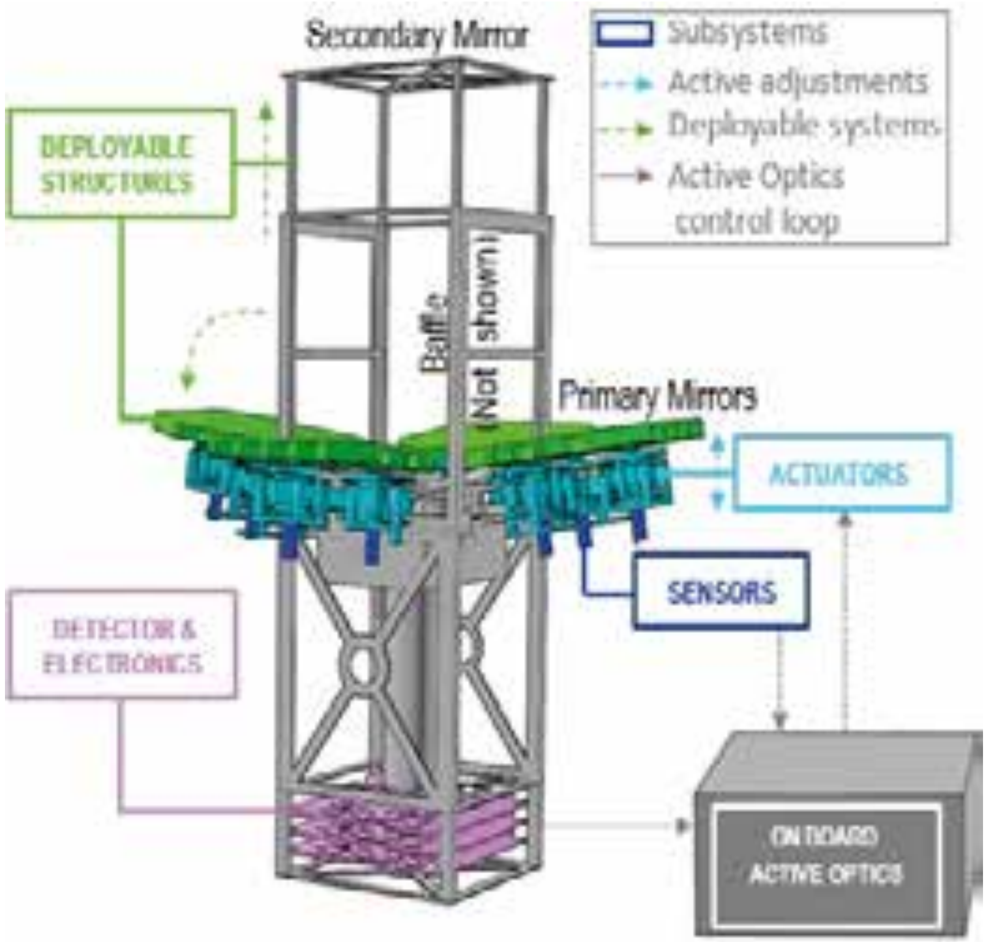
New payload technology

High-resolution at lower costs

- Deployable segmented telescope
- Active mirror phasing
- Standalone & automated
- Cost reduction by drastic miniaturisation (deployable optics) & standardisation (CubeSats)

Key Technical Challenges

1. **Miniaturisation & Accuracy**
   - Fit into CubeSat volume during launch
   - Repeatable deployment of mirrors
2. **Active optics control in space**
   - Accurate measurement & control of mirrors position
   - Automated process



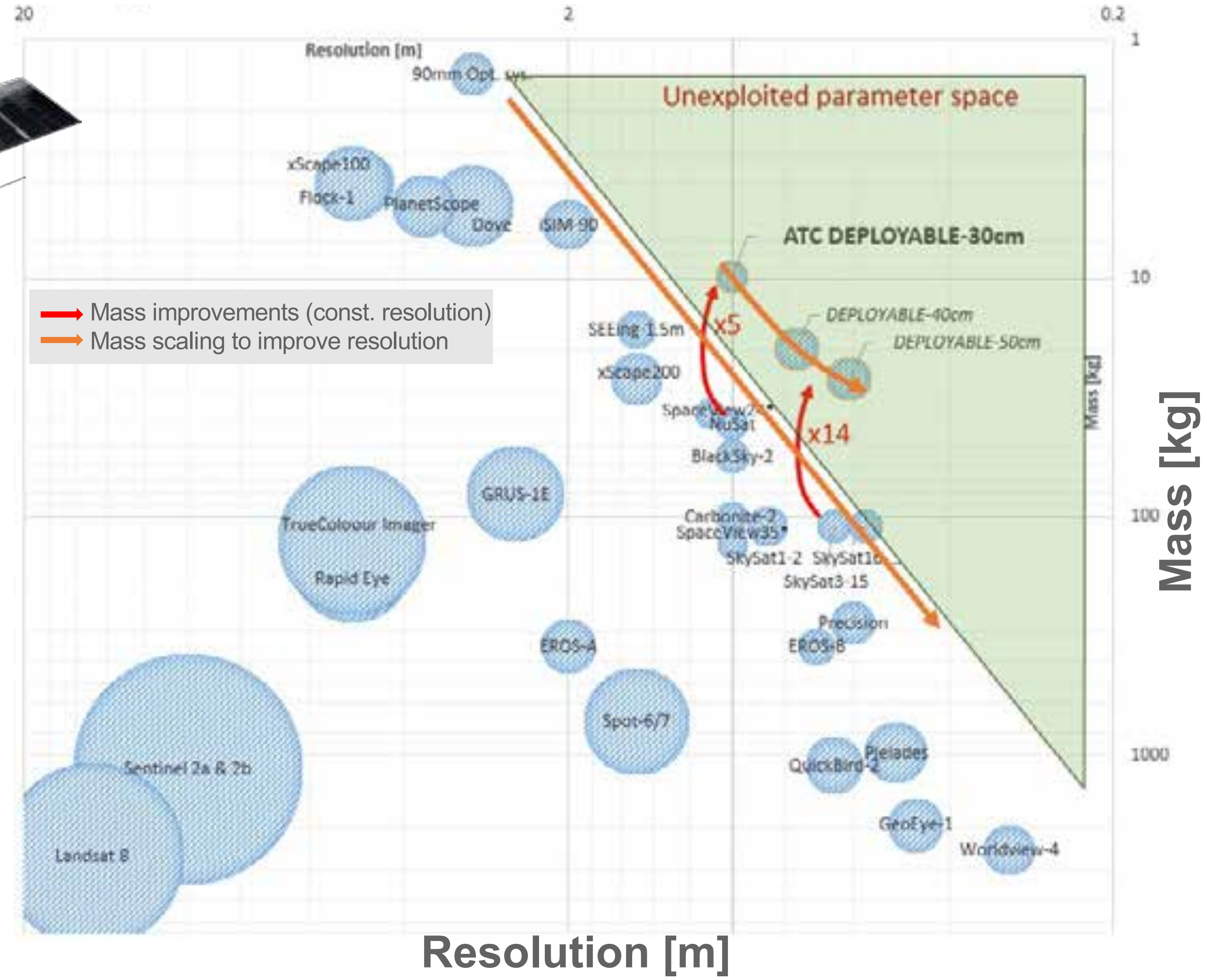
Main payload subsystems
(Conceptual design)

