The Versatile CubeSat Telescope: Going to Large Apertures in Small Spacecraft

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An Interdisciplinary Collaboration

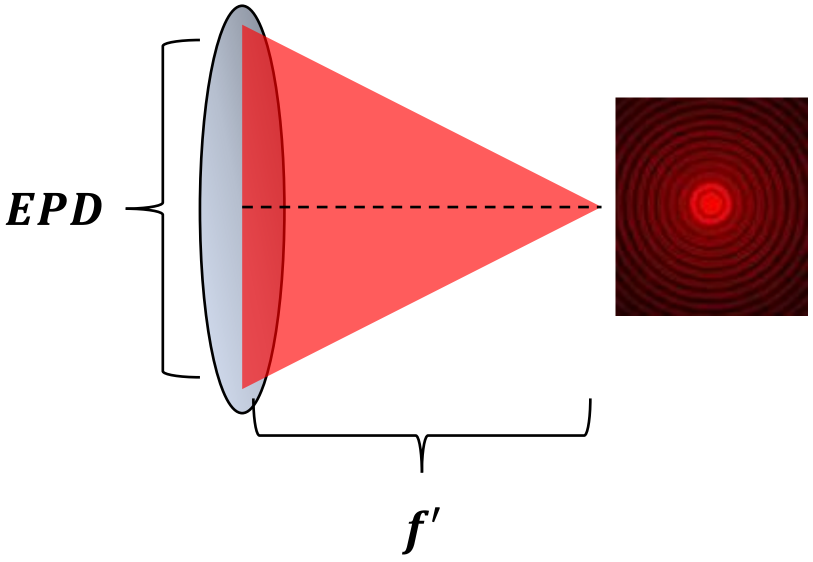
- UArizona Space Astrophysics Lab (UASAL)
  - PI – Ewan Douglas
  - Space mission payload development
  - High-Contrast Imaging

- Large Optics Fabrication & Testing group (LOFT)
  - PI – Dae Wook Kim
  - Optical design
  - Fabrication
  - Freeform optical testing

- MIT STAR Lab
  - PI – Kerri Cahoy
  - Nanosatellite development
  - Remote Sensing
  - Exoplanet Detection

Optical Resolution is Volume-Limited

- **ASTERIA** : 6U, 60mm EPD[1]
- **Lunar Flashlight**: 6U, 70mm EPD[2]



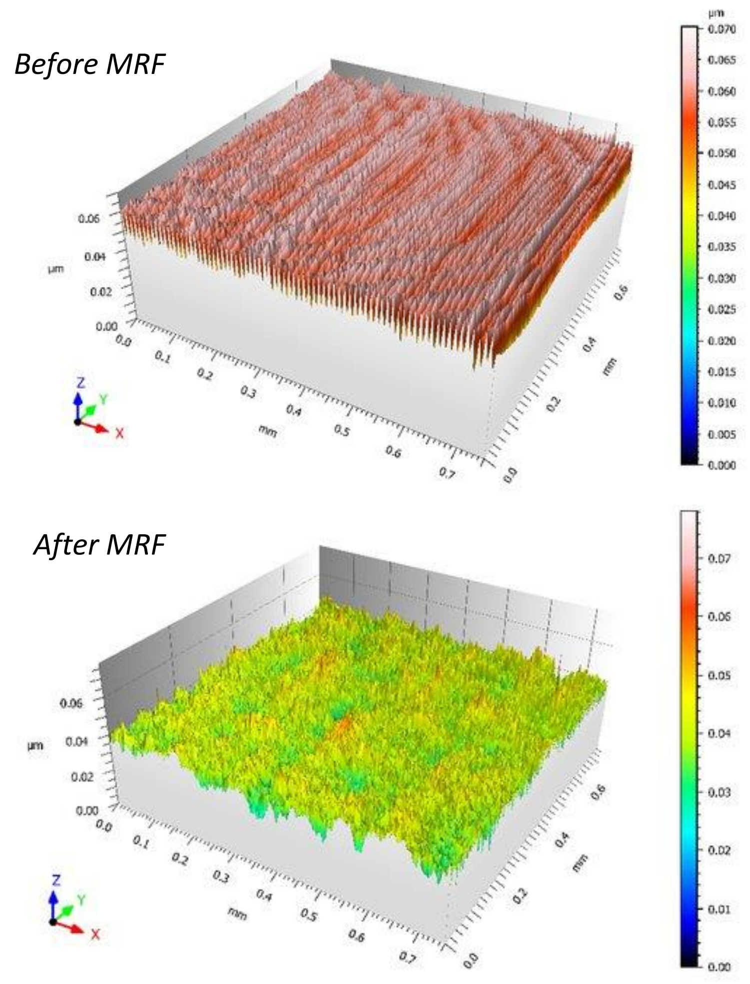
$$\Delta x = 1.22\lambda \frac{f'}{D}$$

Rayleigh criterion

How can we increase EPD To get better resolution & Throughput?

Advances in CubeSat Optics (1)

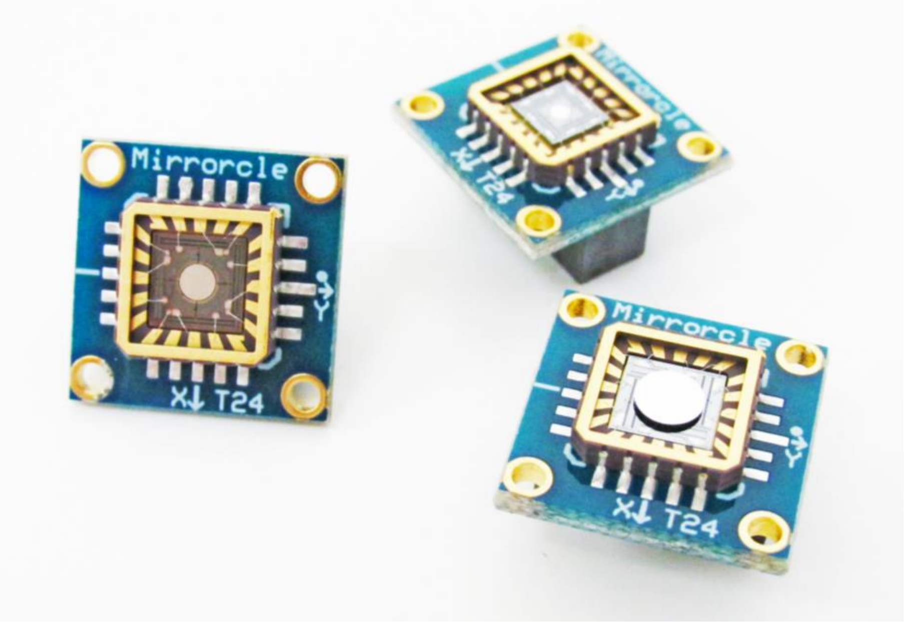
- Diamond-Turning enables all-aluminum optical system
- Wider apertures are accessible!
- Little performance mitigation in the optical from recent advances in optical finishing[3]
  - *Magnetorheological Finishing (MRF)*



