STARSHADES

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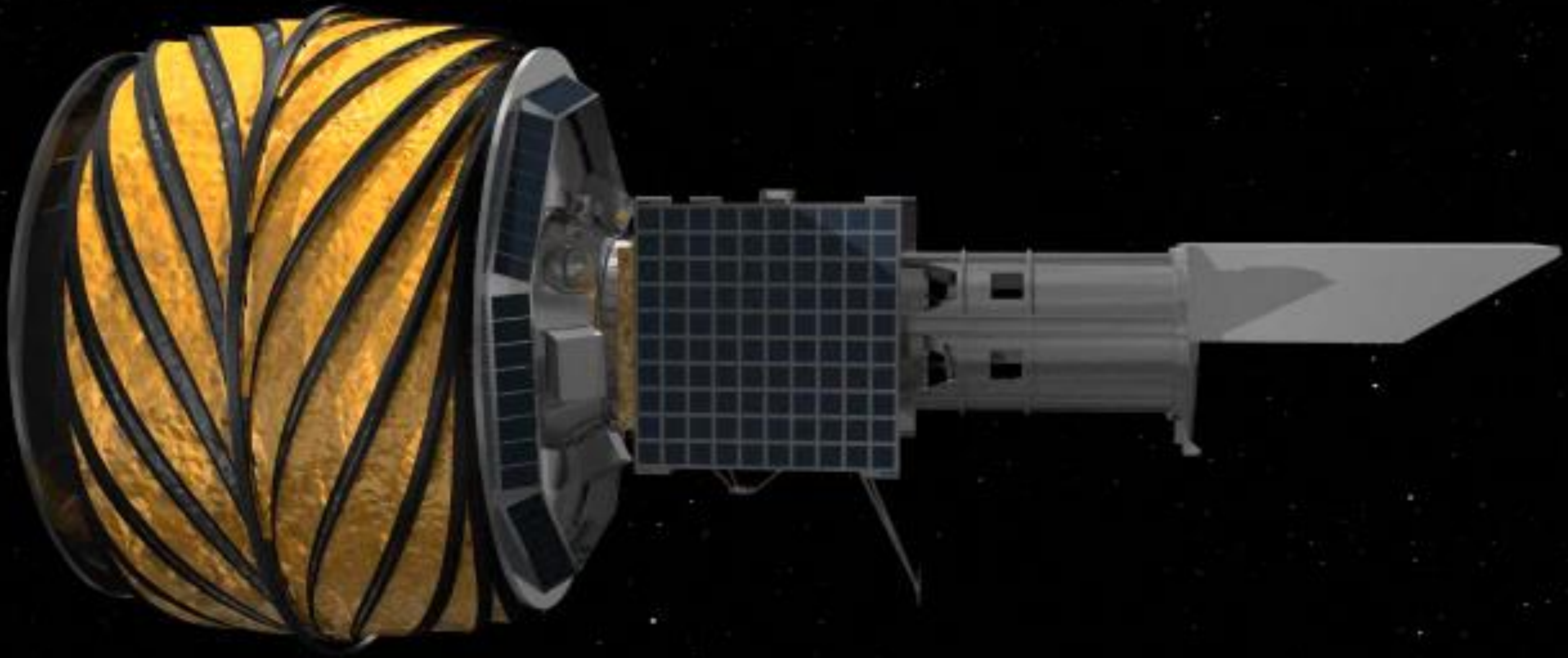
California Institute of Technology

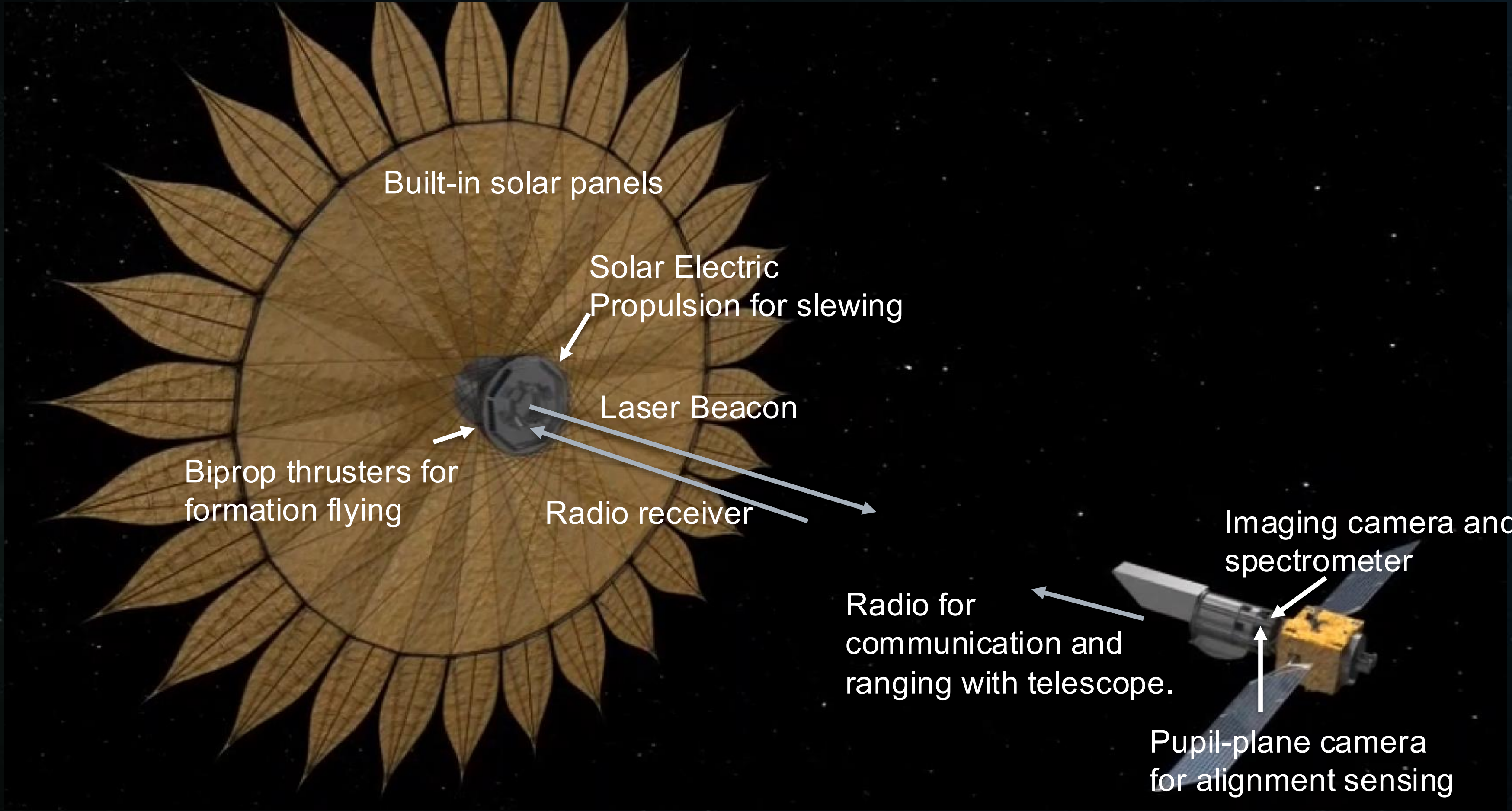
Keck Institute for Space Science Short Course

March 9, 2026

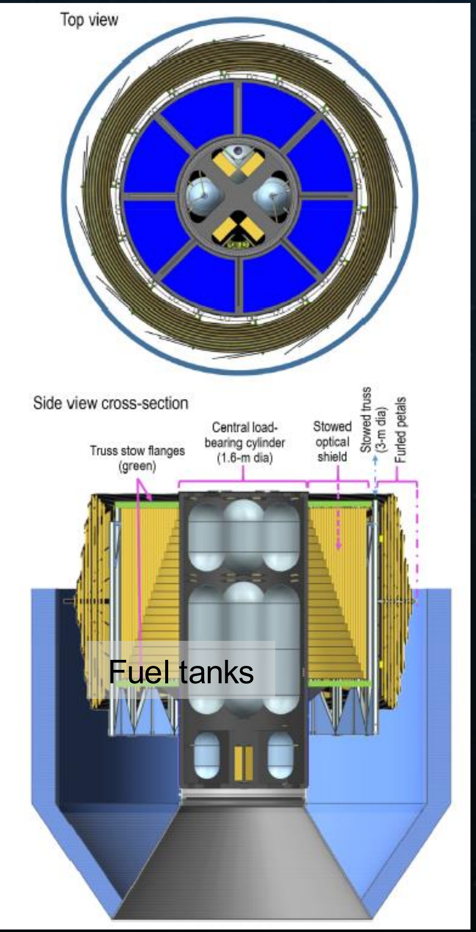


Exoplanet Probe – Starshade Mission Concept, 2014

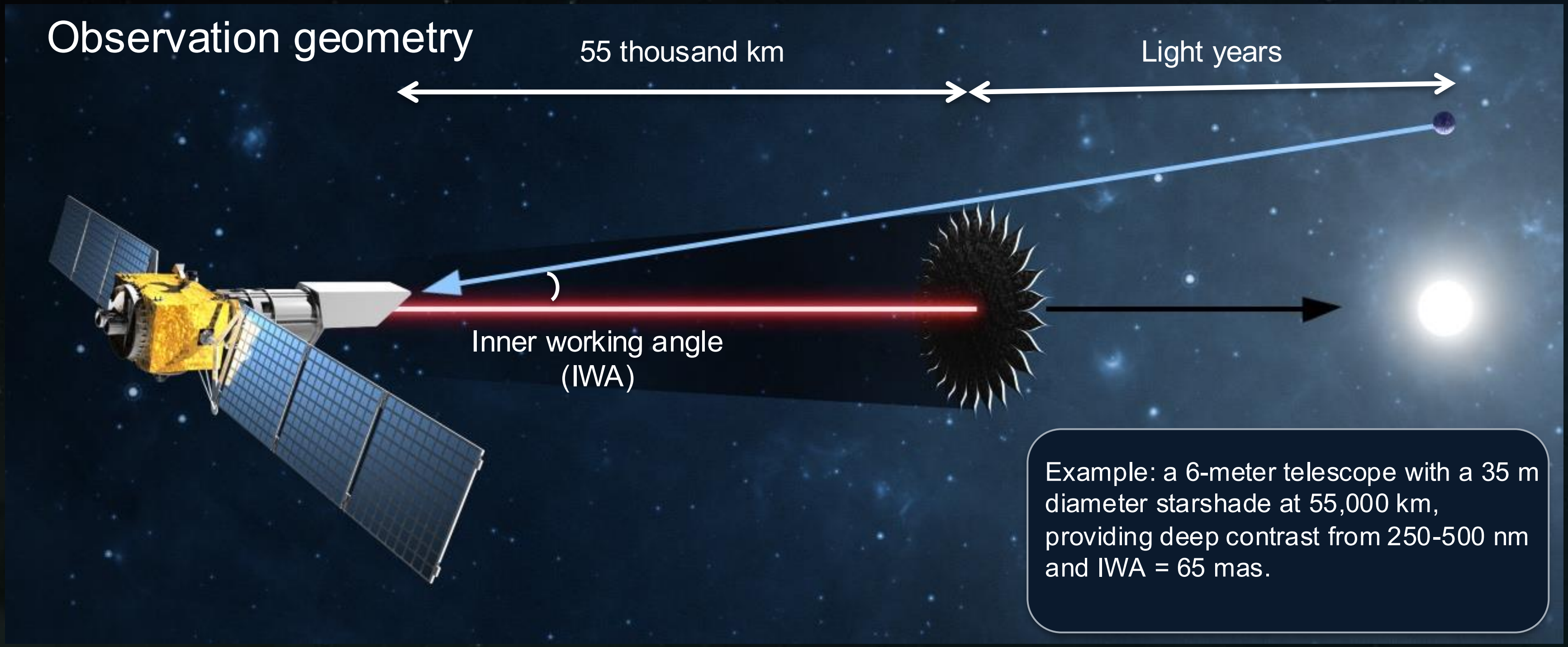
Starshade Subsystems



Launch Configuration



STARSHADE AT WORK

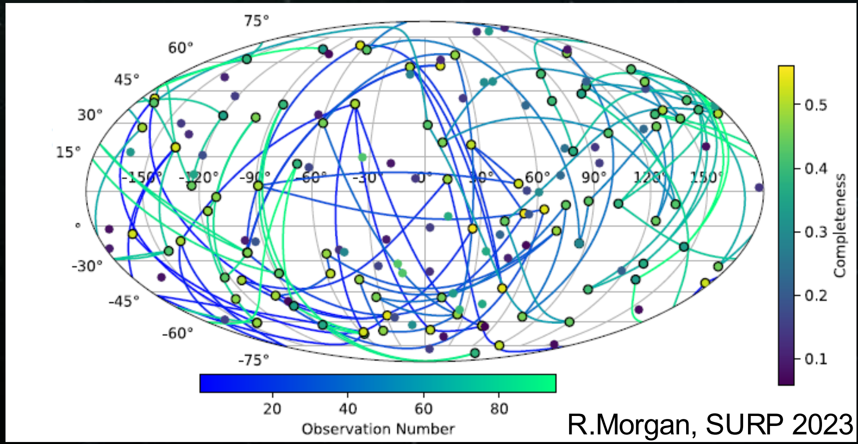


The starshade blocks starlight in space where the signal from the planet and the signal from the star do not overlap.

