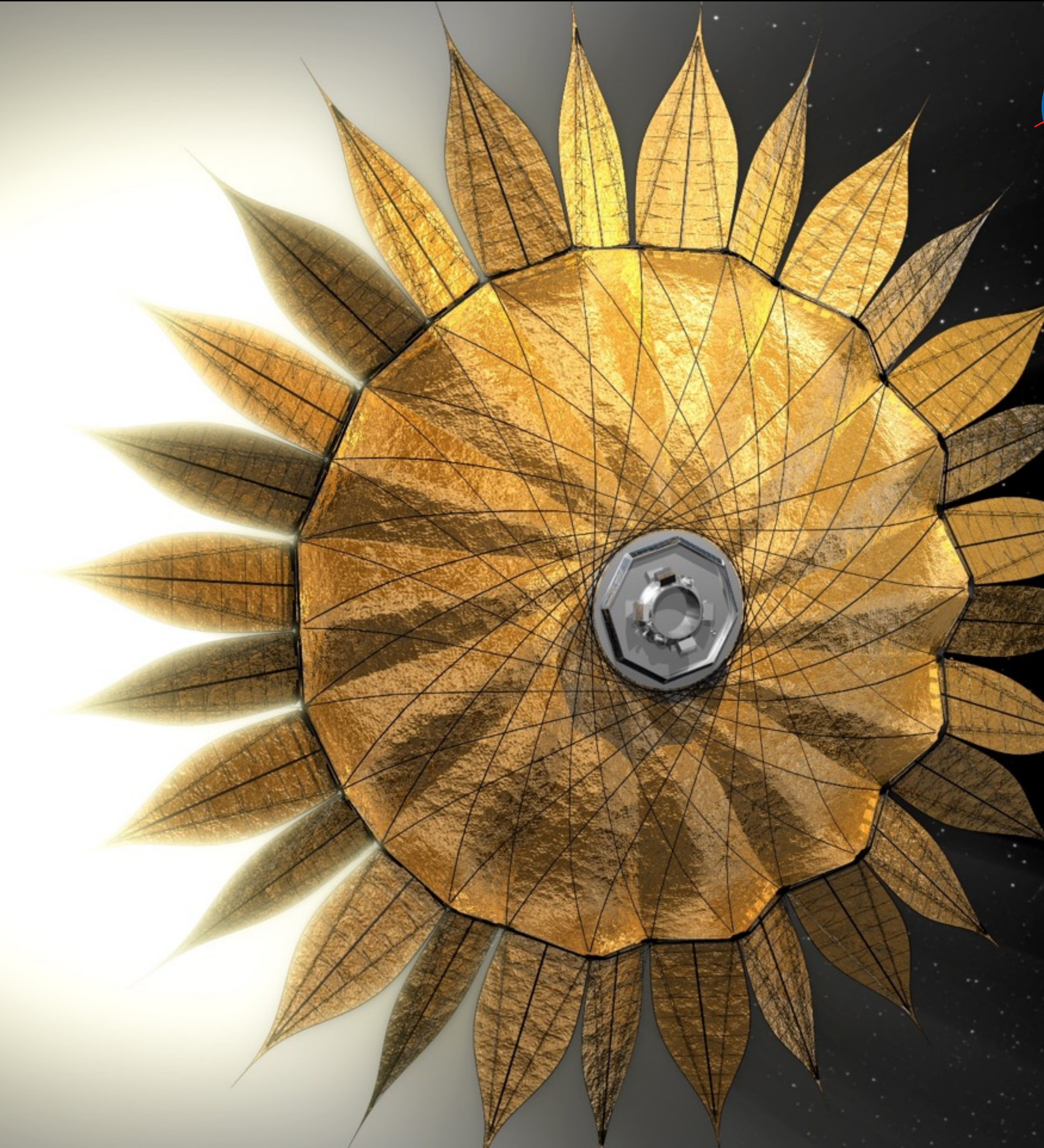
Jet Propulsion Laboratory
California Institute of Technology



Starshade Technology to TRL5 Activity (S5)

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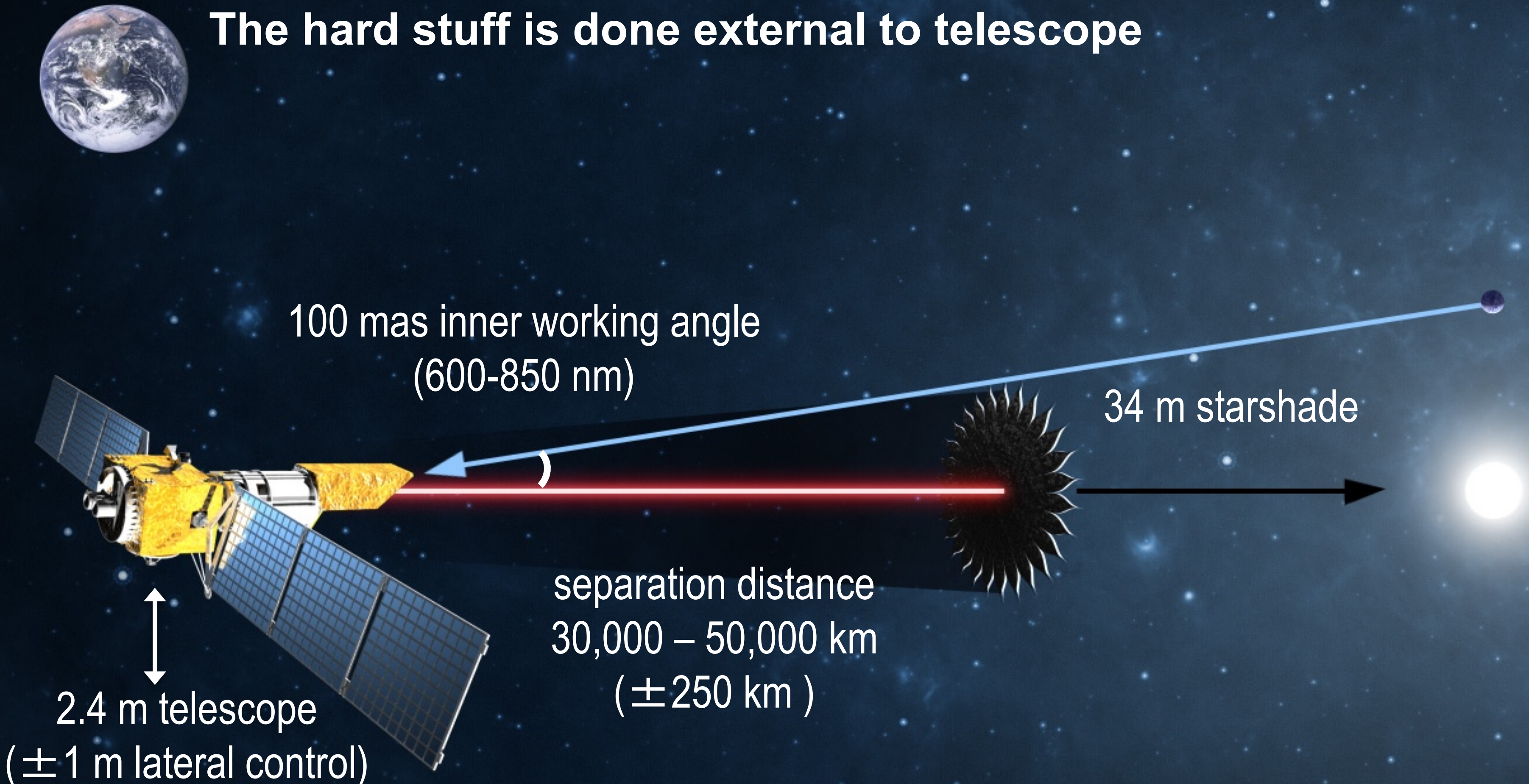
NASA Exoplanets Exploration Program
S5 Activity Deputy Manager
Jet Propulsion Laboratory
California Institute of Technology