Advances in CubeSat Optics (2)

- Pointing is challenging in space
  - Thermal gradients
  - Mechanical oscillations

- Fast-Steering Mirrors (FSMs) can dynamically adjust pointing to mitigate optical performance degradation

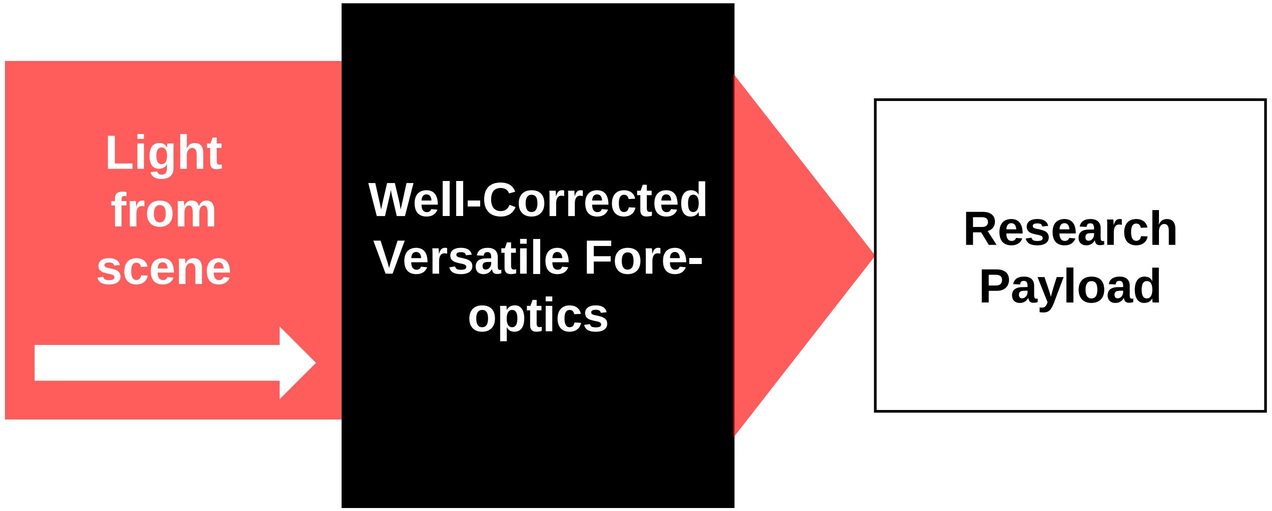


a MEMS mirror that can dynamically correct for pointing.
Image: Mirrorcle

Designing Versatile Fore-optics

- High Performance
  - Light collection
  - High resolution

- Low Sensitivity
  - Misalignment insensitive
  - All-aluminum thermal performance



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Design Requirements

Specification	Value	Description
EPD	**95 mm Obscured, 87.87 mm Unobscured**	Entrance Pupil Diameter, Diameter of Primary Mirror
XP	≅5 mm	Exit Pupil Diameter (FSM)
Wavelength	780 nm	Wavelength of strehl & polarization calculations
Half FOV	0.2°	The half field of view in degrees
FSM Footprint	≅5 mm	Beam Footprint on first FSM
Secondary Obscuration	20%	(M2 Diameter / M1 Diameter) * 100%
Central Field Strehl Ratio	0.99	Strehl ratio of system's central field
Average Field Strehl Ratio	> 0.8	Average of the center, 70% and 100% field of view Strehl ratios
Volume	< 3U	Volume of the system in units of U (10x10x10 cm^3)

Driving Requirement

High magnification systems with a large FOV

Requires diffraction-limited Performance

- *Look to aspheric solutions*

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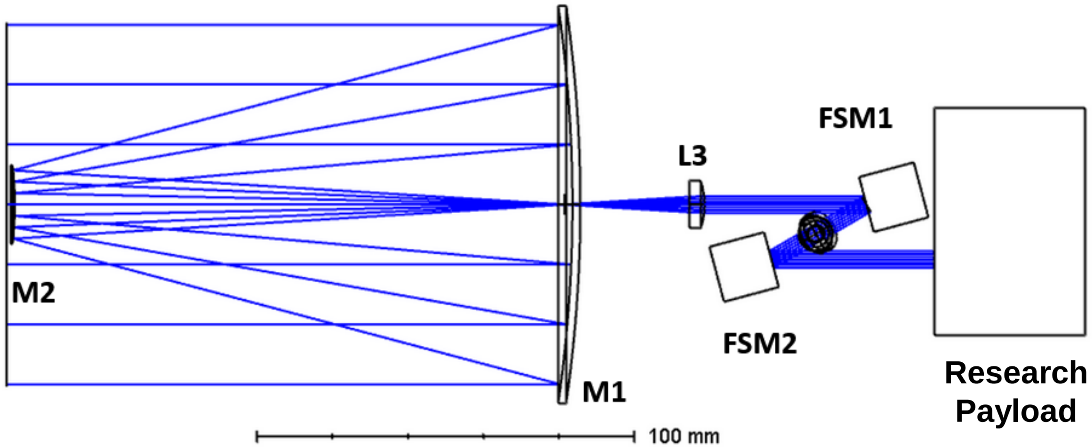
Classical v.s. New