Starshades attributes:

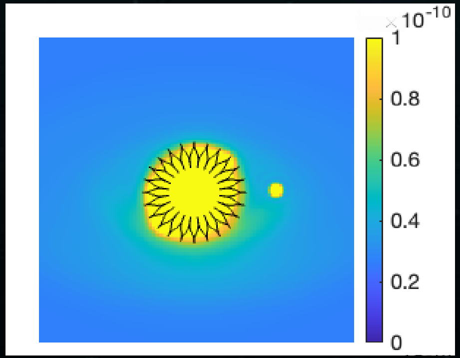
- Deep contrast
- 100% throughput
- Wide bandwidth
- Small Working Angle
- Excellent in the UV, Vis, and NIR
- Standard Machine Tolerances, no picometers
- Works with any telescope, e.g. on- or off-axis, segmented or monolithic

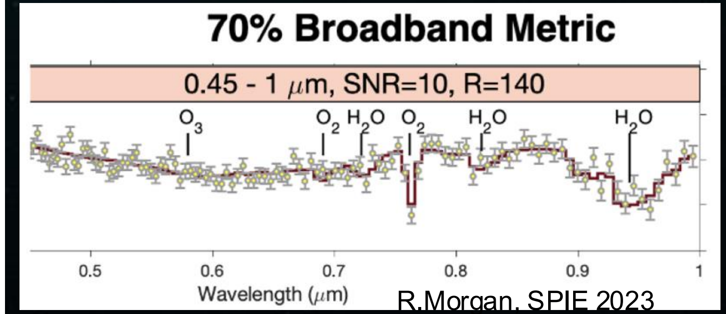
Slew from target to target, 1-2 weeks/slew



R.Morgan, SURP 2023

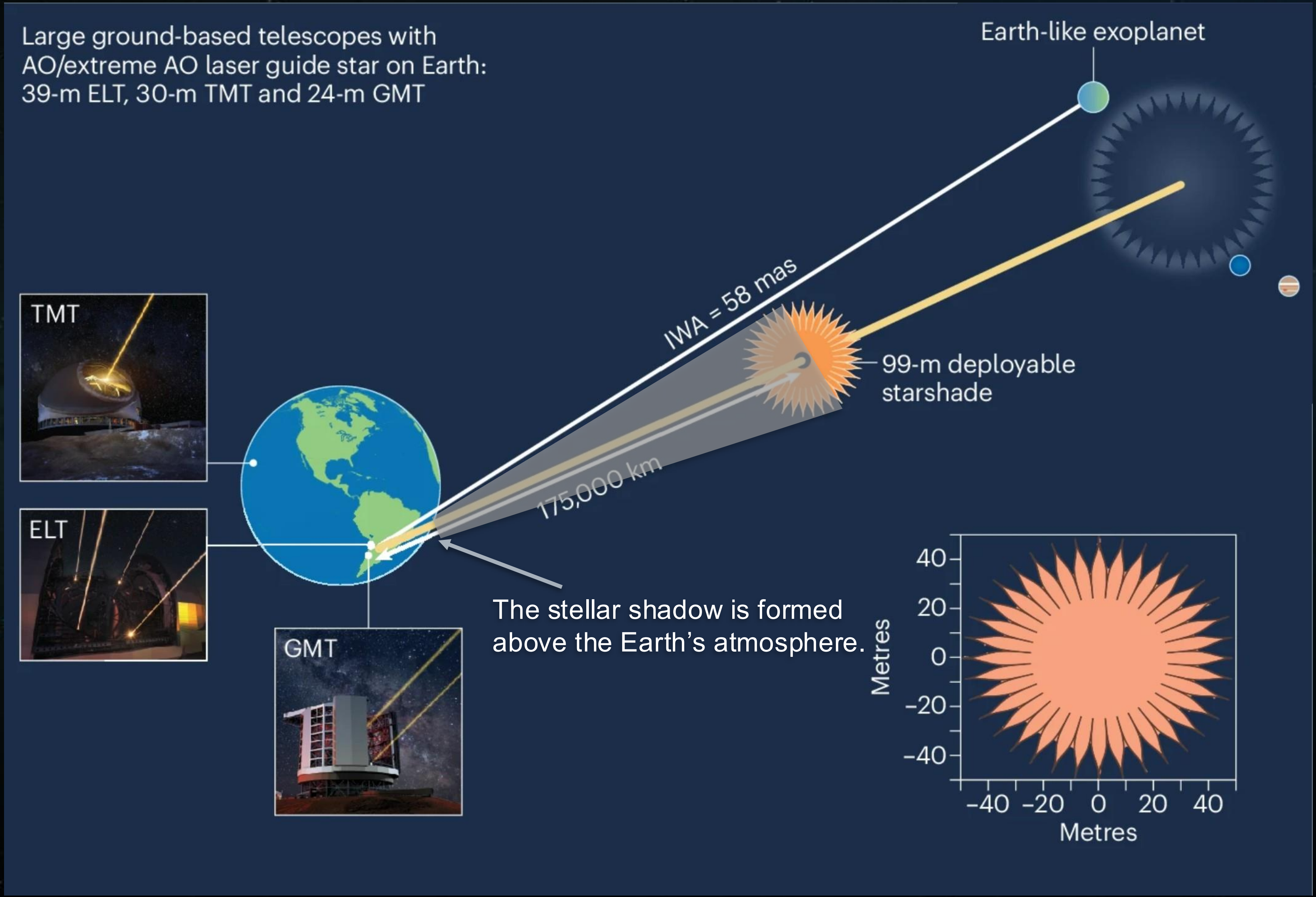
Science products are direct images and spectra





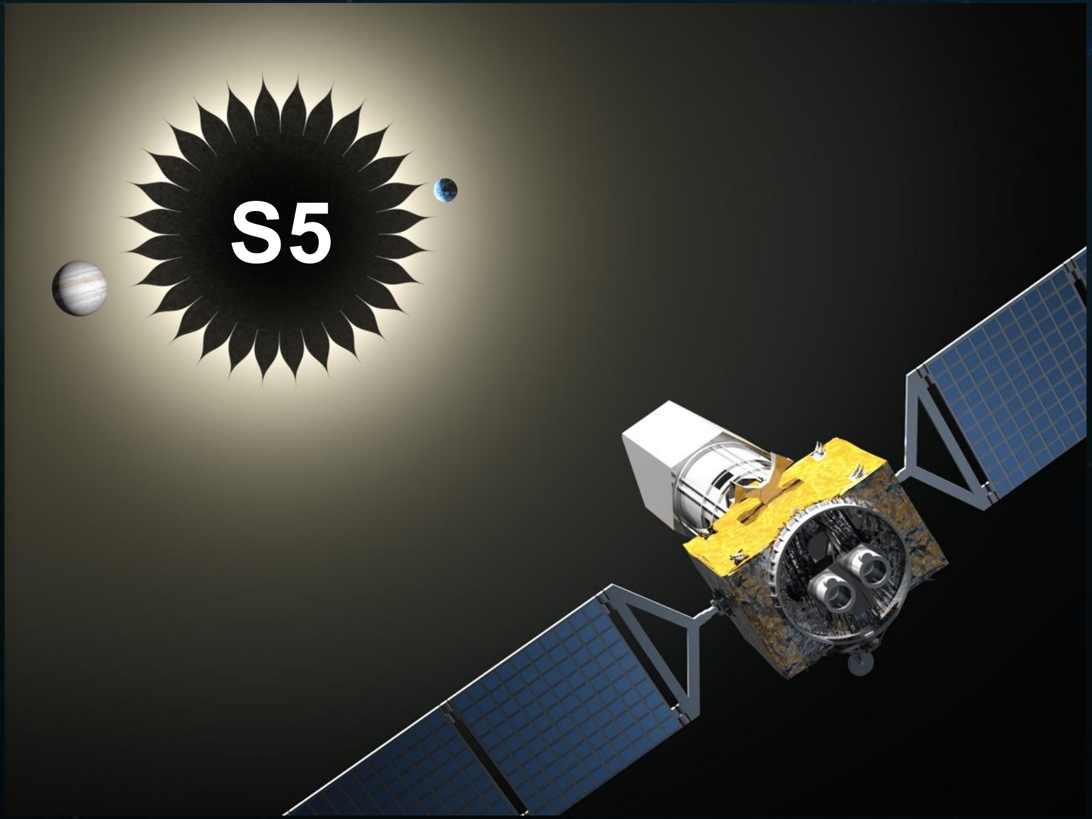
R.Morgan, SPIE 2023

Hybrid Observatory for Earth-Like Exoplanets (HOEE)



Starshade Technology Development (S5) 2016-2025
Four Main Questions:

1. *Diffraction modeling:* If the starshade has the right shape, will it produce a dark shadow?
2. *Mechanical engineering:* Can we fly a starshade with the right shape?
3. *Formation flying:* Can we fly and maintain the telescope in the shadow of the starshade?
4. *Solar glint:* How do we address glare from the Sun?



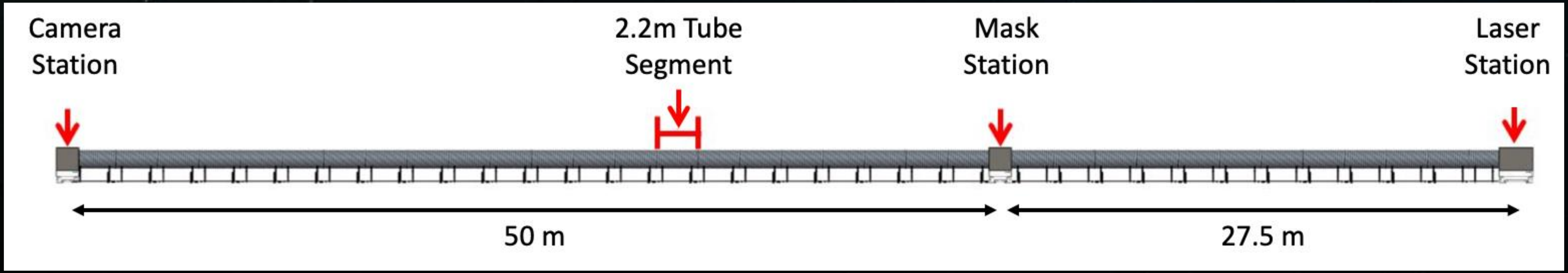
Optical Modeling and Formation Flying

Princeton optical testbed

5-cm diameter Starshade etched in silicon

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

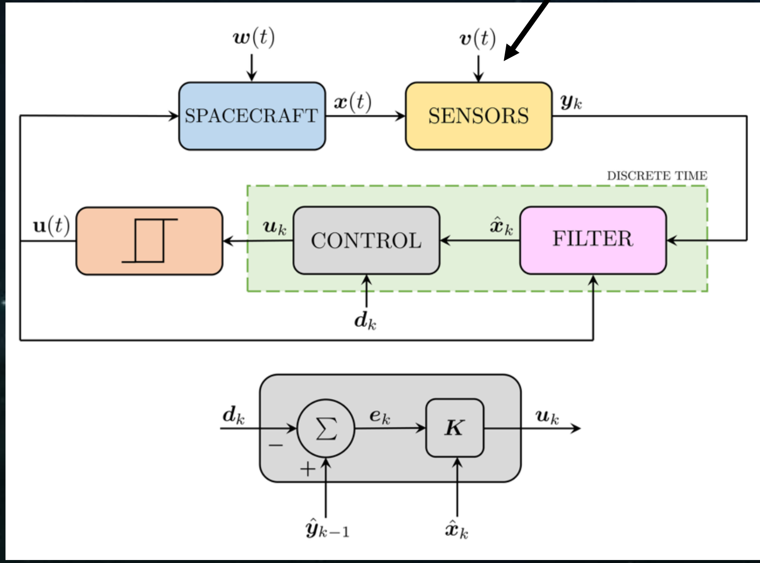
- 80 m long tube in basement of Frick building on Princeton campus
- Not evacuated (1 atm)
- Point source, starshade mask, simple camera.
- Remotely operated
- Settling time for 1e-10 contrast was about 3 days.
- Operational 2017-2022.