November 5, 2018 **SPIE Mirror Technology Workshop**

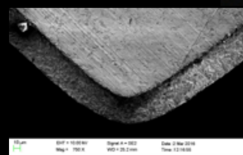
Starshade

The hard stuff is done external to telescope

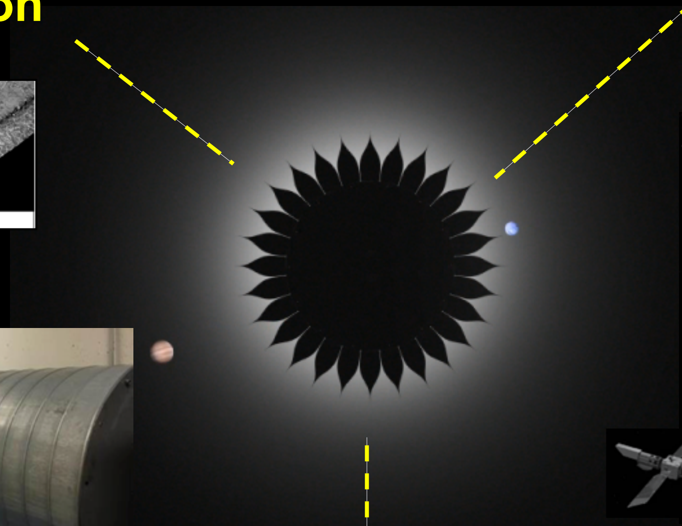


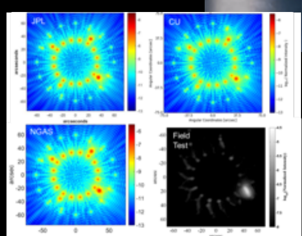
The Three Starshade Technology Gaps

(1) Starlight Suppression



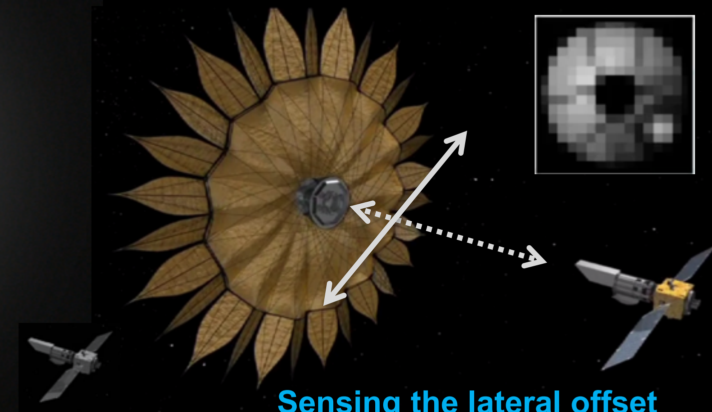
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)





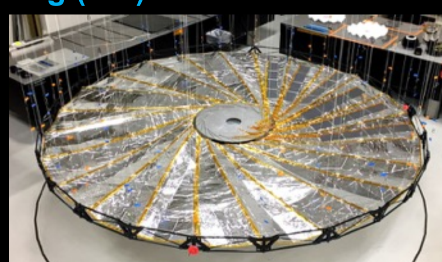
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(2) Formation Sensing

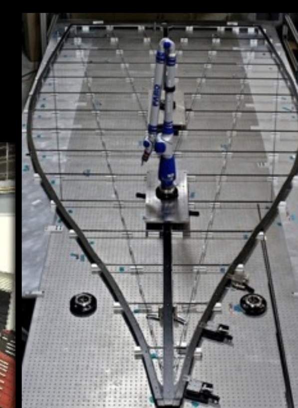


Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability



Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)



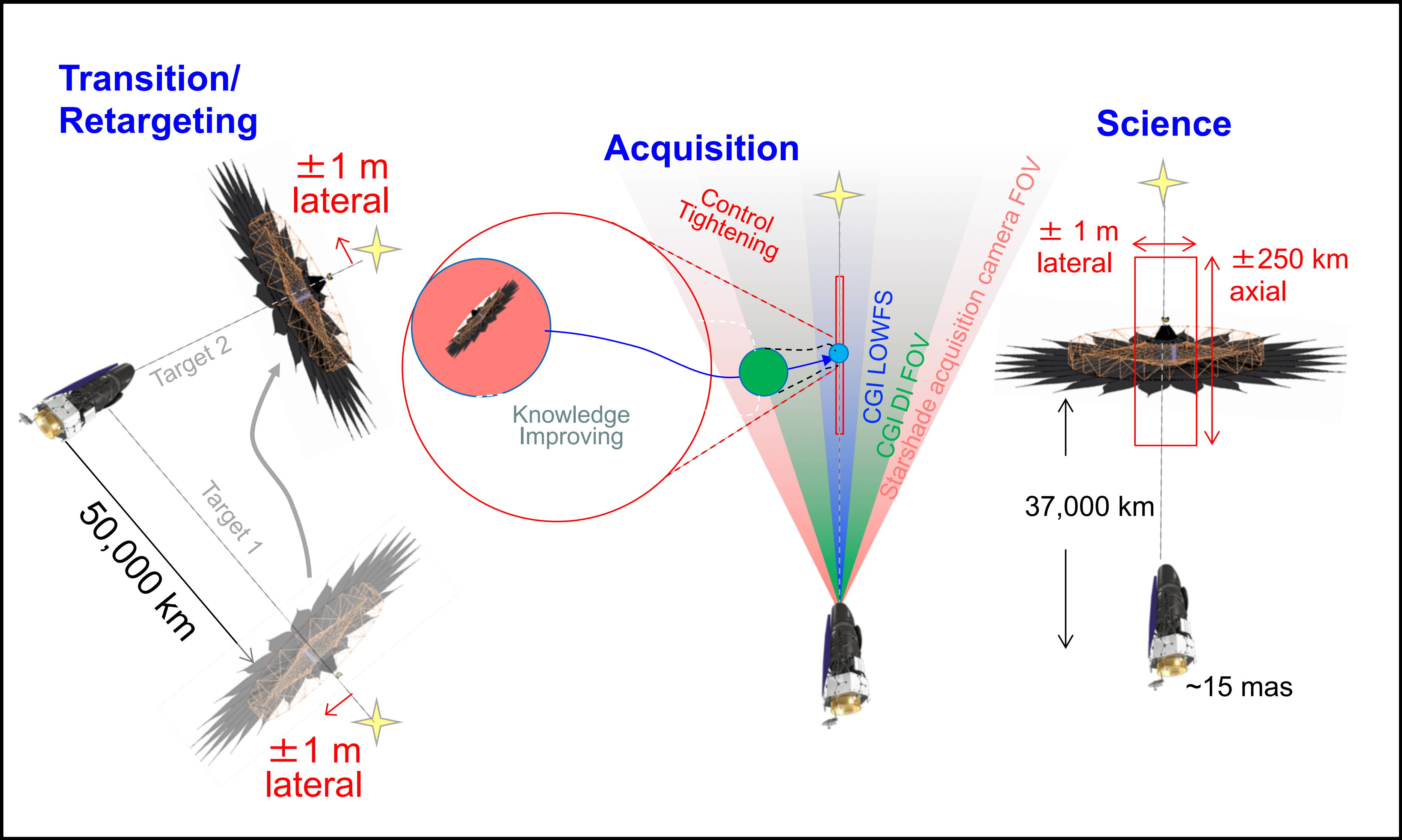
Fabricating the petals to high accuracy (S-4)

S-# corresponds to ExEP Starshade Technology Gap (http://exoplanets.nasa.gov/exep/technology/gap-lists)

Organization of Activity

- NASA previously funded starshade technology development through competed TDEM awards
- NASA merged these (mostly) into coordinated Activity to bring its technical readiness level to TRL5, called S5.
- S5 Technology Development Plan approved by NASA Astrophysics Division in September 2018
  - Brings all technologies to TRL5 by 2023
  - Brings some technologies (e.g. formation flying) to TRL5 prior to Decadal Survey
  - Plan retires as much risk as possible in other technologies prior to Decadal.
- S5 includes Science and Industry Partners (SIP) program to solicit fresh ideas and approaches

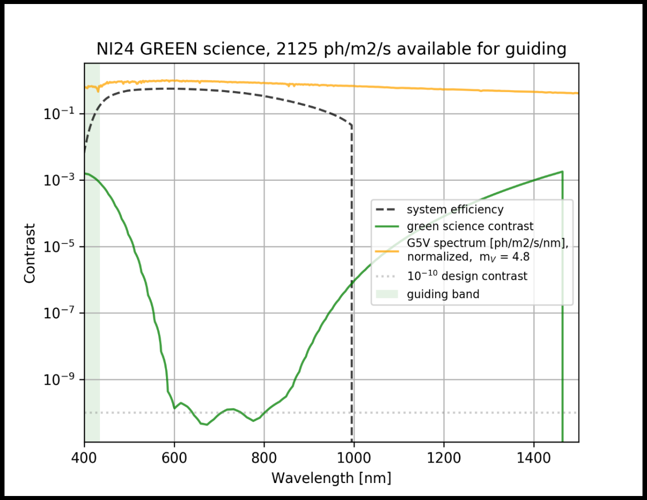
Formation Flying
High Level Operations Concept

