



Jet Propulsion Laboratory
California Institute of Technology

Starshade Technology to TRL5 Activity (S5)

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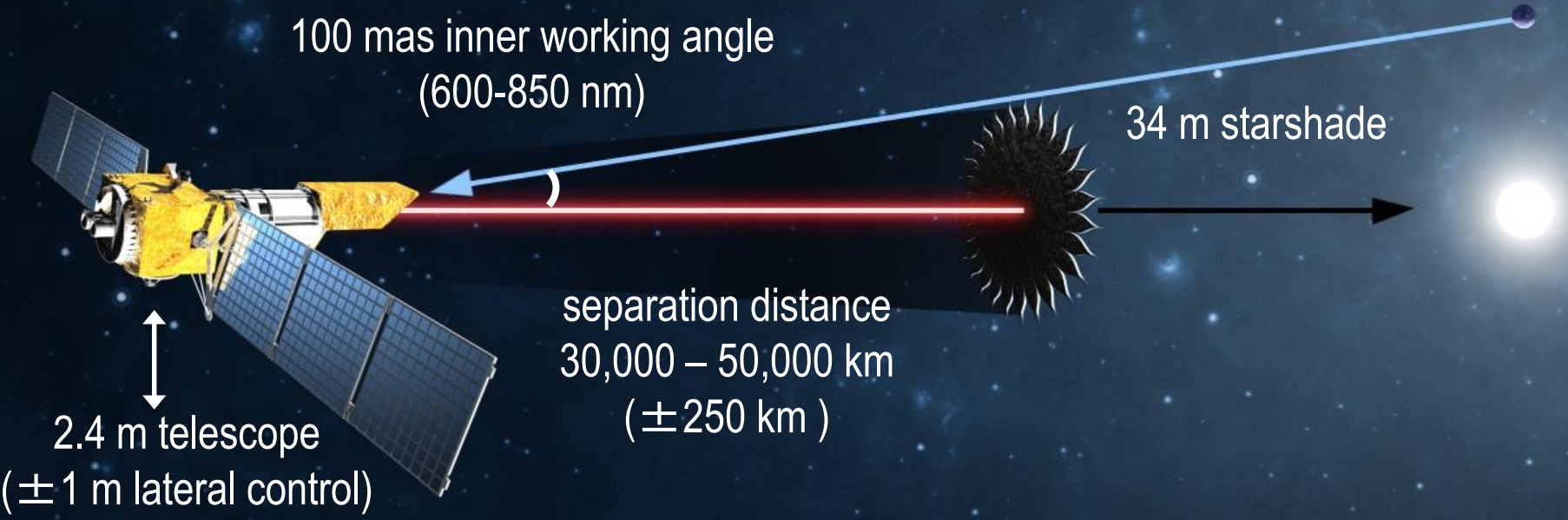
The decision to implement a starshade mission will not be finalized until after the 2020 Astrophysics Decadal Survey and NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

November 5, 2018

SPIE Mirror Technology Workshop

Starshade

The hard stuff is done external to telescope

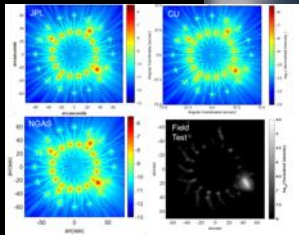


The Three Starshade Technology Gaps

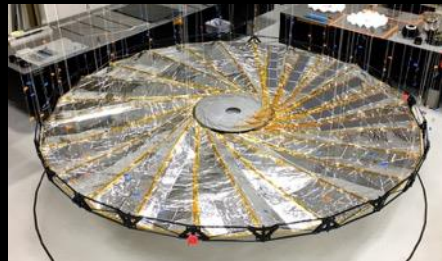
(1) Starlight Suppression



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

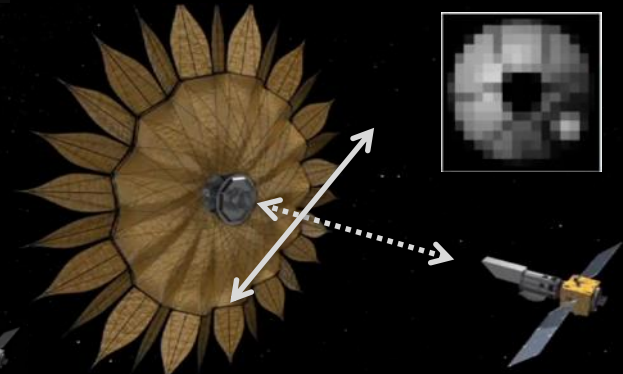


Suppressing diffracted light from on-axis starlight and optical modeling (S-2)



