Science & Technology Facilities Council
UK Astronomy Technology Centre

HighRes: High-resolution deployable CubeSat for Earth observation

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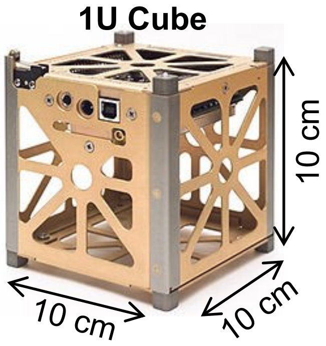
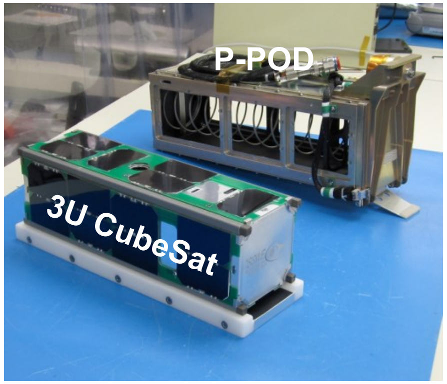
[dstl]

What is a CubeSat?

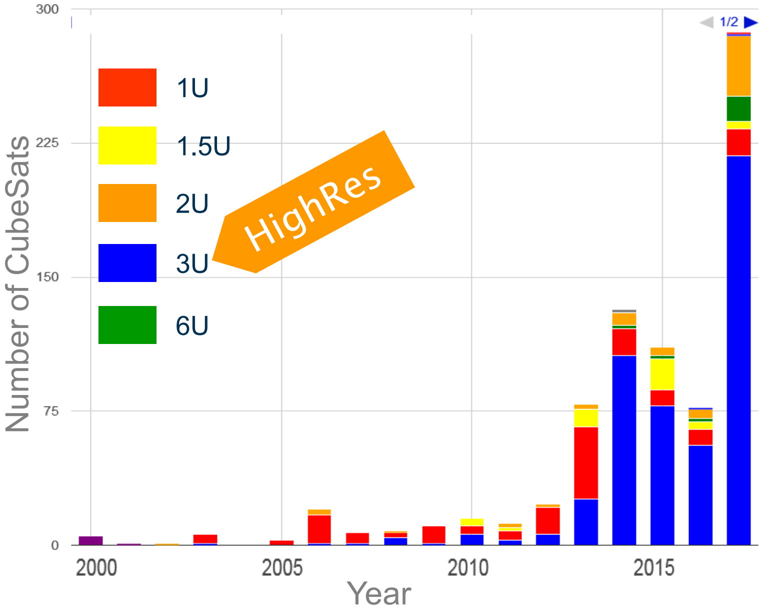
- A CubeSat is a standardised miniaturised satellite
- Made of multiple cubic units “U”
  - 1U = 10x10x10 cm^3 & 1U < 1.33 kg
- Specifications developed in 1999 for students
  - Launched from the ISS or as secondary payload (P-POD)
  - Used for experiment, technology demonstrators, risky missions…
  - Cheap & short development cycle



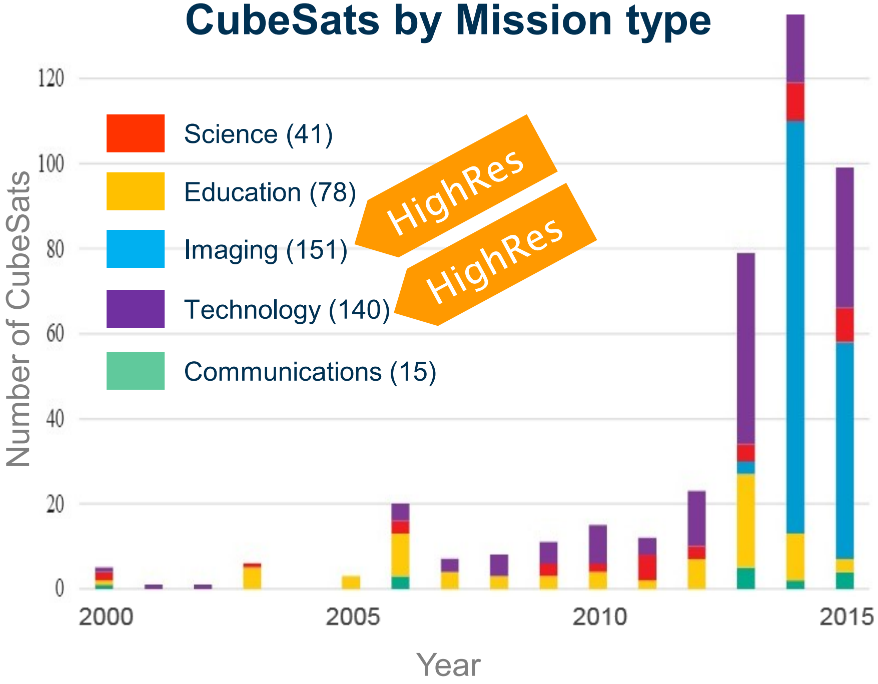


Category	Mass (kg)
Large Sat.	> 1000
Medium Sat.	500 to 1000
Mini Sat.	100 to 500
Micro Sat.	10 to 100
Nano Sat.	1 to 10
Pico Sat.	0.1 to 1
Femto Sat.	< 0.1

CubeSats in number #1



CubeSats by Form factor

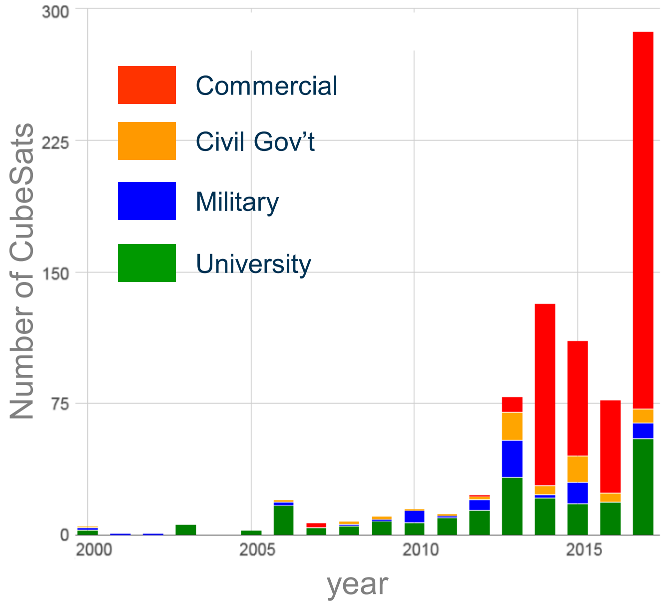


CubeSats by Mission type

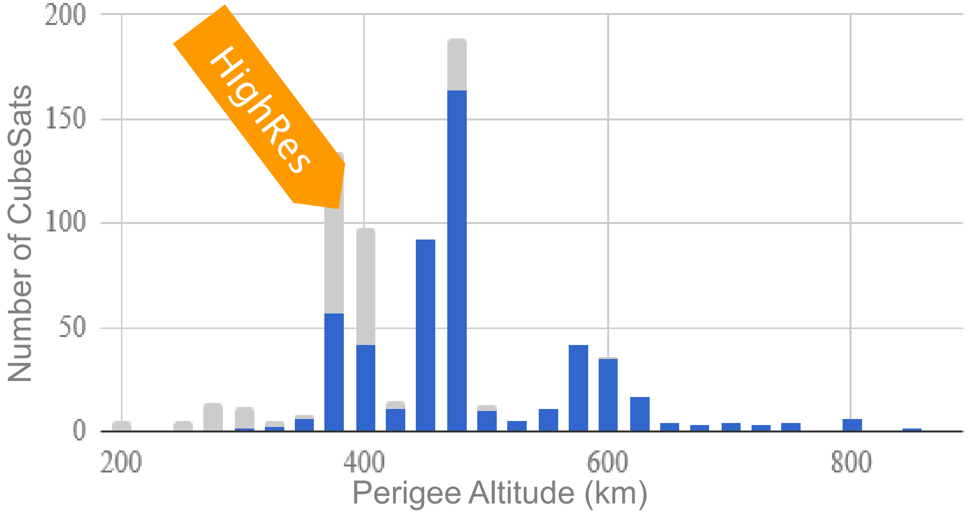
Plots from the CubeSat database from the Saint Louis University:
https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

