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

Jaren N. Ashcraft¹, Ewan S. Douglas², Dae Wook Kim¹,2,3, George Smith¹, Charlotte Guthery¹, Kerry Gonzales², Tom Connors², Corwyn Sauve², Victor Gasho², Kerri Cahoy⁴, Paul Serra⁴

¹Wyant College of Optical Sciences, University of Arizona
²Steward Observatory, University of Arizona
³Large Binocular Telescope Organization
⁴Department of Aeronautics and Astronautics, Massachusetts Institute of Technology
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
- **Lunar Flashlight**: 6U, 70mm EPD

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

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
  - 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

Light from scene → Well-Corrected Versatile Fore-optics → Research Payload
## Design Requirements

| Specification             | Value                                      | Description                                                                 |
|---------------------------|--------------------------------------------|-----------------------------------------------------------------------------|
| EPD                       | 95 mm Obscured, 87.87 mm Unobscured        | Entrance Pupil Diameter, Diameter of Primary Mirror                          |
| XP                        | $\leq 5$ mm                                | Exit Pupil Diameter (FSM)                                                   |
| Wavelength                | 780 nm                                     | Wavelength of strehl & polarization calculations                            |
| Half FOV                  | $0.2^\circ$                                | The half field of view in degrees                                           |
| FSM Footprint             | $\leq 5$ mm                                | Beam Footprint on first FSM                                                 |
| Secondary Obscuration     | 20%                                        | $\left(\frac{\text{M2 Diameter}}{\text{M1 Diameter}}\right) \times 100\%$    |
| 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*
Classical v.s. New

**On-Axis**
- Ritchey-Chretien Objective
- Plano-Convex Collimator

**Off-Axis**
- Unobscured Ritchey-Chretien Objective
- Freeform Collimator
On-Axis

Pros
• Easy to manufacture + test
• Well-characterized solution

Cons
• Secondary obscuration
• Less packaging control
Off-Axis

Pros
• Unobscured
• More packaging control

Cons
• Harder to assemble
• Alignment sensitive
## 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 cm³)                           |
Alignment Sensitivity

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

Evaluate Performance

Performance vs. Perturbation
Strehl Ratio – An Astronomer’s Ruler

• Evaluation of imaging systems
  \[ SR = \frac{\max\left(\sum\sum_{test} PSF_{test,ij}\right)}{\max\left(\sum\sum_{ideal} PSF_{ideal,ij}\right)} \]

• Good for evaluation of performance in diffraction-limited regime
  • Little monochromatic aberration
## 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°        |

|       | Tolerance | **On-Axis** | **Off-Axis** |
|-------|-----------|-------------|--------------|
| **L3 / M3** |           |             |              |
| X Despace | 1.8mm     | -1.8mm      | 0.964mm      | -0.964mm     |
| Y Despace | 1.8mm     | -1.8mm      | 1.11mm       | -0.35mm      |
| Z Despace | 0.085mm   | -0.15mm     | 0.21mm       | -0.065mm     |
| 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°       |
We Have a Winner!

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

| Tolerance       | On-Axis          | Off-Axis         |
|-----------------|------------------|------------------|
| X Despace       | 1.8mm            | 0.964mm          |
| Y Despace       | 1.8mm            | 1.1mm            |
| Z Despace       | 0.085mm          | 0.21mm           |
| X Tilt          | 1°               | 0°               |
| Y Tilt          | 1°               | 0.65°            |
| Z Tilt          | N/A              | 0.55°            |
# 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                    | <20μm positioning                                |
| Launch Survival                      | MAC (100g generalize acceleration)               |
| Operational Temperature Differential | <2°C                                              |
| Survival Temperature Range           | 0-40°C                                           |
Optical Telescope Assembly (OTA)
OTA FEA Model

One model provides:

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

Analyze for survivability, MAC and Modal

Generate M1 figure errors due to assumed machine tolerances

Generate M1 figure errors due to assumed delta thermal between Hex Plate and M1

Export M1 surface deflections files to load into raytrace Software

Refine design / tolerances and thermal assumptions

Performance met w/ margin?

Finalize Design
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
OTA Assembly Review

- Baseline Mass <1kg
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
OTA Printed

OTA Back

OTA Front

M1

Flexures

Hex Plate
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
Acknowledgements

The author thanks Zemax for early access to FEA surface fitting tool in OpticStudio raytrace software
References

1. Smith, M., Donner, A., Knapp, M., Pong, C., Smith, C., Luu, J., Pasquale, P., & Campuzano, B. (2018). On-Orbit Results and Lessons Learned from the ASTERIA Space Telescope Mission. 32nd Annual AIAA/USU Conference on Small Satellites.

2. Udo Wehmeier, Quentin Vinckier, R. Glenn Sellar, Christopher G. Paine, Paul O. Hayne, Mahmood Bagheri, Mina Rais-Zadeh, Siamak Forouhar, Jessica Loveland, Jacob Shelton, "The Lunar Flashlight CubeSat instrument: a compact SWIR laser reflectometer to quantify and map water ice on the surface of the moon." Proc. SPIE 10769, CubeSats and NanoSats for Remote Sensing II, 107690H (18 September 2018); https://doi.org/10.1117/12.2320643

3. Min-Woo Jeon, Sangwon Hyun, Byeong-Joon Jeong, I-Jong Kim, Geon-Hee Kim, "Removal of diamond turning marks with magneto-rheological finishing," Proc. SPIE 10371, Optomechanical Engineering 2017, 103710V (23 August 2017); https://doi.org/10.1117/12.2274028