Starshade Technology Status: Optics

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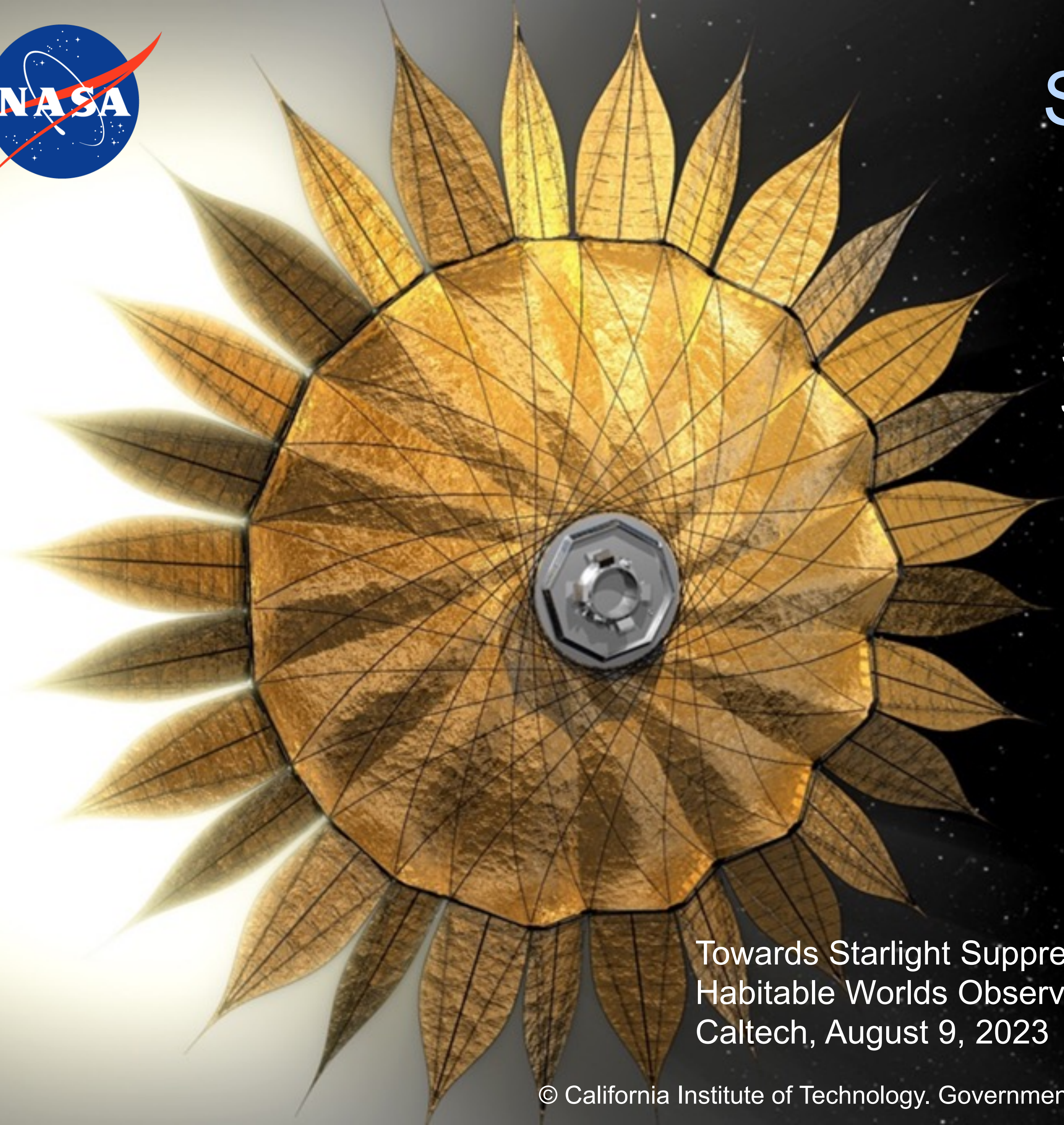


Towards Starlight Suppression for the
Habitable Worlds Observatory Workshop
Caltech, August 9, 2023

State of Technology: Starshade Optics

- **Optical Diffraction:** Demonstrated < 1e-10 contrast, broadband, model validation at flight Fresnel Number
- **Sensitivity to Shape Perturbations:** Measured sensitivity of starlight leakage (contrast) to petal shape and position
- **Formation Flying:** optical demo of sensing signal, model of alignment and telescope pointing, model of control loop
- **Solar glint:** Measured edge sharpness, measured scatter of coated and uncoated edges, detailed modeling of surfaces and interfaces
- **Next Generation Testbed:** 200 m, reduced polarization, other features

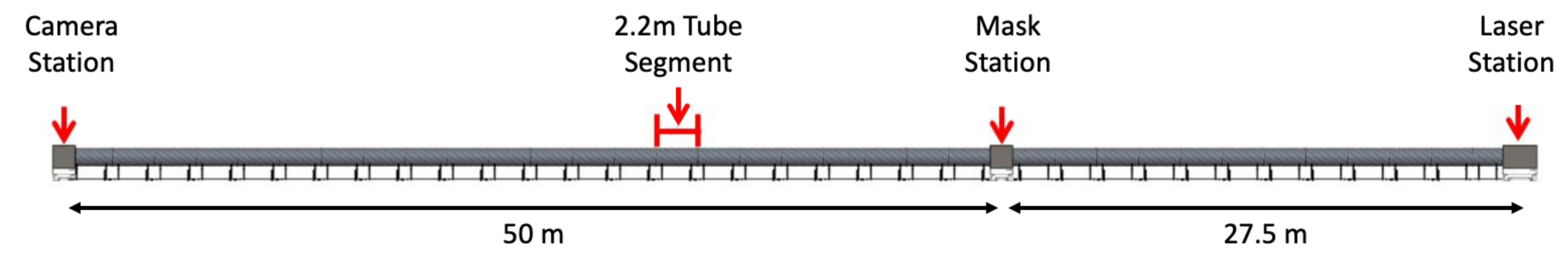
PRINCETON STARSHADE TESTBED

Princeton optical testbed

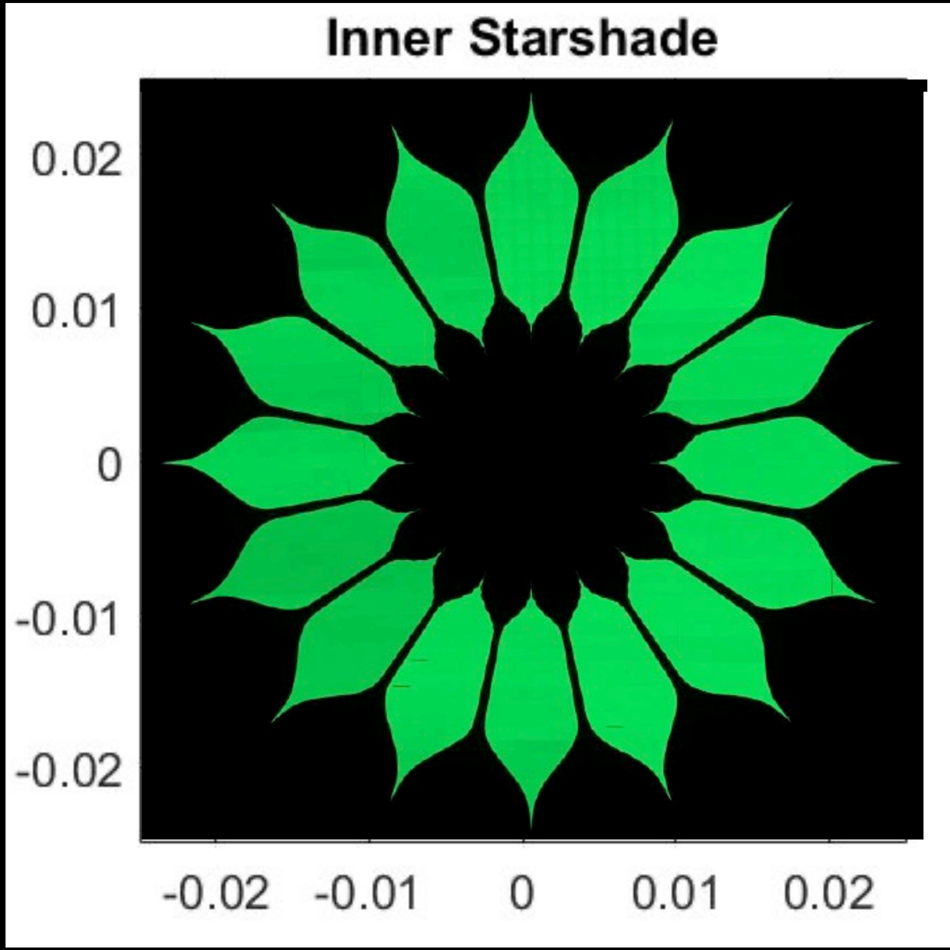

5-cm diameter Starshade etched in silicon

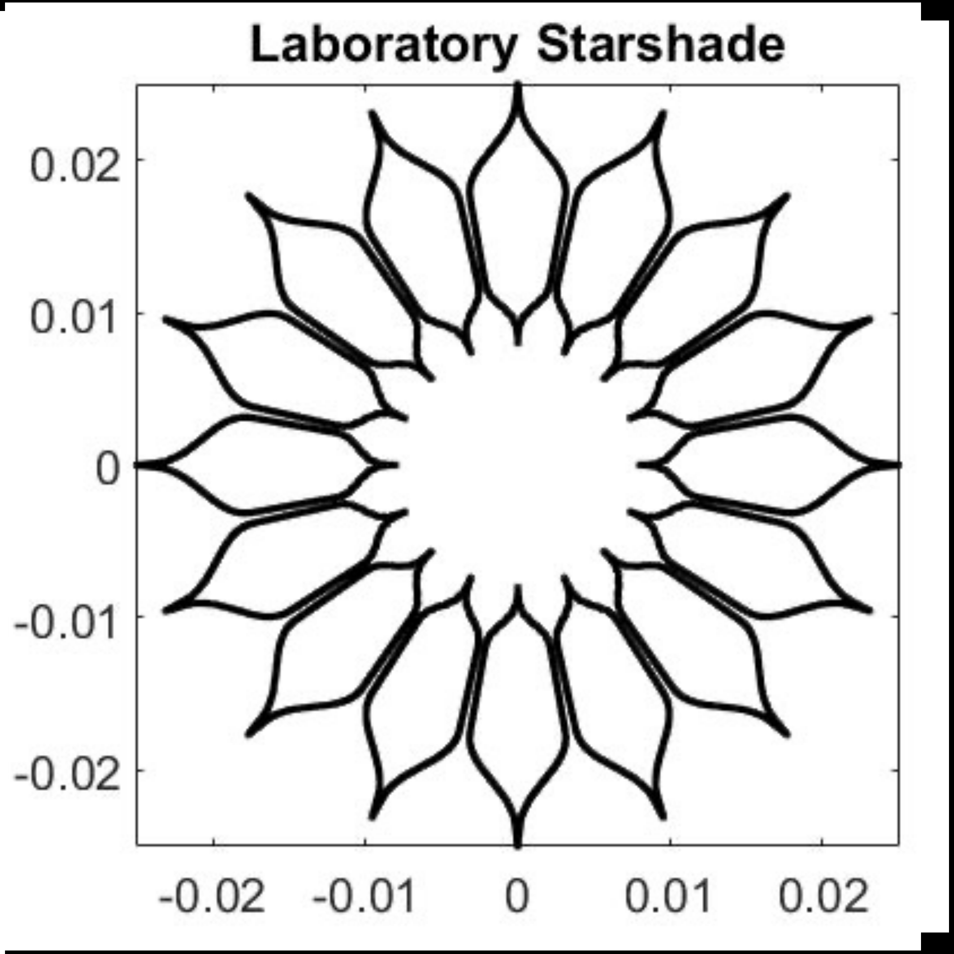
A. Harness et al references: M1a,b reports, JATIS, SPIE
Shaklan et al M2 report

- 80 m long tube in basement of Frick building on Princeton campus
- Not evacuated (1 atm)
- Point source, starshade mask, simple camera.
- Remotely operated
- Settling time for 1e-10 contrast was about 3 days.
- Operational 2017-2022.



Laboratory Starshade Design





How is a miniature starshade similar to an orbiting starshade?