CubeSats in numbers #2

CubeSats by type of organisation

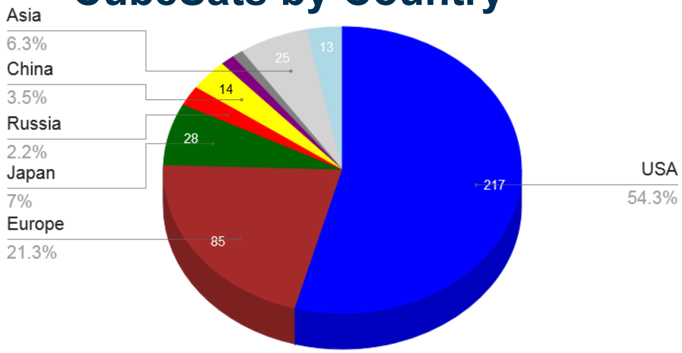


CubeSats by altitude

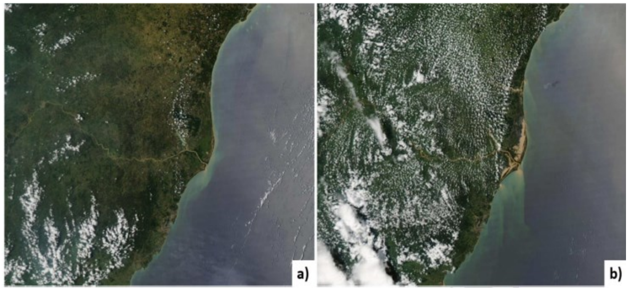


Plots from the CubeSat database from the Saint Louis University: https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

CubeSats by Country



Drivers for higher resolution

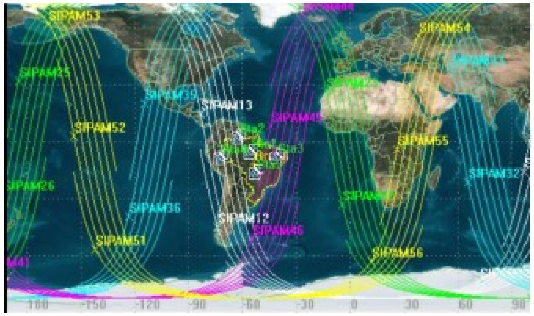


a) Normal conditions **b) Floods**

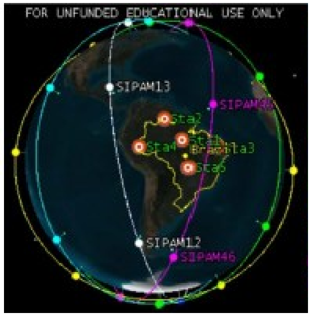
- Tactical/Military objectives
  - Our source of funding!
  - Req.: Interpretability of images
- Disaster monitoring
  - Approx. 1m Ground Sampling Distance (GSD)
  - Use of a constellation to provide time resolution and global coverage

Emergency	Phase	GSD	Time
Floods	Monitoring Management	30–100 m 10–100 m	12h 3–12h
Landslides	Monitoring Management	30–250 m 10–100 m	1d 3–12h
Earthquakes	Management	1–100 m	3–12h
Volcanoes	Monitoring Management	30 m 10–30 m	1d 6h–1d
Fires	Monitoring Management	100 m 30 m	1–3h 0.25h
Sea Pollution	Monitoring Management	1 km 100 m	1d 6–12h
Border	Monitoring	1–10 m	3h
Humanitarian	Management	1–10 m	1–3h

Gupta 1995



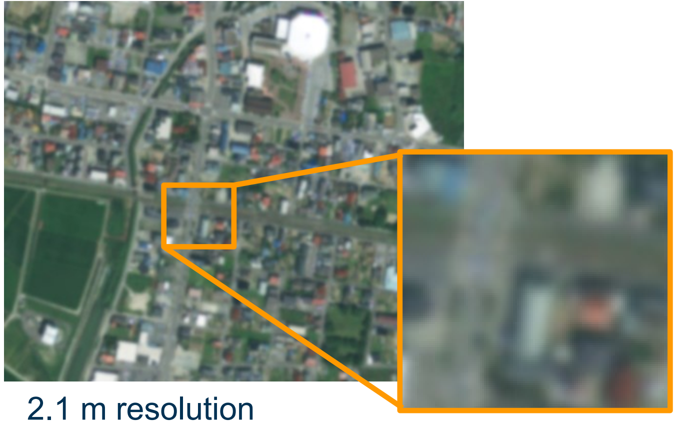
Santilli 2018



The need for deployable optics

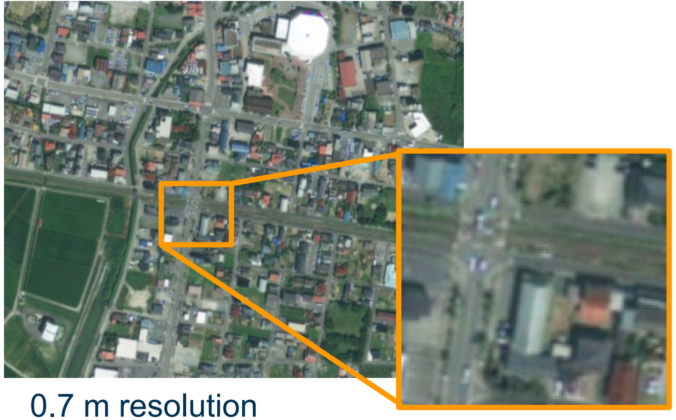
- High-level specifications for HighRes
  - Approx. 1m ground sampling distance at 400 km altitude
  - 2U optical payload (to fit into 3U satellite)
  - Panchromatic imaging system: approx. 450-800 nm
  - Diffraction limited imaging with D ≈ 300 mm

10 cm aperture at 350 km



2.1 m resolution

30 cm aperture at 350 km

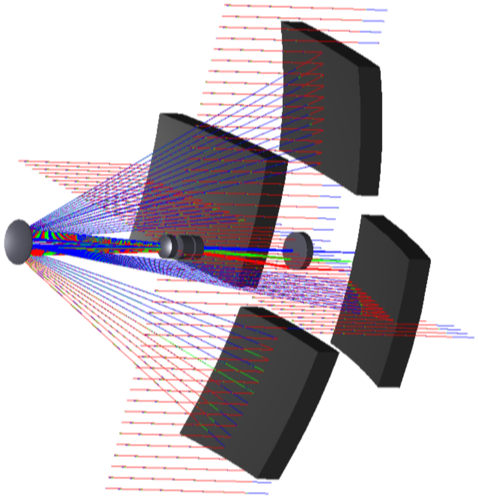


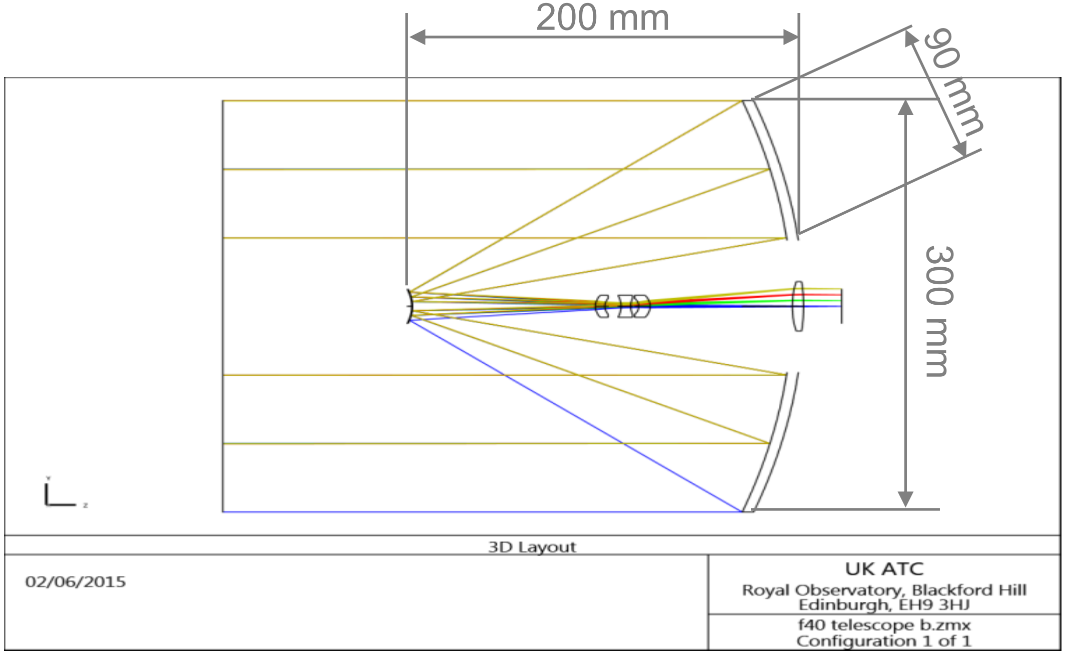
0.7 m resolution

- 3U CubeSat
  - Limited to 9-10 cm apertures
  - ➔ Deploy optics to increase resolution
  - Need proof of concept study!