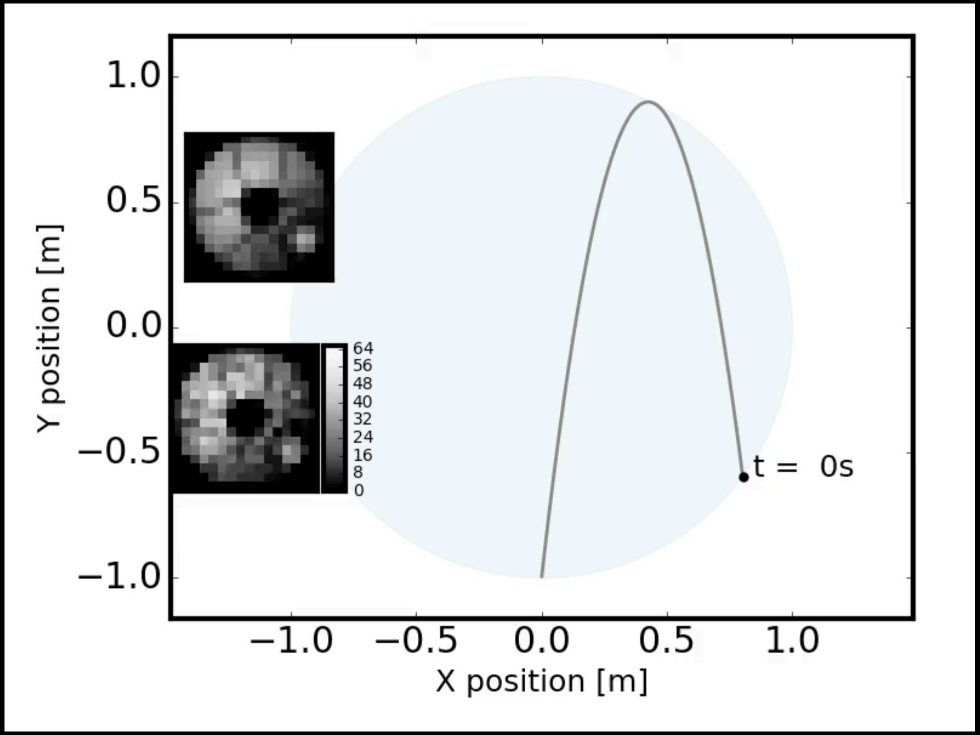


Formation Flying

Lateral Offset Sensing Concept

- Using pupil plane wavefront sensor and out-of-band stellar diffraction allows for accurate sensing at the ~cm level around all target stars
- Pupil image is collected and compared to library of stored offset pupil images to determine direction and distance of lateral offset

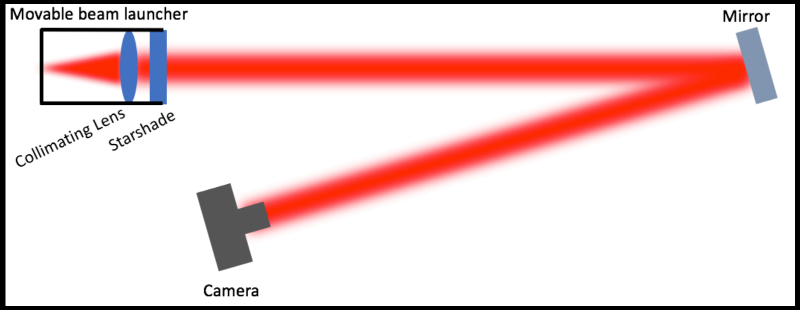


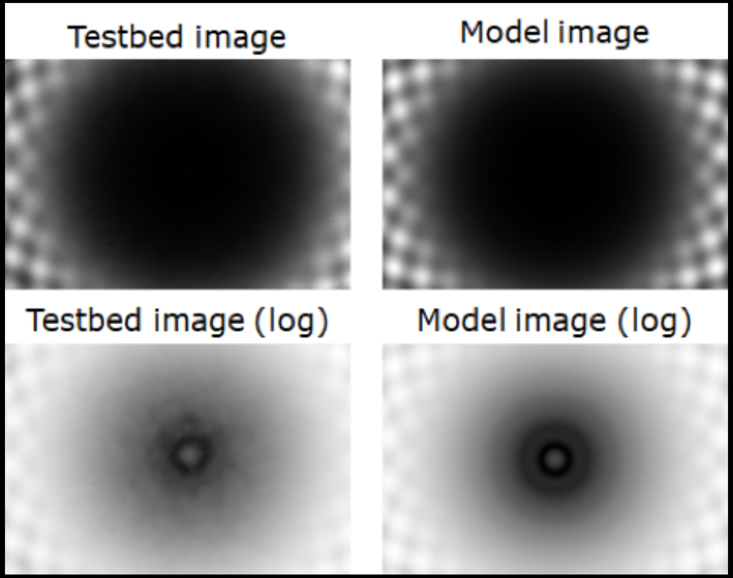


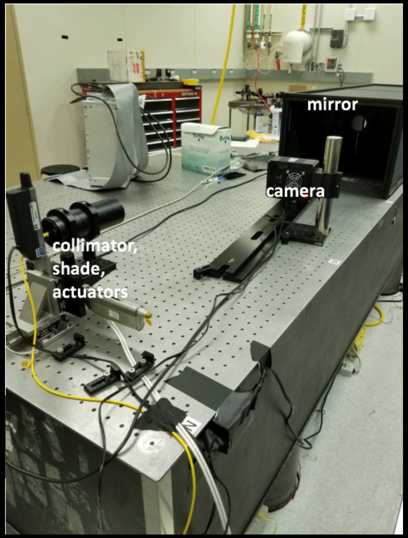
POC: Michael Bottom (JPL)

Formation Flying
SLATE testbed

- Starshade Lateral Alignment Testbed (SLATE) measures out-of-stopband shadows cast in scaled starshade geometry to test optical performance and ability to accurately sense starshade offsets in telescope pupil plane.





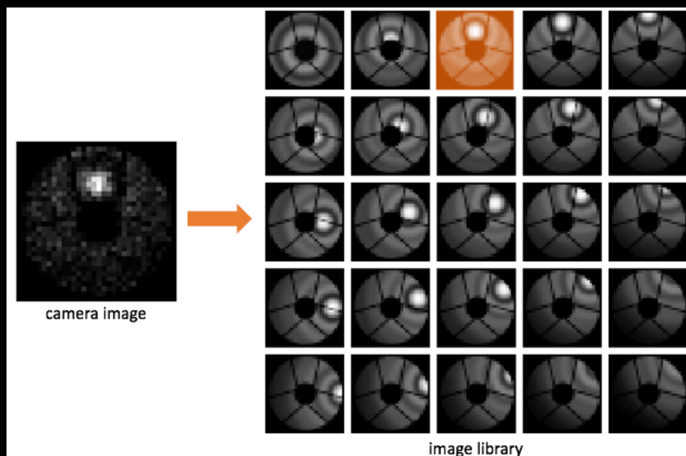


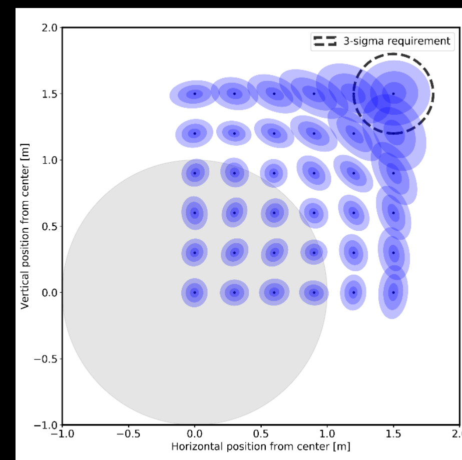
POC: Michael Bottom (JPL)

Formation Flying

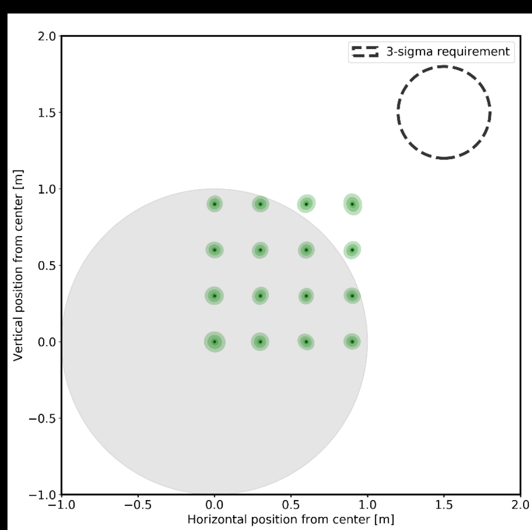
Lateral Offset Sensing

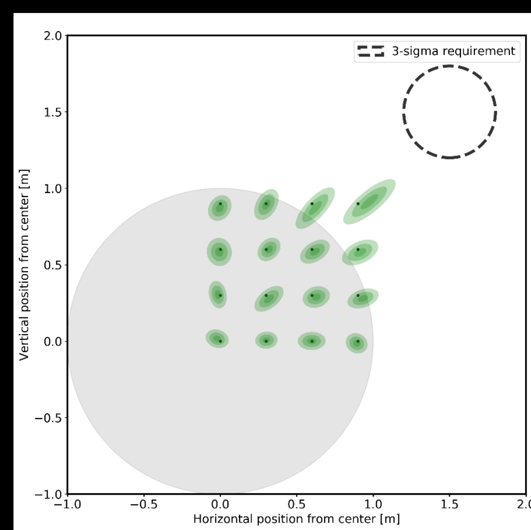
- Pupil image is collected and compared to library of stored offset pupil images to determine direction and distance of lateral offset