Deep Contrast and Formation Flying

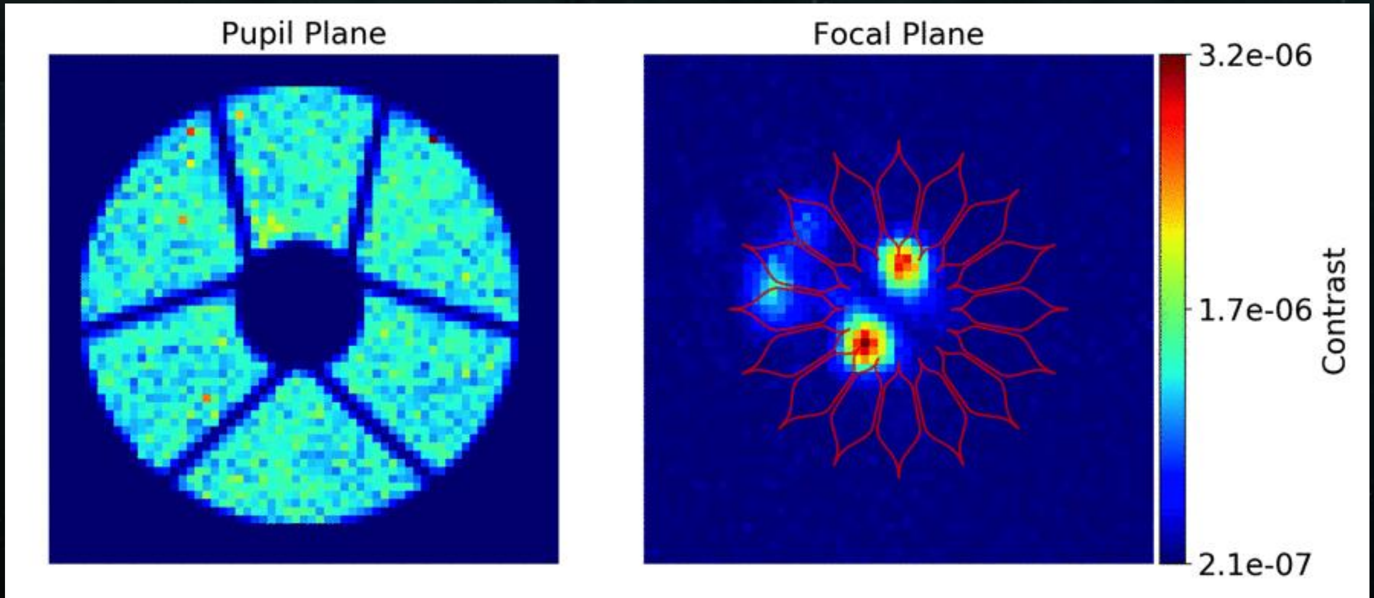
Hardware-in-the-loop Station keeping Test

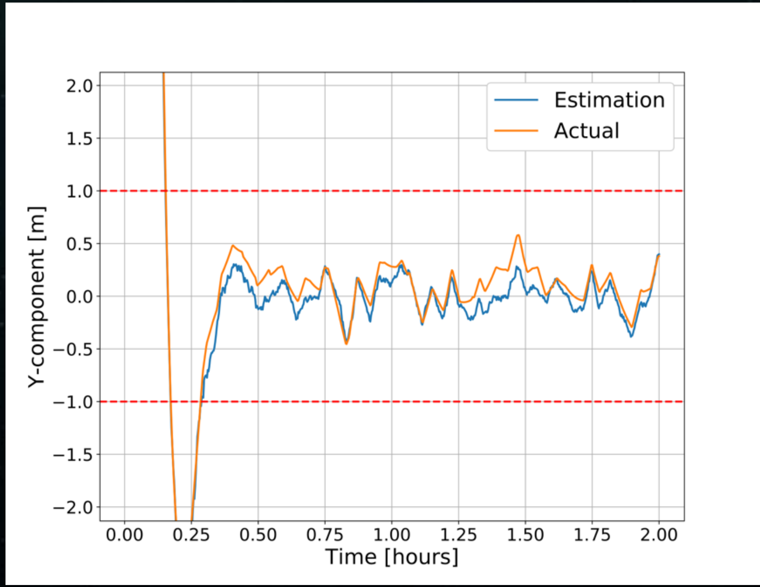
measure position by fitting pupil image



Linear Quadratic Regulator with Integral Control and Unscented Kalman Filtering

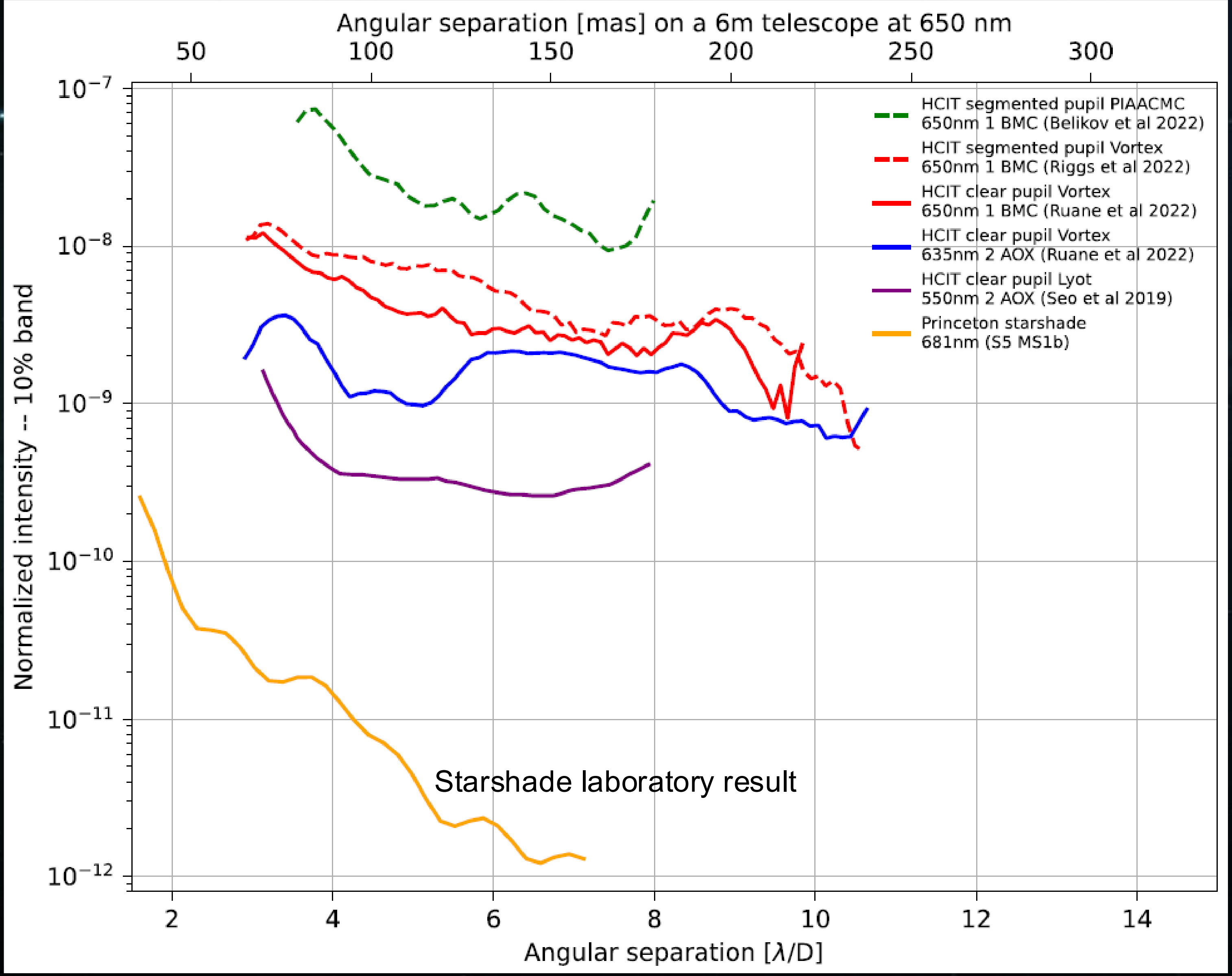
Simulated Formation keeping with actual position measurements from Princeton testbed





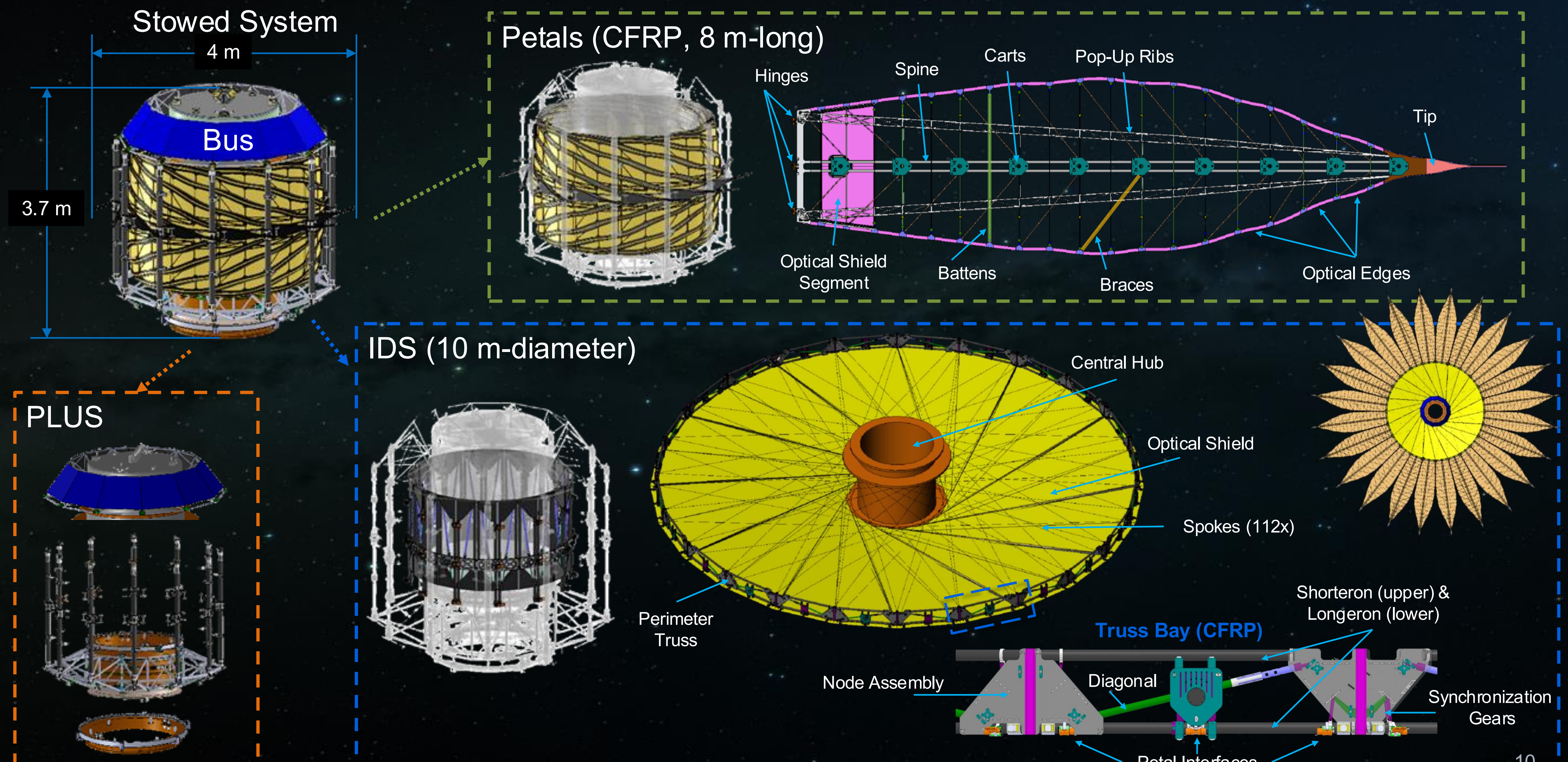
Palacios, Harness, & Kasdin, Acta Astron, 171 (2020): Princeton Frick Testbed H/W in the loop
See also papers by T. Flinois and S. Martin.