Paradigm shift

High-resolution – Low mass

- **6U CubeSat (~10kg)**
  - 4U payload

- **Mass reduction**
  - **x5 Mass** expected compared to current 1m GSD satellites
  - x10-15 for larger platforms
- **Flux**
  - **x10 Flux** compared to current 6U CubeSats
- **Additional design flexibility**
  - Increased flux provides additional mission-level trade-offs (e.g., panchromatic vs. multi-spectral)



Deployable M1- A modular design

1.5U Prototype

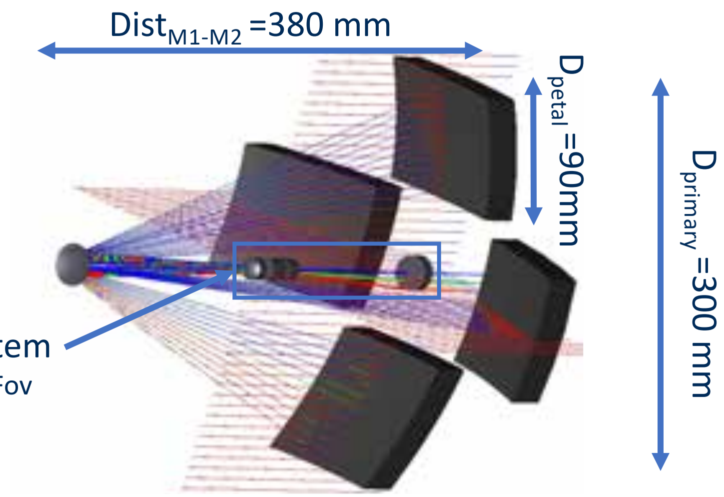
- 1.5U for stowing, deploying, & cophasing M1
- 4-petal M1 design
- Static M2

Cassegrain telescope

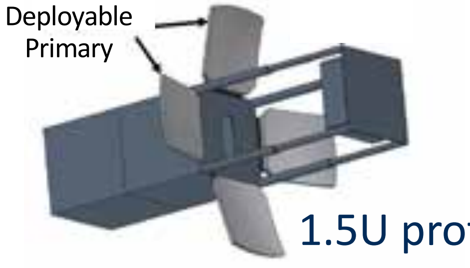
- $D_{primary}$ = 300 mm, $Dist_{M1\text{-}M2}$ = 380 mm
- Requires a fast primary mirror

Modular mechanical design

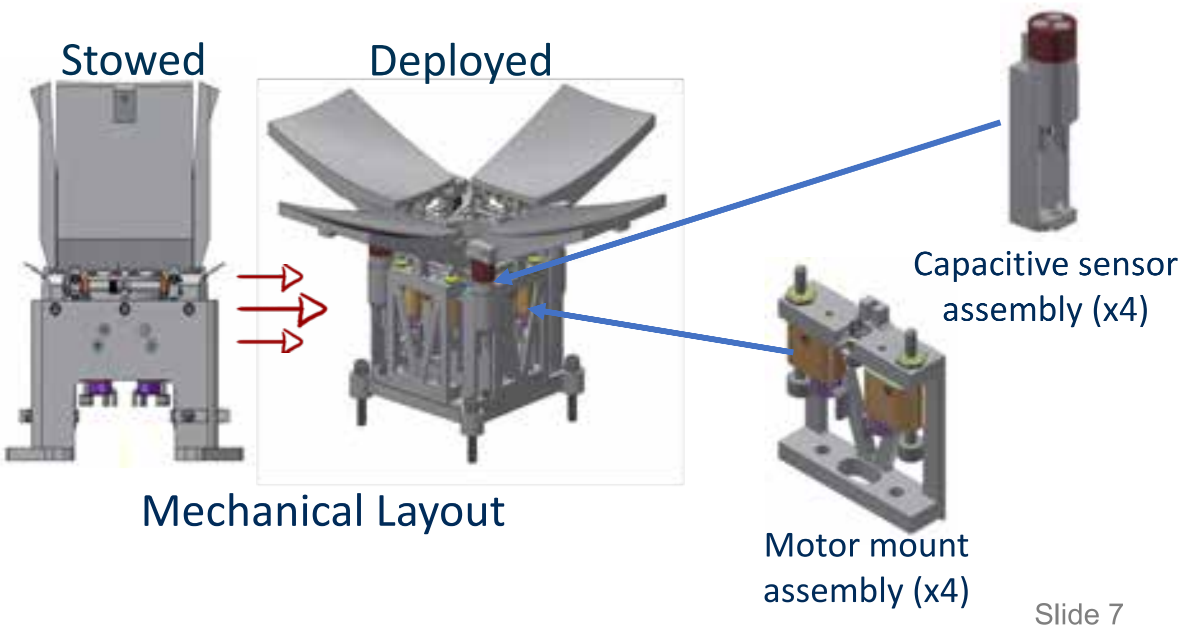
- One mirror can be adjusted or modified without affecting others
- Replacement of faulty hardware
- Disassembly & modifications during MAIT