Optical model





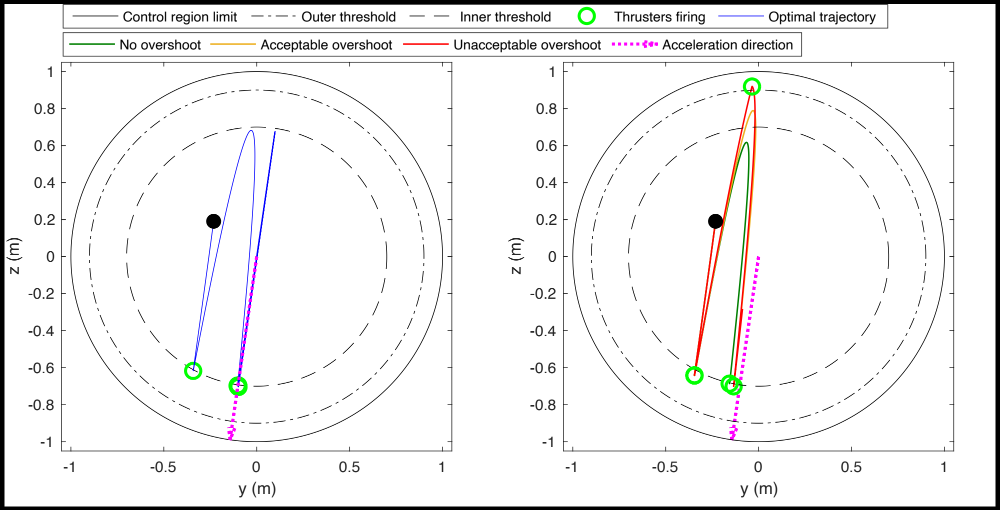
SLATE results

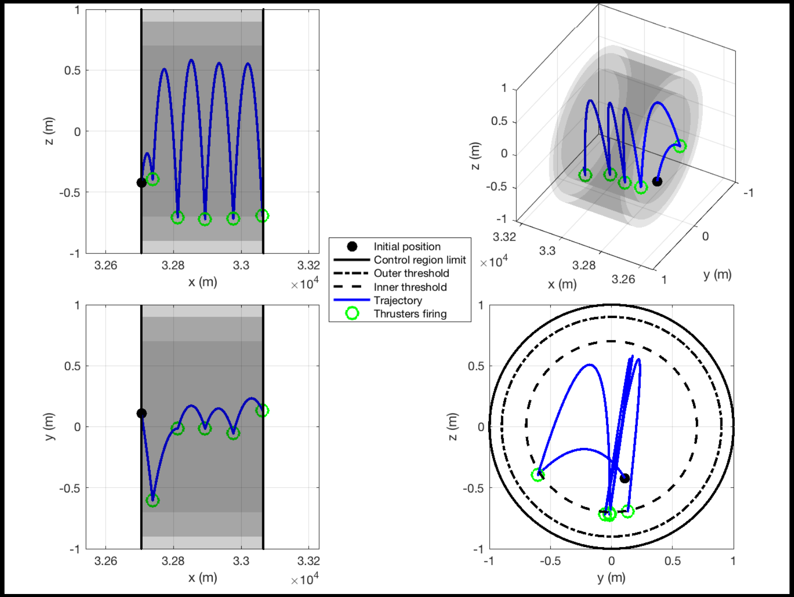
POC: Michael Bottom (JPL)

Formation Flying

Closed Loop Formation Flying Model

- Control scheme attempts to keep starshade ballistically ‘bouncing’ within inner threshold. Outer threshold deal gracefully with ‘overshoots’ to maintain ±1m positioning.

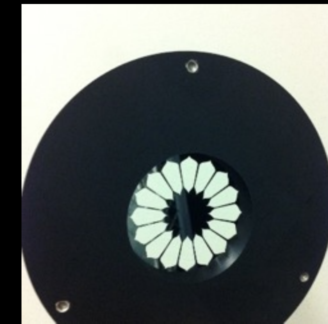


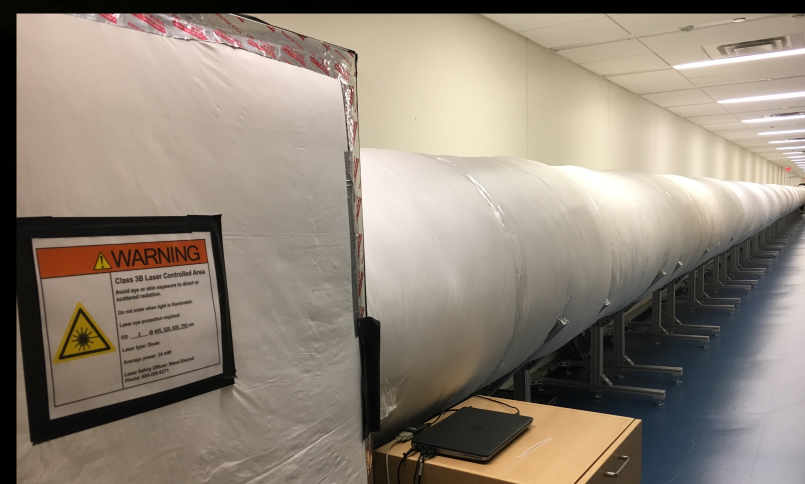


- Models demonstrate successful position control with lab-validated optical performance.

Optical Performance

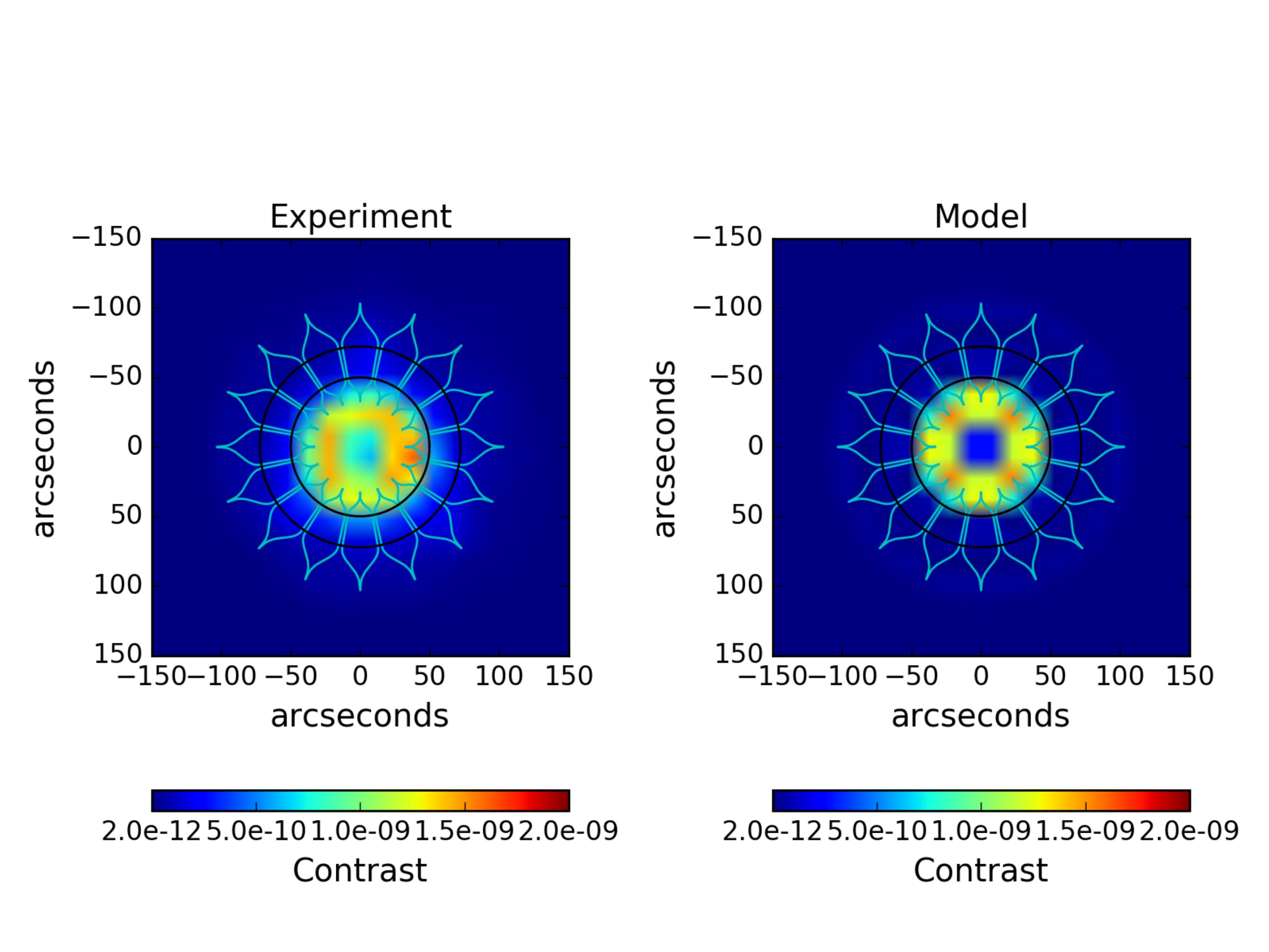
Starshade Testbed at Princeton University