Starlight Suppression: Laboratory Measurements



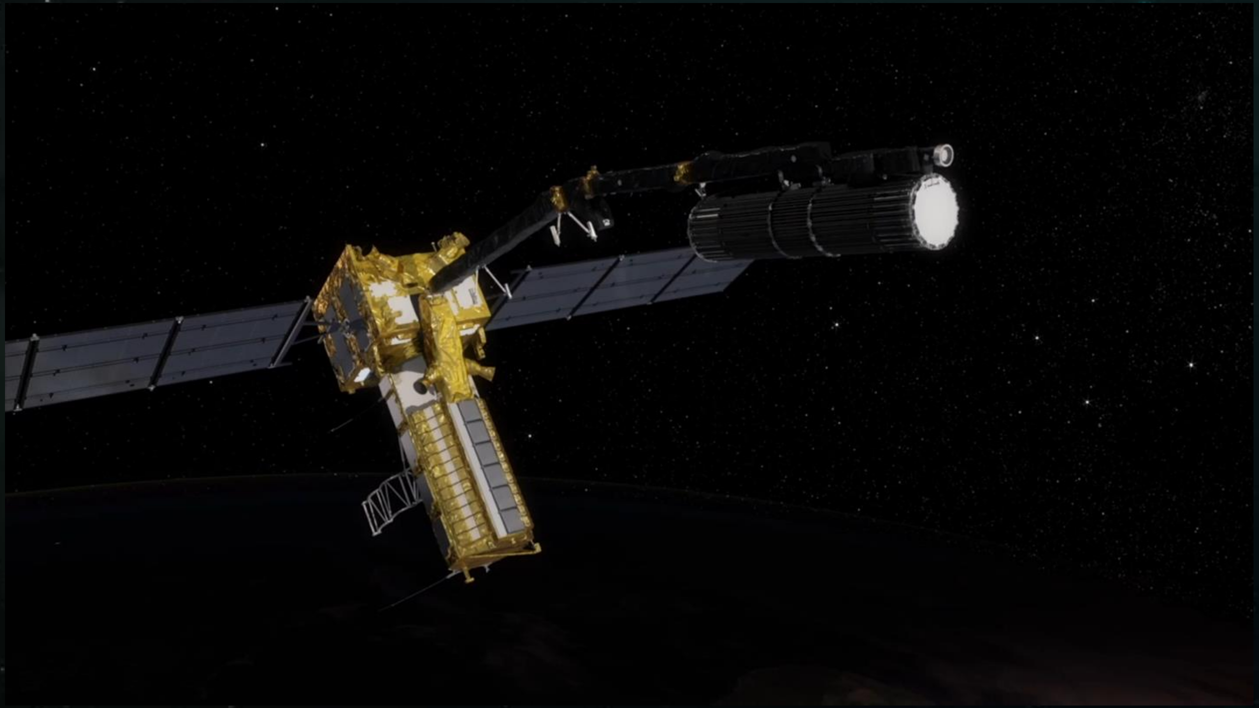
Mennesson et al, JATIS vol 10 (2024).

Starshade configuration: Wrapped Design



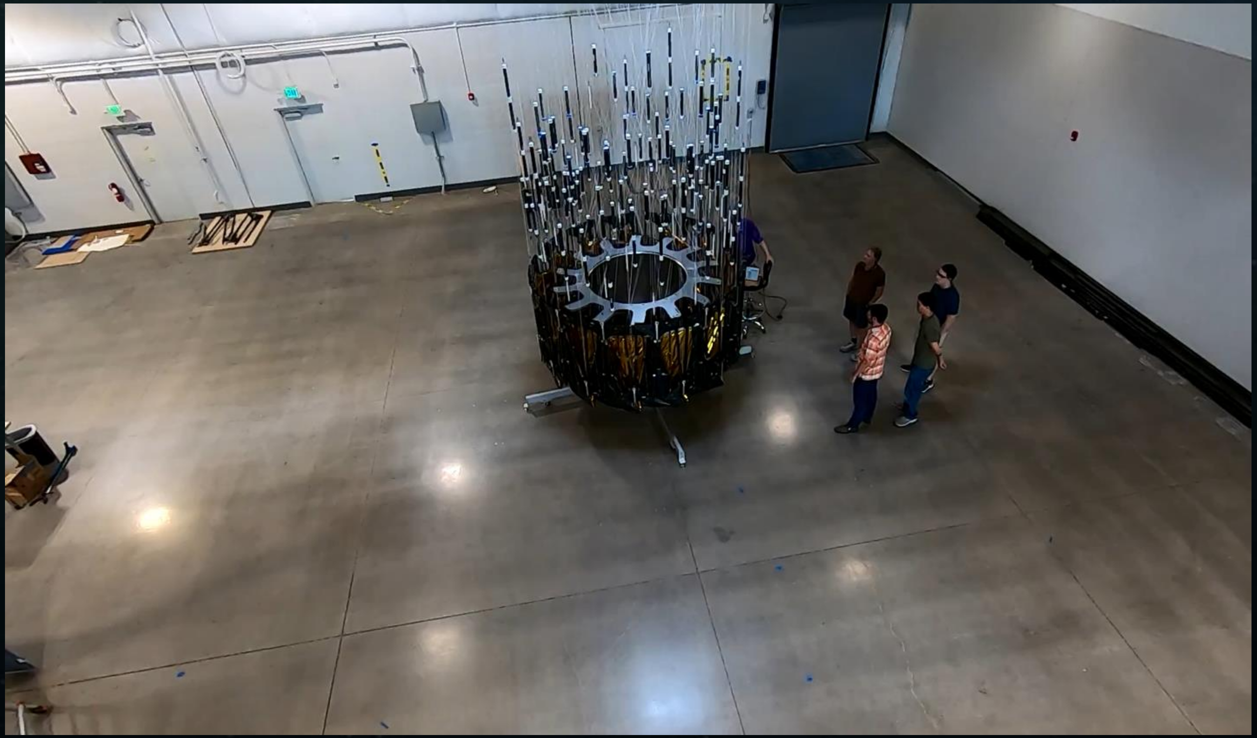
NISAR

Synthetic Aperture Radar, joint project NASA-ISRO.
Launched July 30, 2025
Dish is deployed and supported by a 12-m diameter perimeter truss.



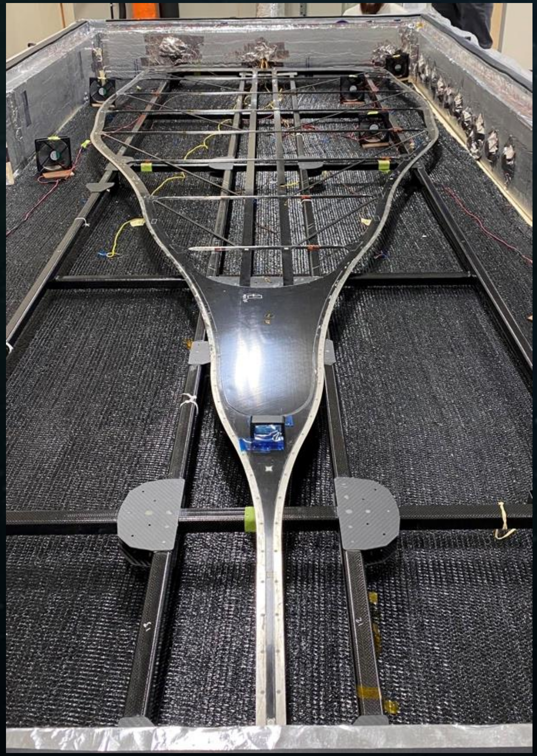
Starshade: Same Architecture, 10 m Demo

Perimeter truss has the same components, flatter geometry, and center deployment.



Petals

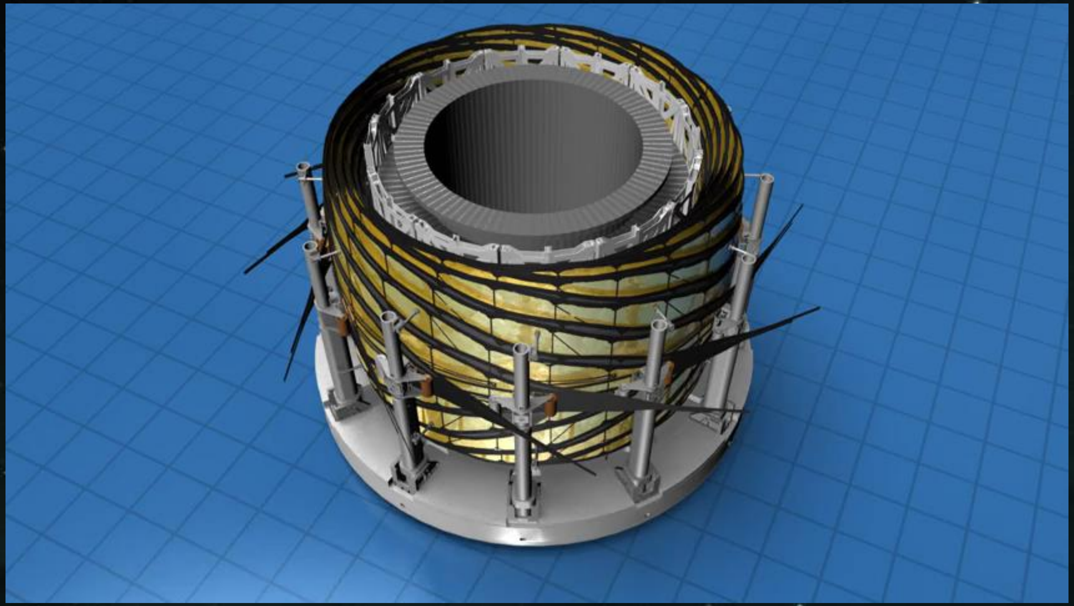
- Subjected petal test article to 50 thermal cycles (± 50°C)
- Subjected petal test article to 5 furl-and-deploy cycles (simulating wrapping around 2.3 m-diameter)
- Measured petal shape after thermal cycles, furl cycles, compare to reference shape to calculate width change
  - MicroVu measurement machine (microscope on a *x-y* translation stage) used for petal shape measurement



Video and photos take at Tendeg Inc., Louisville, CO.