Physics is identical for consistent Fresnel number

- Under scalar diffraction + Fresnel approximations

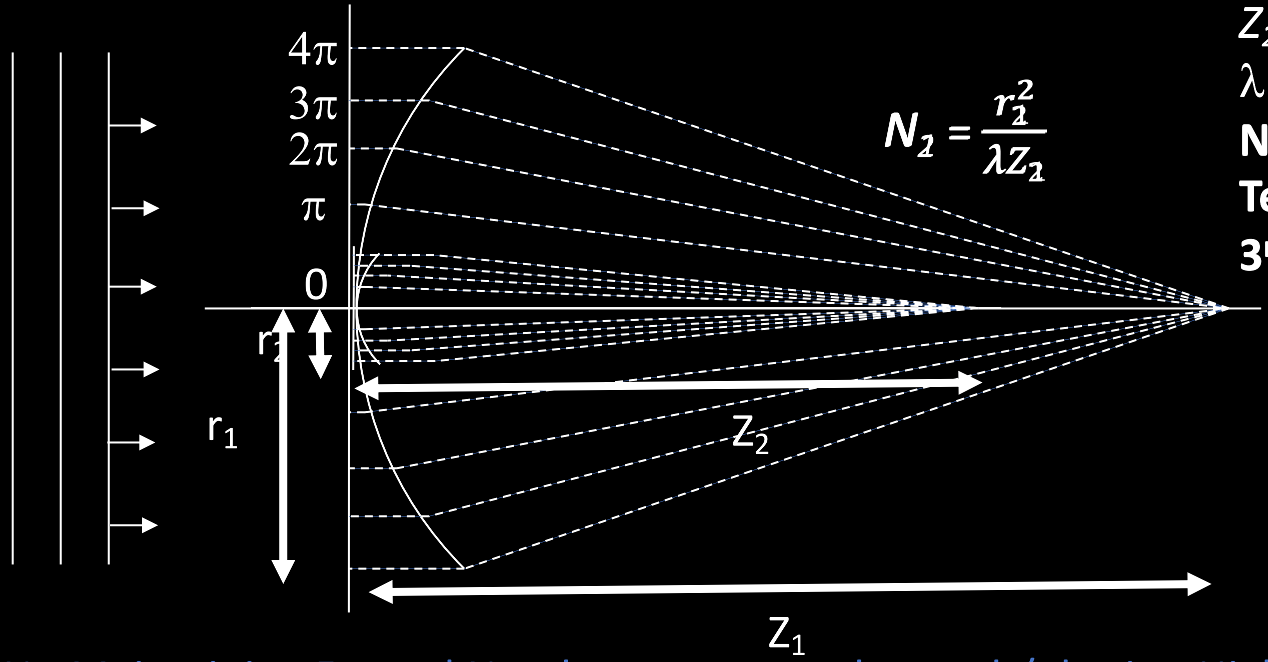
$$U(p) \propto \frac{-i}{\lambda z} \iint e^{\frac{i\pi r^2}{\lambda z}} r dr\, d\theta$$

$$\propto \frac{-i}{2} \iint e^{i\pi N} dN\, d\theta$$

Fresnel Number

$$N = \frac{r^2}{\lambda z}$$

- Same integrand
- Same integration limits relative to integrand
- Small mask has a much larger 3rd order term relative to the Fresnel approximation. Larger starshade is a better Fresnel approximation.



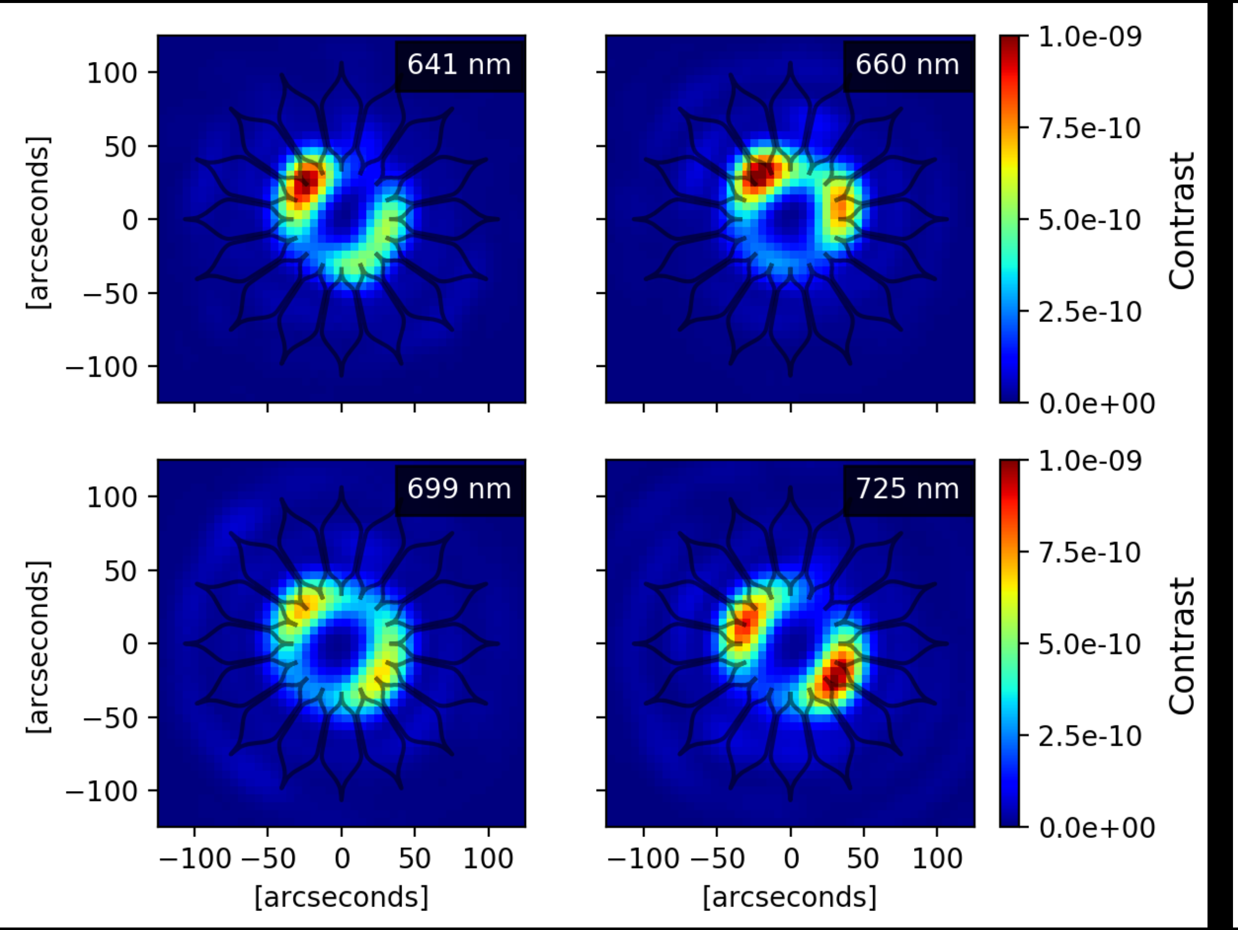
$$N_2 = \frac{r_2^2}{\lambda Z_2}$$

r_2 = 30125 m
Z_2 = 915,7600mk(neff)
λ = 7815 nm
N_2 = 12.1
Tel. Res = 2.74 λ/D
3rd order/2nd order::21.5e-184

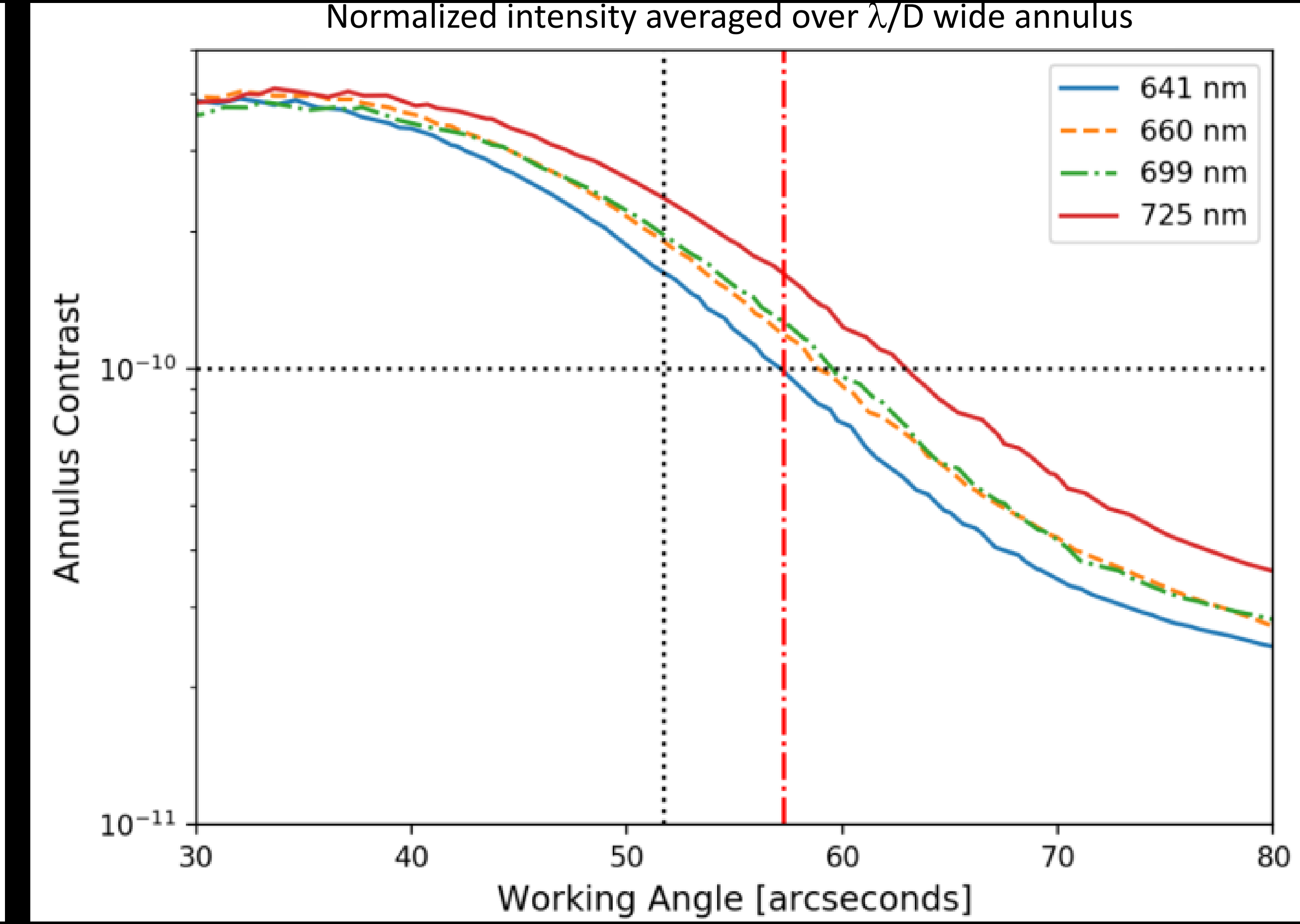
$N_1 = N_2$: Maintaining Fresnel Number preserves the math/physics. Higher order terms are less important at large scale.