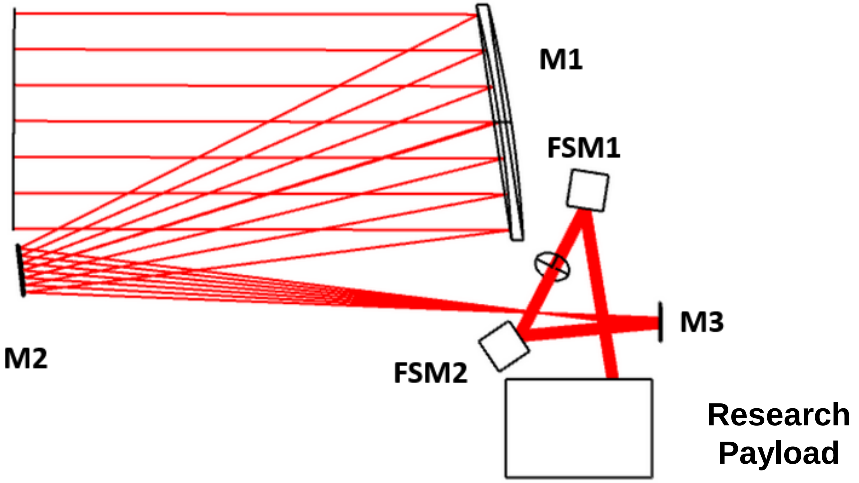
On-Axis

- Ritchey-Chretien Objective
- Plano-Convex Collimator



Off-Axis

- Unobscured Ritchey-Chretien Objective
- Freeform Collimator



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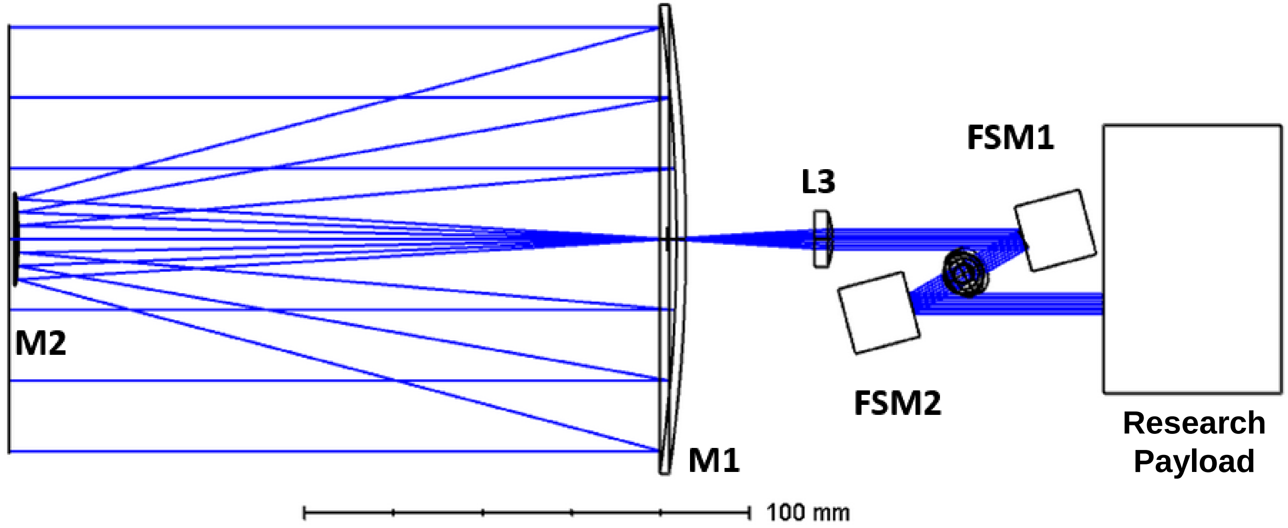
On-Axis

Pros

- Easy to manufacture + test
- Well-characterized solution



Cons

- Secondary obscuration
- Less packaging control

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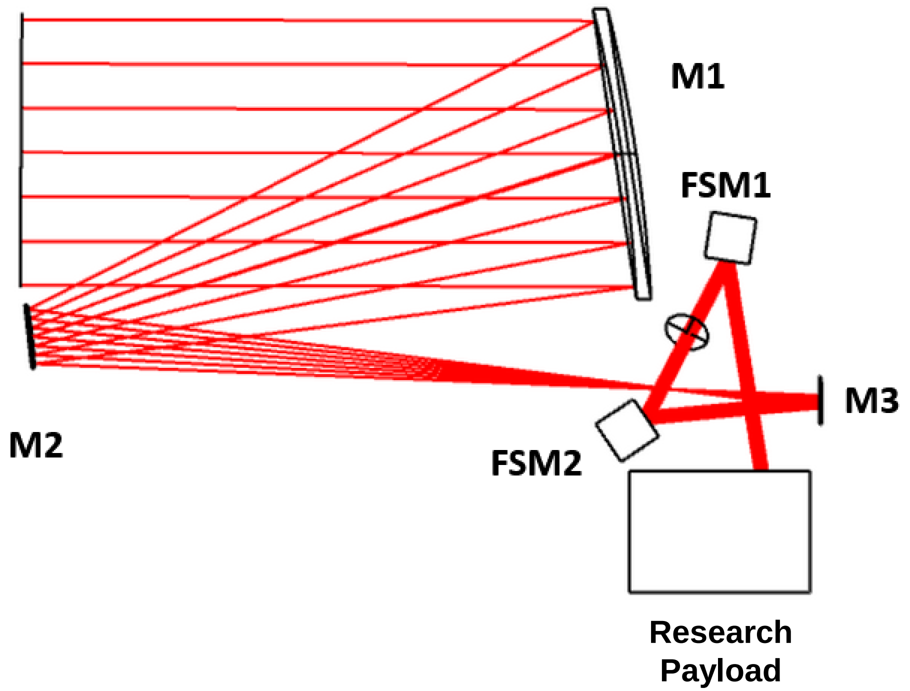
Off-Axis

Pros

- Unobscured
- More packaging control

Cons

- Harder to assemble
- Alignment sensitive



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Evaluation v.s. Specification

Specification	On-Axis	Off-Axis	Description
EPD	95 mm Obscured	87.87 mm Unobscured	Entrance Pupil Diameter, Diameter of Primary Mirror
XP	4.69 mm	5.1 mm	Exit Pupil Diameter
Wavelength	780 nm	780 nm	Wavelength of strehl & polarization calculations
Half FOV	0.2°	0.2°	The half field of view in degrees
FSM Footprint	4.69 mm	5.1 mm	Beam Footprint on first FSM
Secondary Obscuration	20%	N/A	(M2 Diameter / M1 Diameter) * 100%
Central Field Strehl Ratio	0.984	0.997	Strehl ratio of system's central field
Average Field Strehl Ratio	0.910	0.856	Average of the center, 70% and 100% field of view Strehl ratios
Volume	~3U	~3U	Volume of the system in units of U (10x10x10 cm^3)