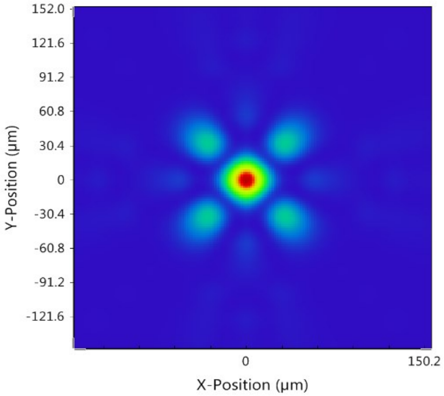
Optical design

- Cassegrain telescope
  - ➢ Segmented parabolic primary of 300 mm
  - ➢ M1-M2 separation of 200 mm
    - Requires a fast primary mirror
- Lens corrector system
  - ➢ Uniform undistorted FoV
  - ➢ Set output focal ratio (match pixel size)

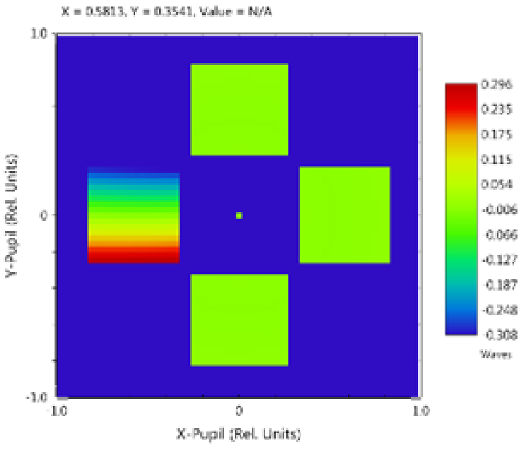
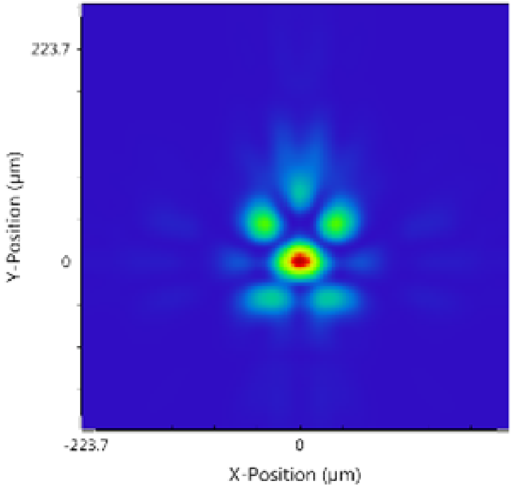




Segment co-phasing



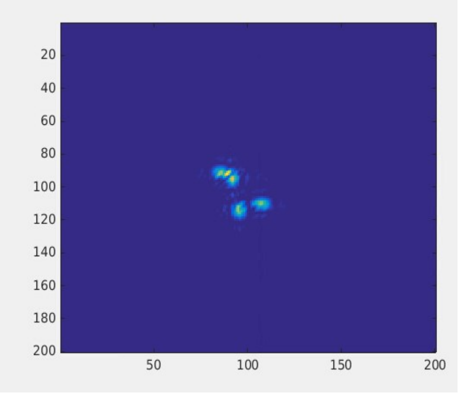
- 4 mirror segment geometry
  - Create a 4-lobed PSF
- Diffraction limited telescope
  - Segments must act as part of a single optical surface
  - Requires an RMS wavefront error <40nm (λ/14)
- Control of segments
  - Each segment needs to be controlled in Piston, Tip & Tilt

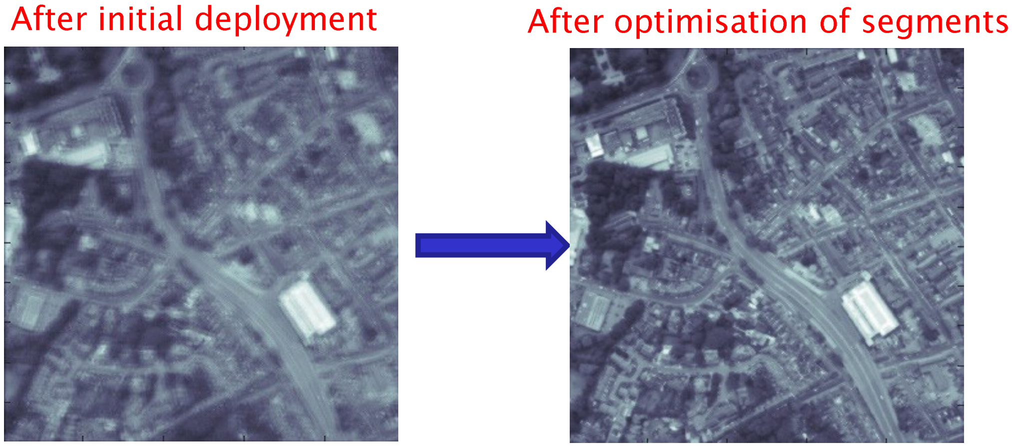
Segment tilt 1.5 x 10^{-4} degrees	 Peak to valley: 0.60λ, RMS: 0.09λ	

Active optics system

- Sensing & control M1 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
- Constrains
  - Very limited real estate
  - Limited electric & computing power

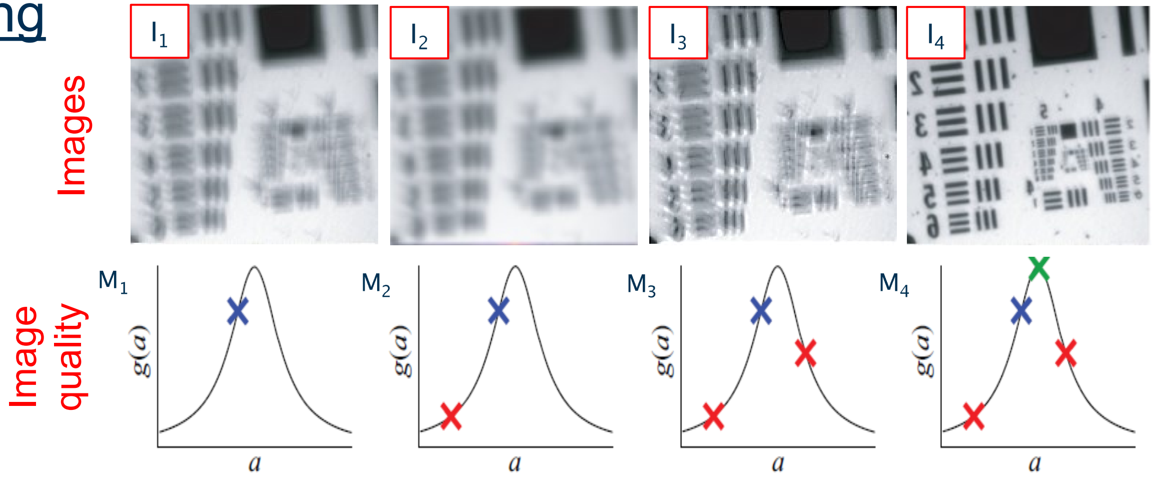
Example of PSF after deployment





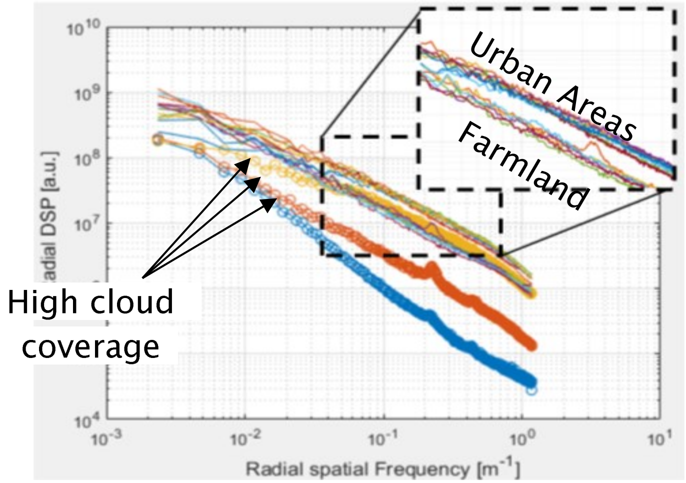
Active optics – Possible options

- Direct wavefront sensing (e.g. SH)
  - ➢ Requires additional hardware
- Displacement sensors
  - ➢ Typically not compatible with CubeSat constrains (TBC)
  - ➢ Measures the back surface or outside of M1
- Focal plane sensing
  - ➢ Phase diversity
  - ➢ <u>Focal plane sharpening</u>
    - ▪ Direct use of image
    - ▪ Iterative process



Scope of the work

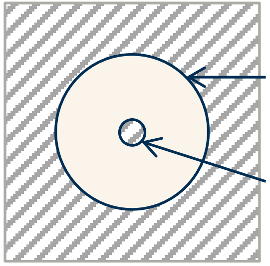
- Correct static alignment errors due to deployment in accuracies
  - No dynamic aberrations using static ground scene
  - Preliminary investigation of implication of moving ground scene
- High-resolution EO scenes taken from a plane
  - Mostly farmland and urban areas
  - Various levels of cloud coverage, contrast & brightness
- Development of an end-to-end model (OOMAO)
  - Validation of correction principle
  - Understand limitations
- Implication of design and focal plane sharpening
  - Image interpretability
  - On-board computing