Optical test results: Broadband

4-band Results full scale



Average normalized intensity in photometric aperture

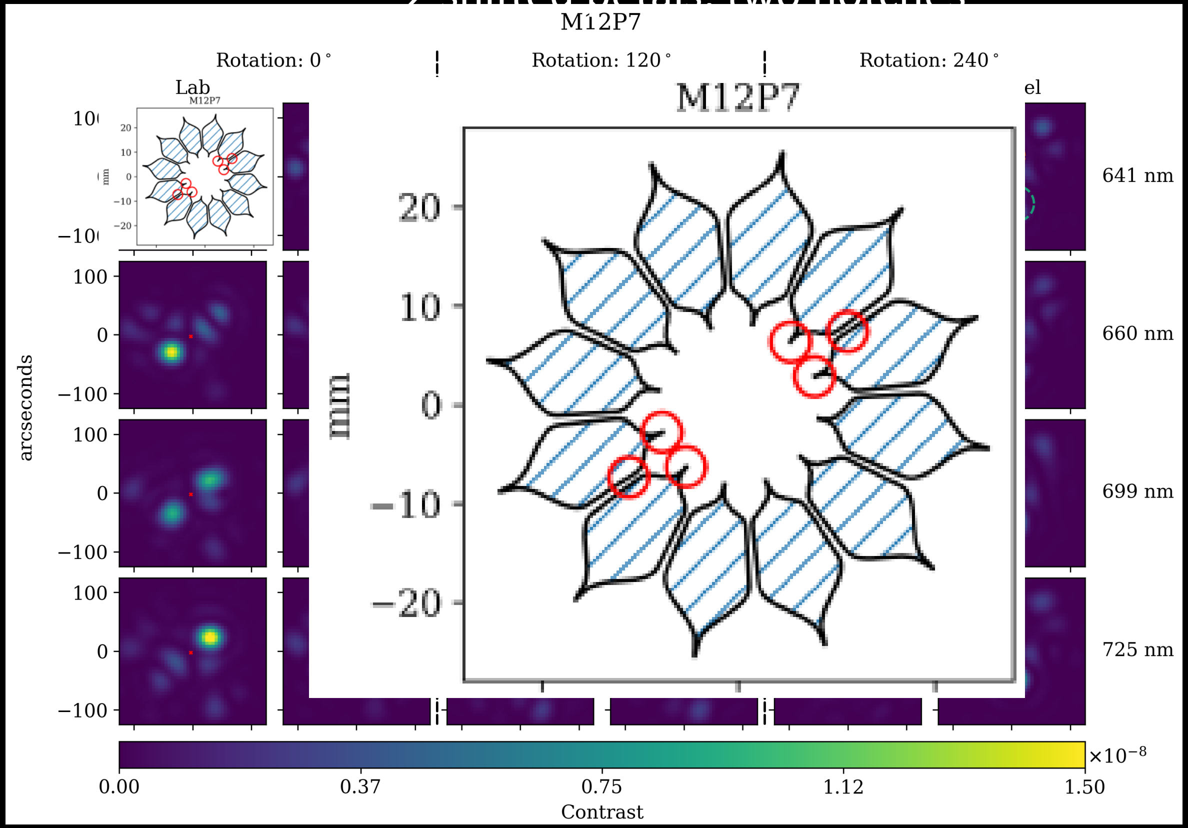


Model Validation Tests (Examples):

Validate sensitivity to key terms in the error budget

Example Model Matching

Mixed Perturbation Mask: 2 shifted petals, two notches

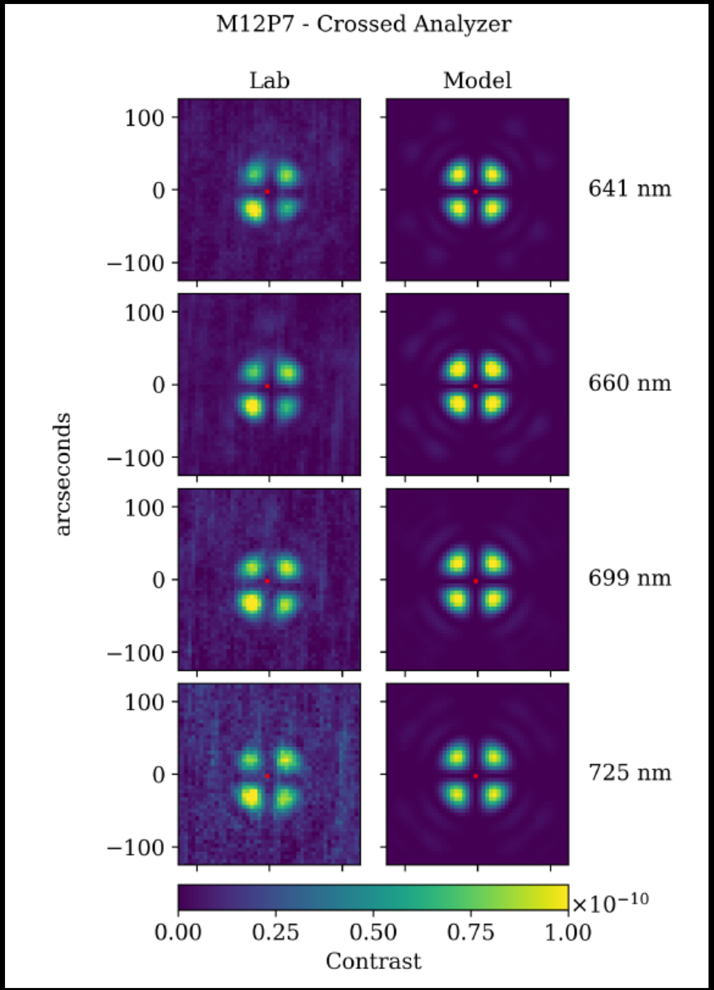


This experiment validated the model prediction of sensitivity to:

- Petal shape: to a factor of 1.25
- Petal position: to a factor of 2.0

The accuracy was limited by polarization lobes.

Crossed-polarization observation



These lobes are entirely due vector diffraction at the miniature starshade edges. Models take into account sub-micron structures on the edges, material properties, polarization.

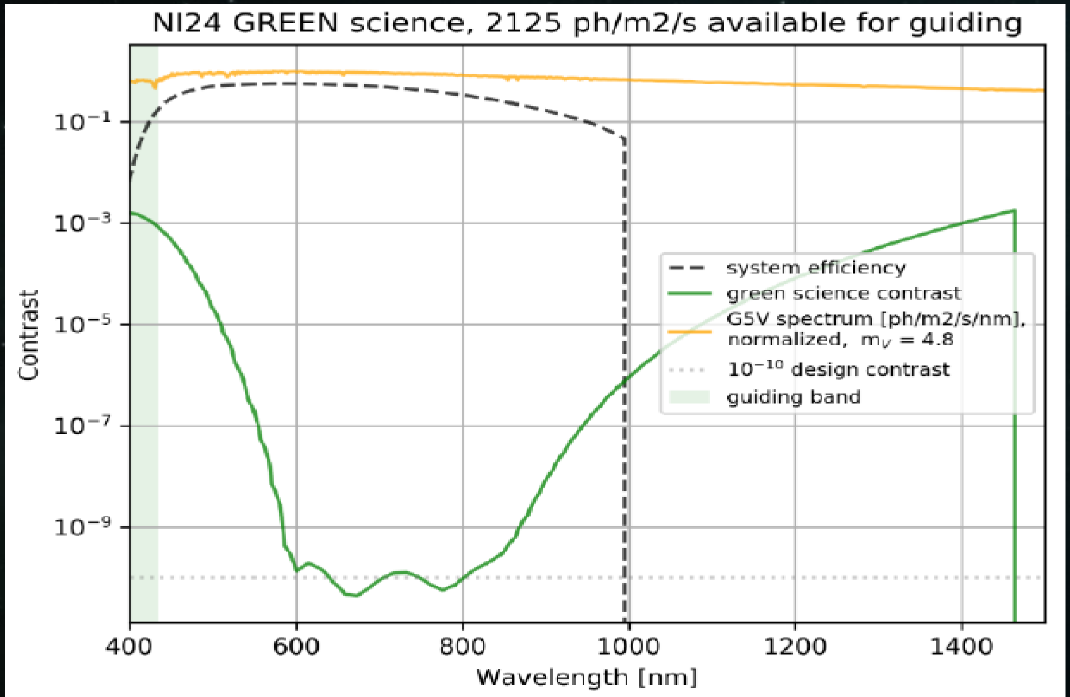
Relevance of Experiment to Flight

- **Testbed is a MORE STRINGENT test of Fresnel diffraction than flight:**
  - **Testbed is at flight Fresnel Number, while**
  - **Testbed 3rd order term is orders of magnitude greater than for flight.**
  - **Testbed has 2 starshades that must both work.**
  - **Testbed has extra edges with the struts**
  - **Testbed is at smaller λ/D.**
- **Polarization limited:**
  - **Experiment limited by polarization yet still has average 2x10-10 at the IWA and < 10^{-10} over 75% of search space.**
  - **Polarization in flight will be orders of magnitude less (ratio of area to edge length)^2**
- **Demonstrated sensitivity to petal edge segment displacement and petal displacement.**

Demonstrated < 1e-10 contrast in broadband at Flight Fresnel Number.

Formation Flying: Principle

The shadow is observed at wavelengths above or below the deepest shadow band.
The shadow has a Spot of Arago at its center that is used for the final stage of alignment.



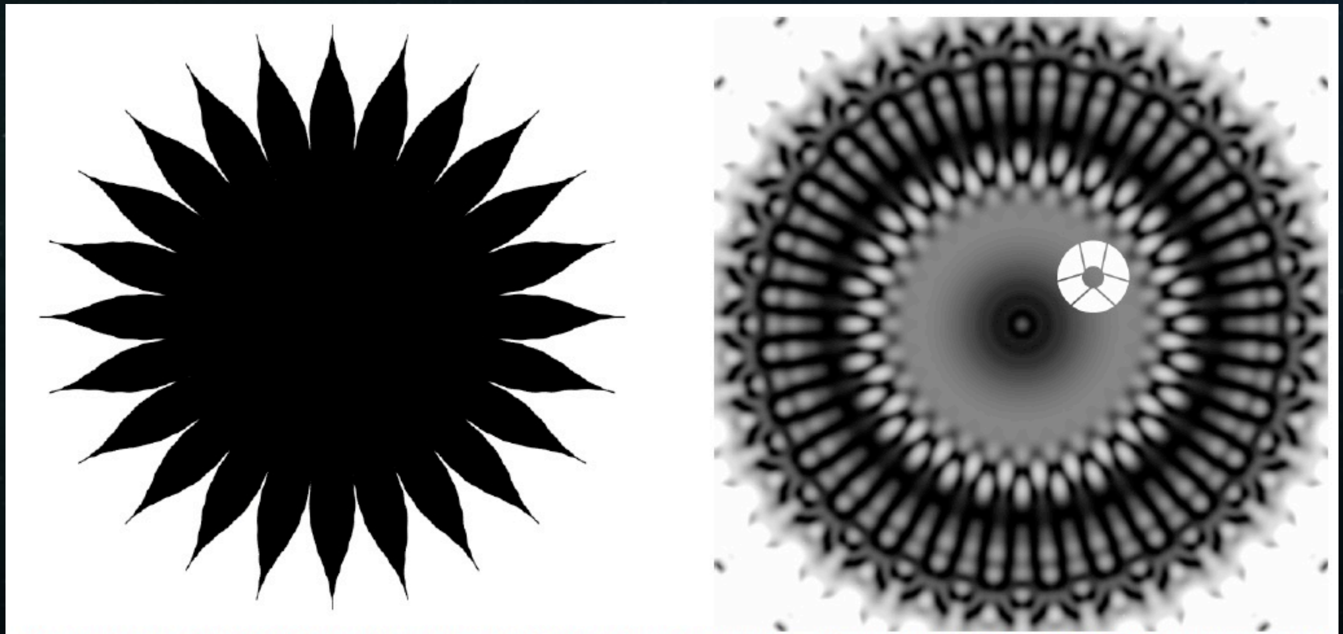
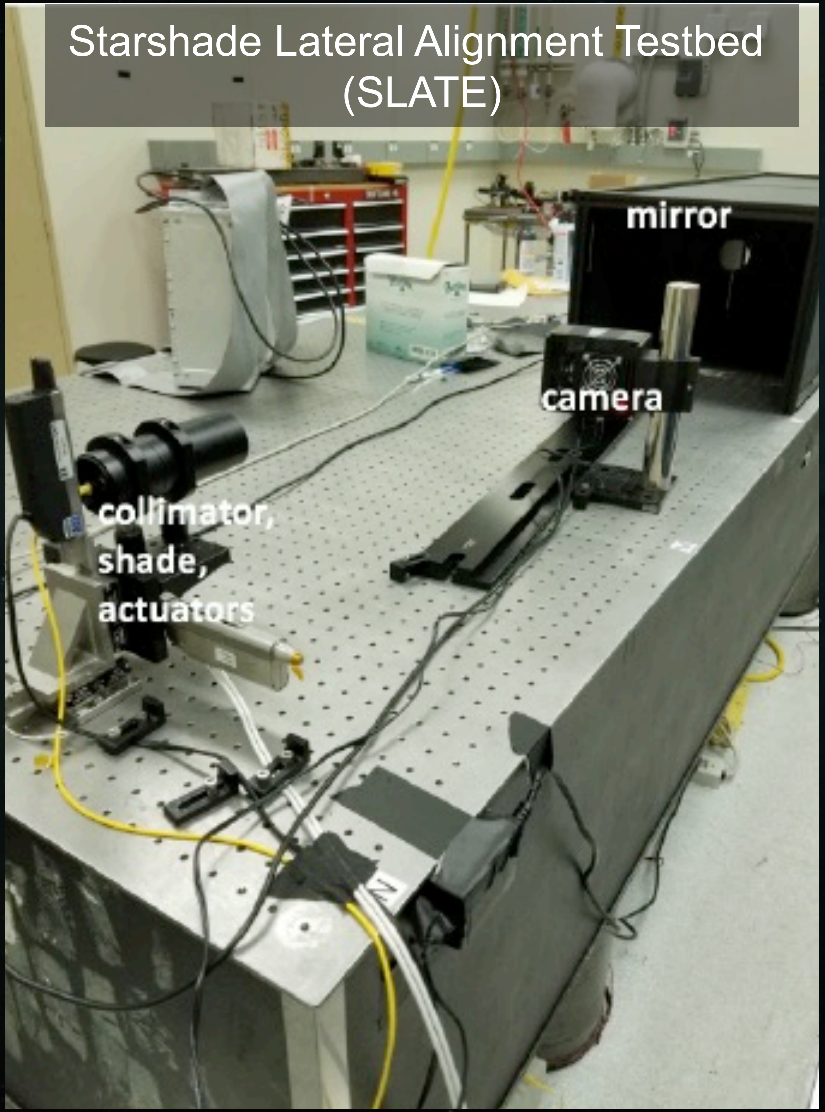
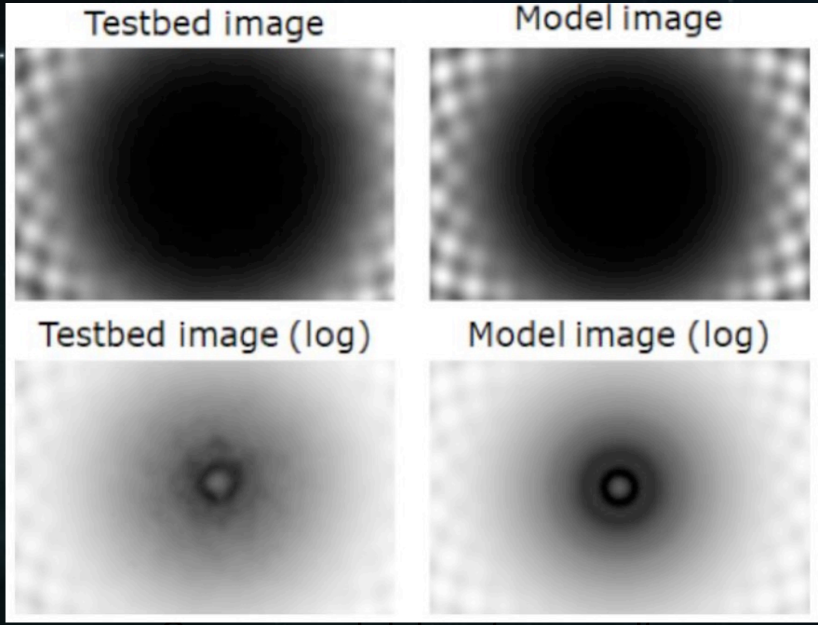