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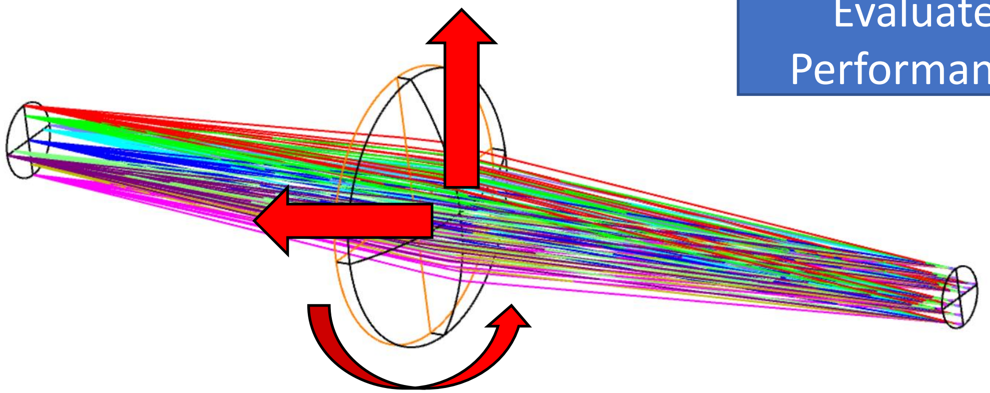
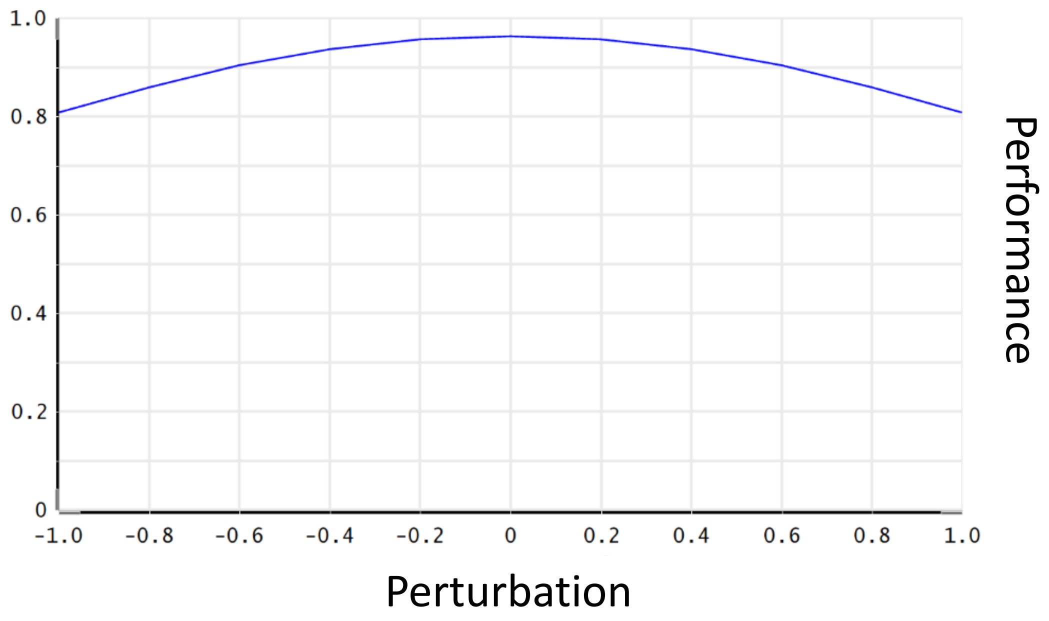
Alignment Sensitivity

Locally Perturb
- dX, dY, dZ
- $d\theta_x$ $d\theta_y$ $d\theta_z$



Evaluate Performance



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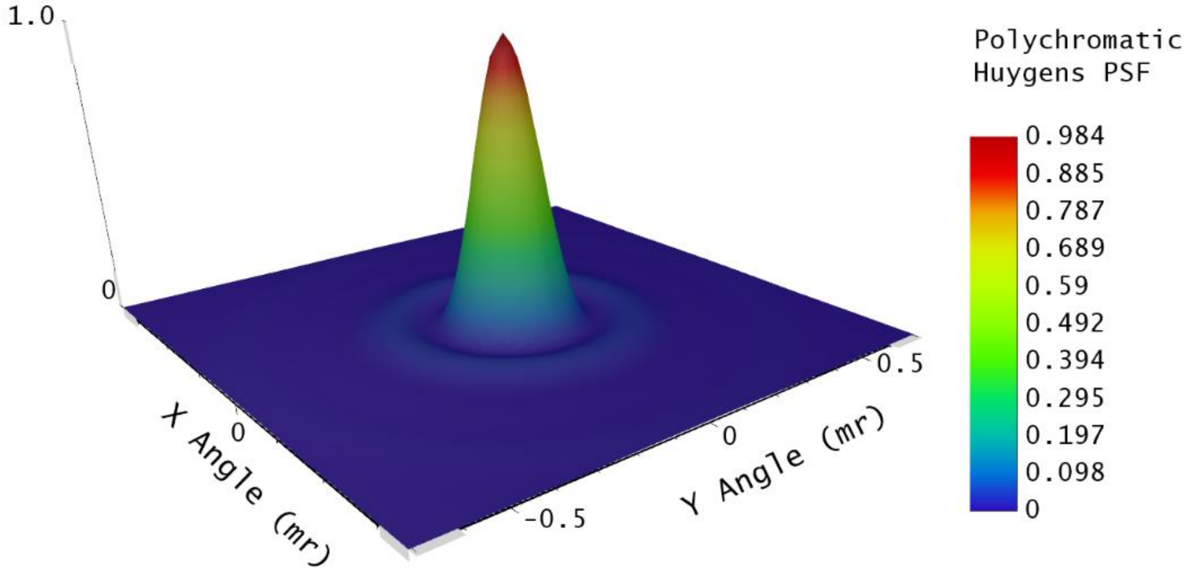
Strehl Ratio – An Astronomer’s Ruler

- Evaluation of imaging systems

$$SR = \frac{\max\left(\frac{PSF_{test}}{\sum\sum PSF_{test,ij}}\right)}{\max\left(\frac{PSF_{ideal}}{\sum\sum PSF_{ideal,ij}}\right)}$$