Focal plane sharpening

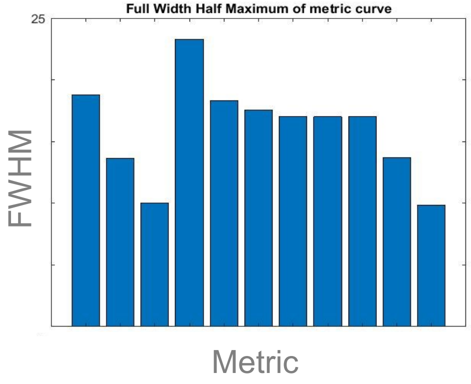
- Quick overview of algorithm
  1. Receive the detector image as input
  2. Measure a quality criteria based on the image
     - Ensquared energy, Spatial frequencies
     - Standard deviation, Haar wavelet…
  3. Change the segments’ tip, tilt & piston
  4. Optimise using the Nelder-Mead downhill-simplex method
- Image metrics
  - ➢ Virtually impossible to find a object-insensitive metric
  - ➢ Ensquared energy & spatial frequency
    - ▪ Robust metrics
    - ▪ Simple to compute
    - ▪ Trade-off necessary to optimise for capture range or noise

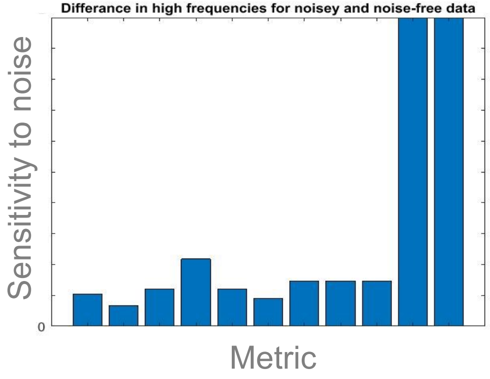
Fourier Transform of image



Filter high spatial frequencies

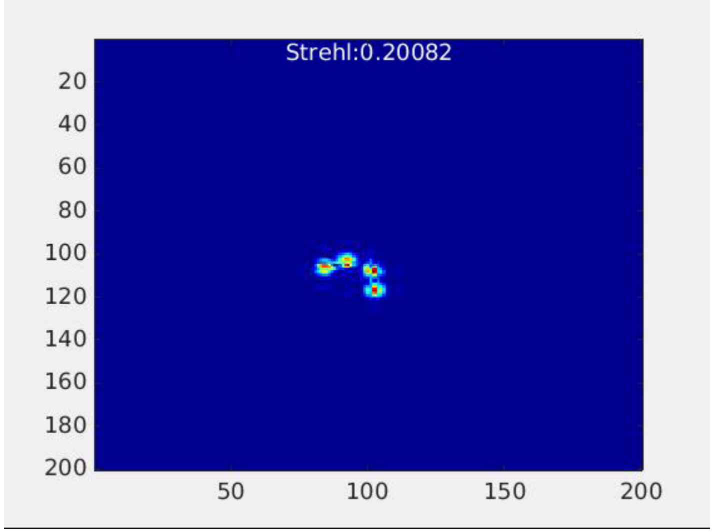
Filter low spatial frequencies

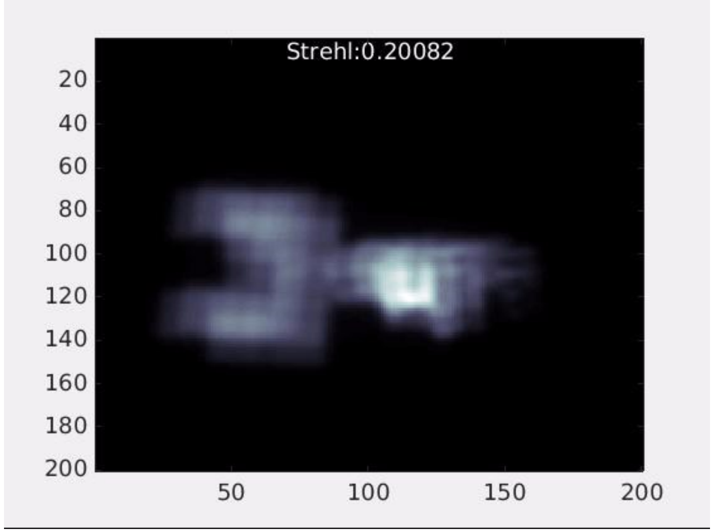




Overview of main results

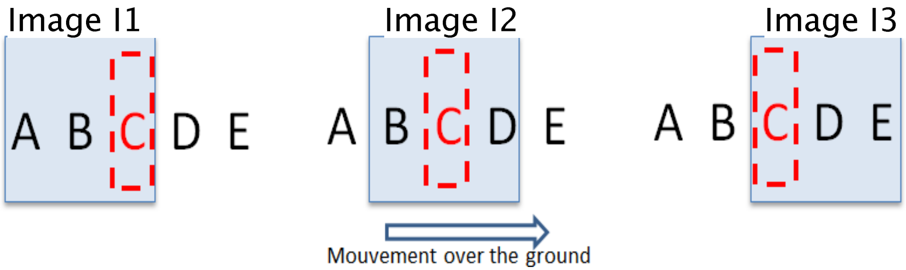
- Final correction quality
  - Reach diffraction limit both on point-source & extended objects
  - Image contrast C is a very good indicator of final correction quality (approx. 75% correlation between C and SR_{Final})
  - Sampling has little impact (i.e. 1 or 2 pixels per λ/D)
- Noise
  - Limited impact of noise under realistic observation conditions
  - Little impact of scattered light from the atmosphere (source of noise)
- On-board computing possible with current technology

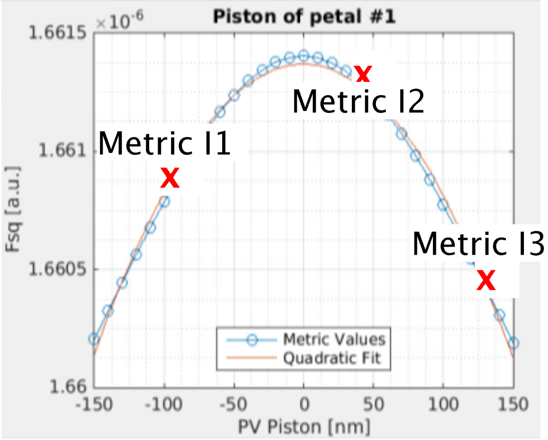


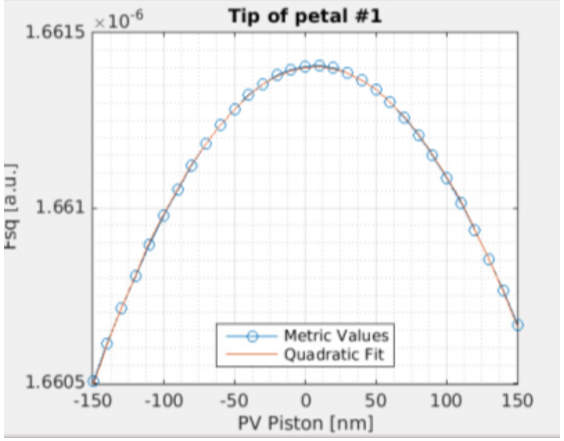


How to maintain alignment during operations?

- Methodology
  - ➢ Mode by mode optimisation
  - ➢ Function fit on N points







- Still on-going investigation
  - ➢ No show stoppers
    - Fairly good overall performance
    - But limited capture range
  - ➢ Requires further investigation