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

(2) Formation Sensing



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

(3) Deployment Accuracy and Shape Stability



Fabricating the petals to high accuracy (S-4)

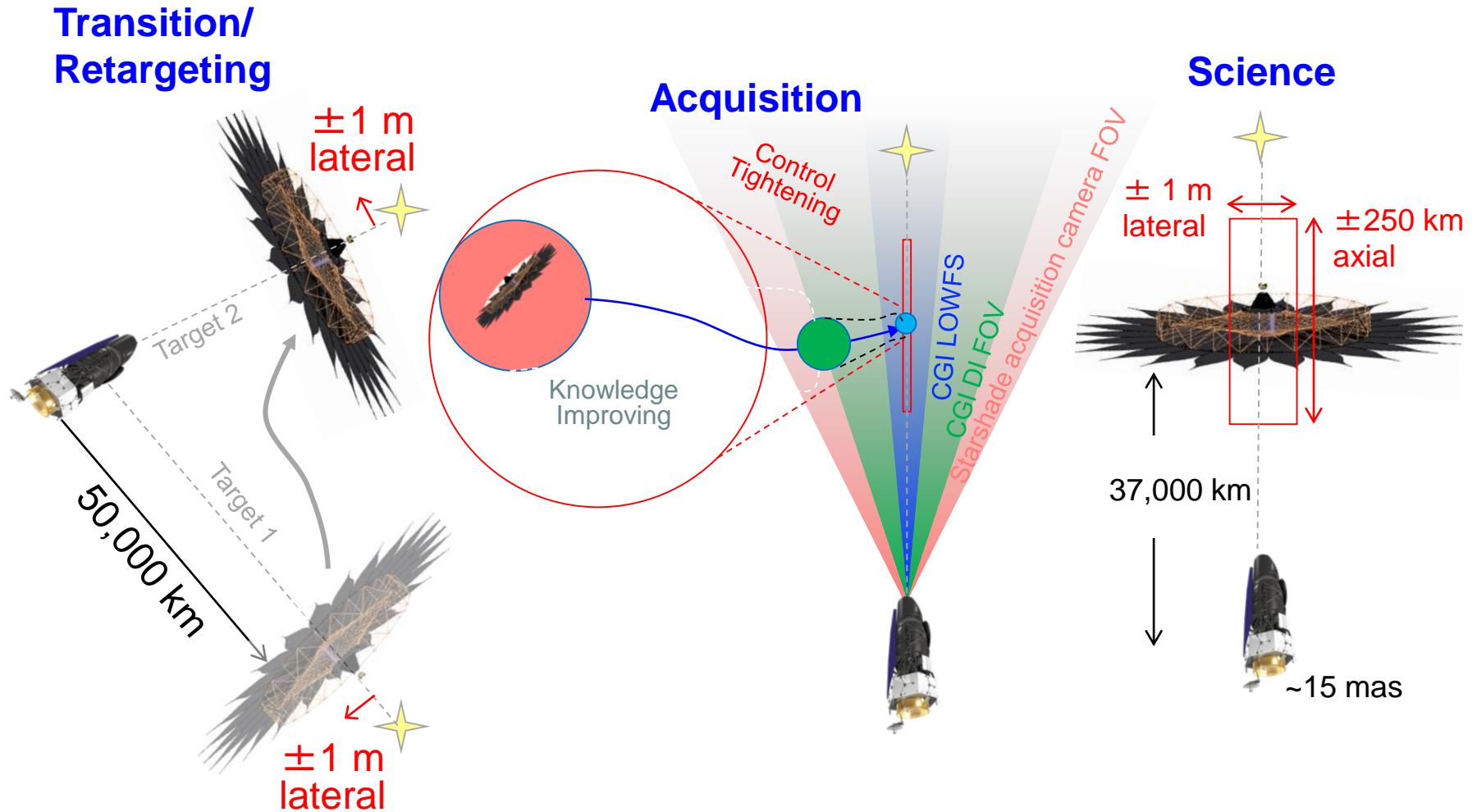
S-# corresponds to ExEP Starshade Technology Gap (<http://exoplanets.nasa.gov/exep/technology/gap-lists>)