- Good for evaluation of performance in diffraction-limited regime
  - Little monochromatic aberration



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Results – where SR > 0.8

	Tolerance	On-Axis		Off-Axis	
M2	X Despace	0.093mm	-0.093mm	0.031mm	-0.031mm
	Y Despace	0.113	-0.113	0.0196mm	-0.0196mm
	Z Despace	0.36mm	-0.558mm	0.0032mm	-0.0166mm
	X Tilt	0.127°	-0.127°	0.021°	-0.020°
	Y Tilt	0.127°	-0.127°	0.03°	-0.03°
	Z Tilt	N/A	N/A	3.0°	-3.0°

L3 / M3	X Despace	1.8mm	-1.8mm	0.964mm	-0.964mm
	Y Despace	1.8mm	-1.8mm	1.1mm	-0.35mm
	Z Despace	0.085mm	-0.13mm	0.21mm	-0.066mm
	X Tilt	1°	-1°	0°	-0.32°
	Y Tilt	1°	-1°	0.65°	-0.65°
	Z Tilt	N/A	N/A	0.55°	-0.55°

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We Have a Winner!

M2	Tolerance	On-Axis		Off-Axis	
	X Despace	0.093mm	-0.093mm	0.031mm	-0.031mm
	Y Despace	0.113	-0.113	0.0196mm	-0.0196mm
	Z Despace	0.36mm	-0.558mm	0.0032mm	-0.0166mm
	X Tilt	0.127°	-0.127°	0.021°	-0.020°
	Y Tilt	0.127°	-0.127°	0.03°	-0.03°
	Z Tilt	N/A	N/A	3.0°	-3.0°

L3 / M3					
	X Despace	1.8mm	-1.8mm	0.964mm	-0.964mm
	Y Despace	1.8mm	-1.8mm	1.1mm	-0.35mm
	Z Despace	0.085mm	-0.13mm	0.21mm	-0.066mm
	X Tilt	1°	-1°	0°	-0.32°
	Y Tilt	1°	-1°	0.65°	-0.65°
	Z Tilt	N/A	N/A	0.55°	-0.55°

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Mechanical Requirements

Quality	Requirement
Telescope Volume	1U x 1U x 2U
Mass	<4kg max; <2kg goal
Instrument Module Interface	Flexible generic hole pattern
Optical Clear Aperture	95mm
Optical Obscuration	<20%
Optical Alignment	<20um positioning
Launch Survival	MAC (100g generalize acceleration)
Operational Temperature Differential	<2^{o}C
Survival Temperature Range	0-40^{o}C

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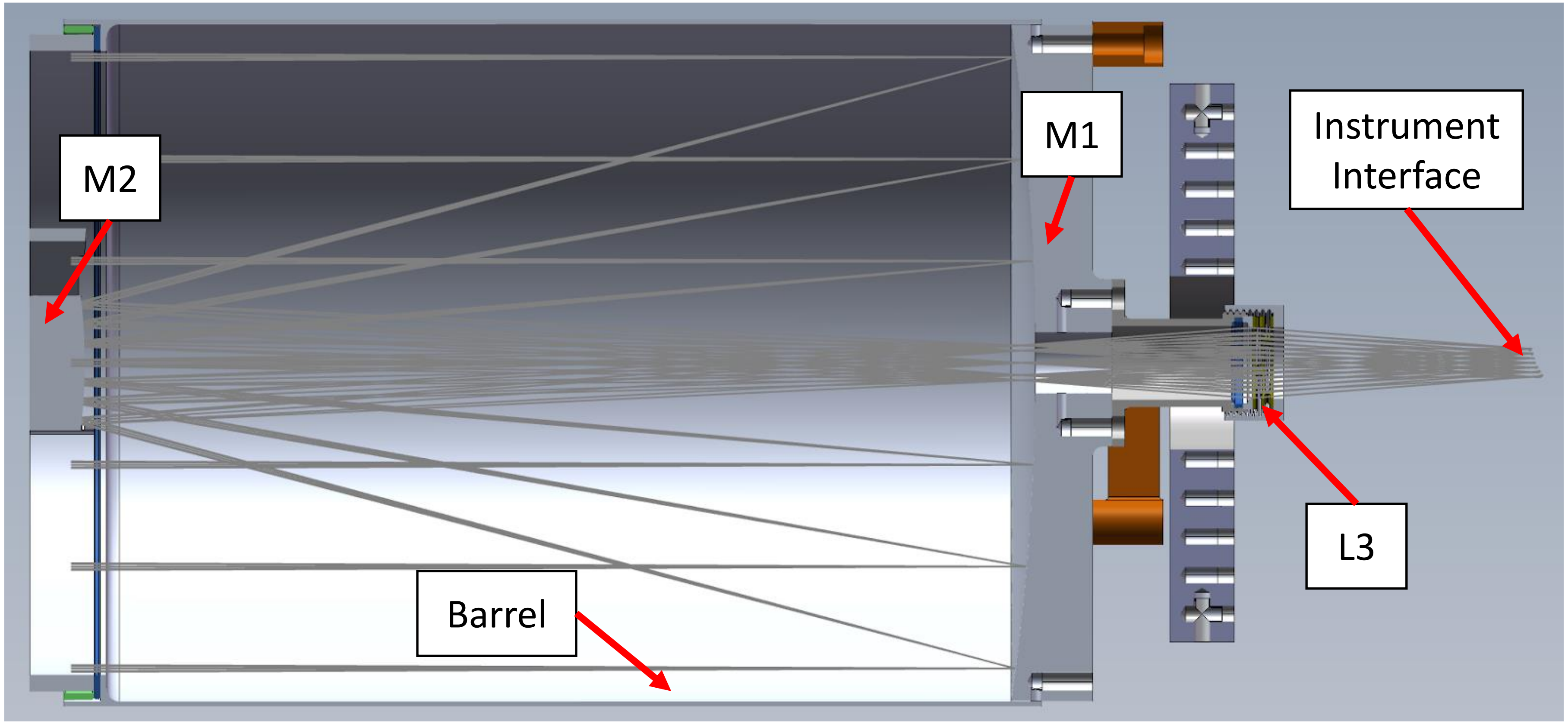
Optical Telescope Assembly (OTA)