M Arya et al.: Demonstration of deployment repeatability of key subsystems of a furled starshade architecture, *JATIS*, vol 7, no 2, pp 021202, 2021

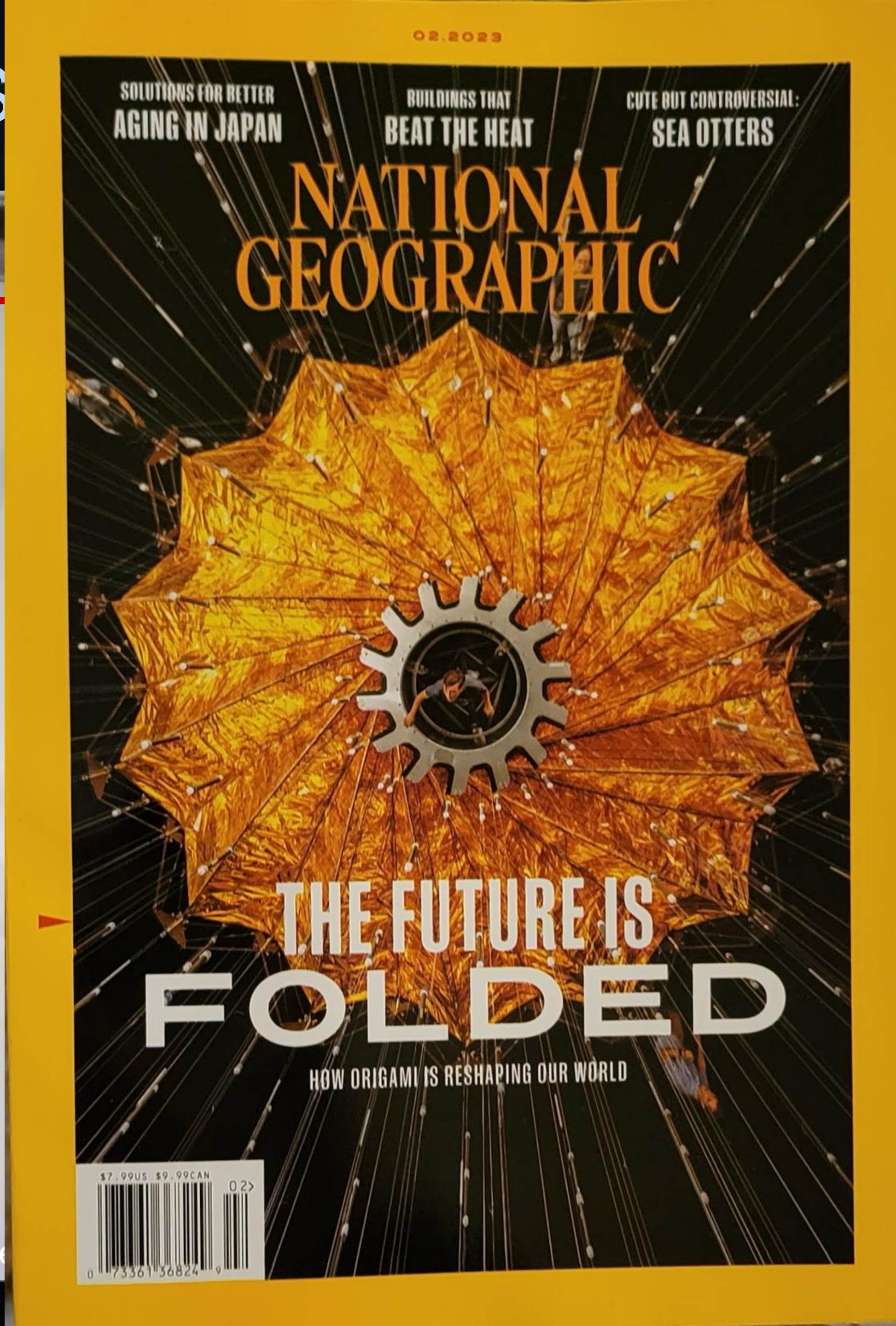
Petal Launch Restraint & Unfurling Subsystem (PLUS)



"Flasher" Origami Demons

Stowed ½-scale truss
(5 m diameter)

Optical Shield 5m (¼-scale) prototype r



HOEE Shape Sensitivity

- The starshade is designed to have better than 3×10^{-12} contrast at the tips, about 33 times fainter than an exo-Earth.
- Shape imperfections allow some starlight to leak. The shadow gets brighter.

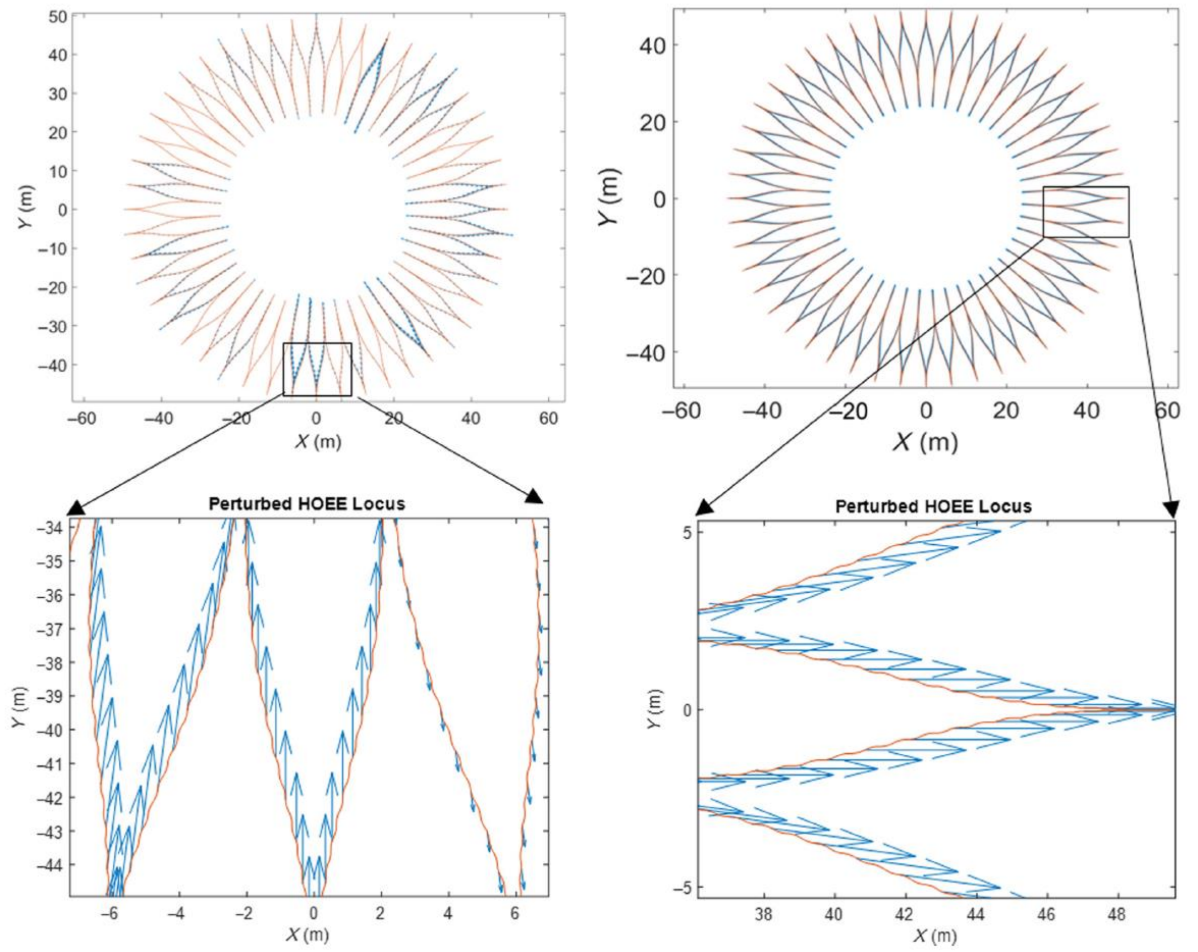


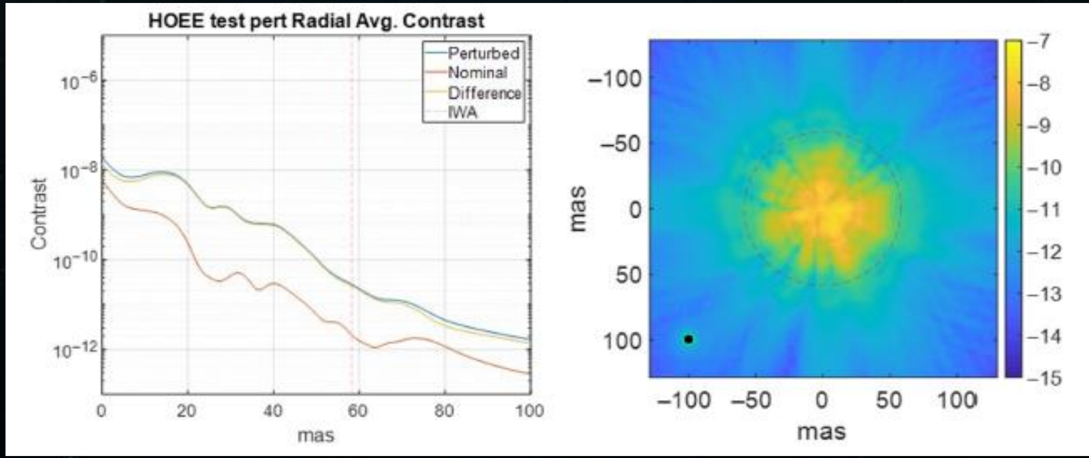
Fig. 4 Ninety-nine-meter starshade analysis of petal perturbation (amplitude = 100 mm). Left: random perturbation. Right: global perturbation.

HOEE Shape/Contrast Sensitivity

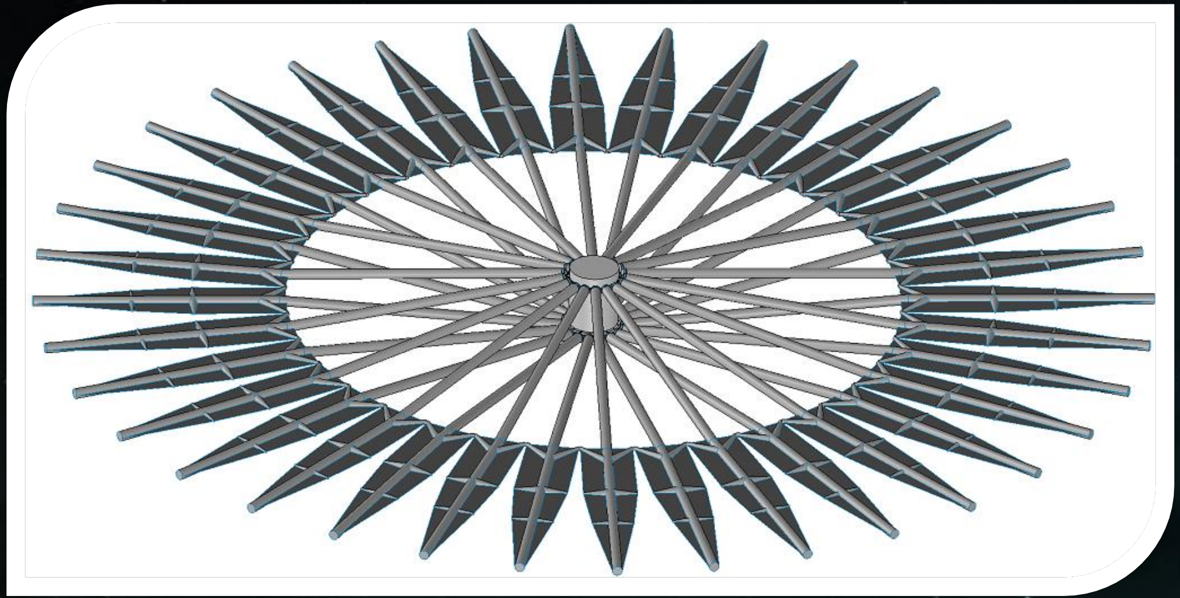
These are shape errors for a change in contrast of 5×10^{-12} at the IWA, per perturbation.

Perturbation List	Perturbation Type	Amplitude	Notes
Petal Displacement	Radial / global (common to all petals)	46 mm	In-plane displacement
Petal Displacement	Radial / random	66 mm 1-sigma	In-plane displacement
Petal Edge Segment Displacement	In-plane, normal to spine, random	280 microns 1-sigma	These contribute to petal width errrors, the most sensitive component of the error budget.
Petal Clocking	In-plane, angular offset from base, random	0.0042 rad (10.5 cm at the tip)	Random motions are more sensitive than coordinated motions.
Formation offset (lateral offset)	Lateral line of sight motion	1.4 m (1.65 milli-arcsec)	Longitudinal motion allowance is > 1000 km

Stellar leakage for petal displacement of 100 mm (radial and global), segment displacement of 100 microns (random) and proportional length and width errors of 500 ppm.