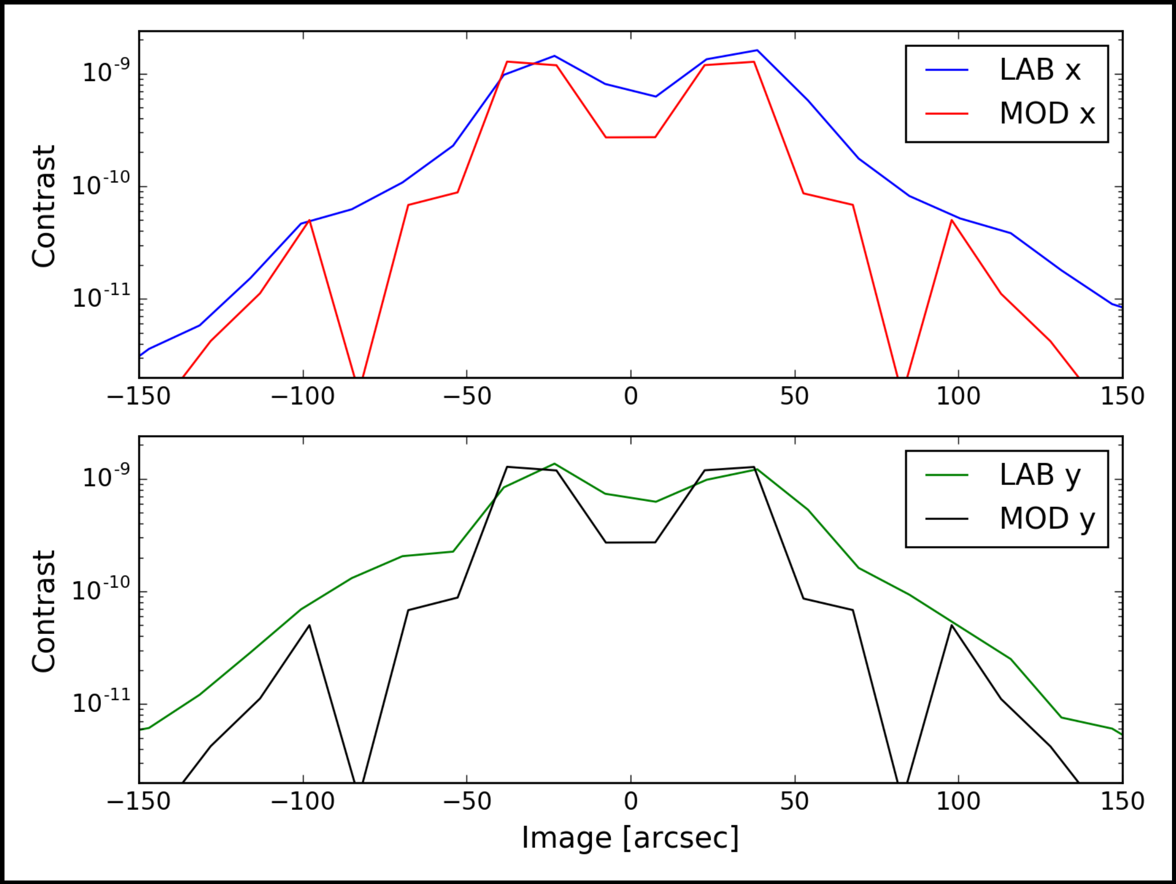
Optical Performance

Testbed Data – Driving toward Model Validation



Optical Performance

Testbed Data – Driving toward Model Validation



Optical Edge Development (Petals)

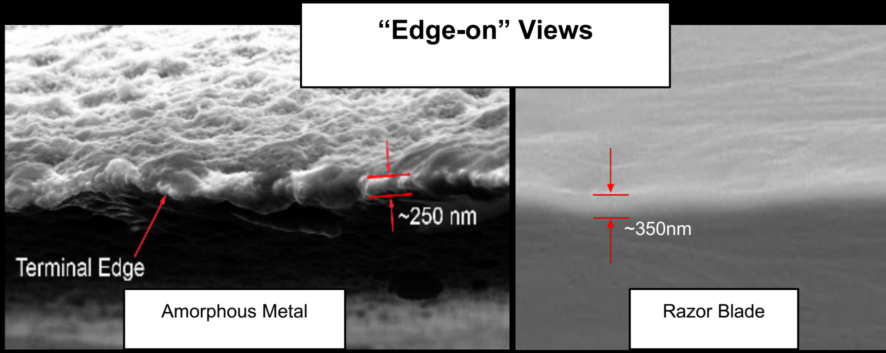
Scattered Sunlight Suppression

Need:

- *Petal edges that reduce solar glint magnitude to levels below that of the apparent zodiacal dust*
    - ❖ *Edge radius (μm) * reflectivity (%) < 10 um%*
- *Petal edges that maintain precision in-plane profile for starlight suppression*

Current Capabilities:

- We know how to fabricate razor-sharp edges to minimize total area available for solar scatter/glint (photochemical etching)
- Amorphous metal is currently the primary material candidate
- We know how to achieve ultra-black surfaces that absorb sunlight incident to petal edges (low-reflectivity coatings)

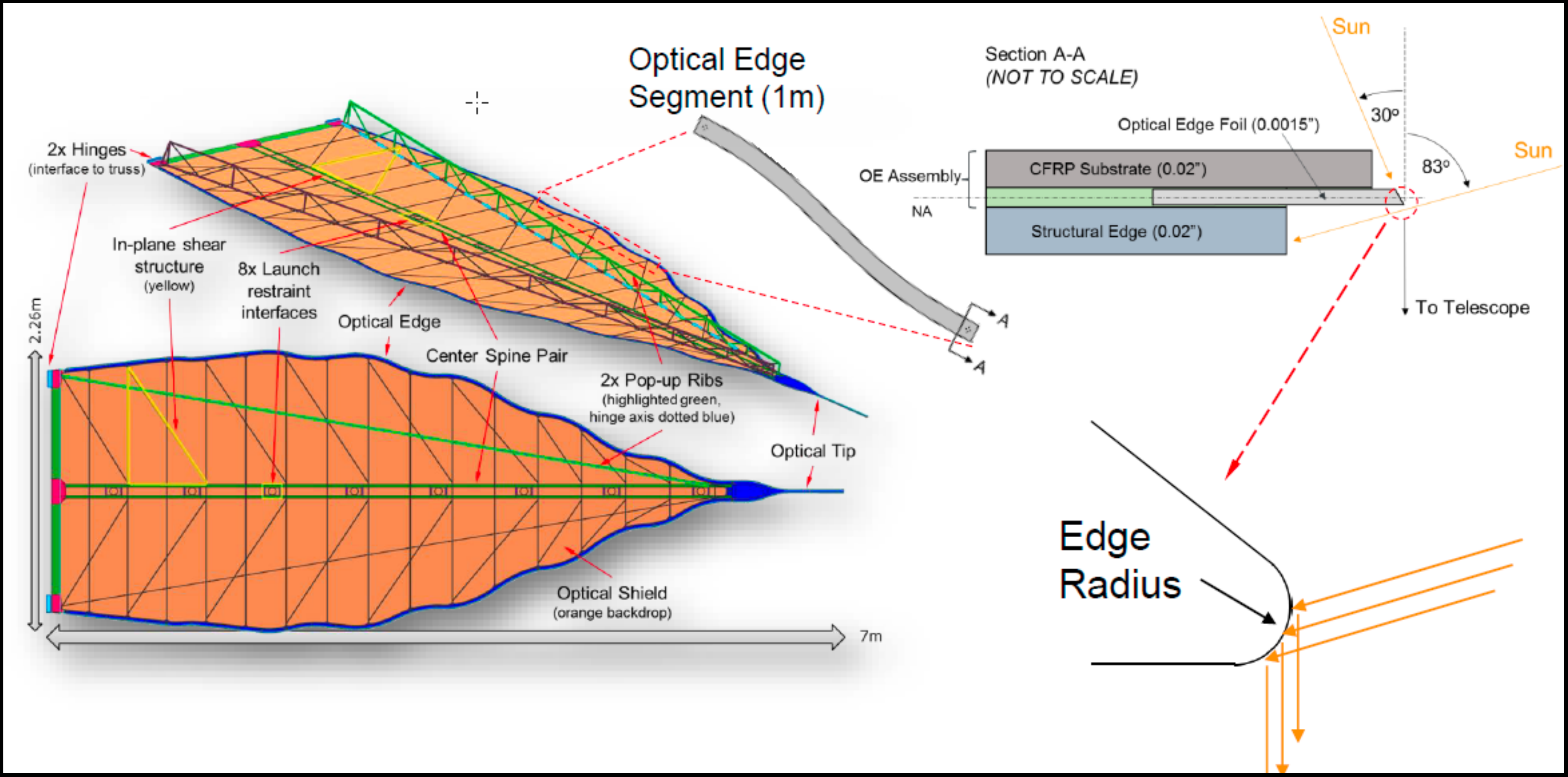


Comparable edge sharpness achieved between etched amorphous metal edges and Gem razor blades