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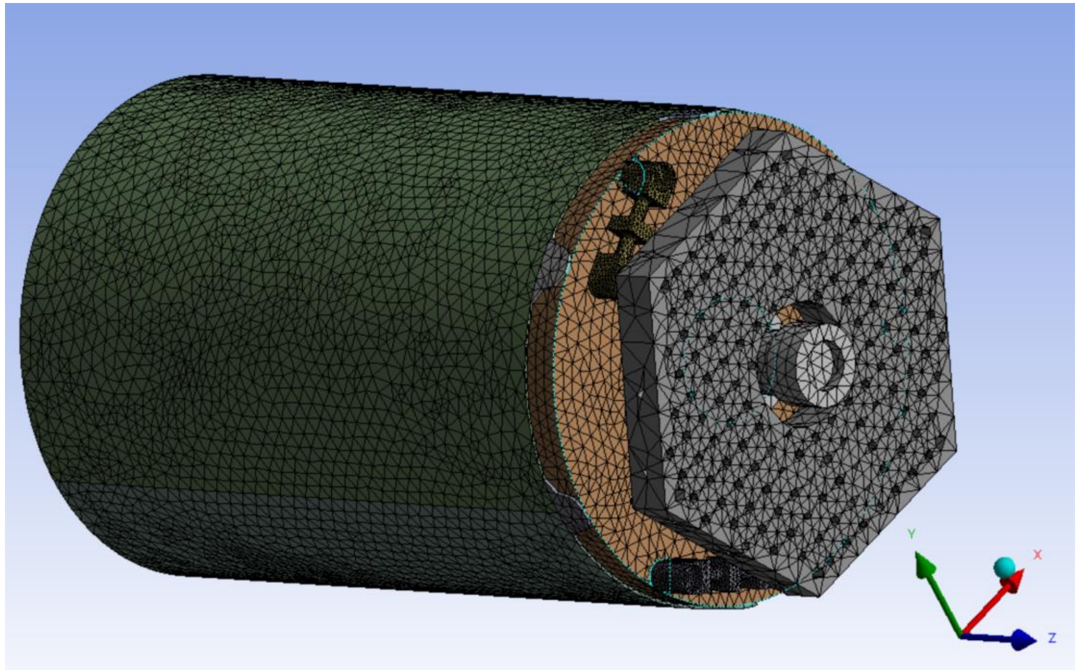
OTA FEA Model



<u>One model provides:</u>

Survivability Margins:

(1) Structural analysis for baseline sizing against MAC loading and Modal requirements

(2) Check of survivability for thermal stress and strains.

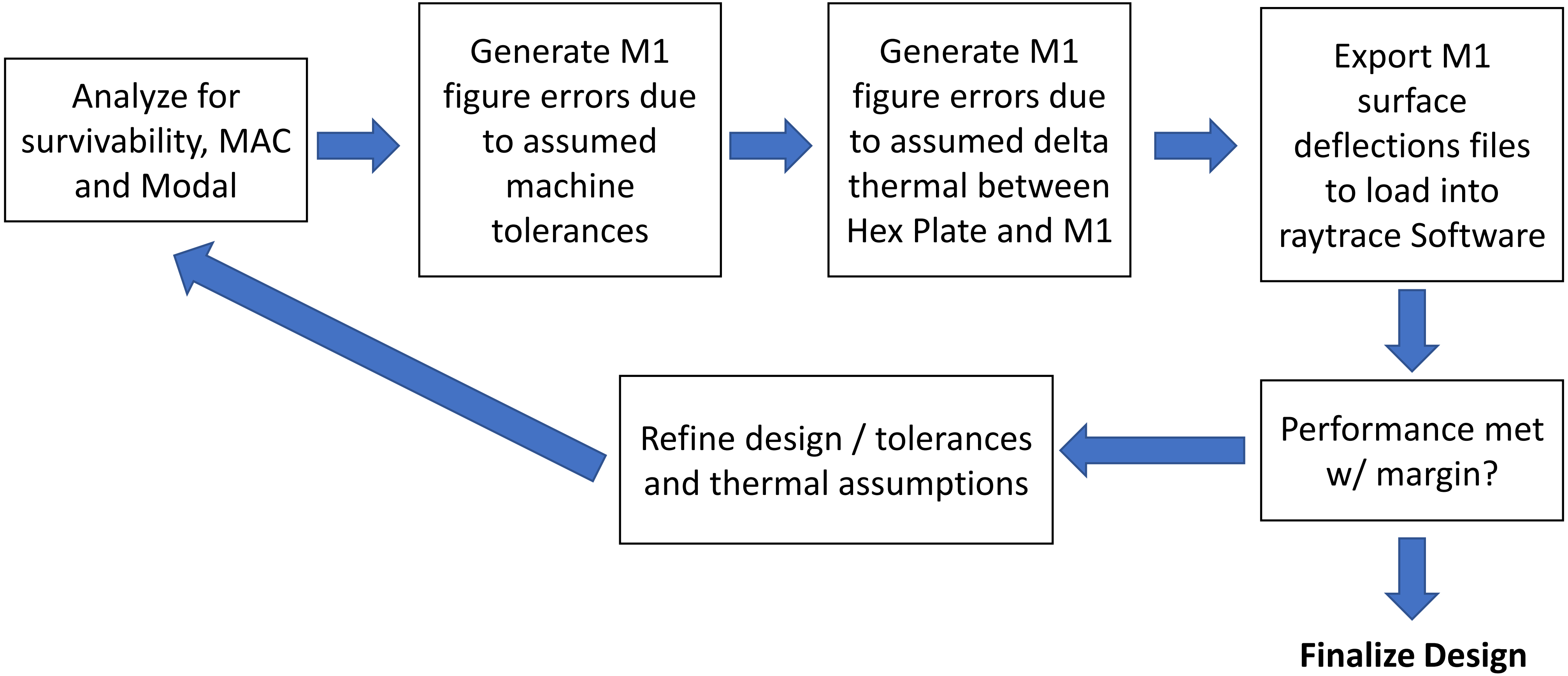
Performance Margins:

(1) Provides machining tolerances required, figure errors introduced by non-perfect surface interfaces distorts M1

(2) Provides and checks allowable thermal gradients for optical performance over expected temp operating range.

This is an iterative process, e.g., when flexure meets structural requirements, its influence on M1 figure is checked due to thermal perturbations and due to surface interfaces. M1 is sensitive to moments and forces transferred thru flexures and metering tube.