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

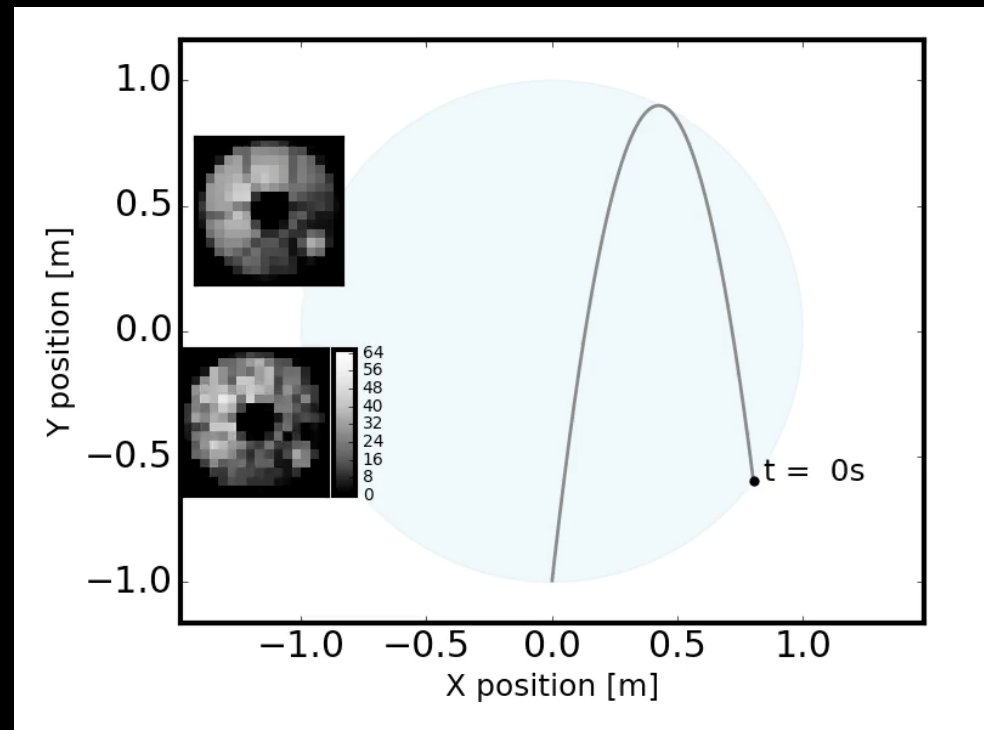
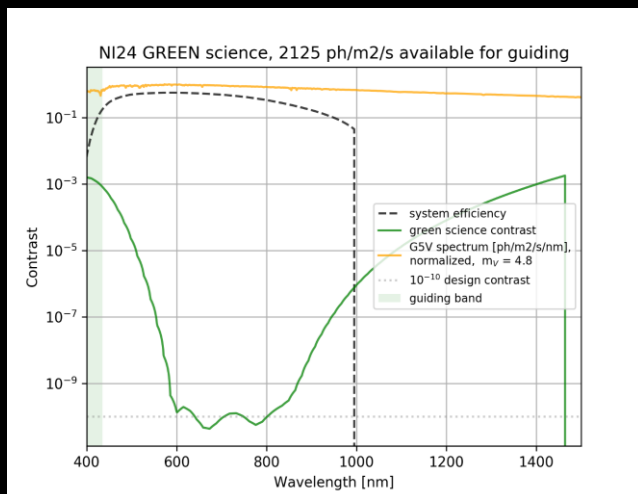
High Level Operations Concept