Optical Layout



1.5U prototype concept

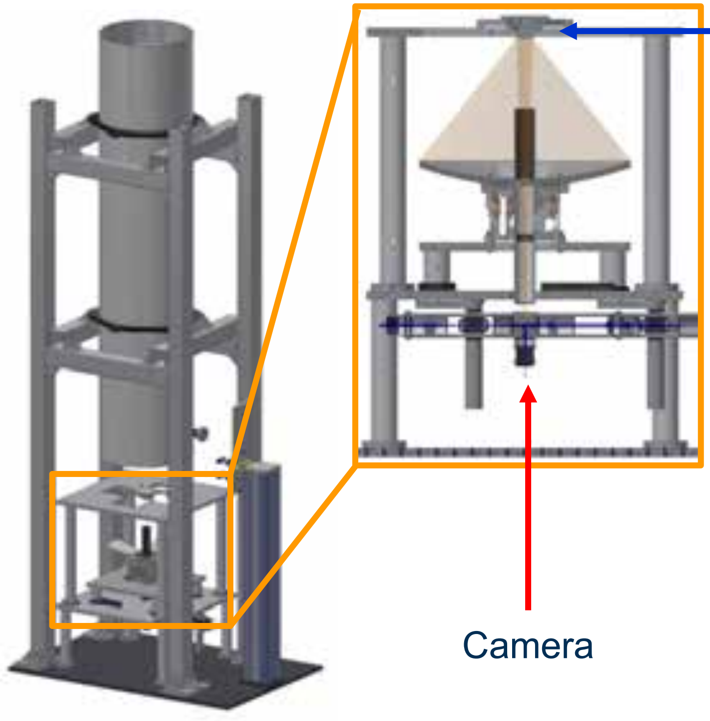


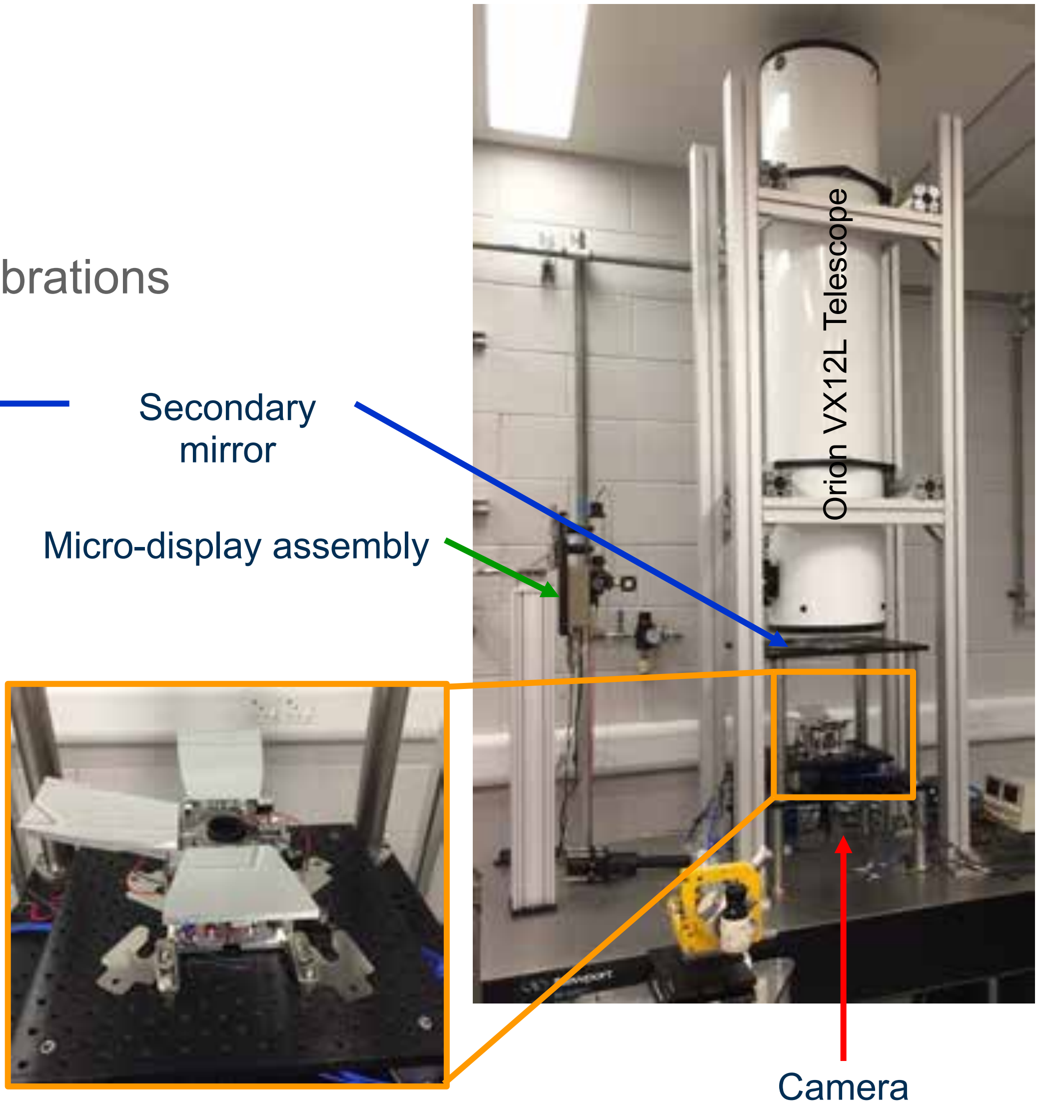
Mechanical Layout

Demonstrator

Commercial Newtonian telescope

- Provides a 300 mm collimated illumination
- Light input
  - Extended objects (FLCoS micro-display)
  - Diffraction-limited source (single mode fibre)
- Vertical setup changed to horizontal to minimise vibrations





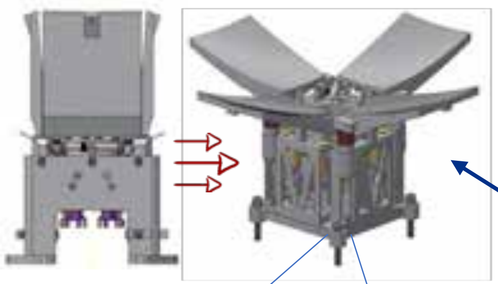
Deployment & Cophasing

Cophasing goal

- Drive the 4 mirror segments in piston / tip / tilt until cophased (fraction of wavelength)

Deployment

Shape Memory Alloy



Cophasing "Toolbox"

Calibrated sensors
Blob detection
Image Sharpening
Machine Learning

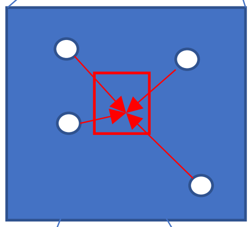
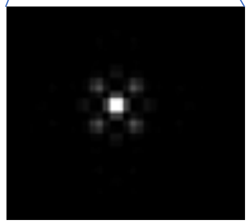
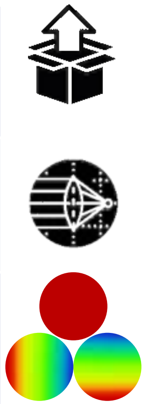


Image Sharpening
Phase Diversity
Machine Learning



Step	Capture range	Precision
Telescope initial deployment	Folded mirror segments	Within the detector FoV
Coarse phasing	Detector Field of View (FoV)	Sub-wavelength
Fine phasing	Few Wavelength	Wavelength / 15



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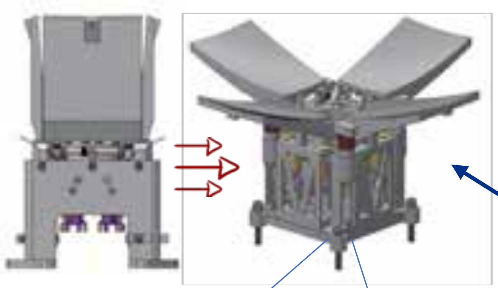