Ultra-black surface coatings can potentially relax requirement on edge sharpness

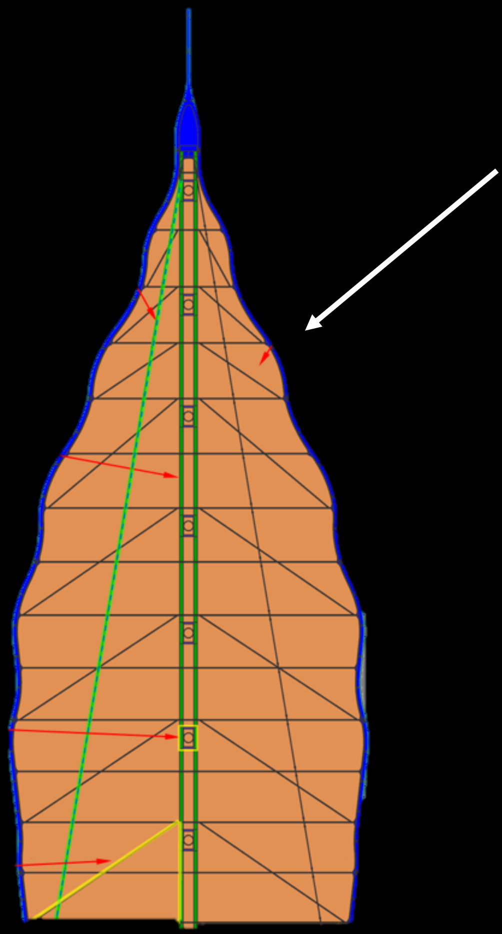
Optical Edge Development

SBIR Award: Tendeg's Petal Optical Edge Integration



Optical Edge Development

SBIR Award: Photonic Cleaning Technologies' "Polymer Edge Coating-Based Contaminant Control"

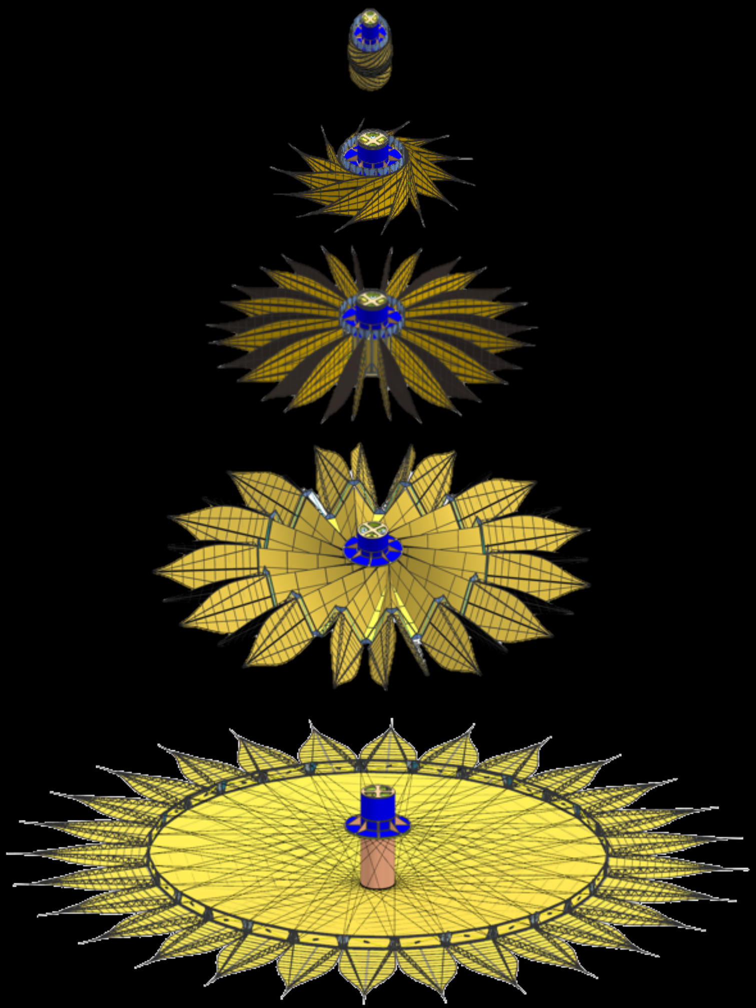


To avoid solar glare and scatter interference petal optical edges must be razor-sharp <u>and</u> exceedingly clean

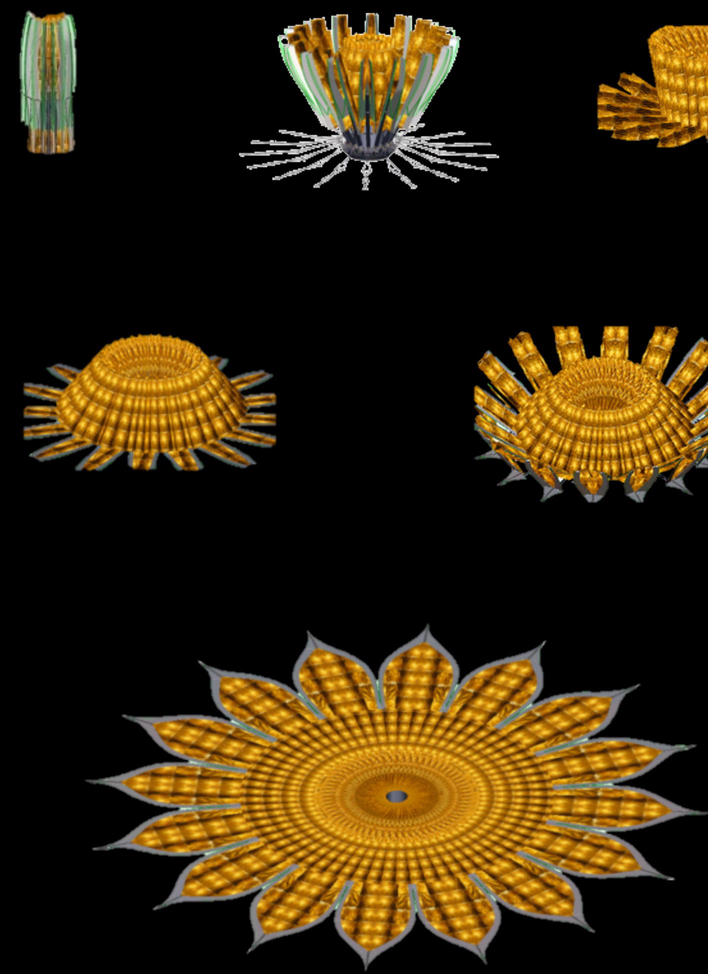
- *a few 100 µm dust particles on an edge scatters light comparable to the signal of an exoplanet.*

Photonic Cleaning Technologies proposes to develop a novel pourable, peelable, low adhesion, residueless polymer coating that will clean and protect the starshade's amorphous metal edges from manufacture to launch.

Trade Study Complete: NASA has Chosen Wrapped Design for Technology Development



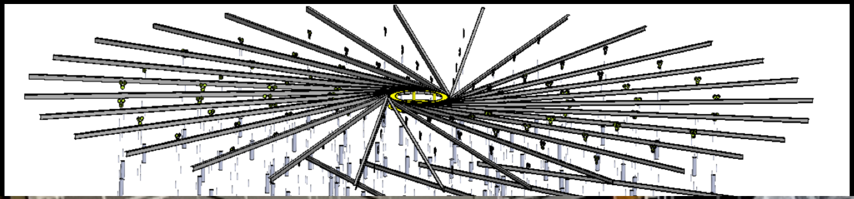
Furled and wrapped petal deployment concept (JPL)