Formation Flying

Lateral Offset Sensing Concept

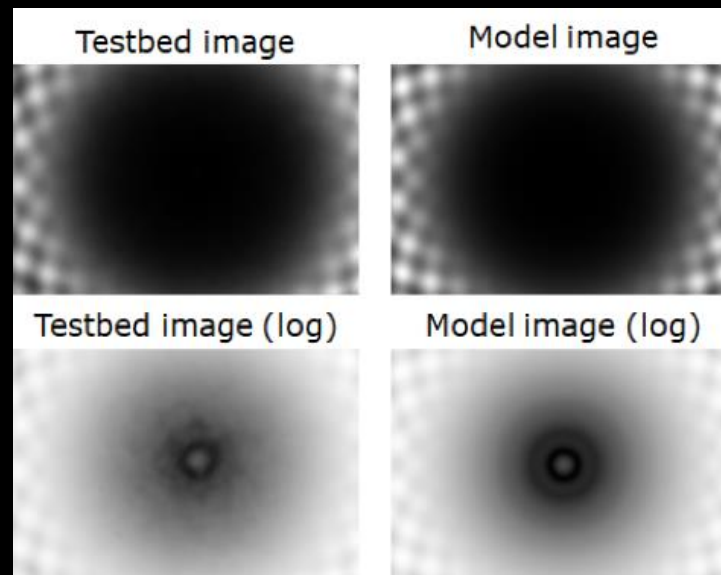
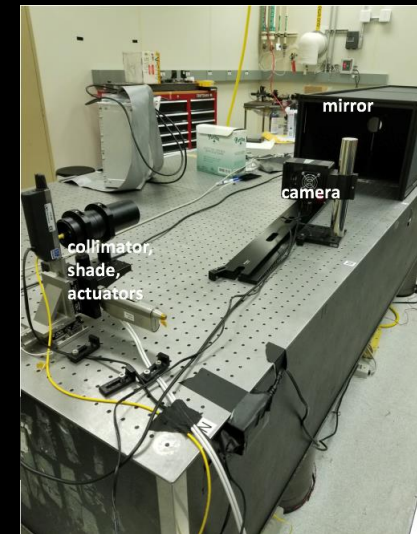
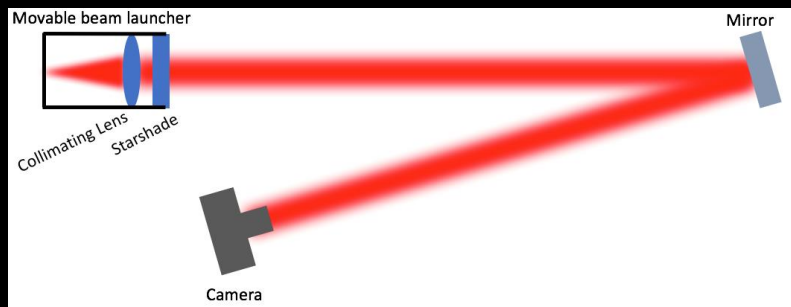
- Using pupil plane wavefront sensor and out-of-band stellar diffraction allows for accurate sensing at the ~cm level around all target stars
- Pupil image is collected and compared to library of stored offset pupil images to determine direction and distance of lateral offset



Formation Flying

SLATE testbed

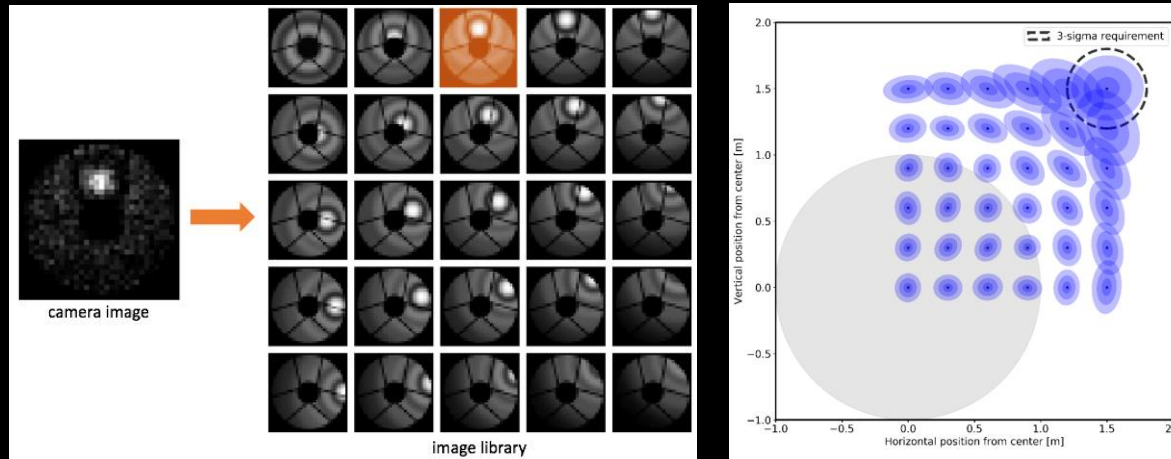
- Starshade Lateral Alignment Testbed (SLATE) measures out-of-stopband shadows cast in scaled starshade geometry to test optical performance and ability to accurately sense starshade offsets in telescope pupil plane.