Figure 3-1: (Left) NI2-24 Starshade design (E. Cady). The Starshade is ~26 meters tip to tip. (Right) Light pattern at the location of the WFIRST telescope, stretched to show detail, with the 2.4 meter pupil shown for scale.

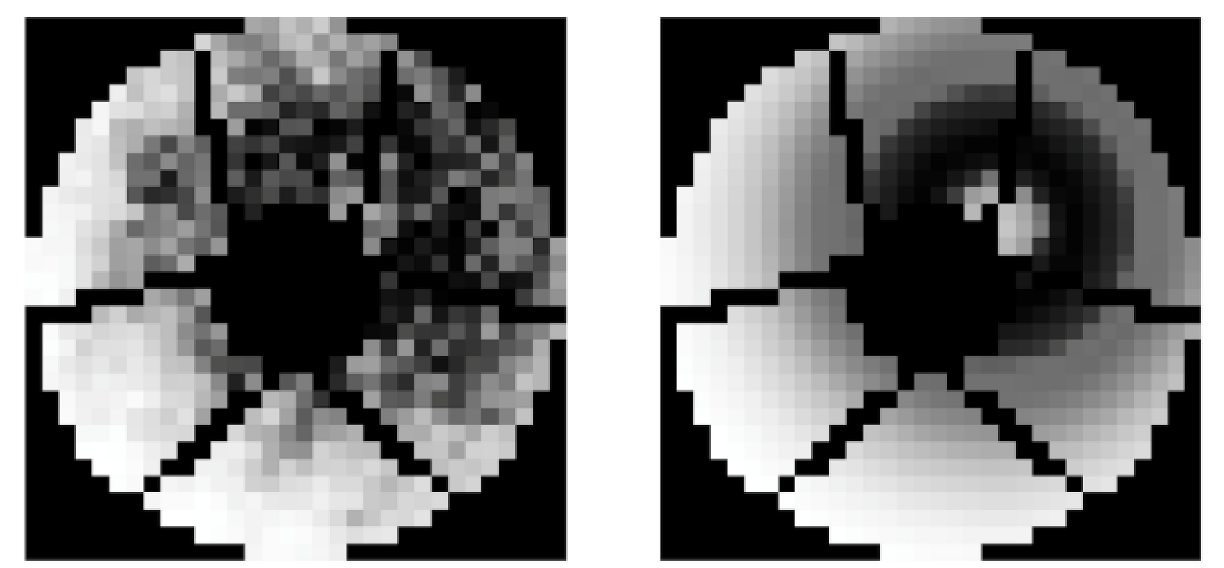
Starshade laboratory result

FORMATION FLYING: TESTBED



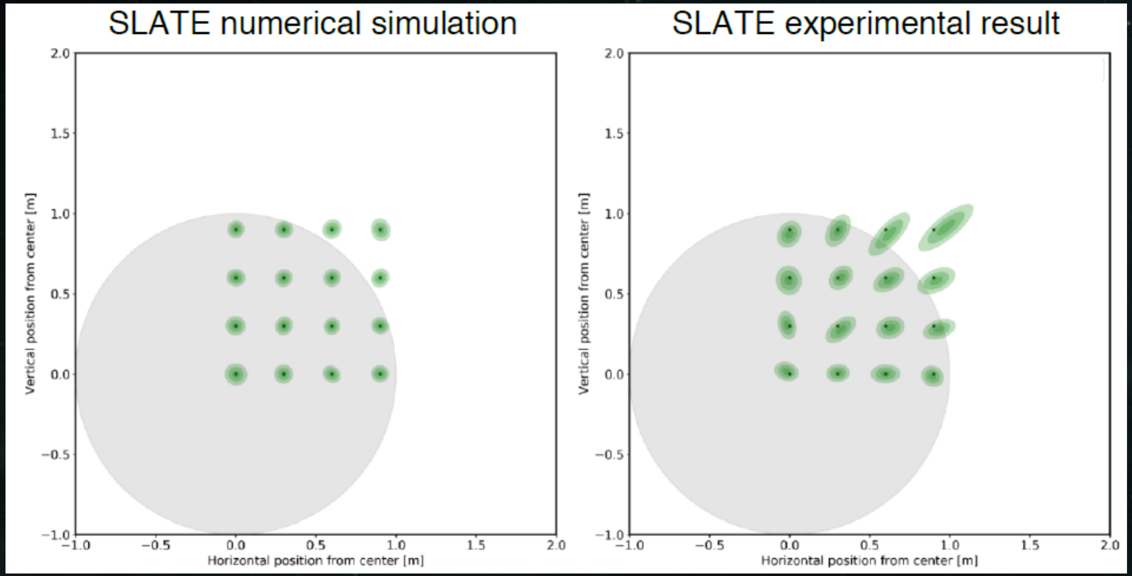


M. Bottom, et al, JATIS 6, 015003 (2020).

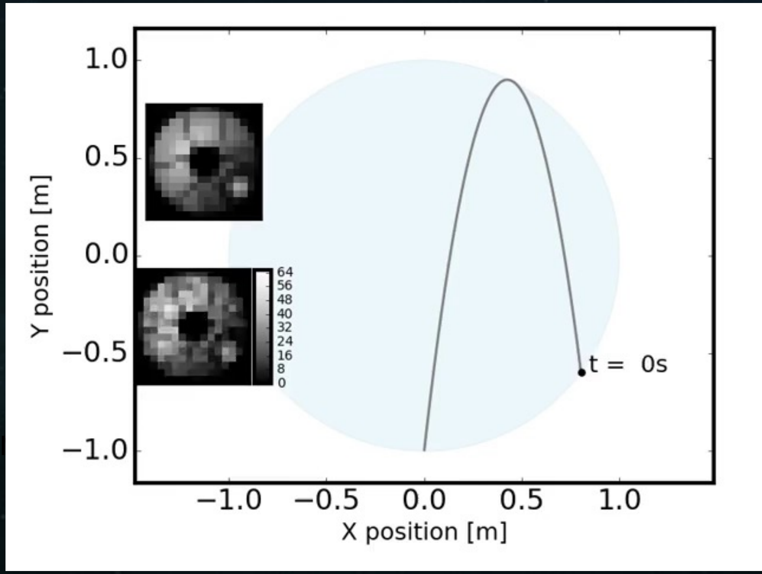


Formation Flying: JPL Results

Laboratory Results compared to model



Control using a V=8 star, based on laboratory measurements and microgravity models for Starshade Rendezvous Mission.



Sim 3σ (worst)	Sim 3σ (median)	SLATE 3σ (worst)	SLATE 3σ (median)	Discrepancy (worst)	Discrepancy (median)
6.7 cm	4.0 cm	10.2 cm	6.2 cm	55%	52%

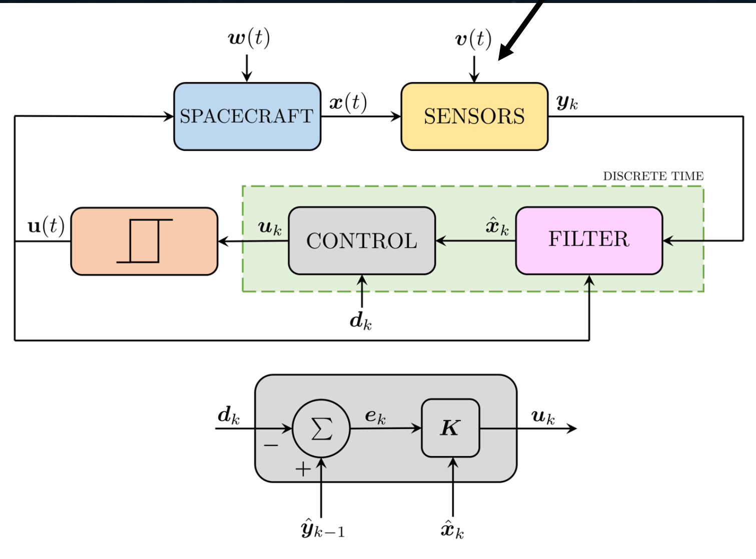
Table 3-3: Comparison between accuracy of lab-generated and simulation-based models

Additionally, Martin & Flinois(JATIS 014010-5, 2022) have shown that a single pupil plane sensor combined with an image-plane phase dimple mask and Neural Net provides an alternative architecture requiring one detector. Similarly, Chen, Harness, Melchoir, JATIS 2023.