OTA – FEA Analysis



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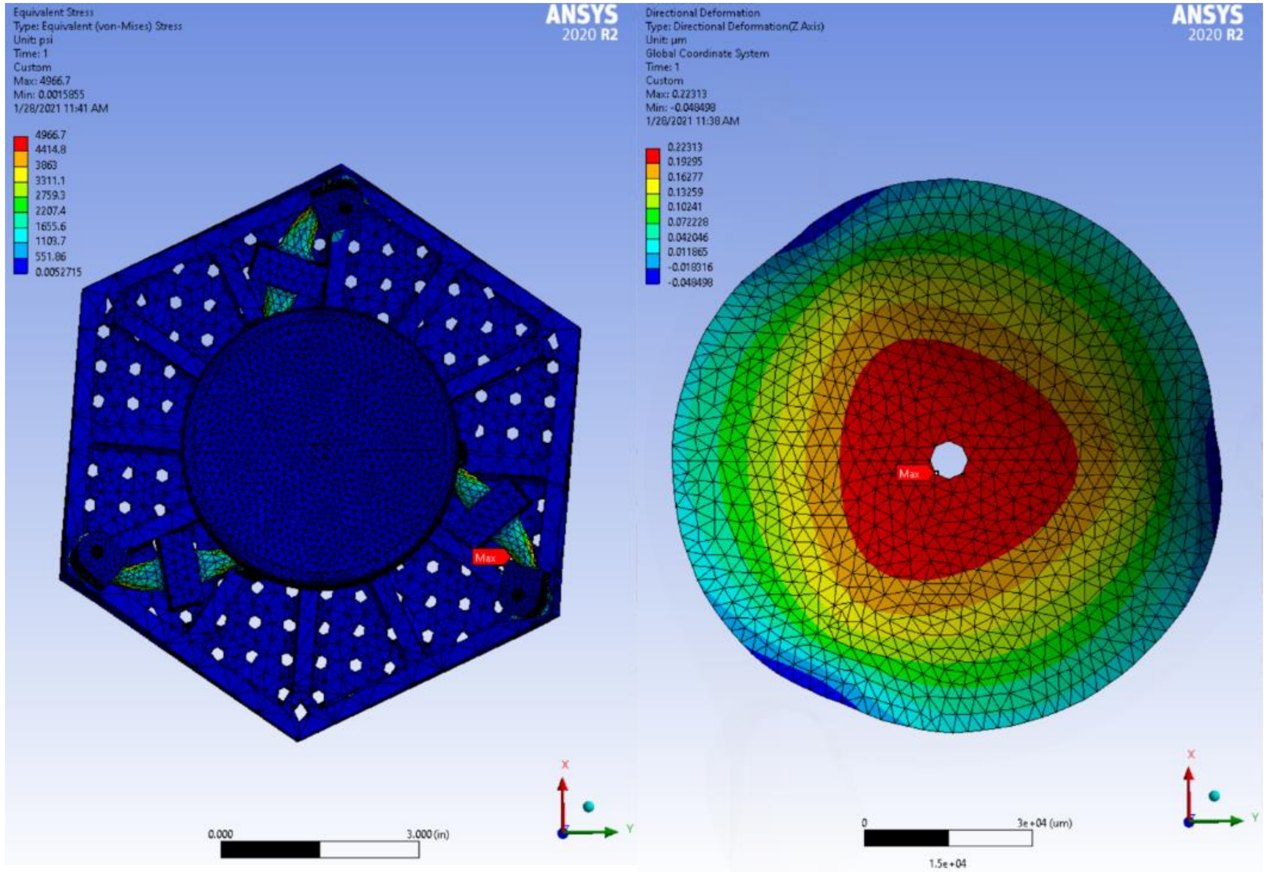
Thermal FEA Results



50°F / 27.8°C Temperature differential (dT) between Hex plate + M1

(Left) Exaggerated flexure deflection from thermal load

(Right) M1 figure deformation in Z due to thermal load

*Anticipate a **10nm/1°C trefoil** magnitude for dT's between the Hex plate and M1*