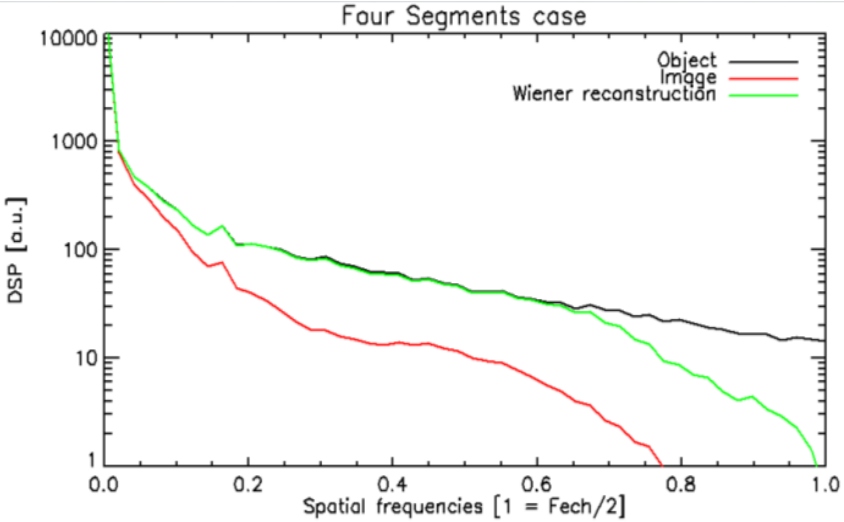
Image interpretability

- Image ‘Waffle’ due to 4-lobed PSF

HighRes

Circular aperture

- Promising initial results using deconvolution



Object

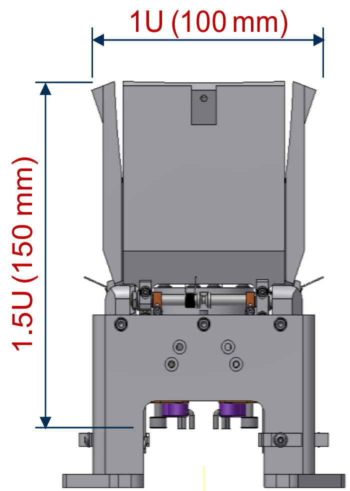
Image

Wiener estimation

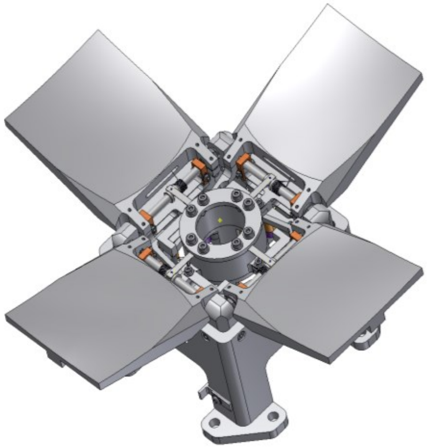
Mechanism design

1. Single-use deployment
   - Deploy the 4 mirror segments
2. Move segments in tip, tilt, piston
   - Actuators with large travel & high resolution
   - 3 motors on each mirror to provide tip/tilt/piston

DoF	Deployment repeatability	Actuator stroke	Actuator resolution
PTT	± 10 μm	1 mm	$\pm \lambda/14$ (± 45 nm)



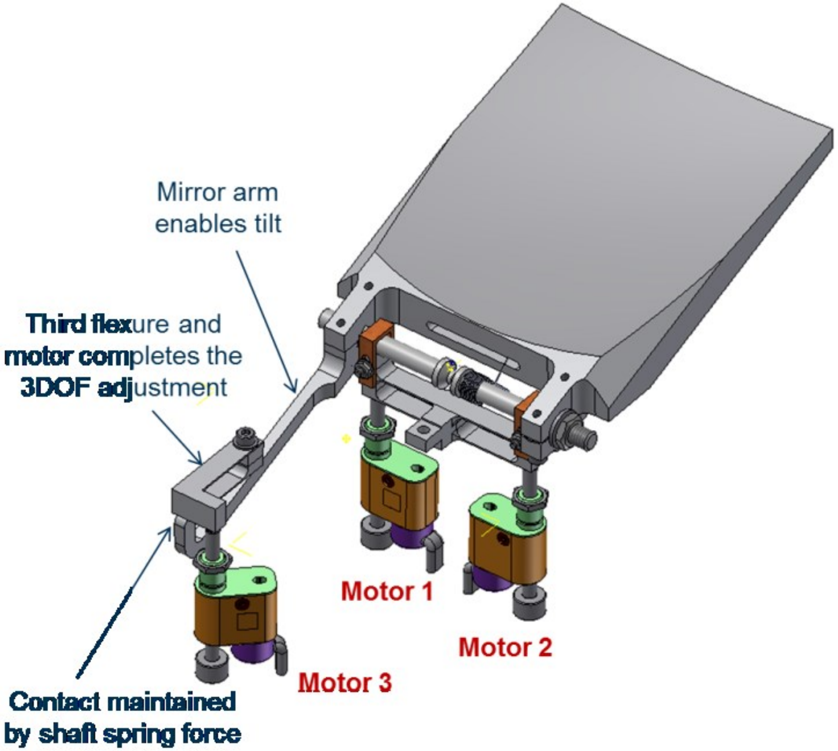
Folded State



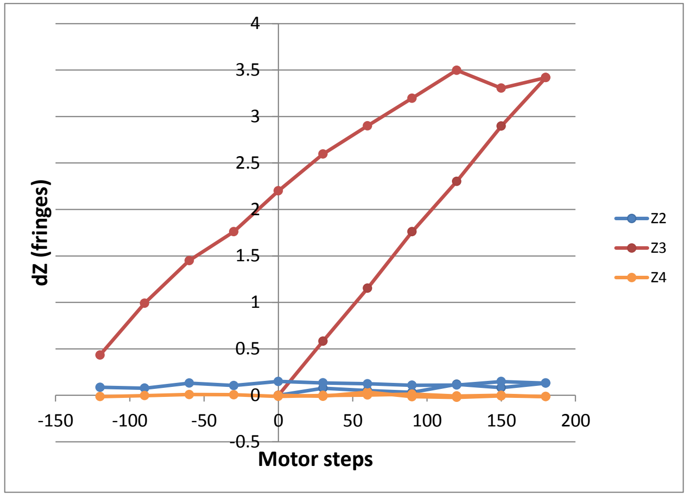
Deployed State

Piezo Motors & Capacitive sensors

- Newfocus Piezo motors
  - 30 nm resolution
  - 12.7 mm of travel
- Issue with repeatability of actuators
  - ➢ Large hysteresis and backlash
  - ➢ Inadequate for co-phasing
- Incorporate capacitive sensors
  - ➢ Absolute positioning capability



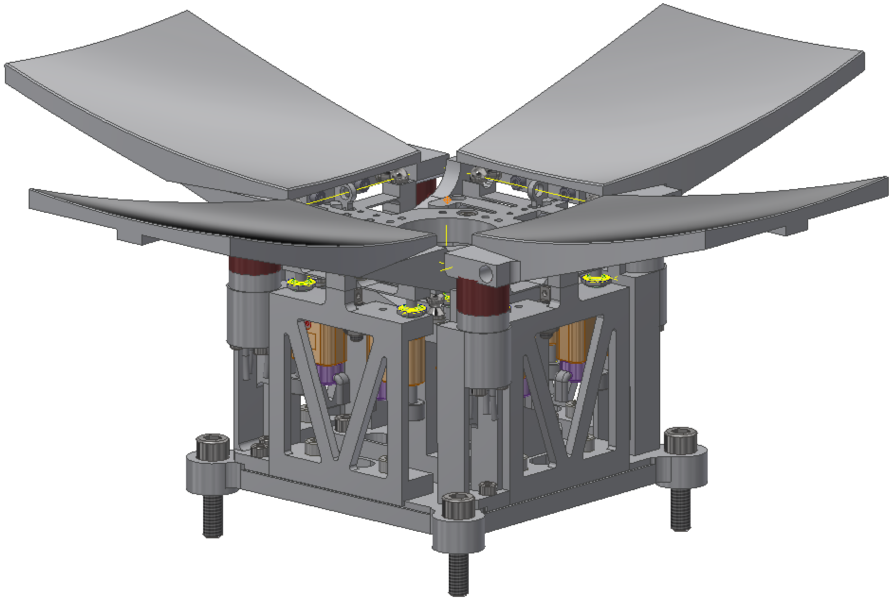
Actuators exhibit large hysteresis

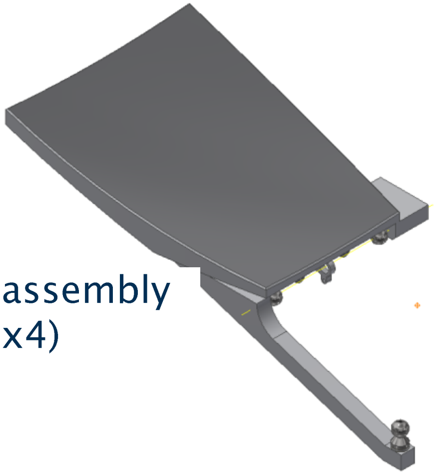


MicroEpsilon CSE05

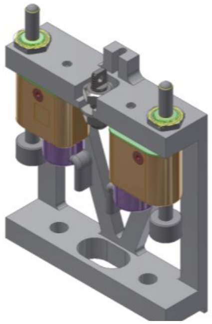
Modular build

- Easy alignment of sensors, hardware and optics
- One mirror can be adjusted or modified without affecting others
- Replacement of faulty hardware
- Disassembly and modifications during MAIT



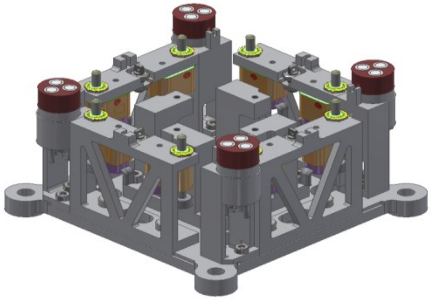


Mirror assembly (x4)