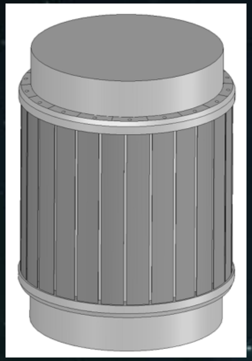
INFLATABLE CONCEPTUAL DESIGN

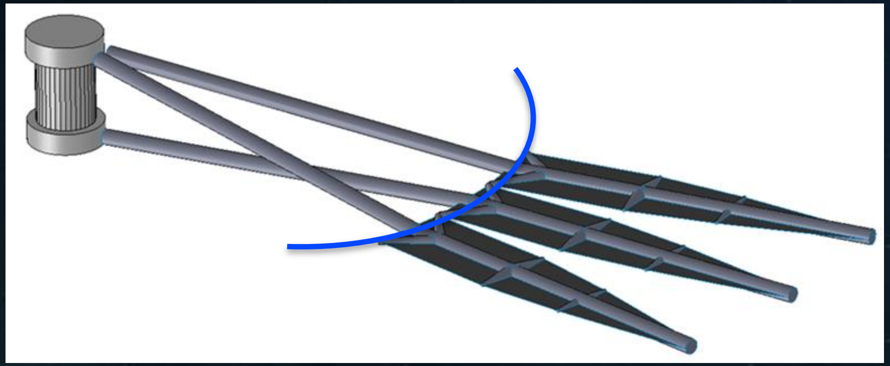


The starshade consists of a central hub connected to 36 radial structural members that support deployable petals arranged symmetrically around the perimeter.

Each petal spine has a diameter of 0.8 m and extends outward from the outer ring. The petals are evenly distributed to maintain rotational symmetry and optical performance.

All petals have a constant cross-section and include reinforcement along their length at several locations.



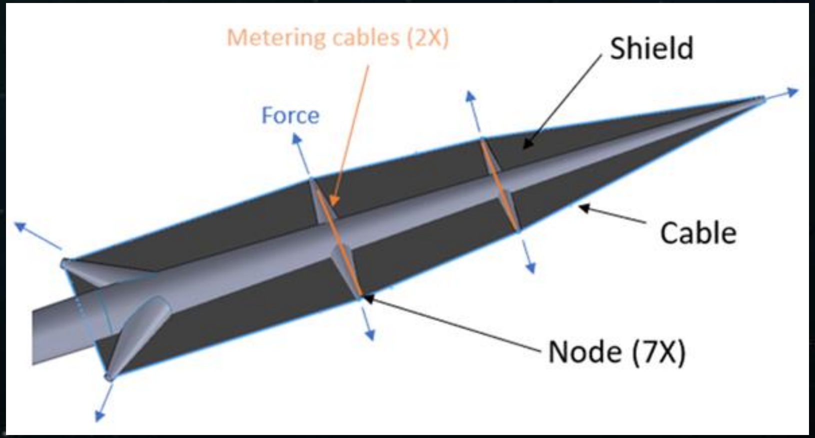


Deployment

The petals are folded directly around the satellite in an accordion pattern. After deployment, the base of the petals is linked together to better control their final position, forming a collar (blue curve). (36 petals in total)

Segment design

A possible approach is to use bladders to tension a cable, which would create the segments. This tensegrity design would allow better error distribution and simplify the folding process.



Thanks to Marc-Andrew Boucher of OMP for providing this chart.

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Project Co-Is:
Alan Cassell, Dan Sirbu (NASA ARC),
Serife Tol, Ellen Arruda (University of Michigan),
Othman Oudghiri-Idrissi (University of Texas at Austin)

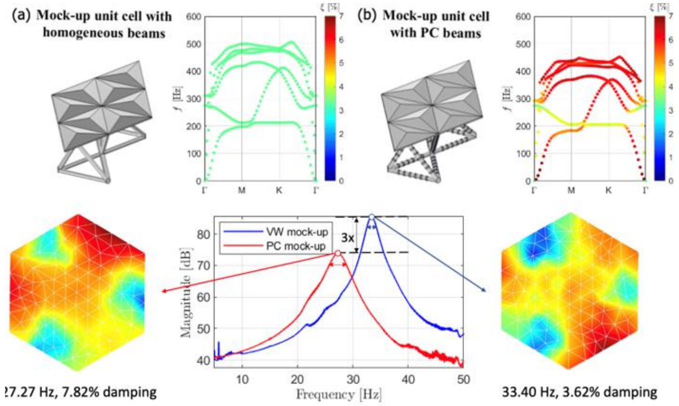
Metashade

Dynamically Stable Large Space Structures via Architected Metamaterials

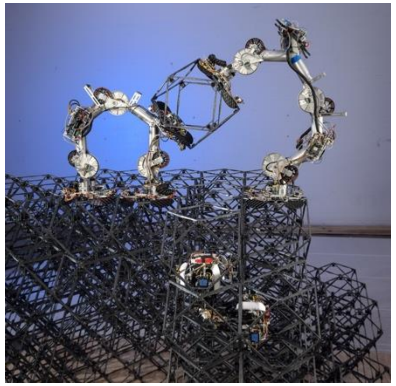
Technology and Innovation

- Metamaterials and robotic assembly may create lower-mass starshade structures for challenging dynamic operational loading requirements
- Dissipative metamaterial designs do not trade stiffness for enhanced damping, allowing faster settling times. This can reduce overall mass while maintaining high precision and overall performance

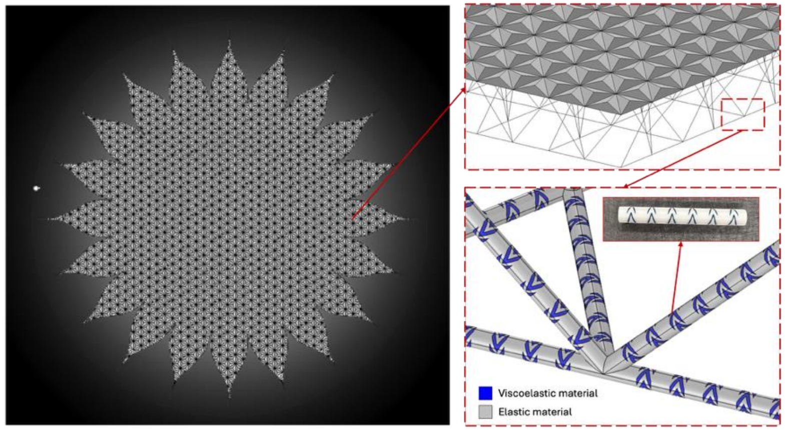
- Band gaps can be tailored to suppress problematic modes
- Structure will be assembled on orbit, integrating metamaterial modules, creased plates occulting layers, and petal structures (which may be hybrid assembly/deployed)



Dispersion and damping level of the prototype array unit cell with (a) homogenous VeroWhite beams and (b) phononic crystal beams. The damping level in the VW and PC-based arrays is 3% and approximately 6%, respectively. The experimental structural tests performed on the solar array verifies this prediction.

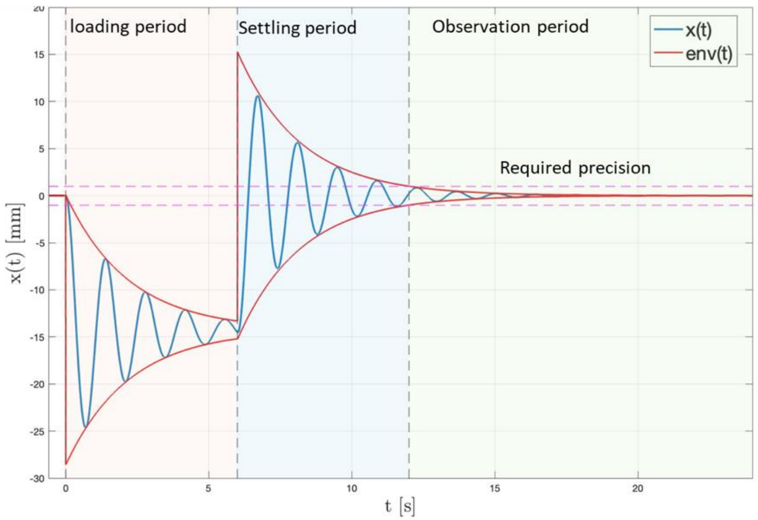


Autonomous construction robots from the NASA ARMADAS project can enable small robots to assemble large metamaterial structures.



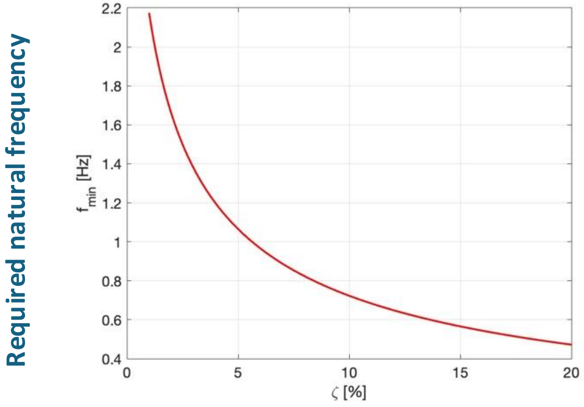
Concept image of the assembled starshade with metadamping metamaterial modules.

Dynamic Requirement Development



- HOEE station keeping requirements present a uniquely dynamic operational environment, with repeated periodic loading and limited time for settling and observation.
- Dynamic deflection requirements must be established for necessary contrast

- The Metashade team is developing single DOF heuristics for frequency and damping requirements, as well as modal analysis for detailed dynamic deflection requirement analysis.



References:

[1] Oudghiri-Idrissi, O., Lu,W.C.,Vijayachandran, A.A., McInerney, J., Poli, A., Danawe, H., Mao, X., Arruda, E., Waas, A. and Tol, S., 2024. In-space manufacturable solar array structures integrating metamaterial technologies, part I:Design approaches, numerical modeling, and experimental validation. In AIAA SCITECH 2024 Forum (p. 0827).
[2] Vijayachandran, A.A., Oudghiri-Idrissi, O., Lu,W.C.,McInerney, J., Poli, A., Mao, X., Arruda, E., Tol, S. and Waas, A.,2024. In-space Manufacturable Solar Array Structures Integrating Metamaterial Technologies, Part II: Numerical Models and Design Optimization. In AIAA SCITECH 2024 Forum (p. 1263).
[3] Vijayachandran, A., Oudghiri-Idrissi, O., Danawe, H., Mao, X., Arruda, E., Tol, S. and Waas, A.M., 2024. Free vibration of thin, creased elastic plates: Optimization and scaling laws. Thin-Walled Structures, 195, p.111393.
[4] Lu, W.C.,Oudghiri-Idrissi, O., Danawe, H. and Tol, S., 2023, June. Design optimization of 3d printed chiral metamaterials with simultaneous high stiffness and high damping. In Society for Experimental Mechanics Annual Conference and Exposition (pp. 95-98). Cham: Springer Nature Switzerland.
[5] C. E. Gregg et al., "Ultralight, strong, and self-reprogrammable mechanical metamaterials," Sci. Robot., vol. 9, no. 86, p. eadi2746, Jan. 2024, doi: 10.1126/scirobotics.adi2746.

NASA Innovative Advanced Concepts

Conclusions

The starshade, when used with a space or ground-based telescope, turns that telescope into a powerful exoplanet observing machine.

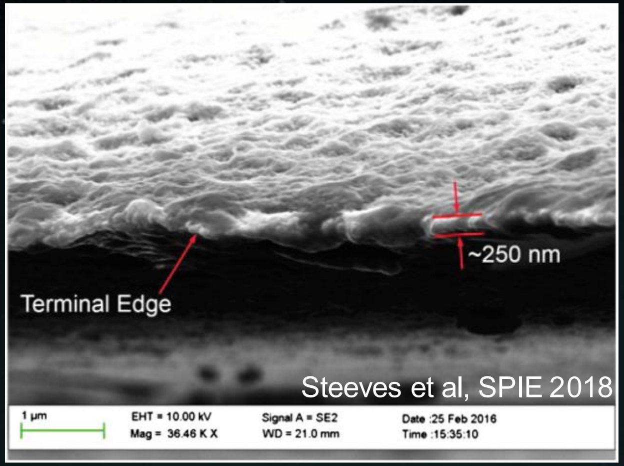
It does so without imposing any strong requirements on the telescope.