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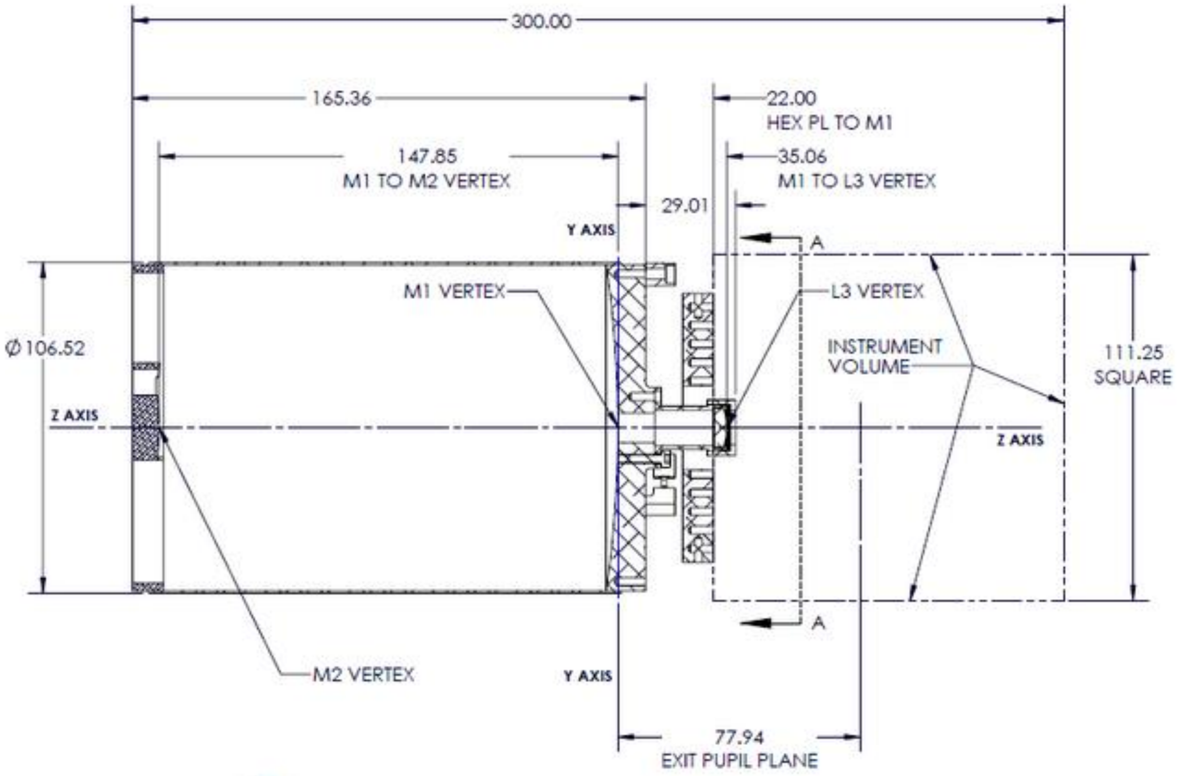
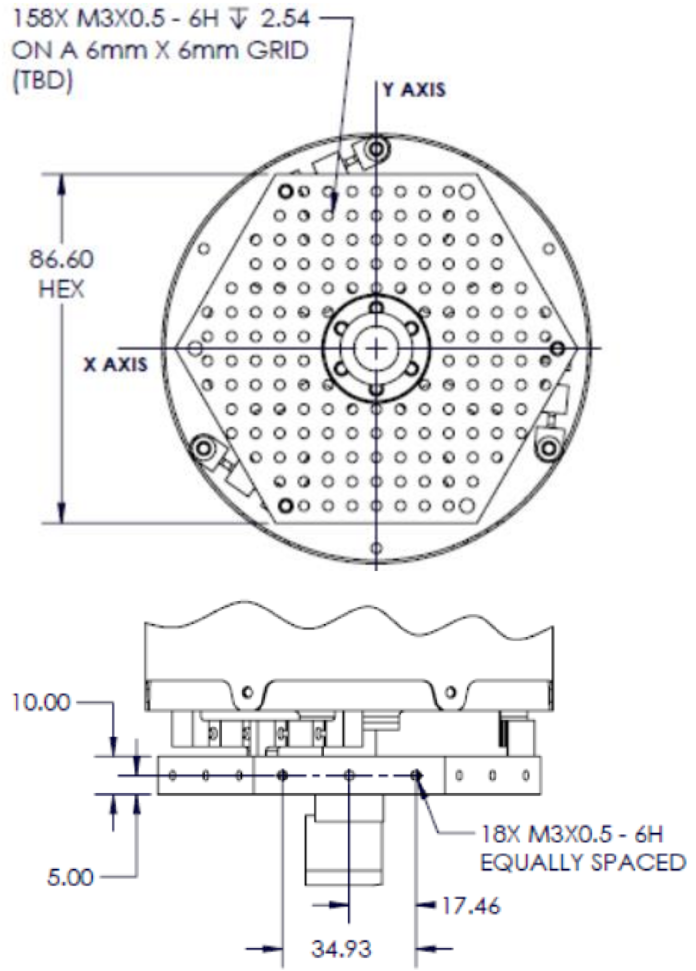
OTA Assembly Review

- Baseline Mass <1kg





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The Path Forward

- Continue flexure development informed by Raytrace software
- Prototype Versatile CubeSat in lab for experimental verification
- CubeSat concept prototype testbed

The Facilities at Korea Basic Science Institute: a candidate manufacturer with diamond turning and MRF polishing capabilities[3]

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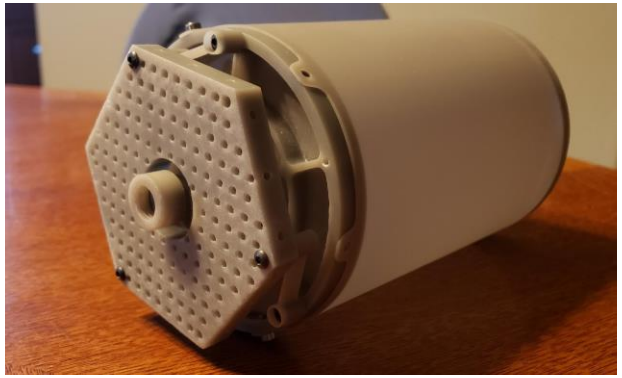
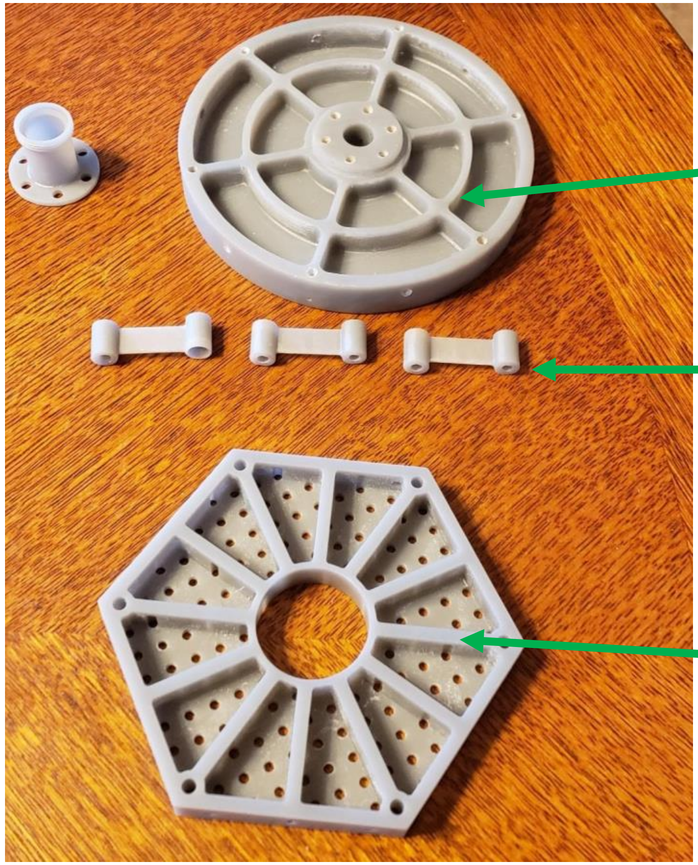
OTA Printed

OTA Back



OTA Front



M1

Flexures

Hex Plate

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In Conclusion

- We demonstrate development of a Versatile CubeSat Telescope tailored for high-performance research payloads
- Diamond turning & active pointing control can enable incredible optical payloads for CubeSats

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UArizona Space Astrophysics Lab

LOFT
Large Optics Fabrication & Testing

STAR lab
Space Telecommunications Astronomy Radiation

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