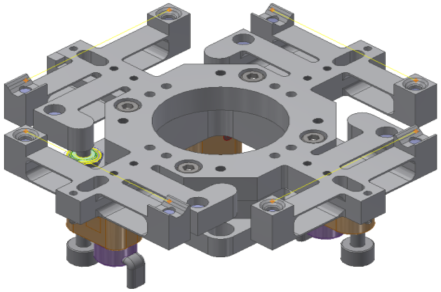


Motor mount assembly (x4)

Sensor assembly (x4)



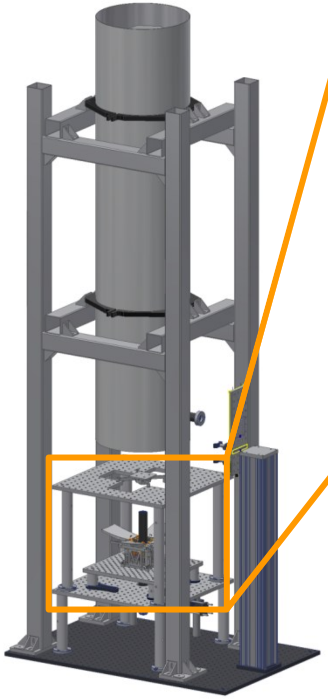
Base assembly

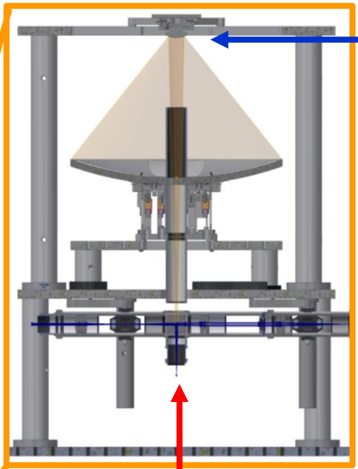


Central flexure assembly

Demonstrator

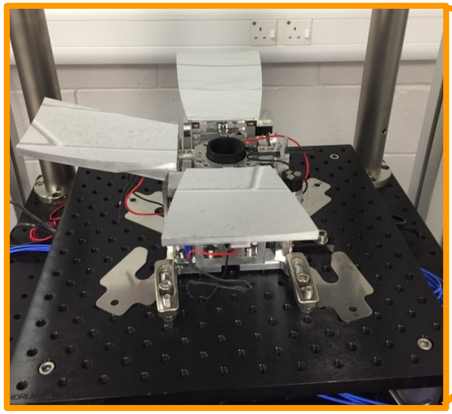
- Commercial Newtonian telescope used to provide 300 mm collimated illumination.
- Light input:
  - FLCoS micro-display to project extended objects
  - Single mode fibre for diffraction limited source
- Vertical setup ensures all petals see identical gravitational forces.