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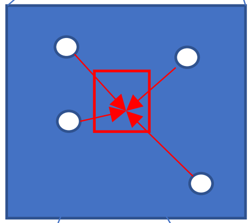

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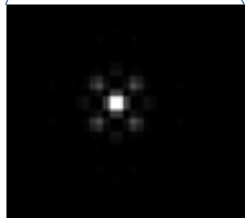
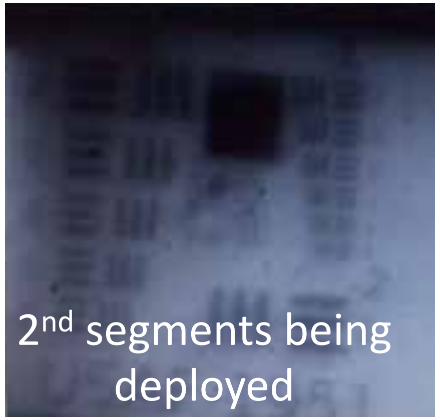


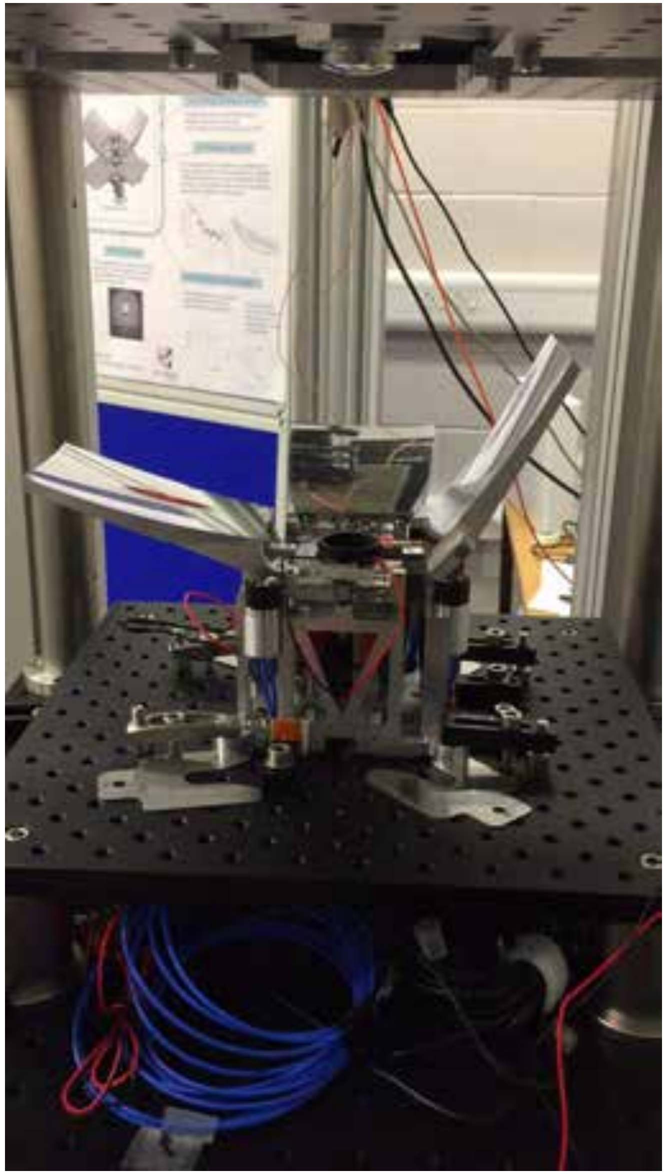
Step	Capture range	Precision
Telescope initial deployment	**Validated in laboratory on CubeSat**	
Coarse phasing	**Validated in simulation & laboratory**	
Fine phasing	**Validated in simulation**	

Telescope initial deployment

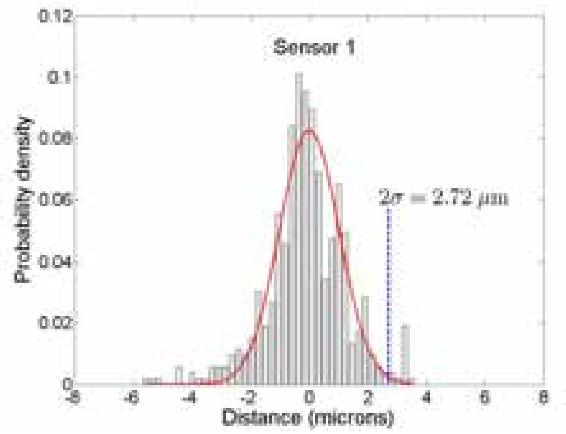
Single-use deployment mechanism

- Use of Shape-Memory Alloy (SMA) to deploy
- Ohmic heating of SMA in close loop

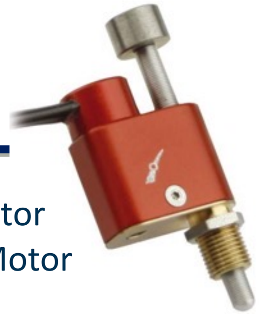




- Mirrors were retracted & deployed 200 times
    - **Accuracy << ±5 µm**
- PSFs well within detector FoV



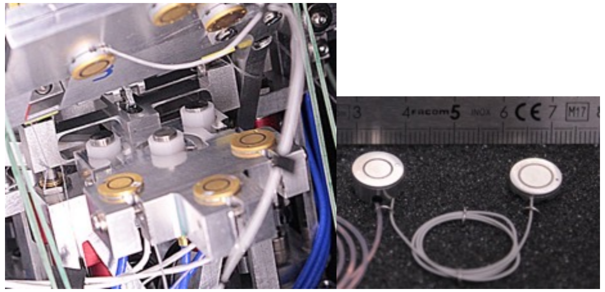
Coarse phasing: close-loop



Piezo actuator
8354 PicoMotor

Principle

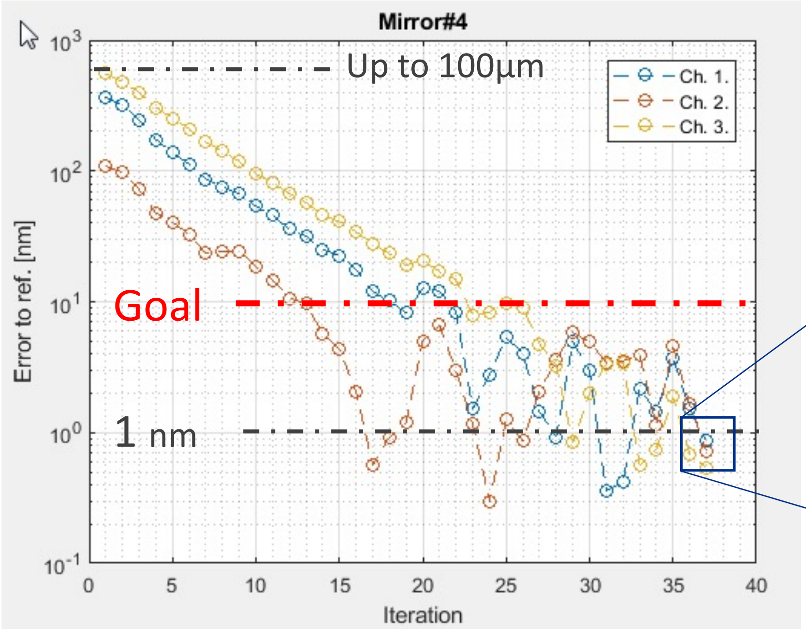
- Control segments in close-loop: using displacement sensors + actuators
- Requires a calibration step to record optimal sensor measurement
  - Any movement of the structure will affect image quality