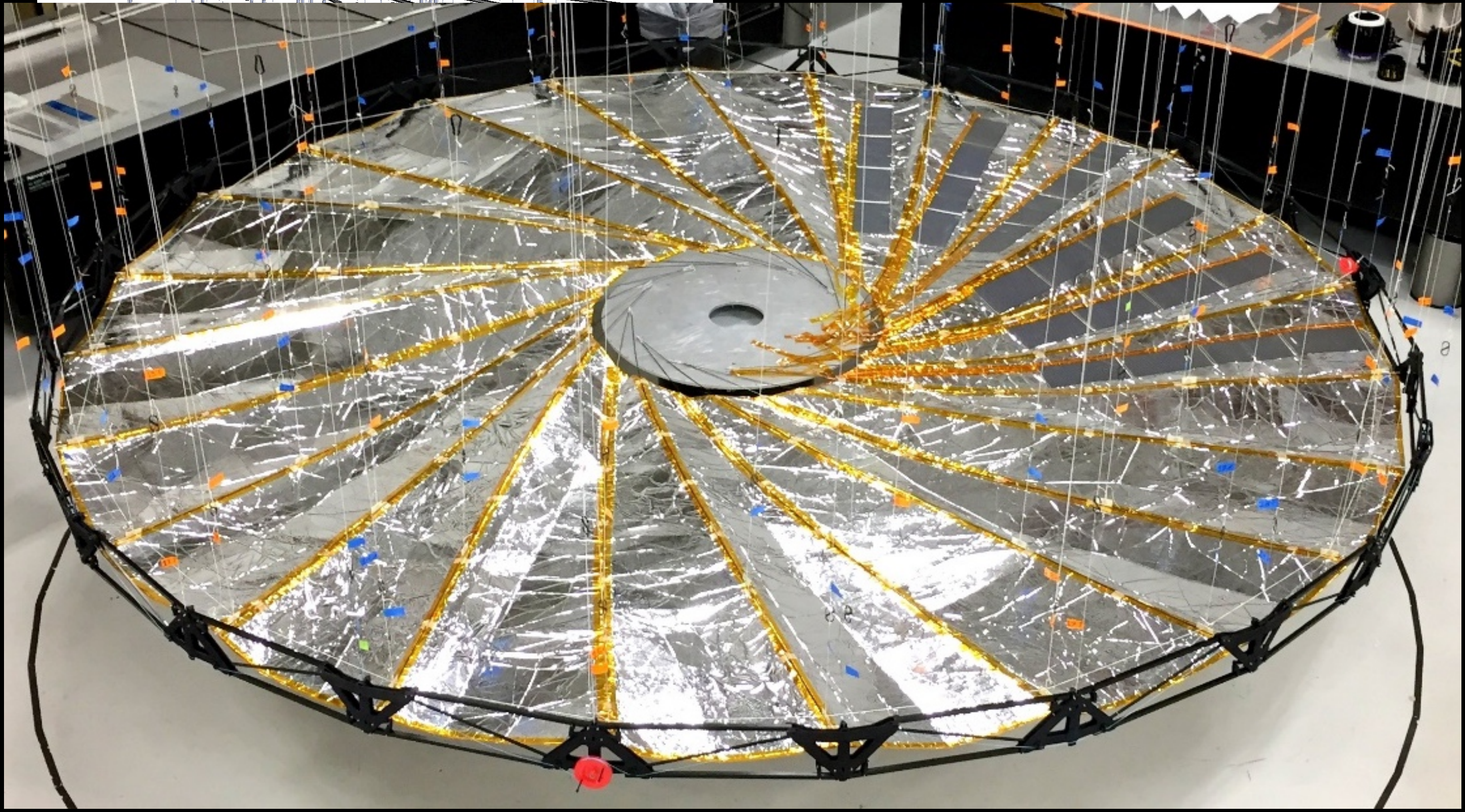
Boom supported and folded petal deployment concept (Northrop Grumman)

Optical Shield Testbed Gravity Offloading

SBIR Award: Roccor / Tendeg

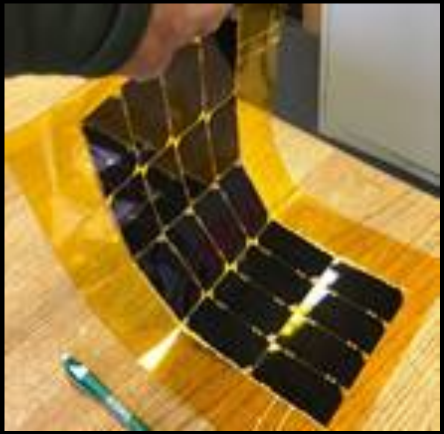


Roccor and Tendeg are made up of experts in composite materials, space mechanisms, and deployable structures