Secondary mirror

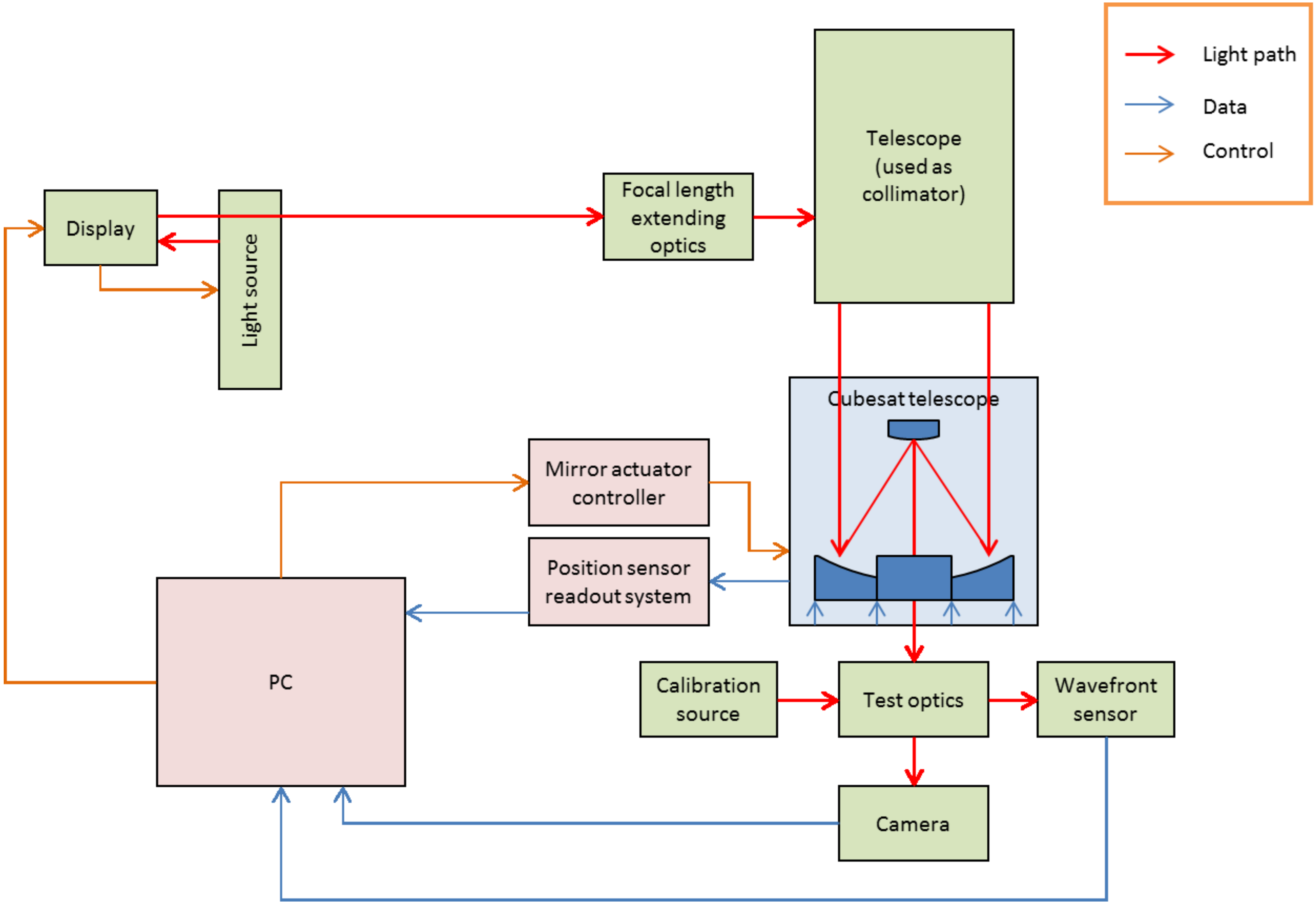
Camera



Micro-display assembly

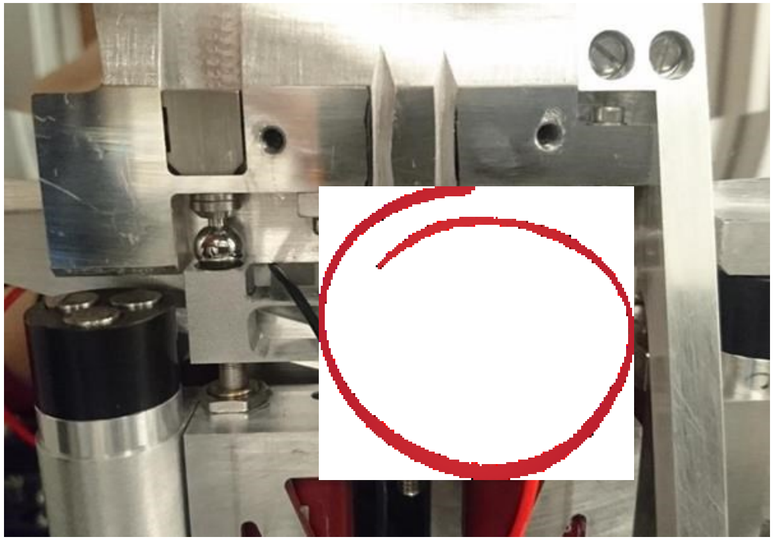
Camera

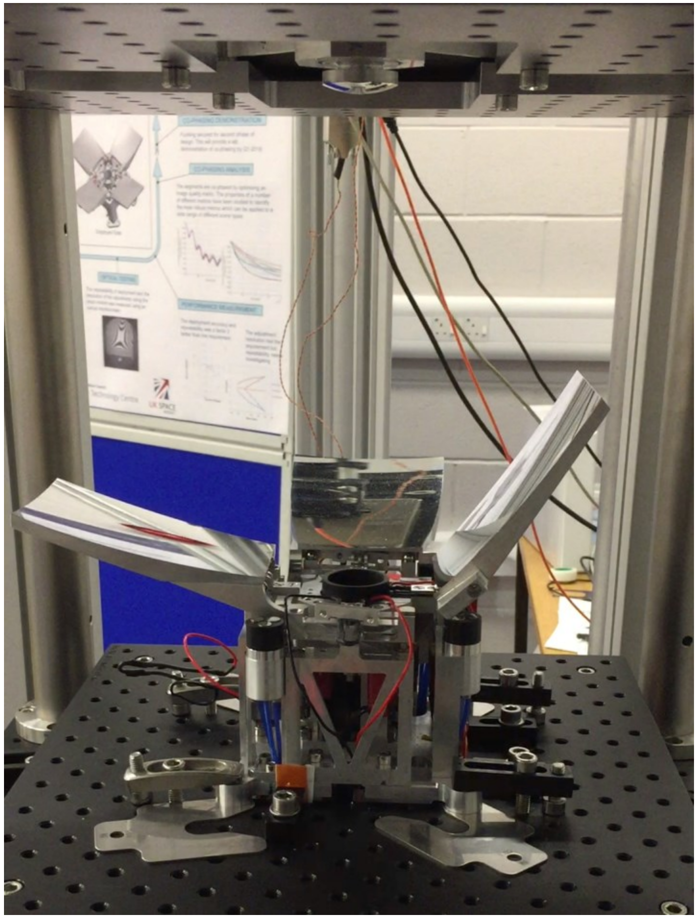
Bench schematic overview



Deployment mechanism

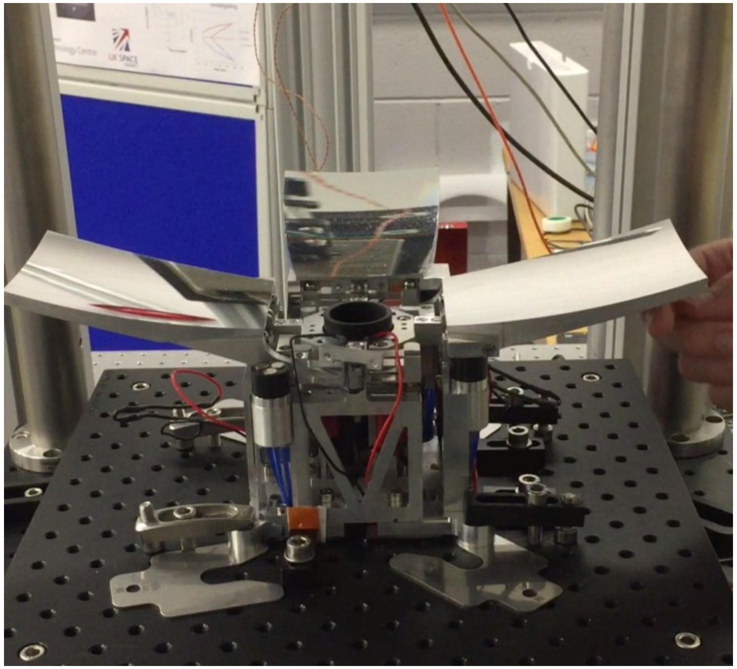
- Single-use deployment capability
  - Use of Shape-Memory Alloy (SMA) to deploy
  - Ohmic heating of SMA in close loop

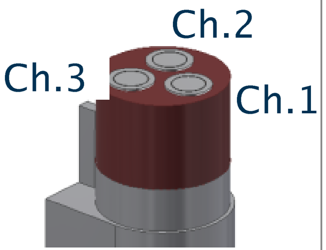


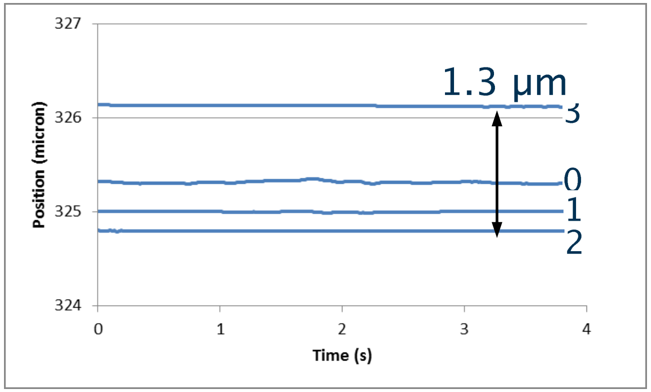


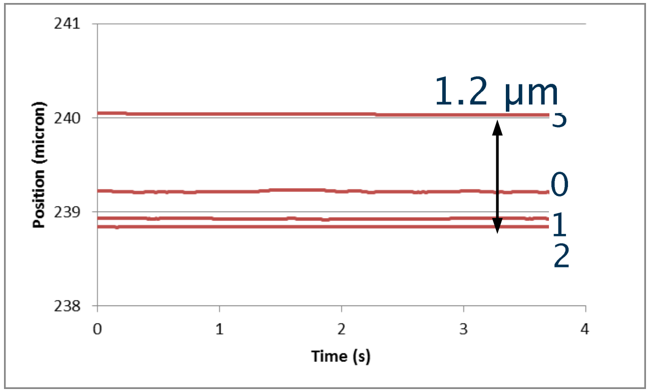
Repeatability

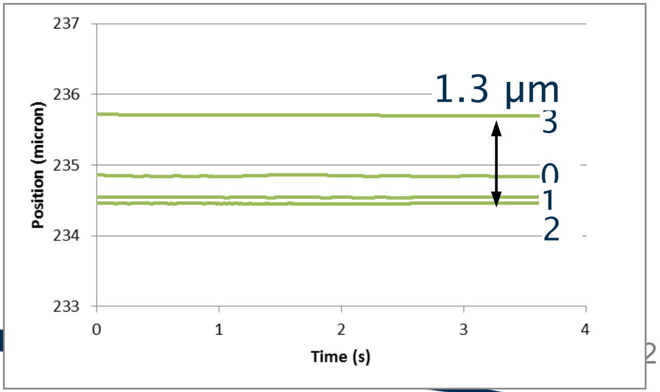
- Mirror repositioned within 1.3 microns on all three sensors
- More tests required to obtain statistics