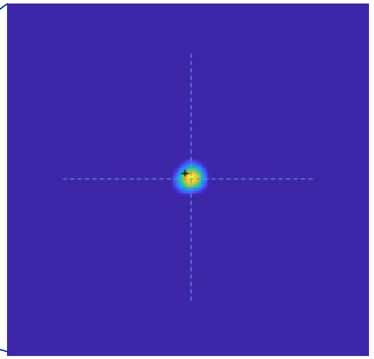
Razorbill Instrument’s gold-plated ZED-CAP

Results

- Excellent control of position thanks to excellent sensors
  - **Final error <5nm**
- Poor actuator behaviour!
  - Backlash
  - Hysteresis
  - Large step size
  - Motor/flexure combination
  - …
- ➔ **New actuator required**

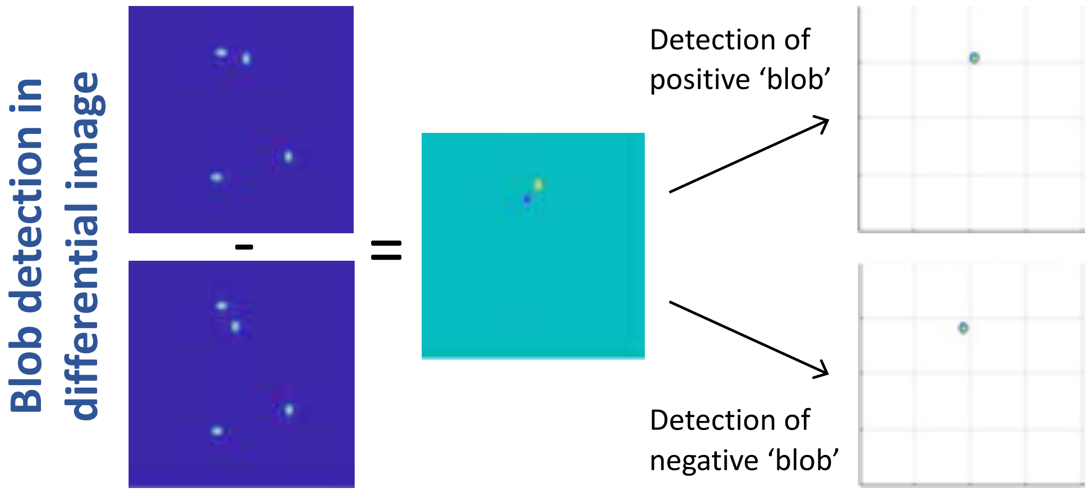


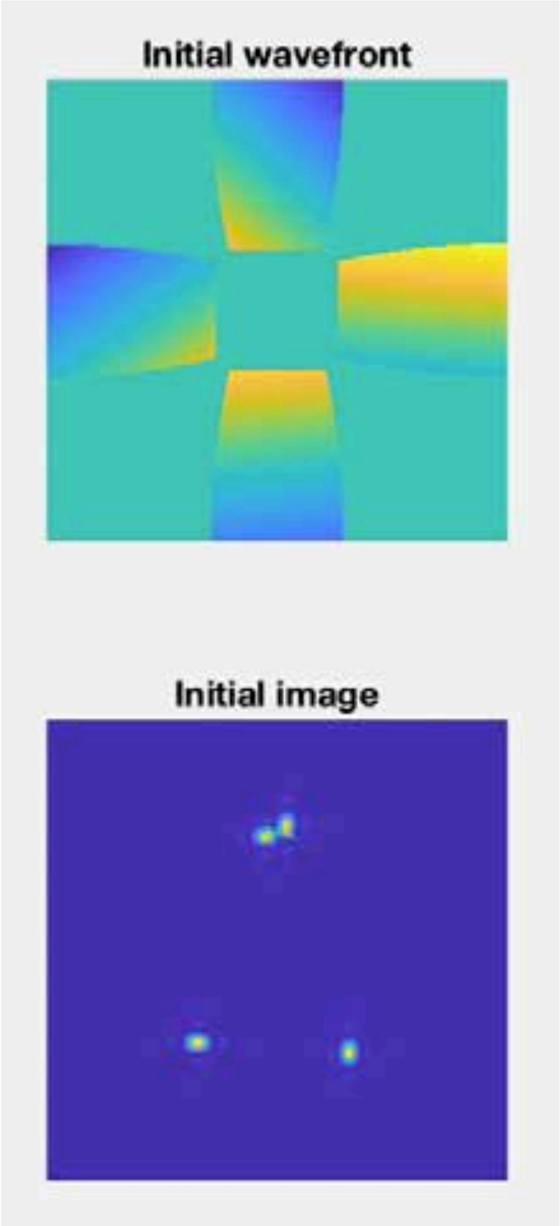
Lab. final image



Coarse phasing: Blob alignment

1. **Each petal is 'dithered' individually and a new image is taken**
   i. The difference between the new and previous image is computed.
   ii. The PSF which belongs to the petal is identified.
   iii. The move required to align the PSF with the centre of the detector is computed.
2. **The alignment commands are sent to the petals**