FORMATION FLYING: PRINCETON TESTBED

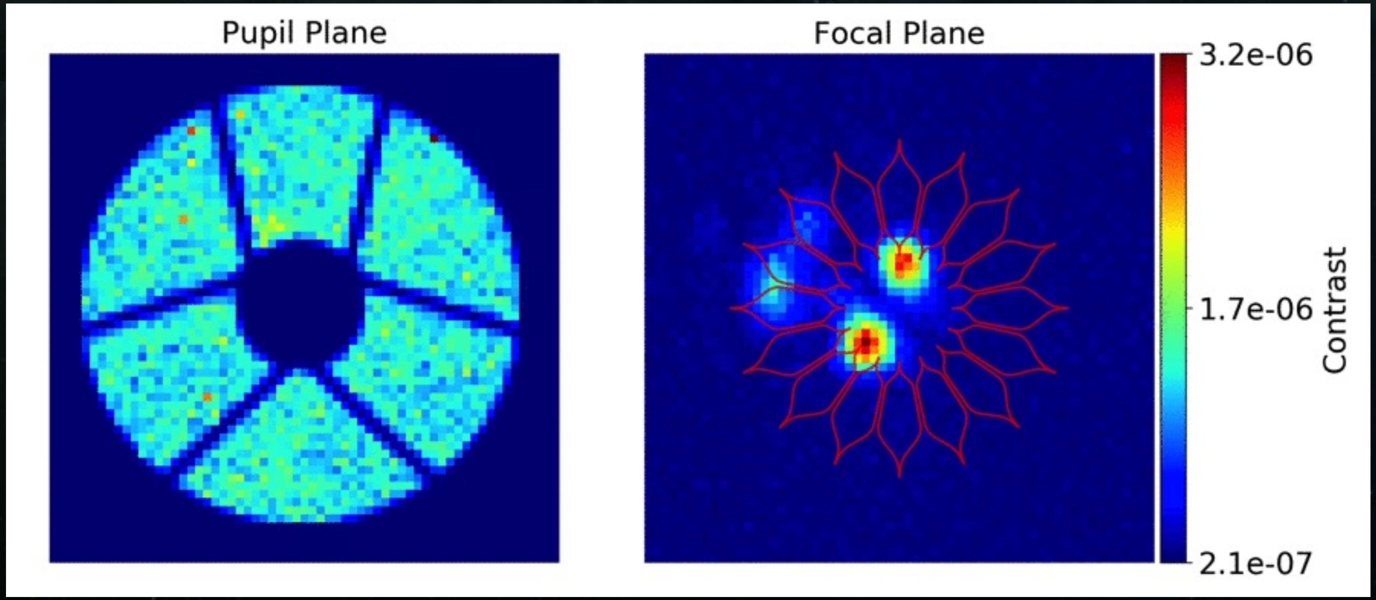
measure position by fitting pupil image

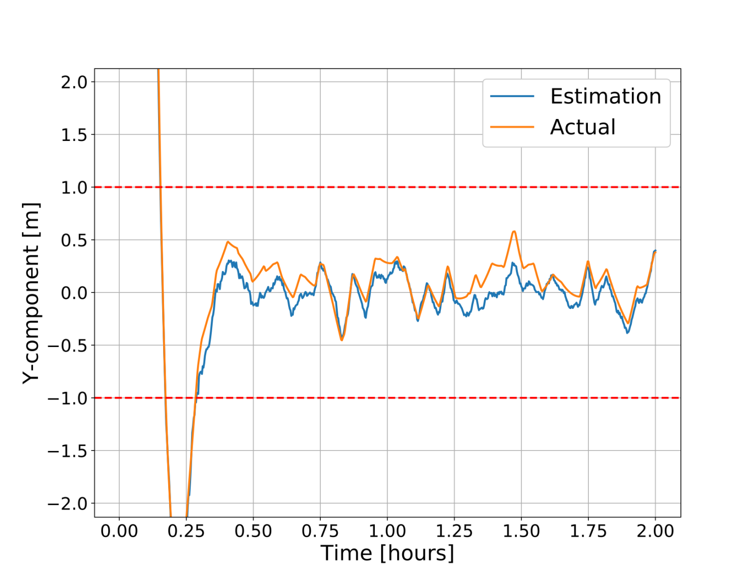
Hardware-in-the-loop Station keeping Test



Linear Quadratic Regulator with Integral Control and Unscented Kalman Filtering

Simulated Formation keeping with actual position measurements from Princeton testbed





Palacios, Harness, & Kasdin, Acta Astron, 171 (2020): Princeton Frick Testbed H/W in the loop

OPTICAL EDGE DESIGN AND PERFORMANCE

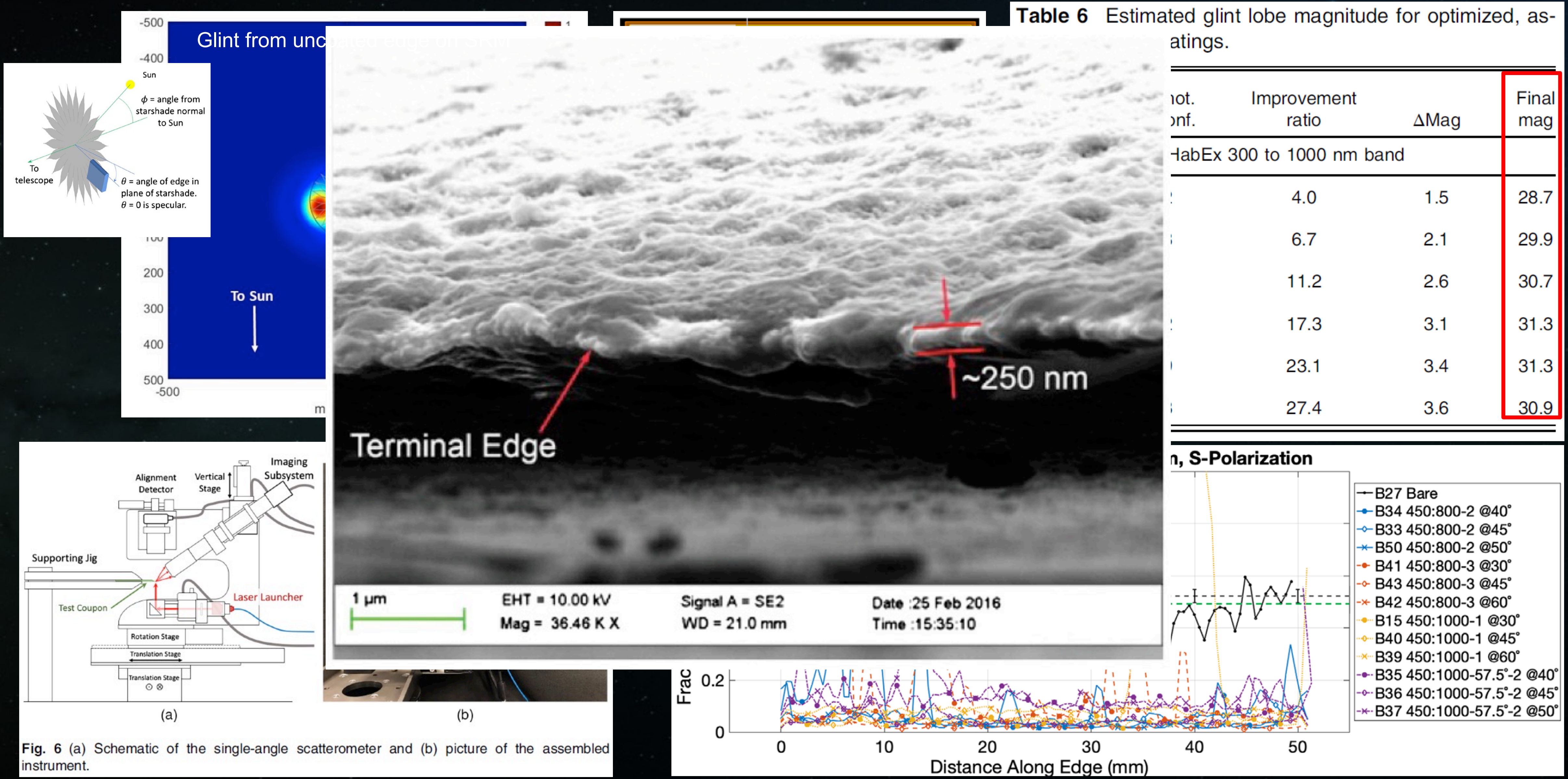


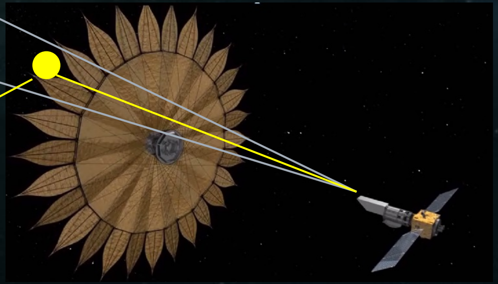
Table 6 Estimated glint lobe magnitude for optimized, as- ...atings.

...ot. ...onf.	Improvement ratio	ΔMag	Final mag
...abEx 300 to 1000 nm band			
	4.0	1.5	28.7
	6.7	2.1	29.9
	11.2	2.6	30.7
	17.3	3.1	31.3
	23.1	3.4	31.3
	27.4	3.6	30.9

McKeithen et al, JATIS (2021), McKeithen et al, SPIE 11443 (2020).

Optical Edge Contamination

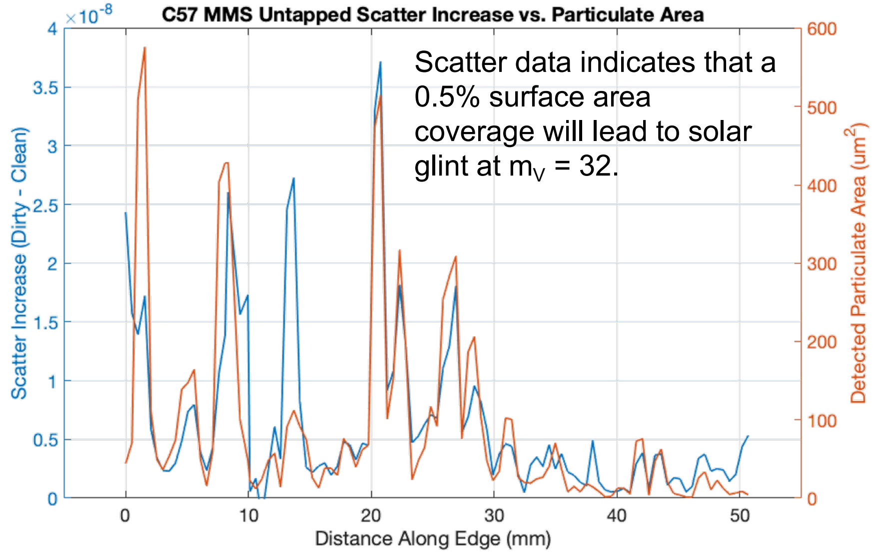
An Earth-size planet at 10 parsecs projects as a 4 mm diameter particle on the edge of the HWO starshade.

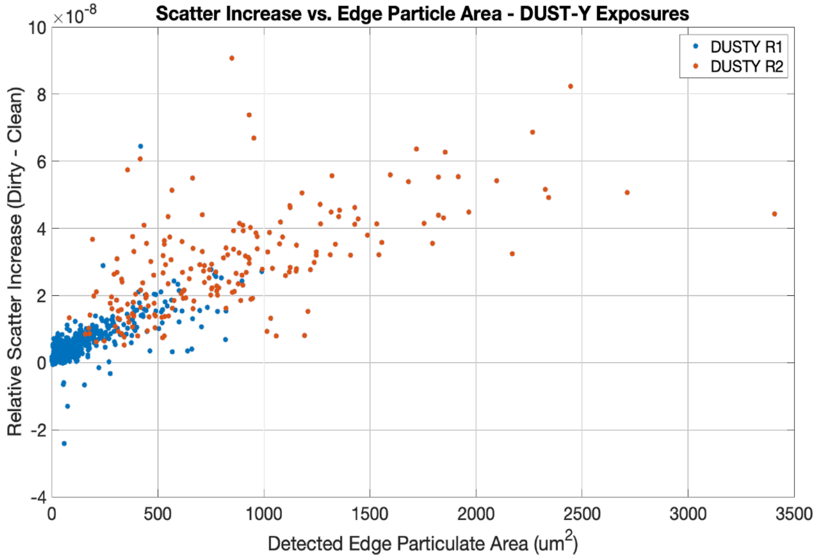


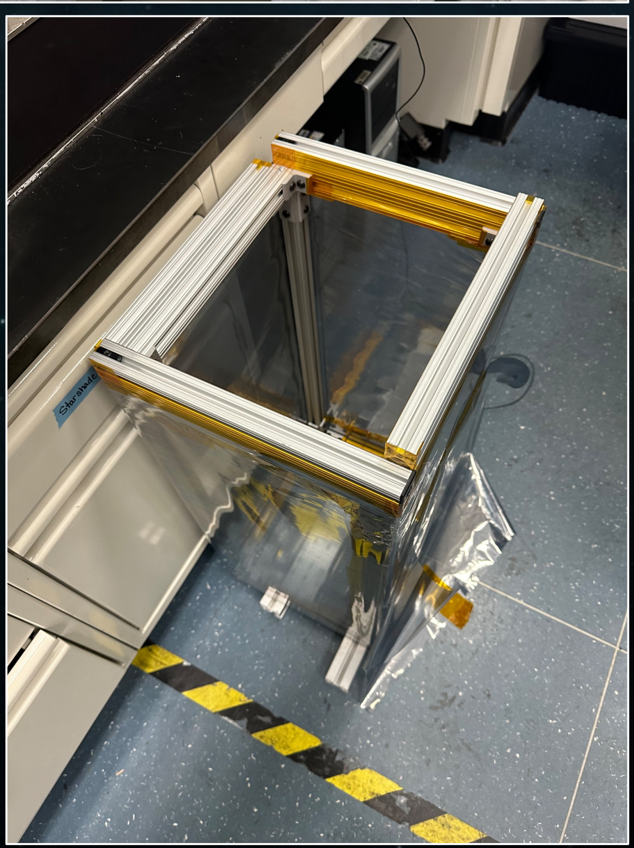
4 mm^2 is equivalent to 10,000 particles of dust 40 um in diameter, spread over about 40 m of the starshade edge.
Is this a problem?