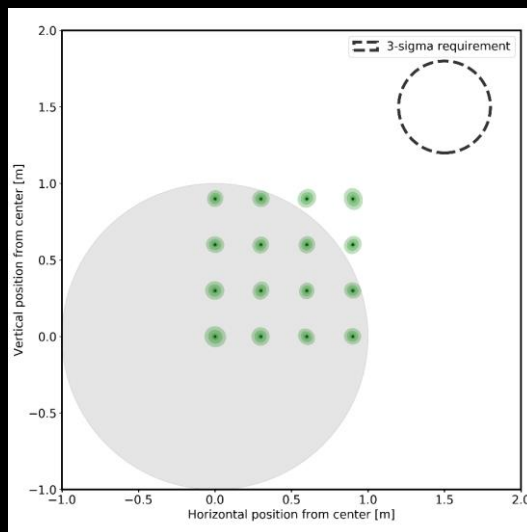
Formation Flying

Lateral Offset Sensing

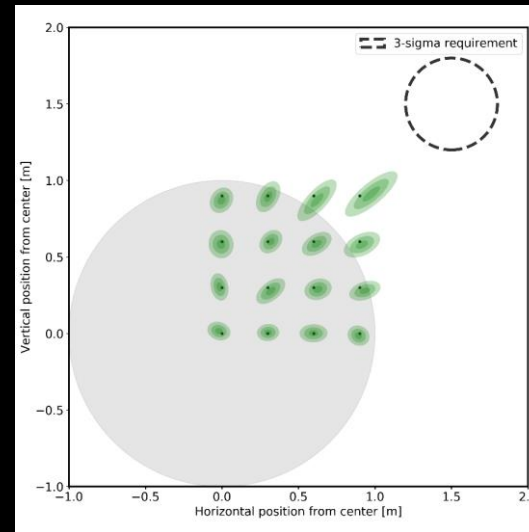
- Pupil image is collected and compared to library of stored offset pupil images to determine direction and distance of lateral offset



Optical
model



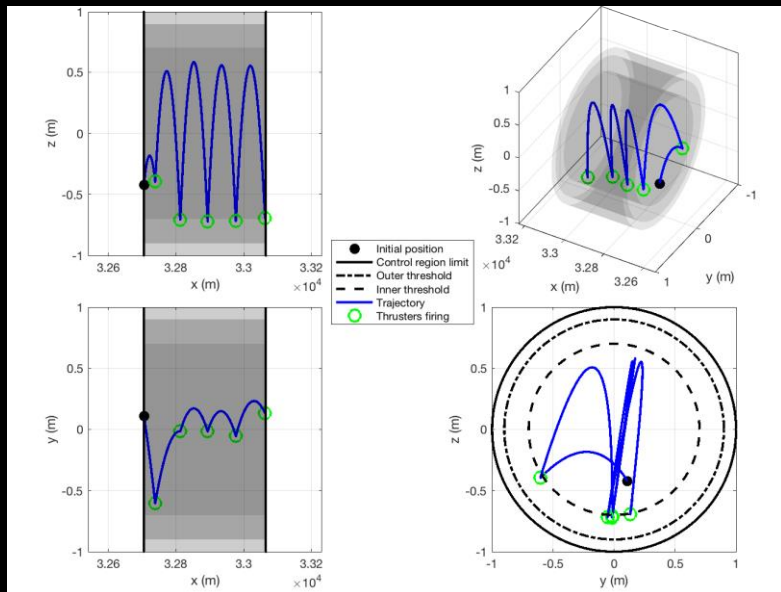
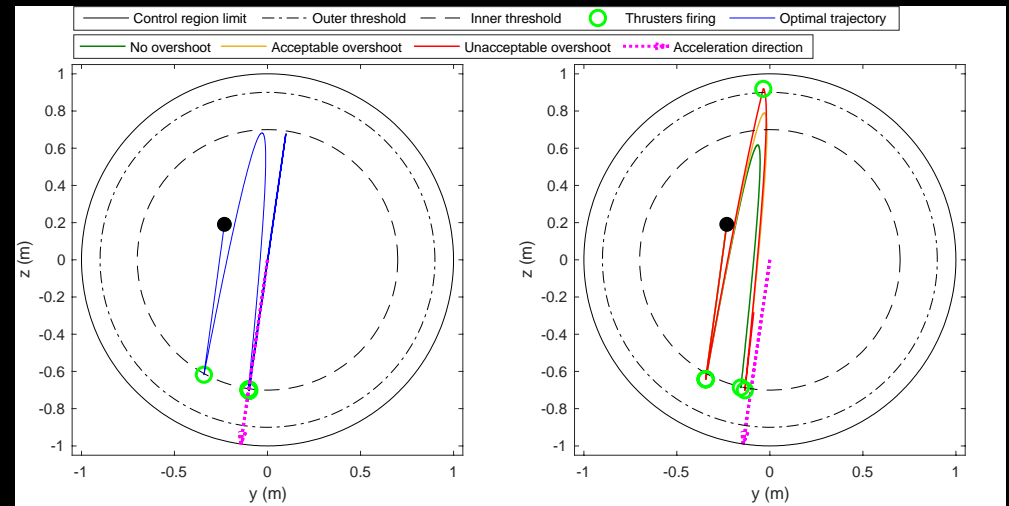
SLATE
results