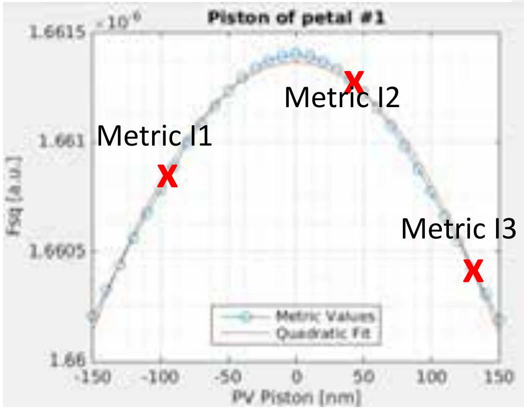


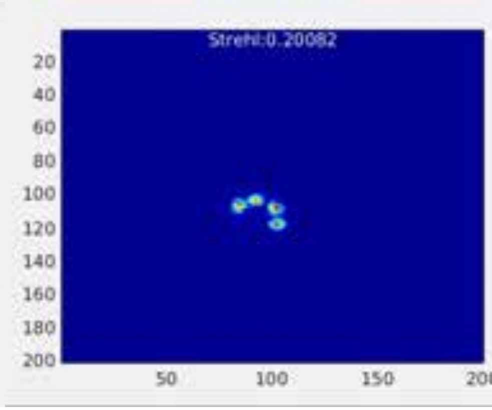


Fine phasing

Image Sharpness

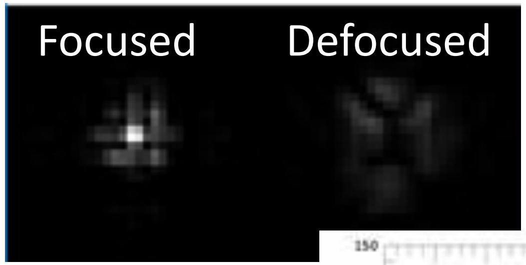
- Use N images with N different piston-tip-tilt
- Iteratively improve image quality (using a quality metric)
- Requires accurate motor movements!
- Excellent performance both on point & extended sources

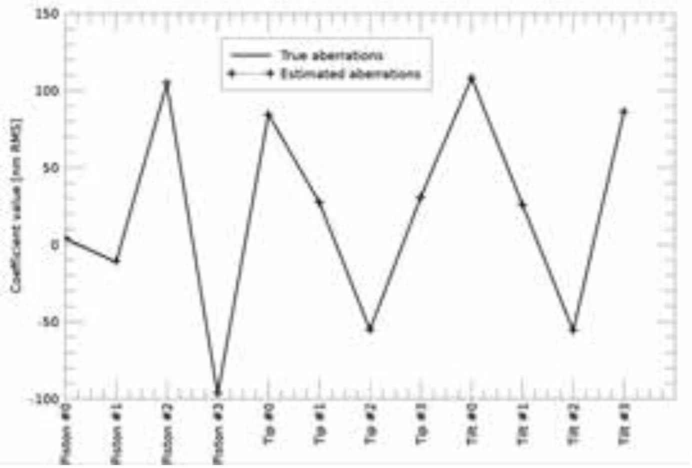




Phase diversity

- Use 2 images to estimate the aberrations
- Images should differ from a known diversity (defocus) Algorithm **estimates a phase map**
    - Includes Tip-Tilt and Piston on segments
    - Includes high order aberrations





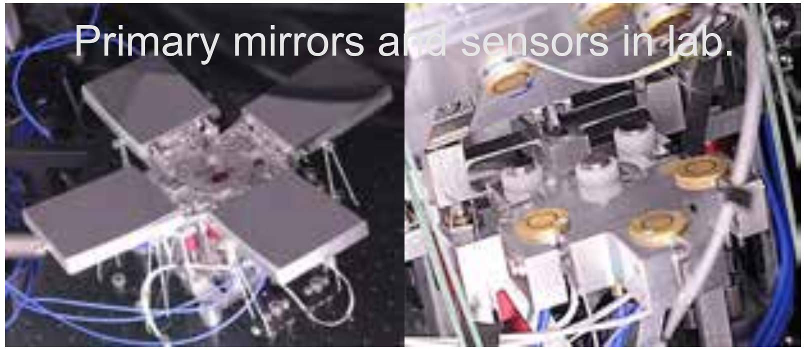
Future work: Machine Learning

- Measurement and control residual aberrations and maintain the optical quality.
- Optimally control the optics with non-invasive methods

Current status

1.5U prototype

- Packaging 4 segments into 1.5U volume
- Laboratory demonstration of accurate and repeatable deployment
  - ➢ Shape memory Alloy (patent granted)



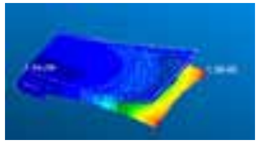
- Excellent position control thanks to embedded displacement sensors
- Precise optical alignment of segments demonstrated in lab.

Current work (CLASP)

- Packaging
  - ➢ Increase in volume (4U payload)
  - ➢ **M2 deployment, incl. baffle**
  - ➢ Detector, electronics…

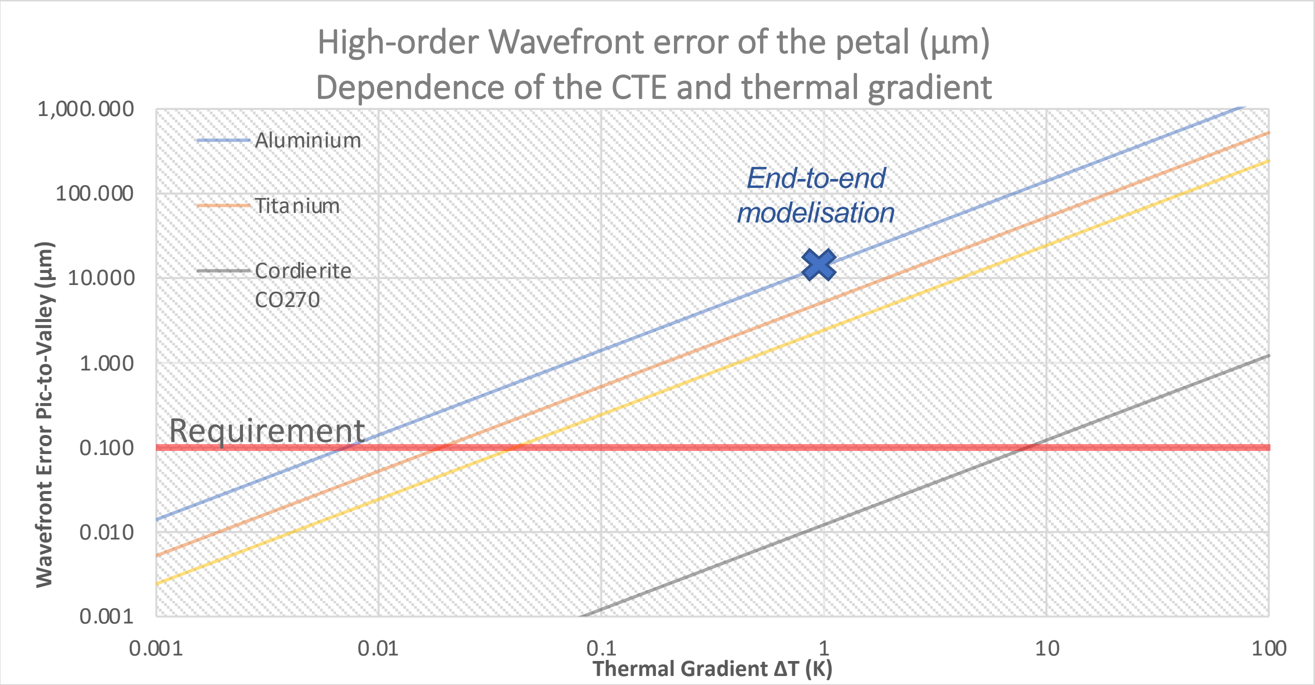
- Number of degrees of freedom
  - ➢ New opto-mechanical design to reduce number of mirrors
  - ➢ Adding static reference mirror
- Mirror position control
  - ➢ Find suitable actuators
  - ➢ Improve mechanical interface