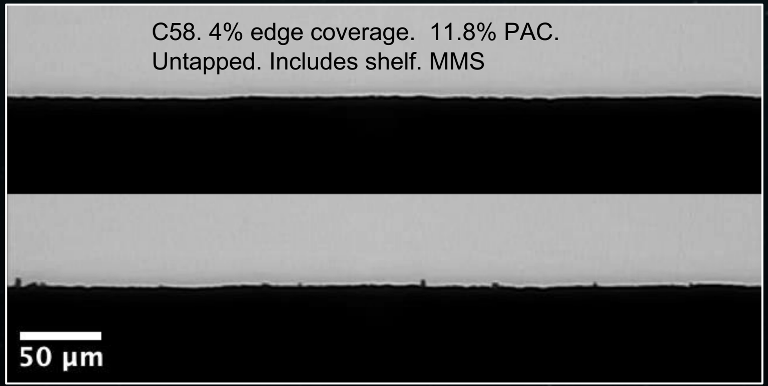
Optical Edge Contamination

We are studying the scatter from particulates that can contaminate the starshade's sharp edge. With almost no literature on edge contamination, we are studying the relationship between surface contaminants and edge contaminant.





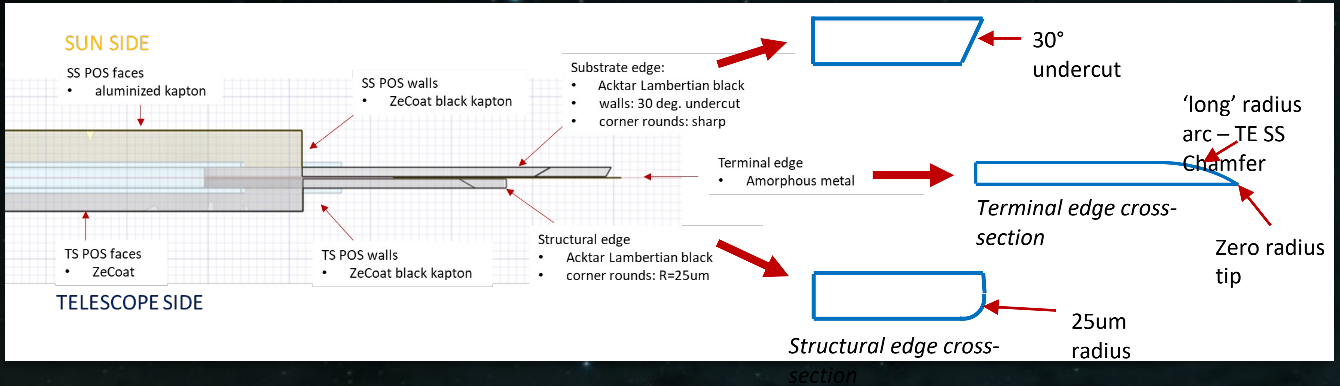


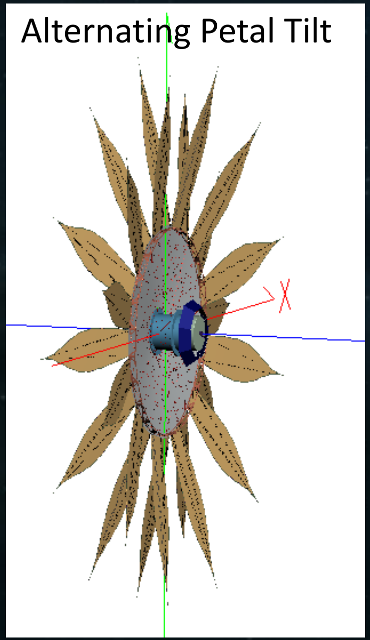


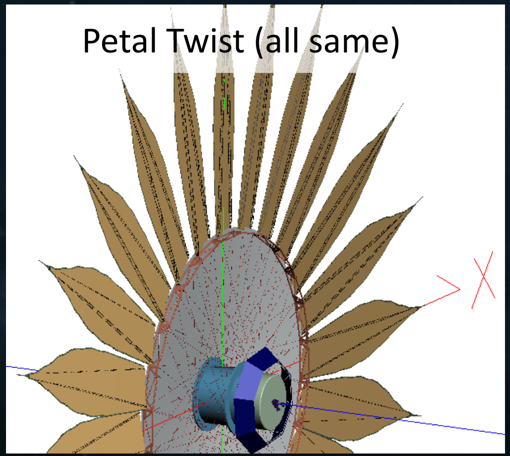
McKeithen et al will have a detailed paper on this subject at SPIE this month.

STRAY LIGHT (OTHER THAN SINGLE EDGE SCATTER)

The starshade is designed so that there are no specular ray paths from the Sun to the telescope, except, unavoidably, at the petal edges. Non-specular paths with multiple bounces exist and have been extensively modeled.



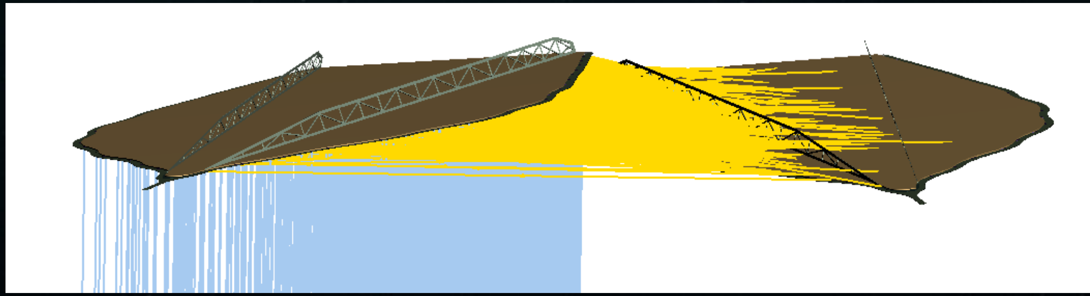




- Modeled 26 m starshade for Roman Rendezvous mission
- Detailed design of all exposed edges and surfaces, e.g. undercut walls, edge radii and tapers.
  - Lacks detail at petal bases and inner disk termination at hub.
  - Includes pop-up stiffening ribs.

- INTEGRATED MAGNITUDE ~ V=29.
- AVERAGE MAGNITUDE AT IWA = 32. *Most of the light is at r < IWA.*

- *Key Tolerances: petal piston, +/- 0.6 mm, petal twist +/-0.086 deg, petal tilt +/-0.036 deg (5 mm at tips).*



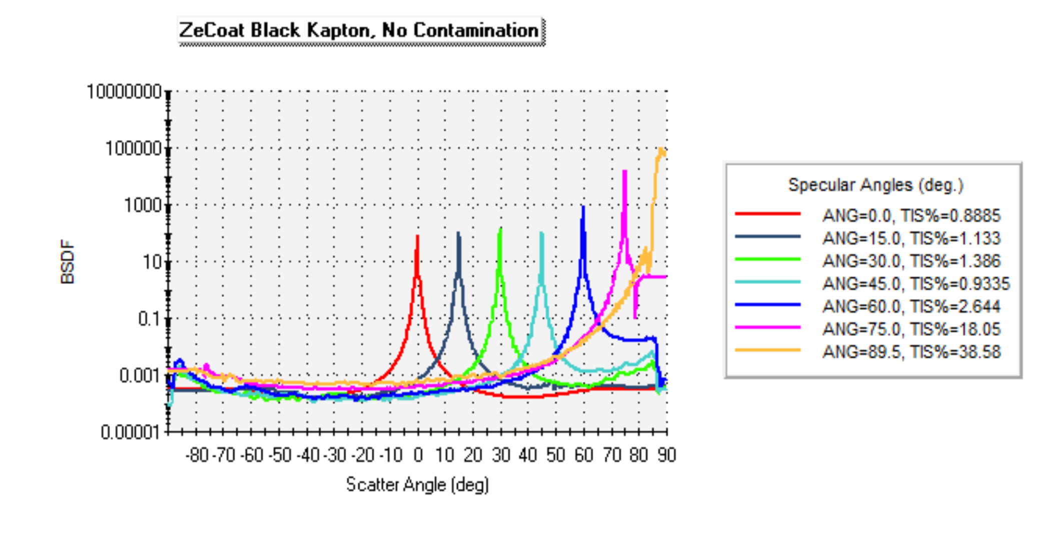
See Martin, Ellis, Shaklan et al, SPIE 11823 (2021)

Modeling work and rendering performed by Scott Ellis, Photon Engineering LLC, under contract to JPL.

Stray Light Details

Our study assumes that most surfaces are coated with anti-reflection multi-layer or absorptive coatings. It assumes that all surfaces have particulate contamination (0.4% area coverage).

- Coating performance is measured or based on published values.
- The telescope-facing side is coated with a Zecoat black AR coating, as are the pop-up ribs.
- All CFRP is coated with Acktar Lambertian Black
- The contamination level is PCL 550, Percent Area Coverage = 0.4%.



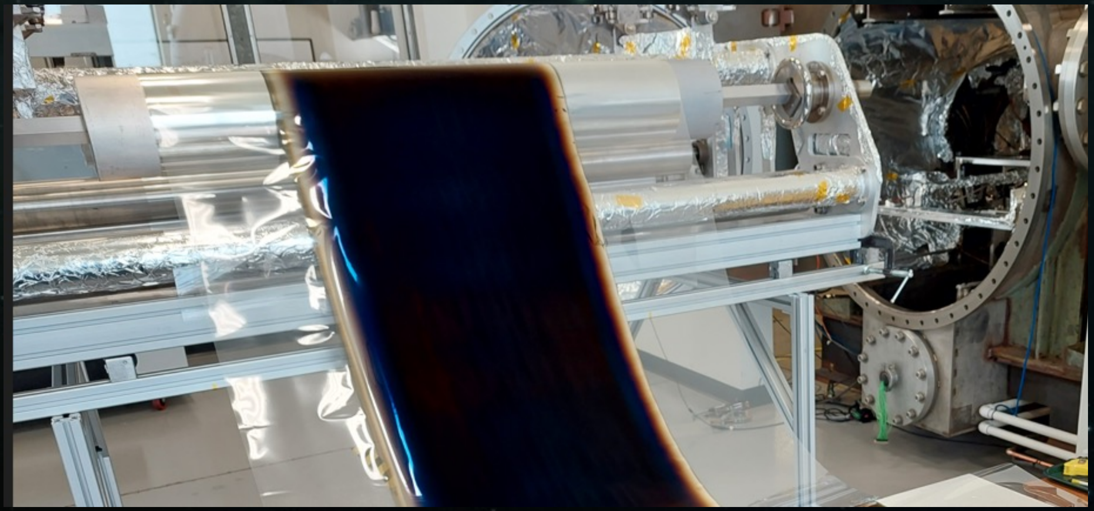
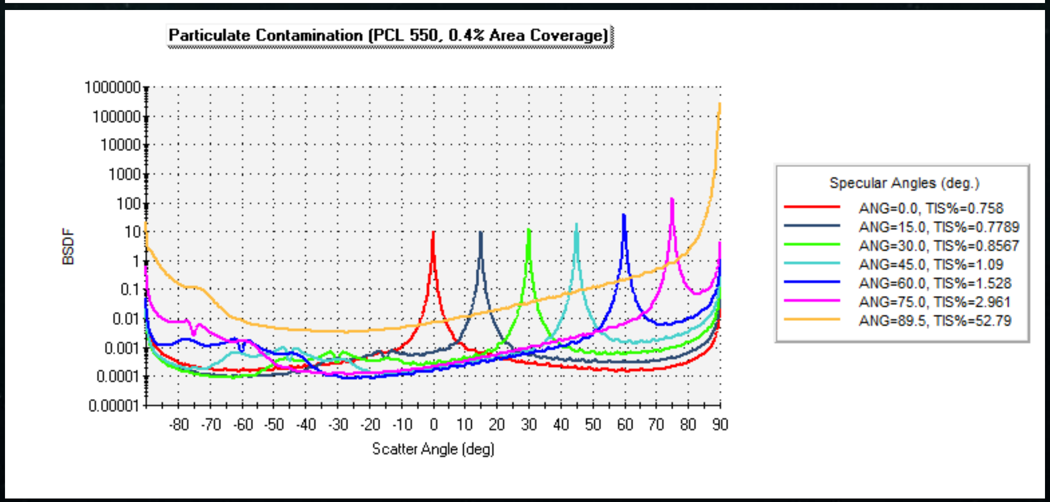


Photo of multilayer membrane 0.5 m wide coated by Zecoat under a Phase II SBIR. (Courtesy David Sheikh, Zecoat Corp.)