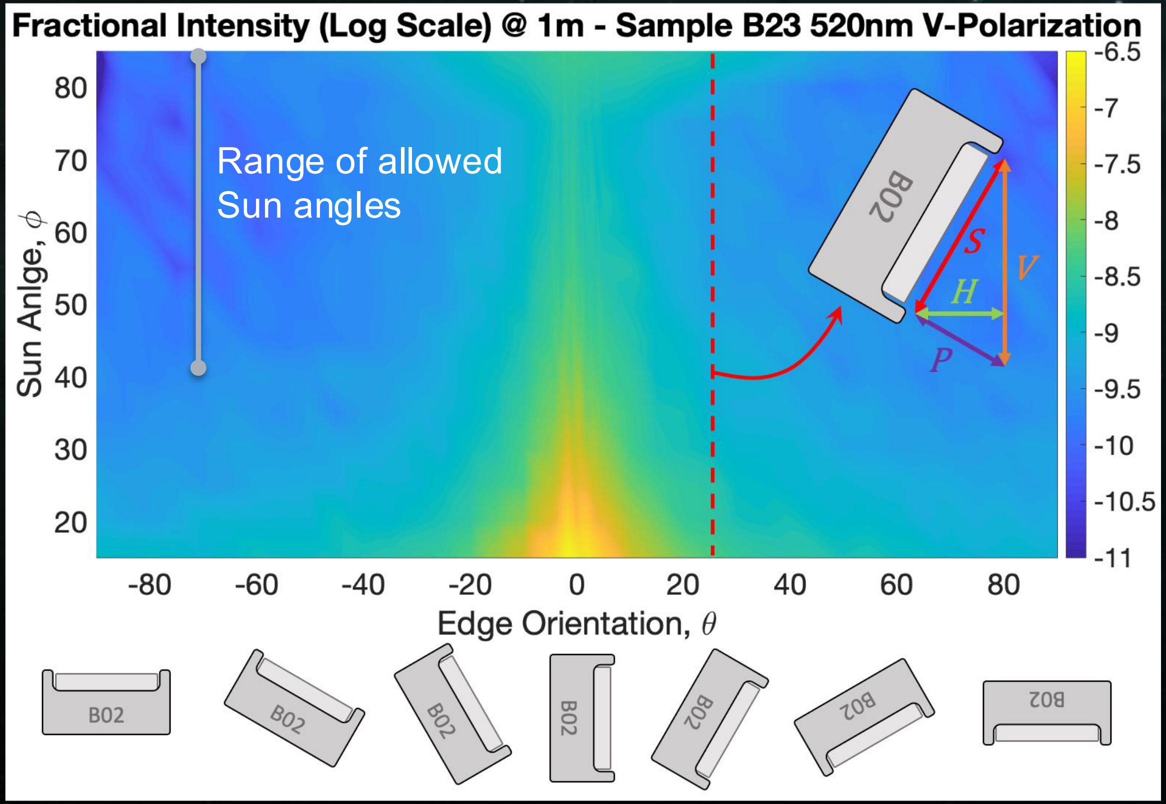
Starshade technology is highly advanced and has demonstrated deep contrast as well as the ability to control the starshade shape to well within required levels.

The HOEE concept is exciting because it takes advantage of enormous apertures to allow them to see the faintest objects in the search for extraterrestrial life.

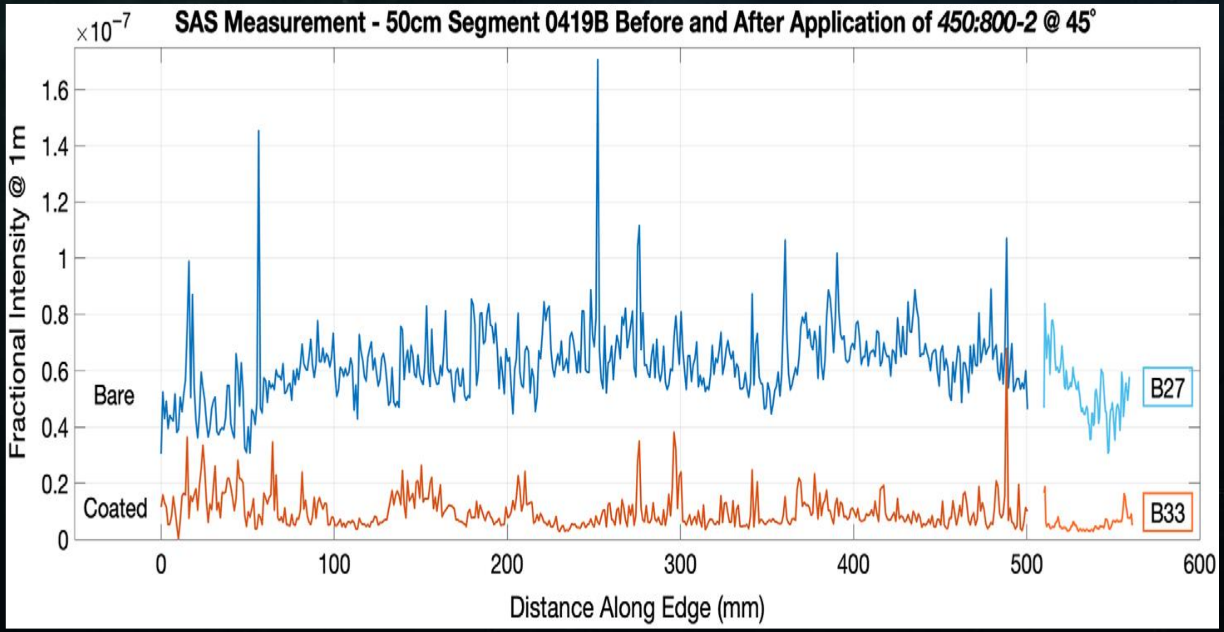
Backup Slides

COUPONS AND EDGE SEGMENTS





McKeithen et al, SPIE 2020



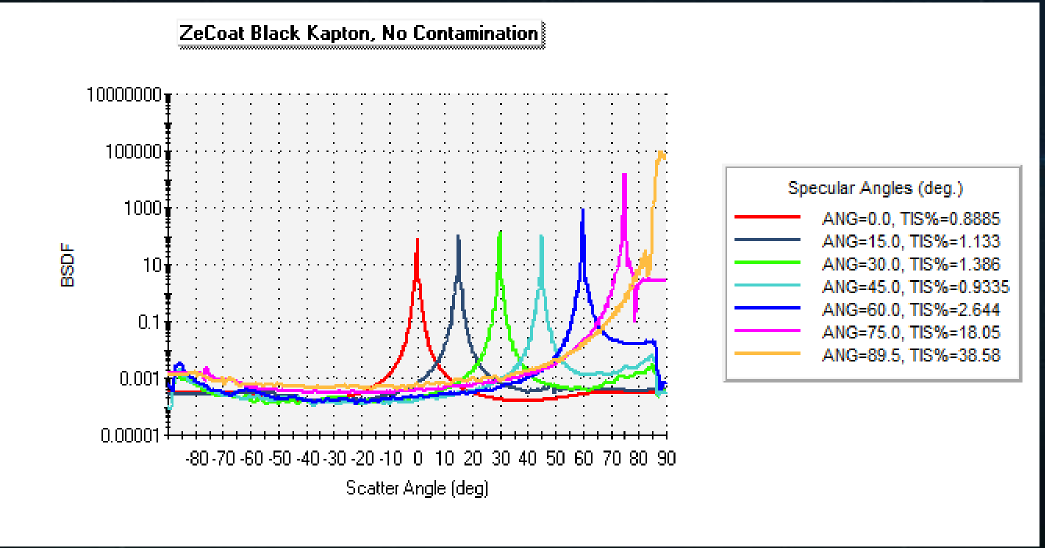
McKeithen et al, JATIS 2021

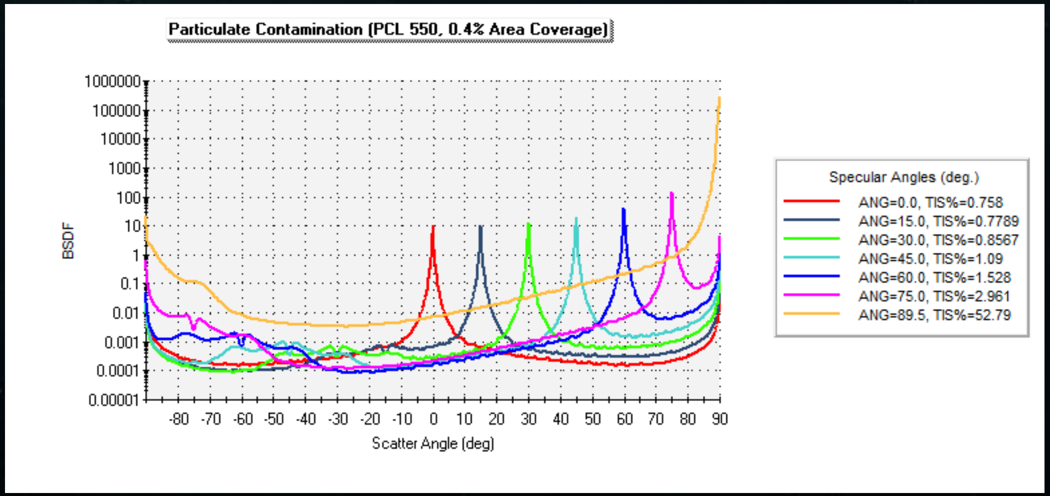
Stray Light Coatings and Contamination

Our scatter 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.)