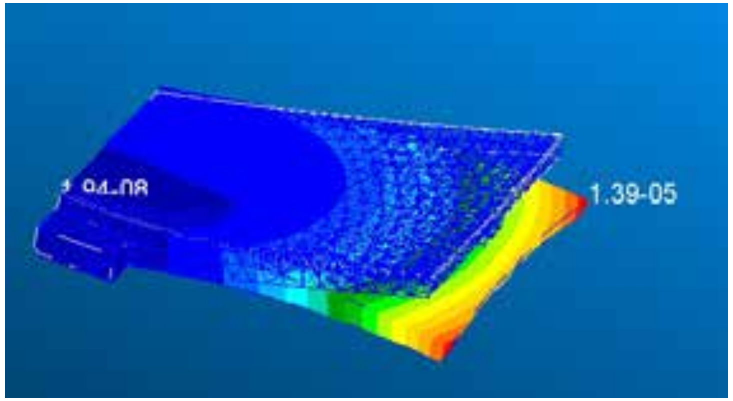
- Co-phasing
  - ➢ **High-order wavefront error**
  - ➢ Investigate new solutions (e.g. ML, TDI…)



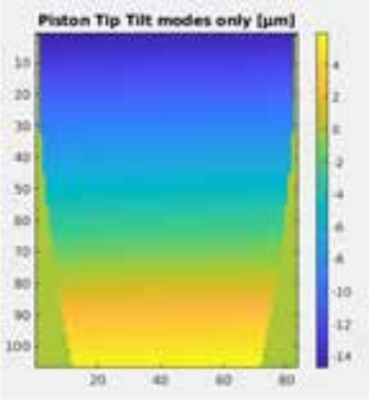
Thermal analysis

Preliminary results

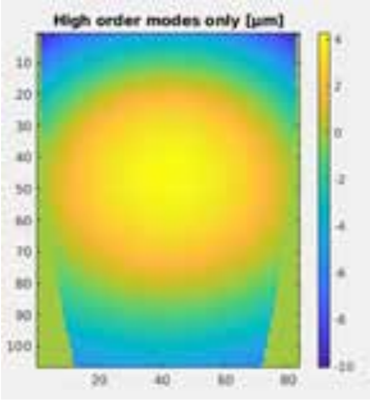




Example of Nastran/Patran E2E modelization for 1 mirror segment deformation.



Wavefront error. Piston, Tip, & Tilt only



Wavefront error. Remaining high-orders

The reference case is obtained by an end-to-end modelization of the petal geometry, using aluminium and ΔT=1K.

Considering the linear behaviour of the deformation in T°C and CTE, we were able to plot the graph.

Deployable M2- Optical requirements

Sensitivity analysis

- M1-M2 separation most sensitive DoF
- ↗ M1-M2 separation reduces sensitivity
- Defocus requirement of ±0.7μm
- Trade-off shown telescopic booms to be most promising