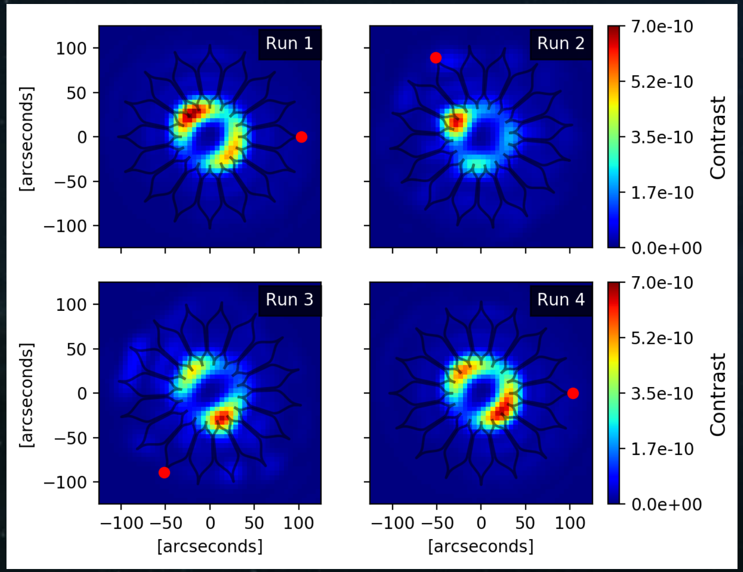


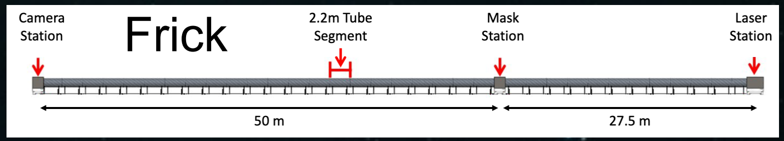
Next Generation Optical Testbed

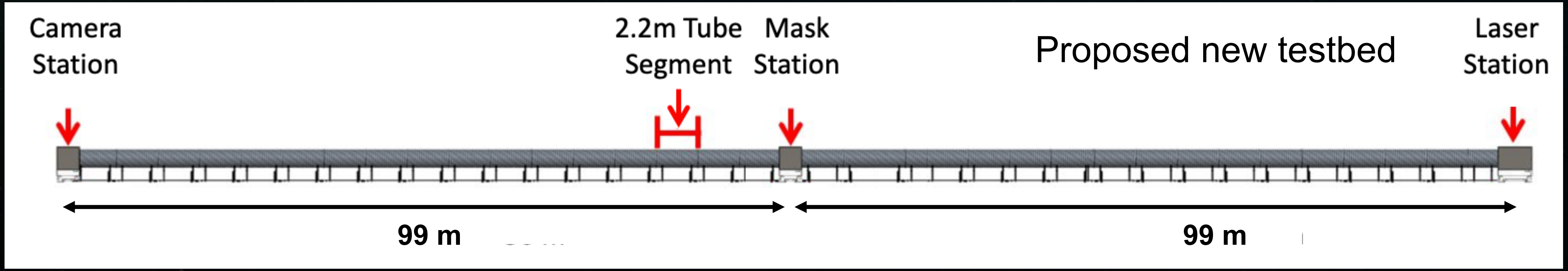
The goal is to demonstrate end-to-end performance while observing an artificial planet in a laboratory experiment.

- 200 m long, symmetric, 1 m diameter, at atmospheric pressure
  - ➢ Inner starshade diameter = 42 mm
- Polarization lobe contrast scales inversely with Z_{eff}, the effective distance between starshade and telescope.
  - ➢ Polarization lobes will be reduced to 2-3e-10 peak. *Average contrast at IWA will be < 6e-11.*
  - ➢ Effective Z is 49.7m compared to 17.8 m in Frick testbed.
- True broad-band performance
  - ➢ Instead of sequential laser lines
- Observe 1e-10 artificial planet
- Closed-loop out-of-band formation flying
- Spinning starshade
  - ➢ Demonstrate azimuthal averaging of starlight leakage due to manufacturing or other error.
- Also consider UV and IR demonstrations

Frick monochromatic results







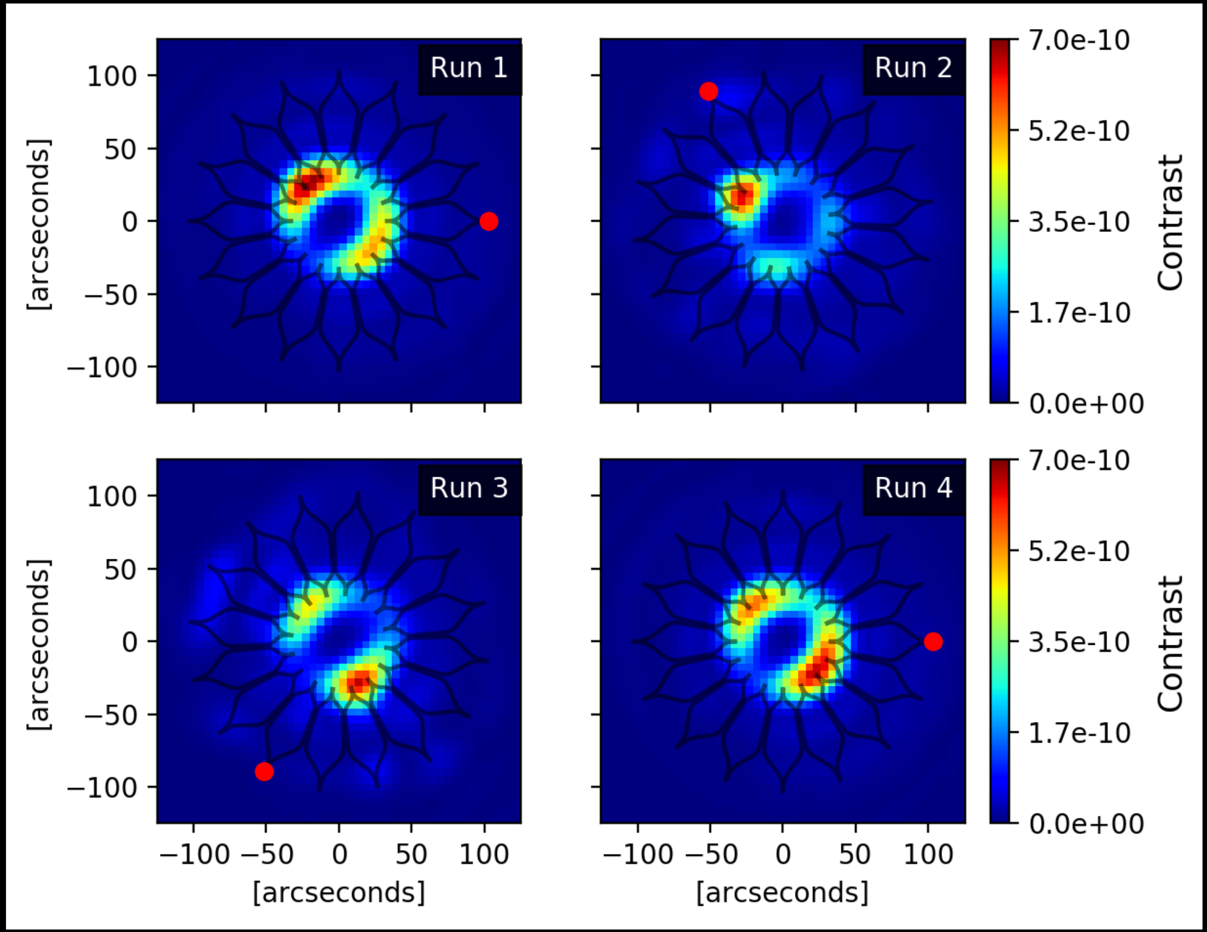
Starshade Optical Technology Conclusions

- **Optical Diffraction:**
  - Demonstrated < 1e-10 contrast, broadband, model validation at flight Fresnel Number, showed contrast improving with angle
  - Measured sensitivity to shape errors. The measured Model Uncertainty Factor is included in starshade error budgets.
- **Formation Flying:**
  - Optical demo of sensing signal, model of alignment and telescope pointing, showed lateral sensing accuracy of 10 cm on an $m_v = 8$ star (equivalent noise).
- **Solar glint:**
  - Measured edge sharpness, measured scatter of coated and uncoated edges, showed that edge glint will be ~ $m_v = 31$ on HWO.
  - Detailed modeling of surfaces and interfaces shows that glint will be ~ $m_v = 32$ on HWO.
- **Next Generation Testbed:**
  - At 200 m long, it will reduce the polarization to below 6e-11 at the IWA and will include an artificial planet, a spinning starshade, and out-of-band formation control.