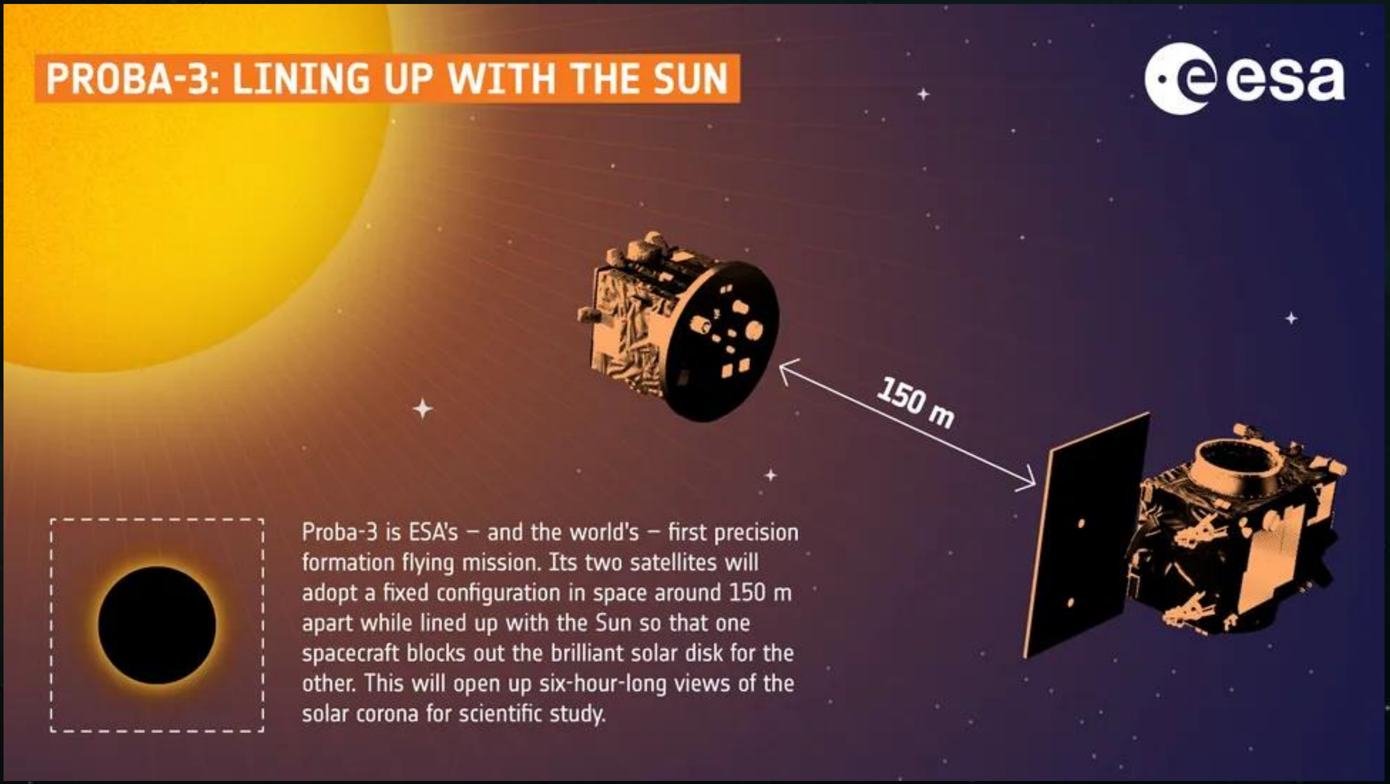




PROBA-3: An External Occulter on Orbit

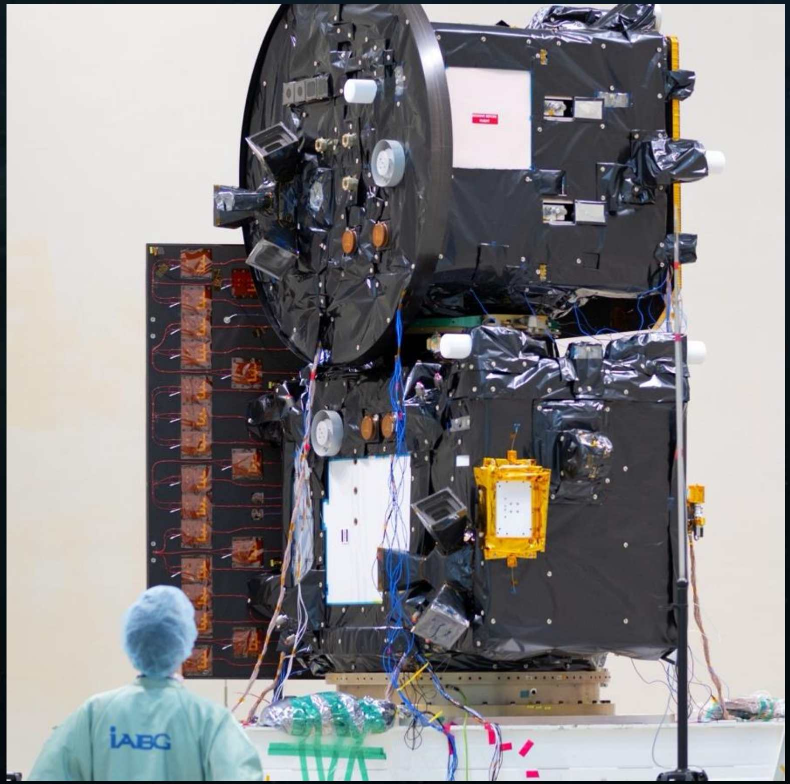
PROBA = PRoject for On Board Autonomy

Developed by ESA, launched by Indian Space Agency, December 2024. 20 hour highly-elliptical orbit. Autonomous formation flying to 1 mm over a distance of 150 m, for up to 6 hours of each orbit.



Configuration Overview

Image credit: ESA – F. Zonno



The two spacecraft stacked in launch configuration.

Image credit: https://www.group.sener/en/project/proba-3-formation-flying-mission/

Solar Glint: Two Lobe Pattern

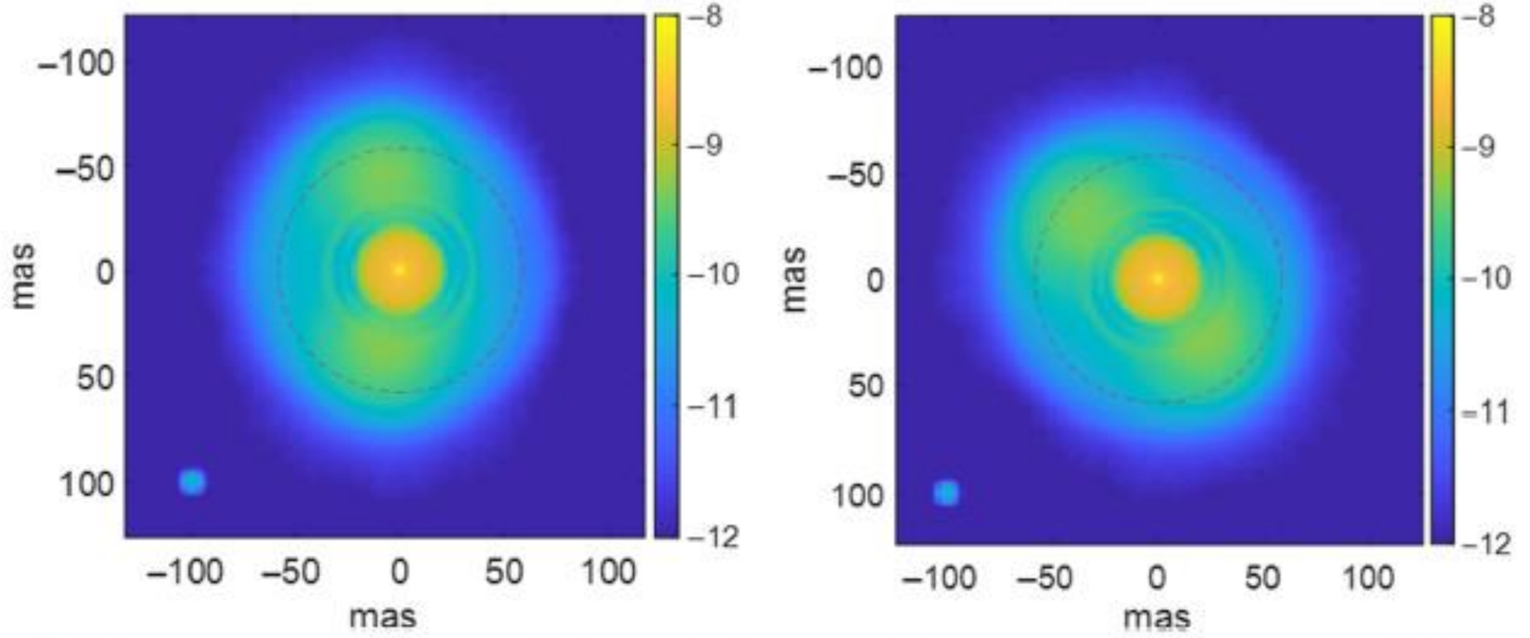


Fig. 10 Effect of solar glint at the image plane with different rotations of the Sun around the plane ($\alpha = 90$ deg and 45 deg) from uncoated metallic edges. When the Sun is positioned to the side and behind the starshade, it reflects sunlight toward the telescope, resulting in a prominent two-lobed glint effect around the edges. The 10^{-10} star images at the lower left corners show the PSFs on a log scale.

Spinning vs. non-spinning starshade trade:
Spinning smooths out the local "speckles" from local perturbations. This relaxes starshade tolerances and simplifies calibration, but may complicate thrusting and station keeping.
By not spinning, we can use serrated edges, like a stealth fighter jet, to eliminate the solar glint.

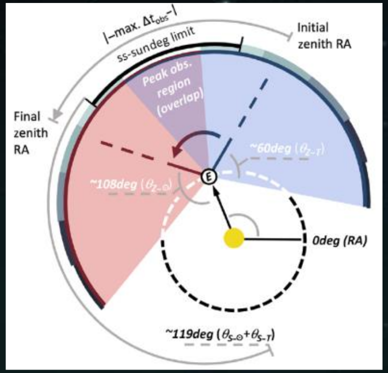
HOEE: Observing Geometry

Constraints:

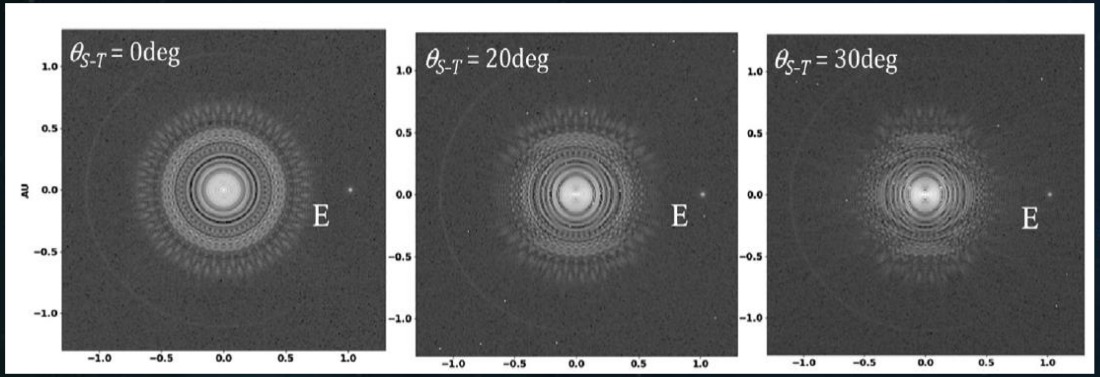
Sun at least 18 deg below horizon
- dark sky

Starshade facing anti-Sun hemisphere
- no direct sunlight on telescope-facing side

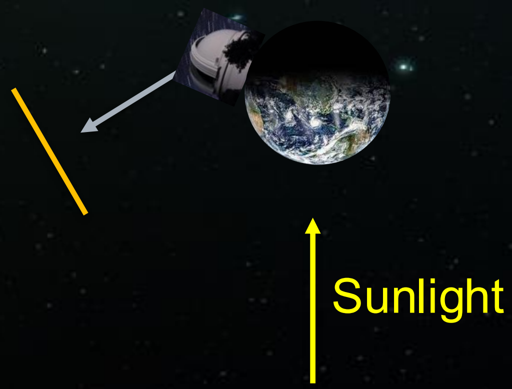
Target > 30 deg above horizon
- telescope pointing constraint



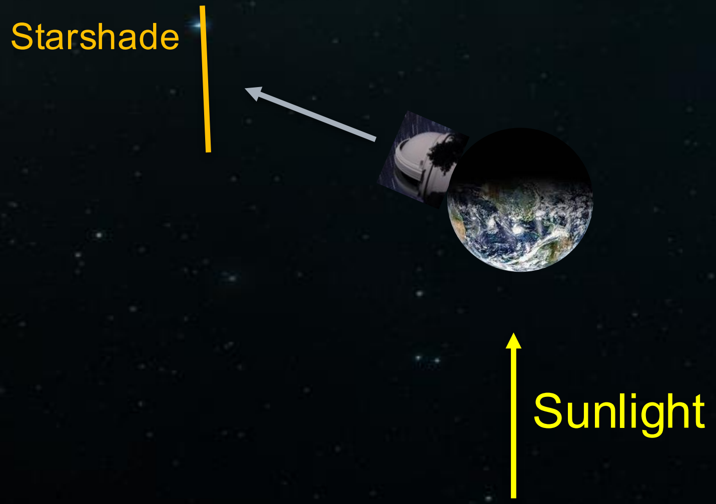
Peretz et al, JATIS 2021



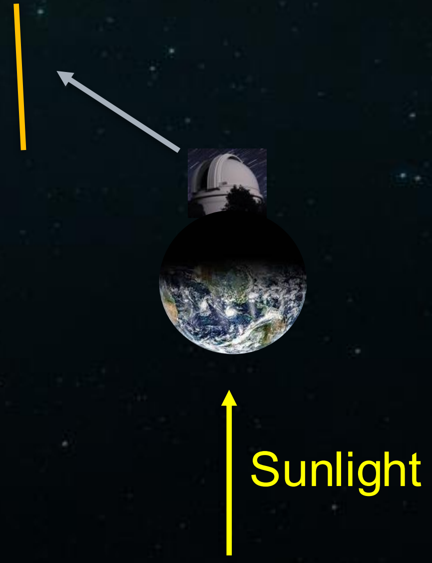
End of night (Sun 18 deg below horizon):
Target > 30 deg above horizon.
Starshade normal target.



End of night (Sun 18 deg below horizon):
Target at zenith
Starshade tilted 19 deg from target.



Midnight:
Target > 30 deg above horizon.
Starshade tilted > 31 deg to target.



Imaging an Exoplanetary System

Solar type star at 17 pc, 20 minute exposure, 40-1000 nm, Strehl Ratio 0.4 – 1.0.