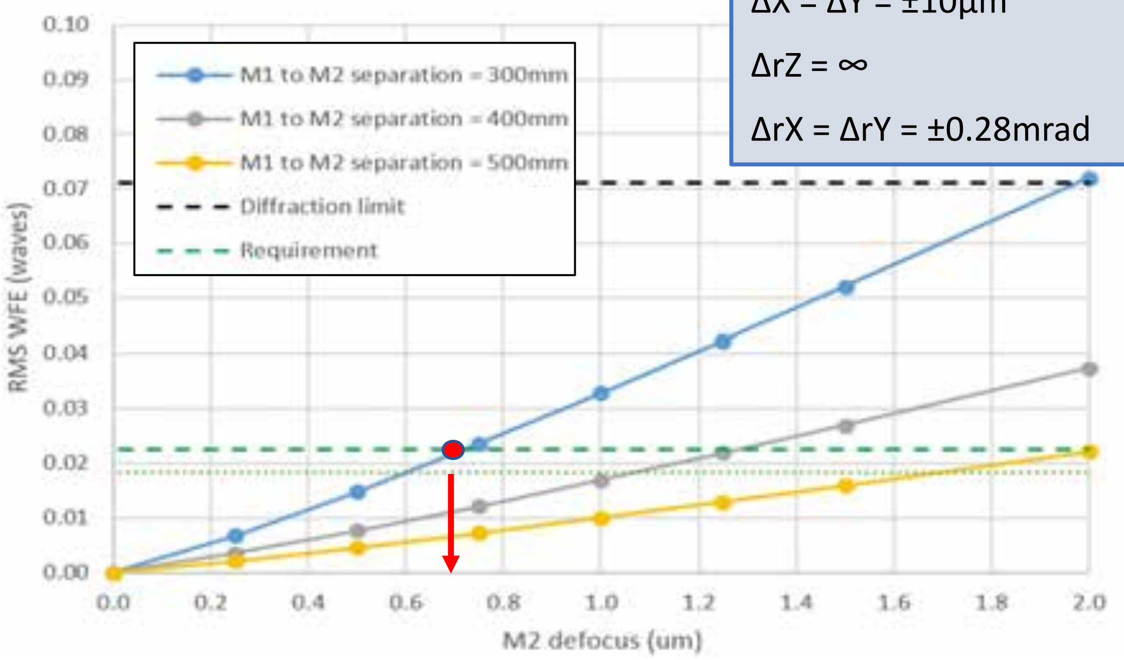
Requirements

ΔZ = ±0.7μm

ΔX = ΔY = ±10μm

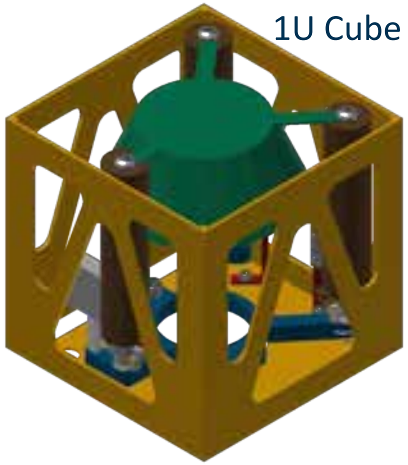
ΔrZ = ∞

ΔrX = ΔrY = ±0.28mrad

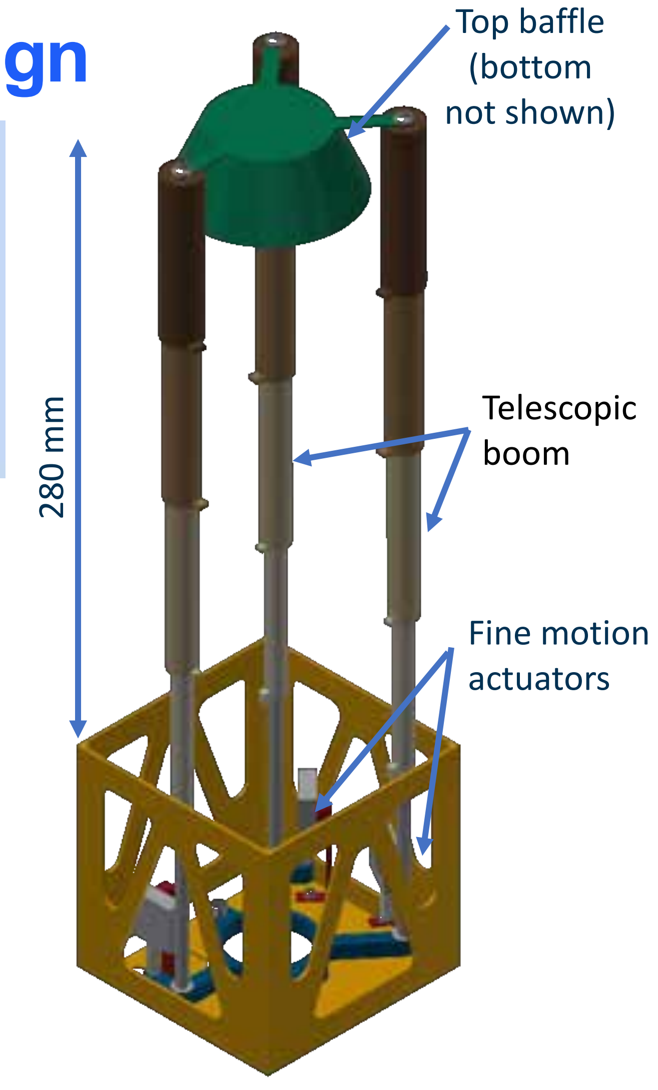


Conceptual design

Dynamic simulation of M2



Stowed



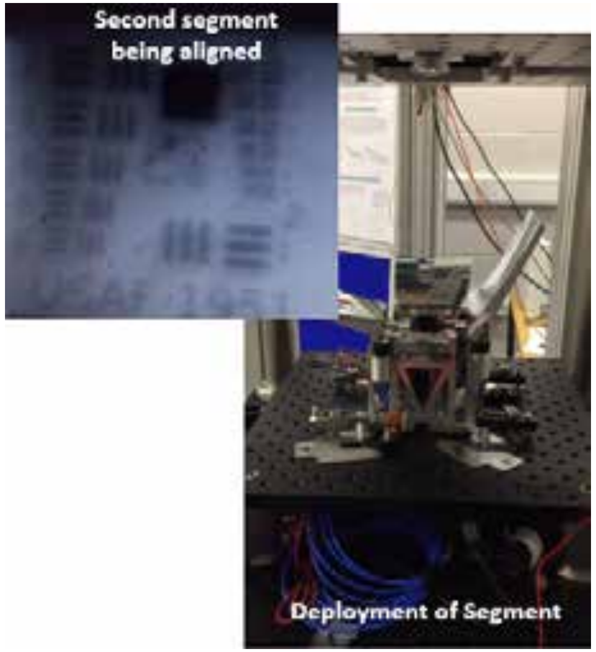
Deployed

Thank you for your attention

HighRes (2015-2019)

1.5U Prototype

(CDE, UKSA, STFC, …)

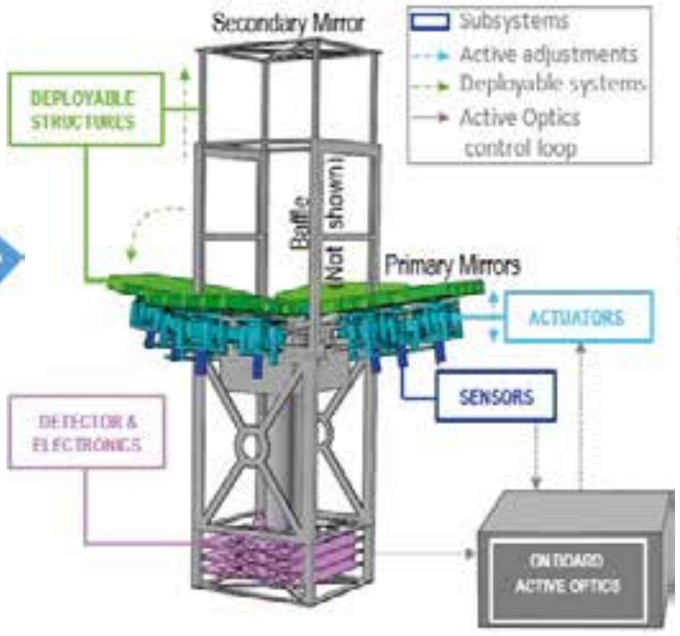


TRL3

ISAAC (2020-2023)

6U Ground demonstration

(CLASP, …)

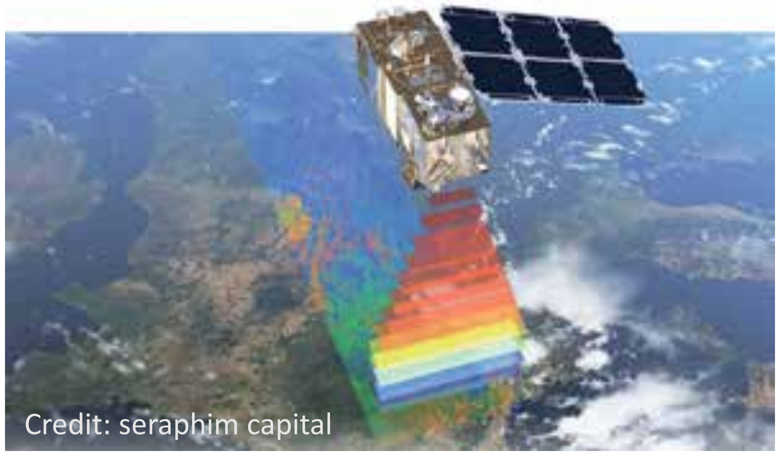


TRL5/6

ISAAC+ (2023+)

In-orbit demonstration

Commercialisation



TRL9

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