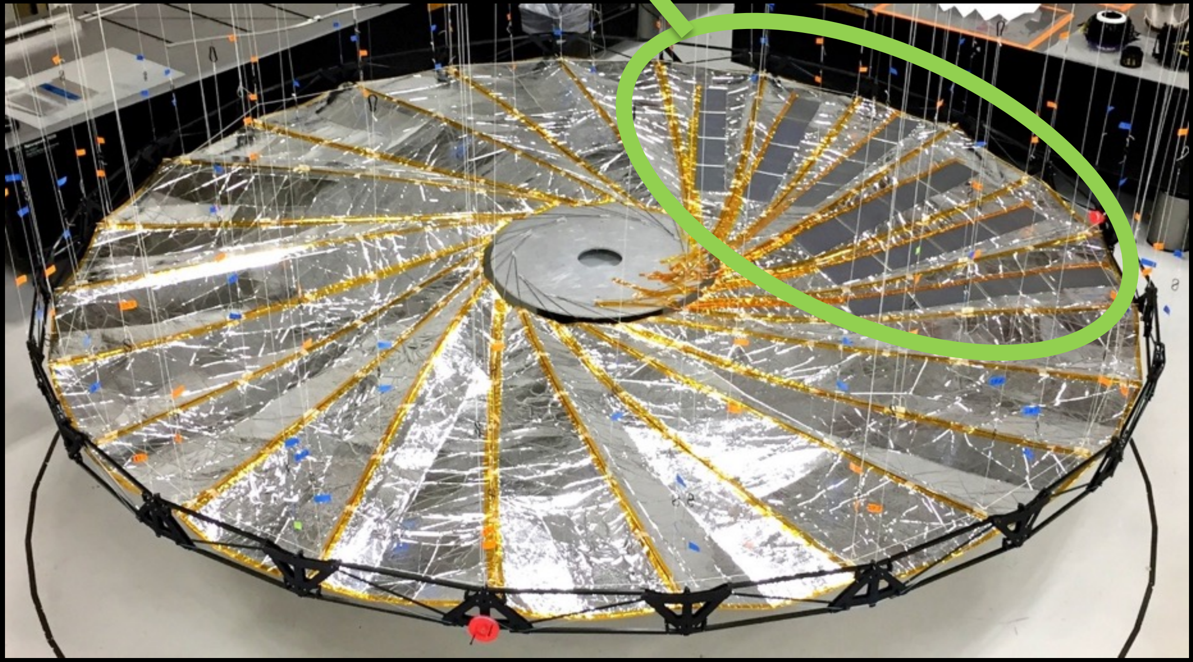


Optical Shield Solar Arrays

SBIR Award: Tendeg's Solar Array Integration

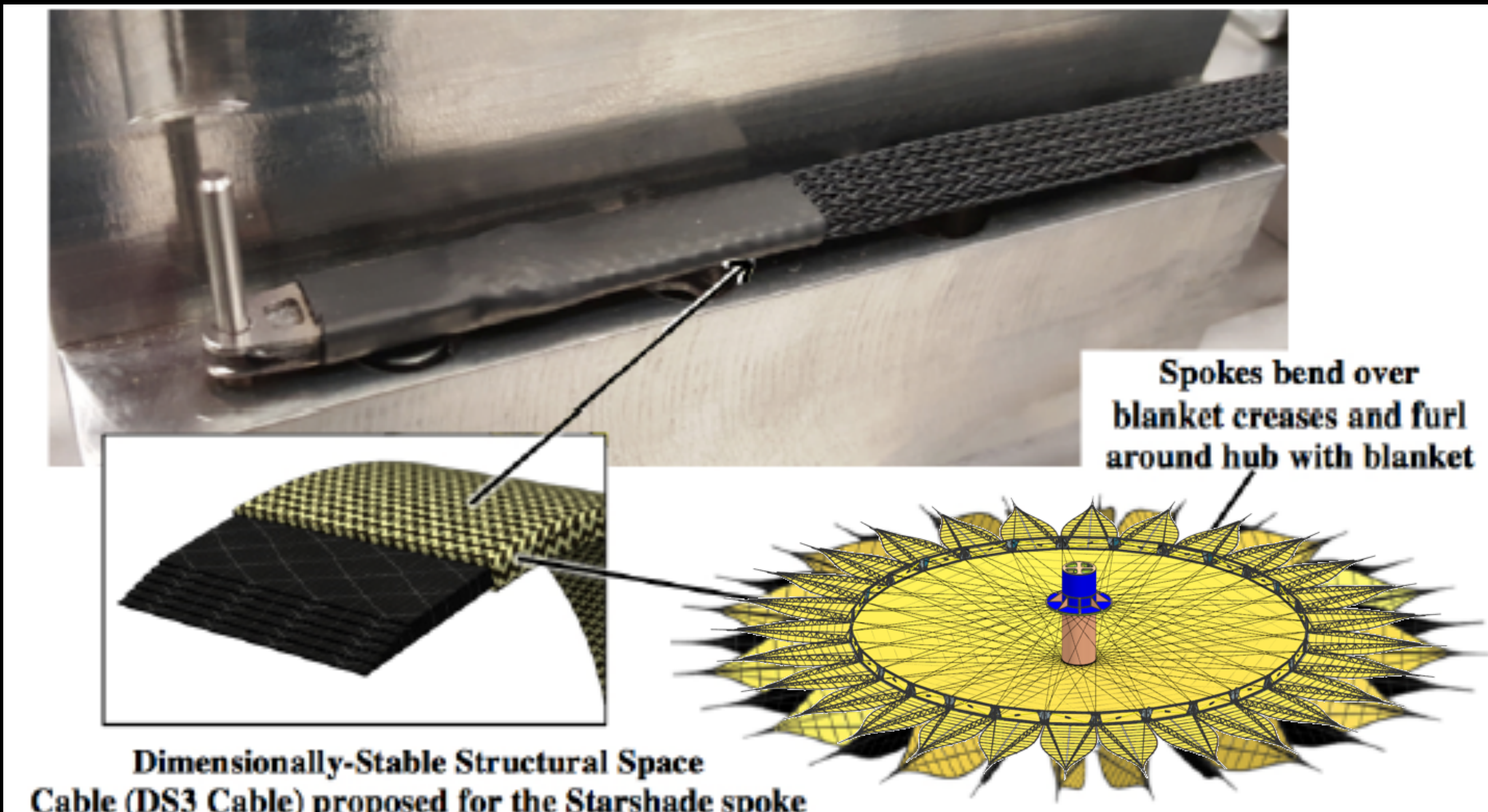


thin photovoltaic



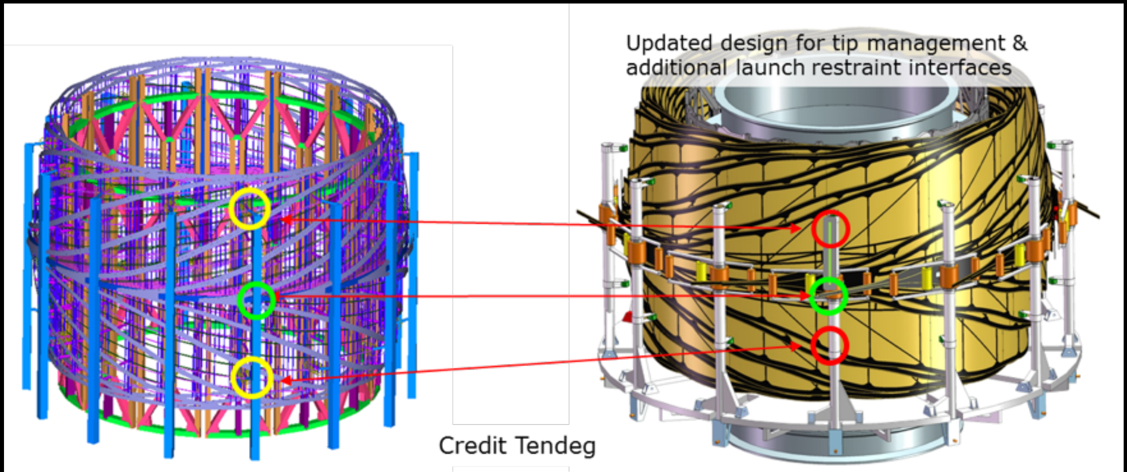
Inner Disk and Optical Shield Deployment

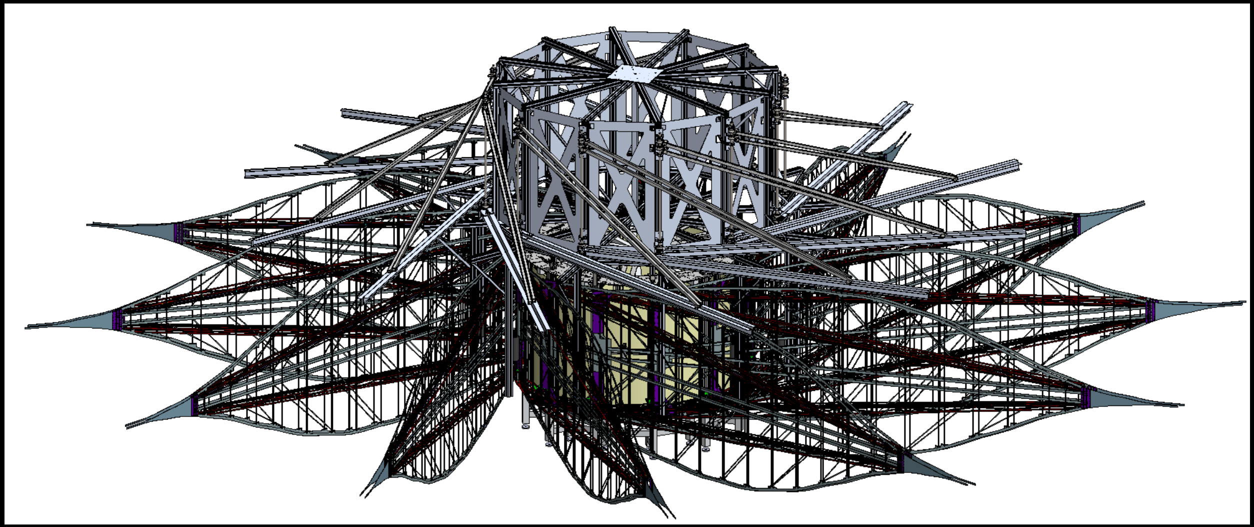
SBIR Award: Roccor's Dimensionally-Stable Structural Spoke



Petal Unfurler 2.0

SBIR Award: Tendeg's Petal Launch Restraint and Unfurl System





S5 Starshade Key Performance Parameters

Technology Gaps	KPP #	KPP Specifications	KPP Threshold Values	Threshold Contrast	KPP Goals
Starlight Suppression	1	Demonstrate flight **instrument contrast** performance at inner working angle is viable via small-scale lab tests	1×10^{-10}	N/A	5×10^{-11}
	2	Validate **contrast model accuracy** relative to flight-like shape errors	$\leq 25\%$	N/A	$\leq 10\%$
Solar Scatter	3	Verify **solar scatter** lobe brightness visual magnitude	$V \geq 25$ mags	N/A	$V \geq 26$ mags
Lateral Formation Sensing & Control	4	Verify lateral **position sensor accuracy** and that it supports $\pm$ 1 m control via simulation	$\leq \pm$ 30 cm	1×10^{-11}	$\leq \pm$ 10 cm
Petal Shape	5	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	$\leq \pm$ 70 µm	1×10^{-11}	$\leq \pm$ 50 µm
	6	Verify on-orbit **thermal shape stability**	$\leq \pm$ 80 µm	8×10^{-12}	$\leq \pm$ 40 µm
Petal Position	7	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	$\leq \pm$ 300 µm	1×10^{-12}	$\leq \pm$ 212 µm
	8	Verify on-orbit **thermal shape stability**	$\leq \pm$ 200 µm	1×10^{-12}	$\leq \pm$ 100 µm

S5 Starshade Technology Milestones

MS #	Milestone	Report Completion Date	Exo-TAC Confirm by Decadal	% Risk Retired by Decadal
1A	Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle in narrow band visible light and Fresnel number $\leq$ 15.	1/28/19	X	100
1B	Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning $\geq$ 10% bandpass at the Fresnel number $\leq$ 15 at the longest wavelength.	3/30/19	X	100
2	Small-scale starshade masks in the Princeton Testbed validate contrast vs. shape model to within 25% accuracy for induced contrast between 10^{-9} and 10^{-8}.	1/15/20	X	100
3	Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles.	11/1/19	X	100
4	Starshade Lateral Alignment Testbed validates sensor model by demonstrating lateral offset position accuracy to flight equivalent of $\pm$ 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within $\pm$ 1 m.	11/14/18	X	100
5A	Petal subsystem with *shape critical features* demonstrates shape stability after deploy cycles (deployed) consistent with a total pre-launch shape accuracy within $\pm$ 70 µm.	12/20/19	X	80
5B	Petal subsystem with *all features* demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, and storage) to within $\pm$ 70 µm.	6/2/23		
6A	Petal subsystem with *shape critical features* demonstrates on-orbit thermal stability within $\pm$ 80 µm by analysis using a validated model of critical dimension vs. temperature.	12/20/19	X	80
6B	Petal subsystem all *features* demonstrates on-orbit thermal stability within $\pm$ 80 µm by analysis using a validated model of critical dimension vs. temperature.	6/2/23		
7A	Truss Bay *longeron and node subassemblies* demonstrate dimensional stability with thermal cycles (deployed) consistent with a total pre-launch petal position accuracy within $\pm$ 300 µm. (Note: SBIR funding dependency)	12/20/19	X	80
7B	Truss Bay *assembly* demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within $\pm$ 300 µm.	6/2/23		
7C	Inner Disk Subsystem with optical shield assembly that includes *deployment critical features* demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within $\pm$ 300 µm. (Note: SBIR funding dependency)	12/20/19	X	80
7D	Inner Disk Subsystem with optical shield assembly that includes *all features* demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within $\pm$ 300 µm.	6/2/23		
8A	Truss Bay *longeron and node subassemblies* demonstrate on-orbit thermal stability within $\pm$ 200 µm by analysis using a validated model of critical dimension vs. temperature.	12/20/19	X	80
8B	Truss Bay *assembly* demonstrates on-orbit thermal stability within $\pm$ 200 µm by analysis using a validated model of critical dimension vs. temperature.	6/2/23		