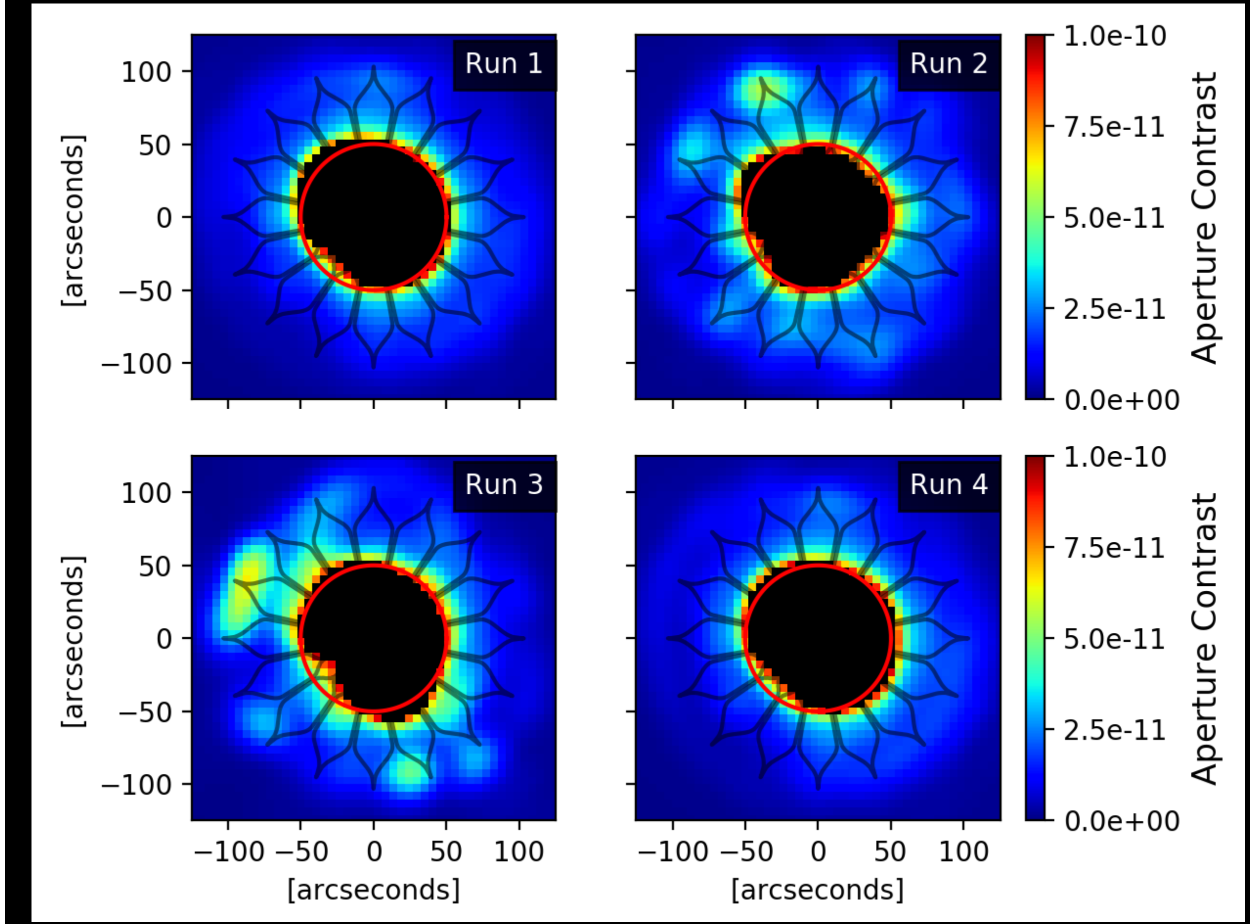
Backup Slides

OPTICAL TEST RESULTS: MONOCHROMATIC

Monochromatic Results full scale

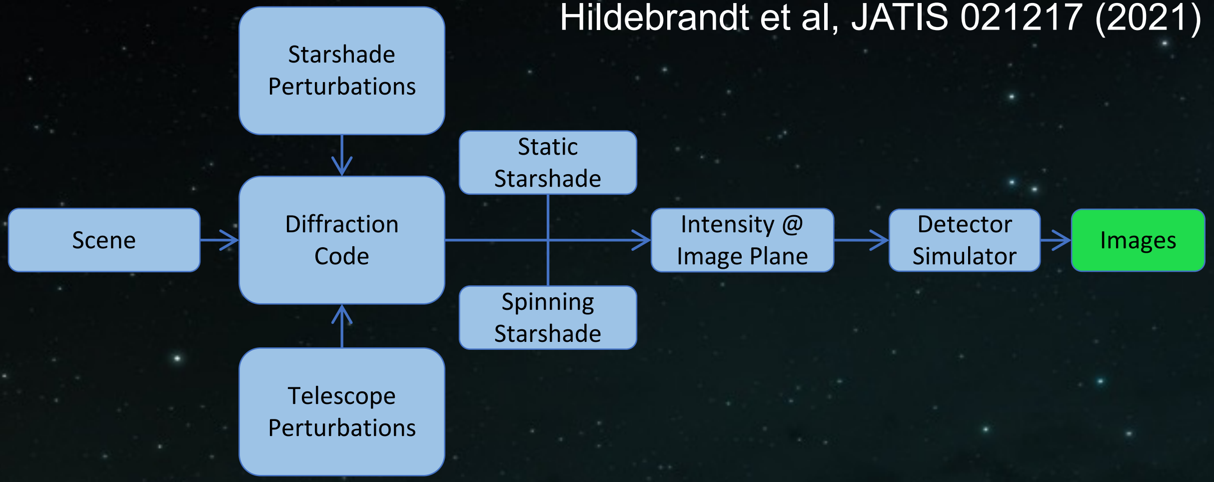


Inner Working angle and beyond



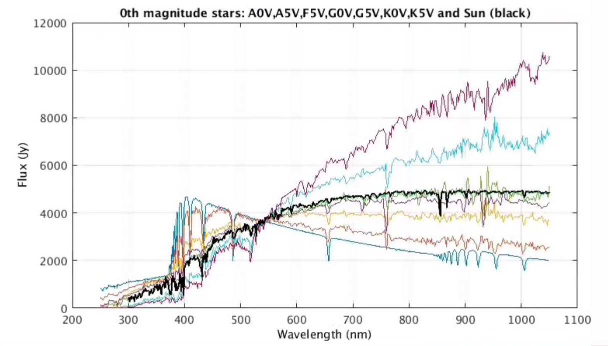
Simulation Toolkit: SISTER

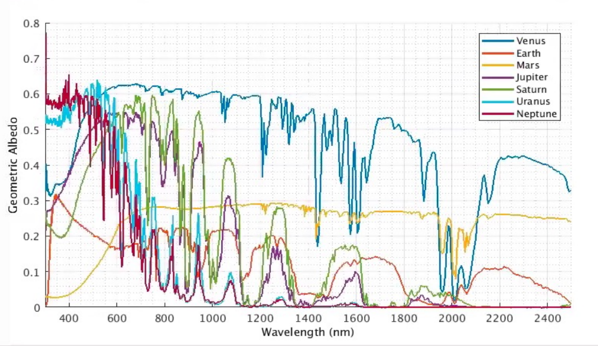
Hildebrandt et al, JATIS 021217 (2021)



- Any star in ExoCAT can be selected, or stars can be defined by the user through a few simple parameters.
- Stellar spectra are represented to the nearest 0.5 spectral type.
- Spectra are integrated over the user-selected imaging band.

- User can specify a planet in static position or a Keplerian orbit.
- User can specify planet characteristics (r, albedo) or choose a solar-system planet with a spectrum from Haystacks
- Choose from Lambertian or Rayleigh phase function, or specify the phase.



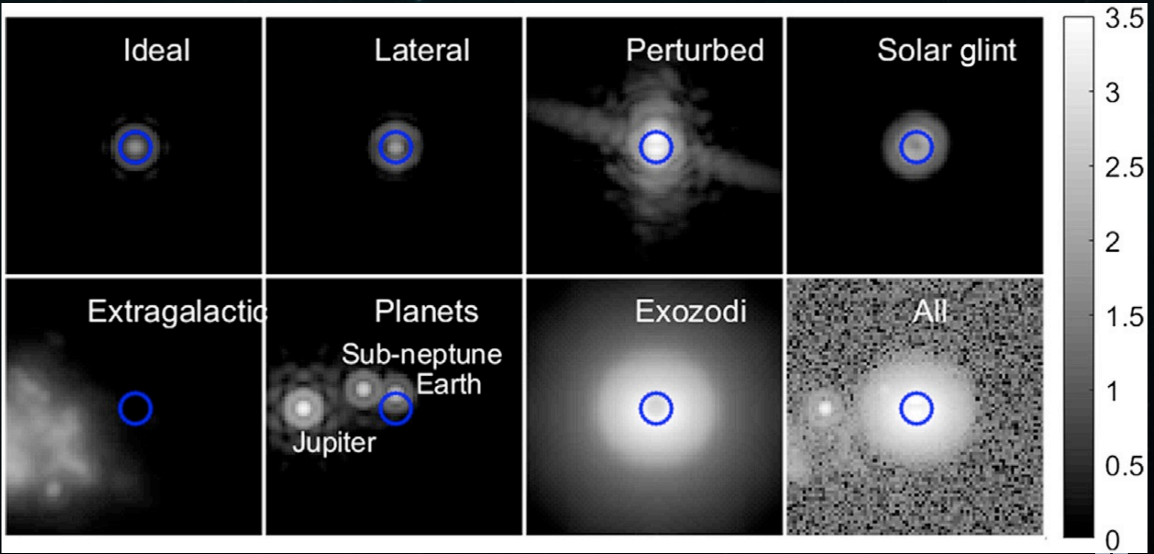


SISTER was developed by Sergi Hildebrandt, JPL/Caltech.
Code/handbook available at Sister.Caltech.edu

1. **Telescope:** primary, secondary mirror, pupil, optical efficiency, pointing jitter.
2. **Detector model:** read noise, dark current, Filters, QE. For WFIRST.
3. **Starshade mode:** spinning, or non-spinning.
4. **Non-ideal Starshade:** shape deformations.
5. **Solar glint:** target Star-Starshade-Sun angle, and Sun angle about the orbital plane.
6. **Local Zodiacal light:** surface brightness model from STSCI, helio-centric coordinates.
7. **Star:** the user may define any star (its sub-spectral type will be approximated by either 0 or 5, e.g. G3 will be G5). Or one may choose among any of the 2,347 stars from ExoCat (M. Turnbull, 2015).
8. **Exo-dust emission:** any external model (for instance, from the Haystacks Project*). SISTER has as a proxy a very simple model scaled, rotated and resized from one run of Zodipic.
9. **Planets and Keplerian orbits:** direct location, or 2-body motion with independent Keplerian parameters. No stability assessment.
10. **Reflected light from planets:** phase angle, phase functions (Lambert, Rayleigh).
11. **Extragalactic background:** deep field prepared by the Haystacks Project*.
12. **Proper motion and parallax:** given star coordinates and proper motion.

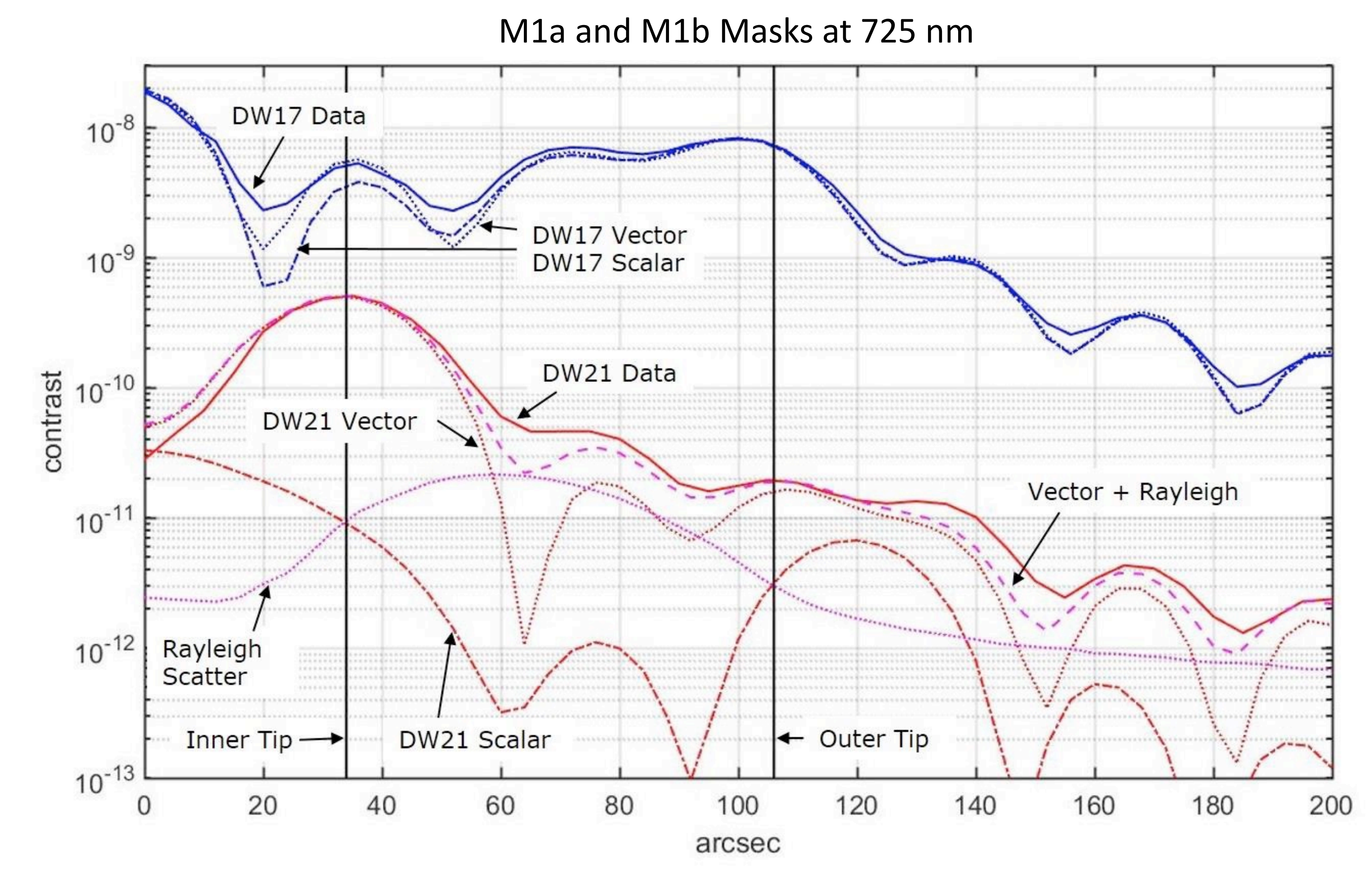
Imaging Capability Example

Intensities are displayed in log scale



MODEL VALIDATION TEST

Out-of-Band Leakage



GROUND-BASED STELLAR OBSERVATIONS

Harness, Warwick, Shipley, Cash, “Ground-based testing and demonstration of starshades,” SPIE 99043 (2016).