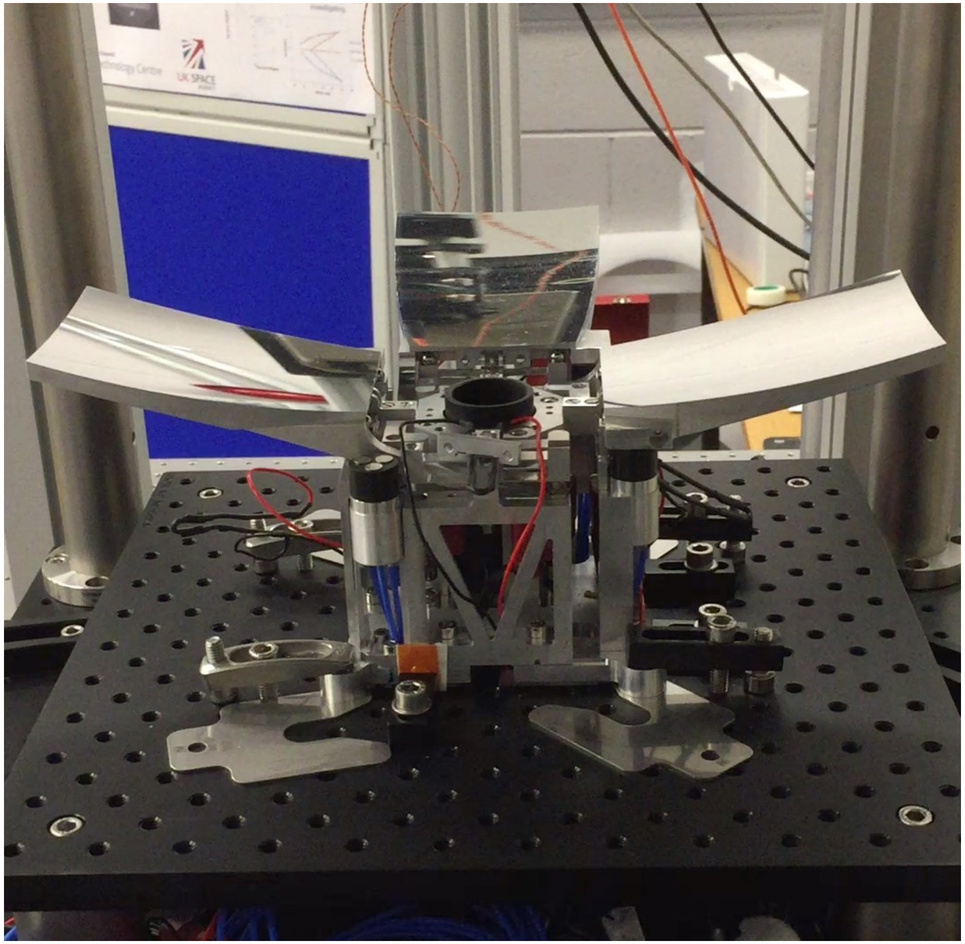


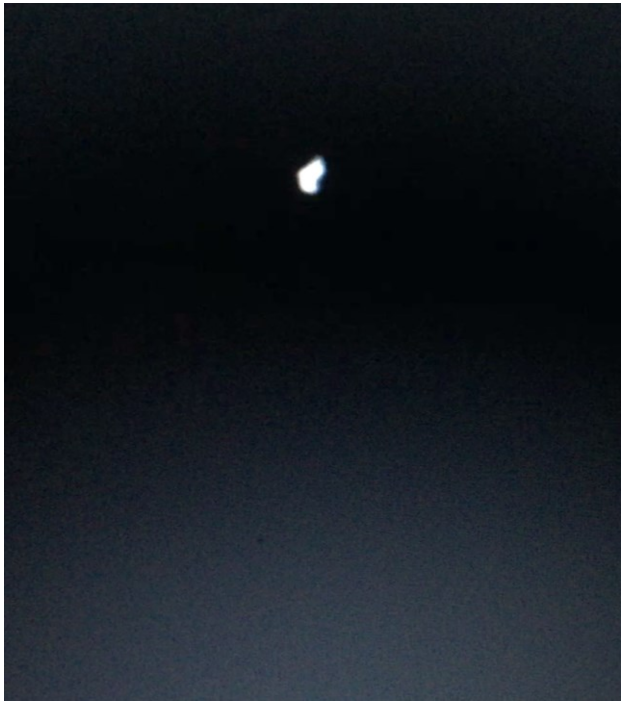






Robustness test

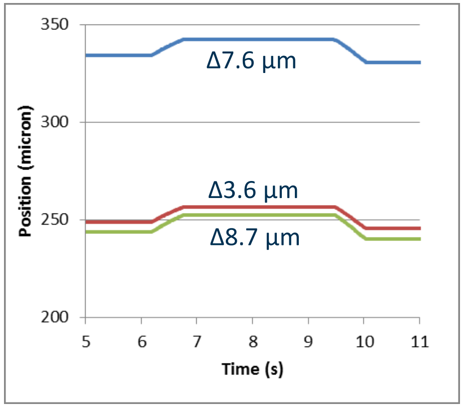




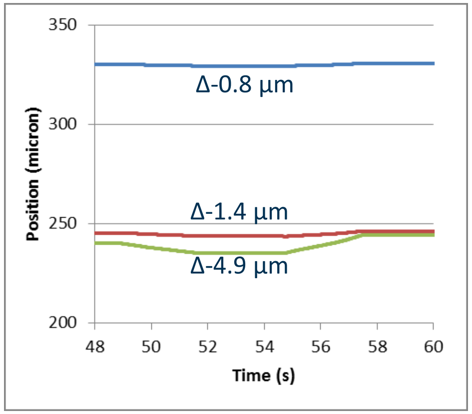
Segment adjustments

- Sensor / actuator / flexure combination provides adjustment resolution in excess of that required to align mirrors for diffraction limited system

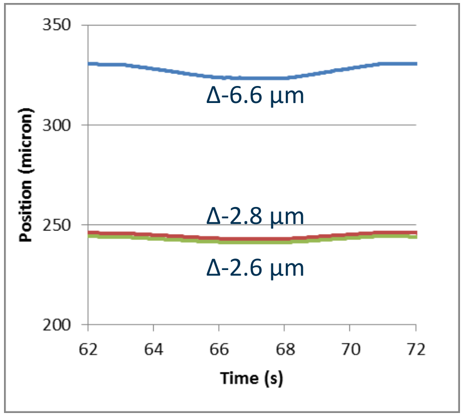
Motor1 1000 STEPS



Motor2 5000 STEPS



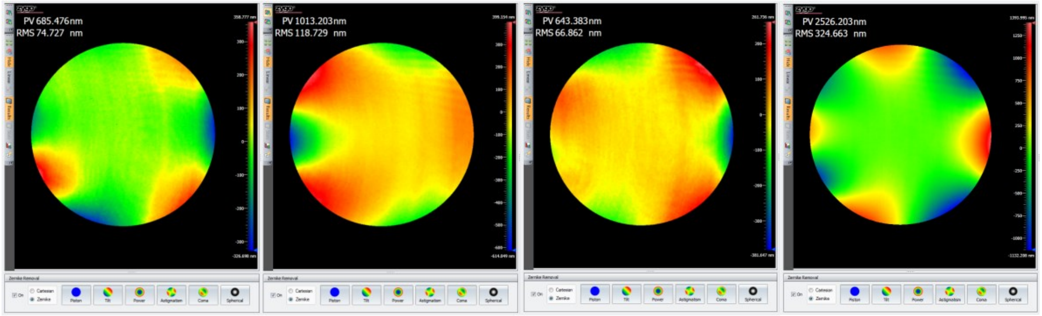
Motor3 5000 STEPS



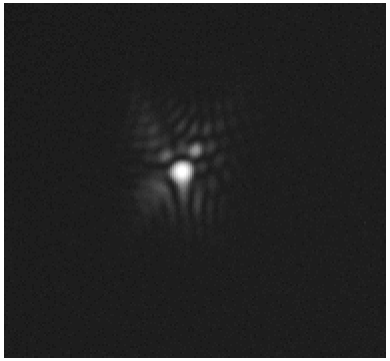
Second segment being aligned

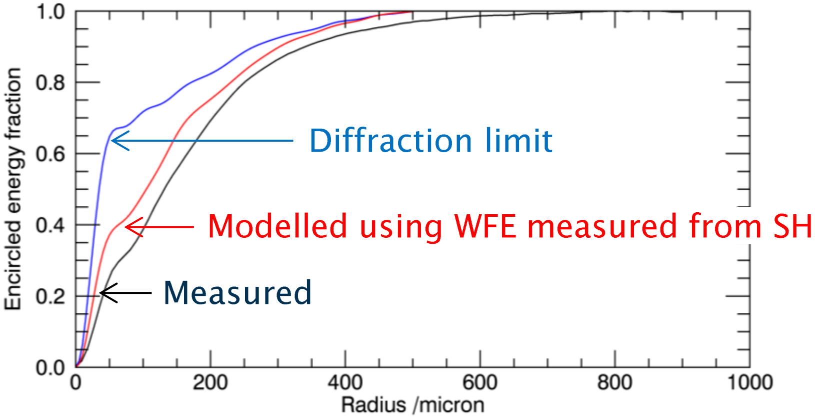
Mirrors & optical quality

- All 4 mirrors were diamond machined
- Difficulties in achieving the surface error specifications
  - ➢ Residual wavefront error approx. 70-100 nm RMS
  - ➢ Best possible Strehl Ratio < 20-40%



- Alignment of mirror segments quite tricky





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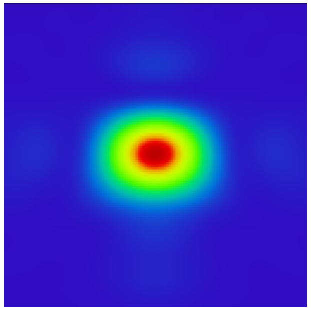
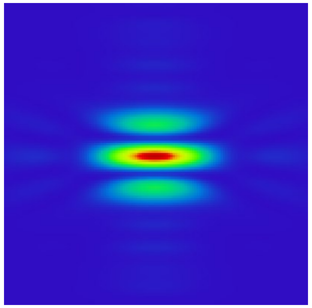
Implications

- High spatial frequency errors
  - Central sport surrounded by a halo of speckles
  - Implication on extended scenes to be quantified
    - Will produce a substantial loss of contrast
- Careful alignment can achieve a spot with compact central core
  - Alignment is challenging due to the tight tolerances (i.e. fast mirror)
  - In hindsight, alignment procedure could be improved (absolute ref. points, central fixed mirror…)
- Delays in implementation of the focal plane sharpening

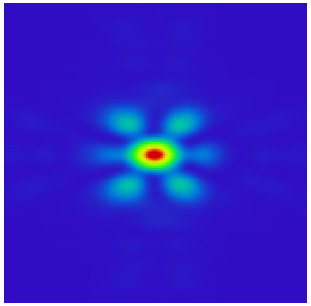
Ideal PSF 1 mirror



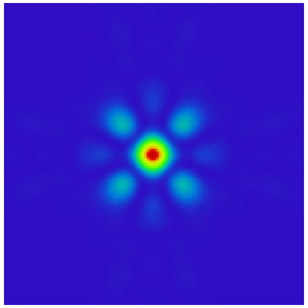
Ideal PSF 2 mirrors



Ideal PSF 3 mirrors



Ideal PSF 4 mirrors



Next steps

- Imminent (i.e. following weeks)
  - Continue experimental aspect of Focal Plane Sharpening

- Further investigation
  - Design M2 deployment mechanism
  - Reduce the need for high tolerances by design
    - e.g. increase M1-M2 distance
  - Compare focal plane sharpening to other sensing strategies
    - e.g. phase diversity

- Even further
  - Launch from the ISS