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 ± 1 m positioning.



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

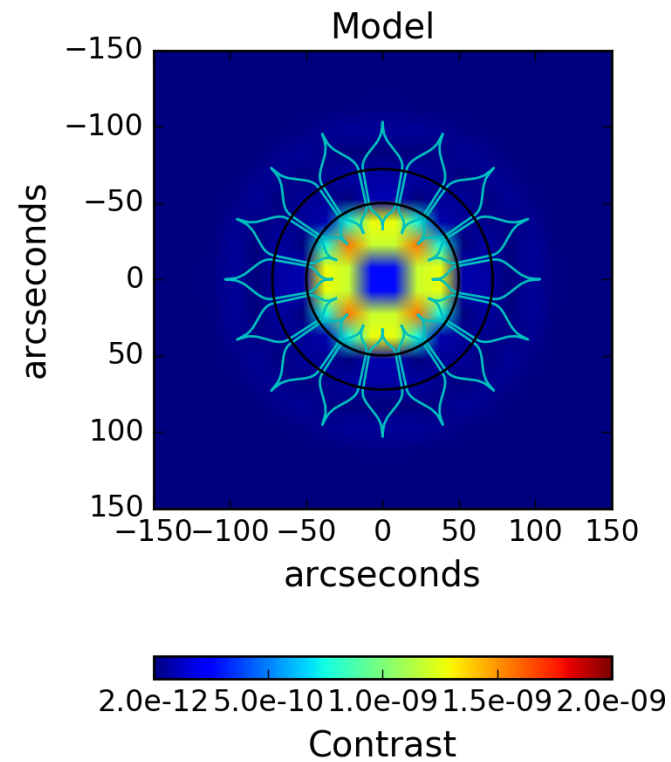
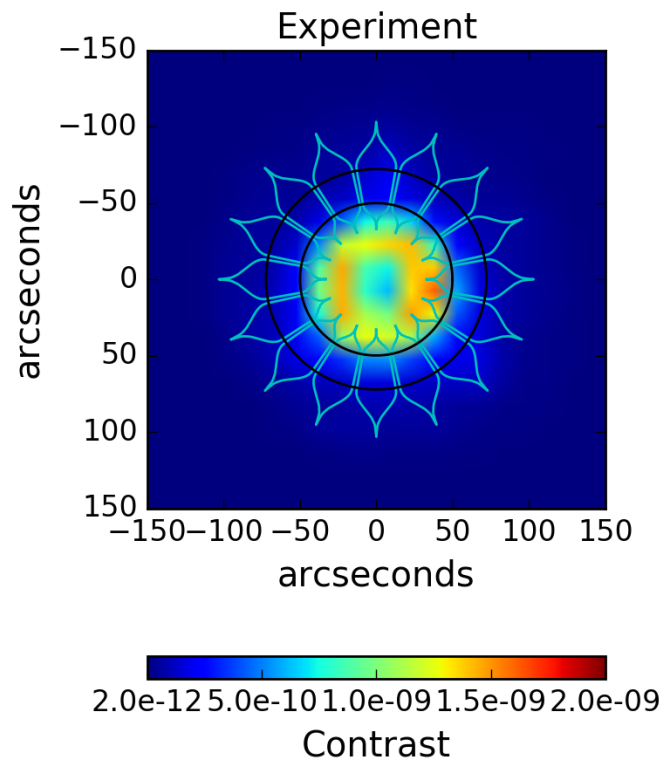
Optical Performance

Starshade Testbed at Princeton University



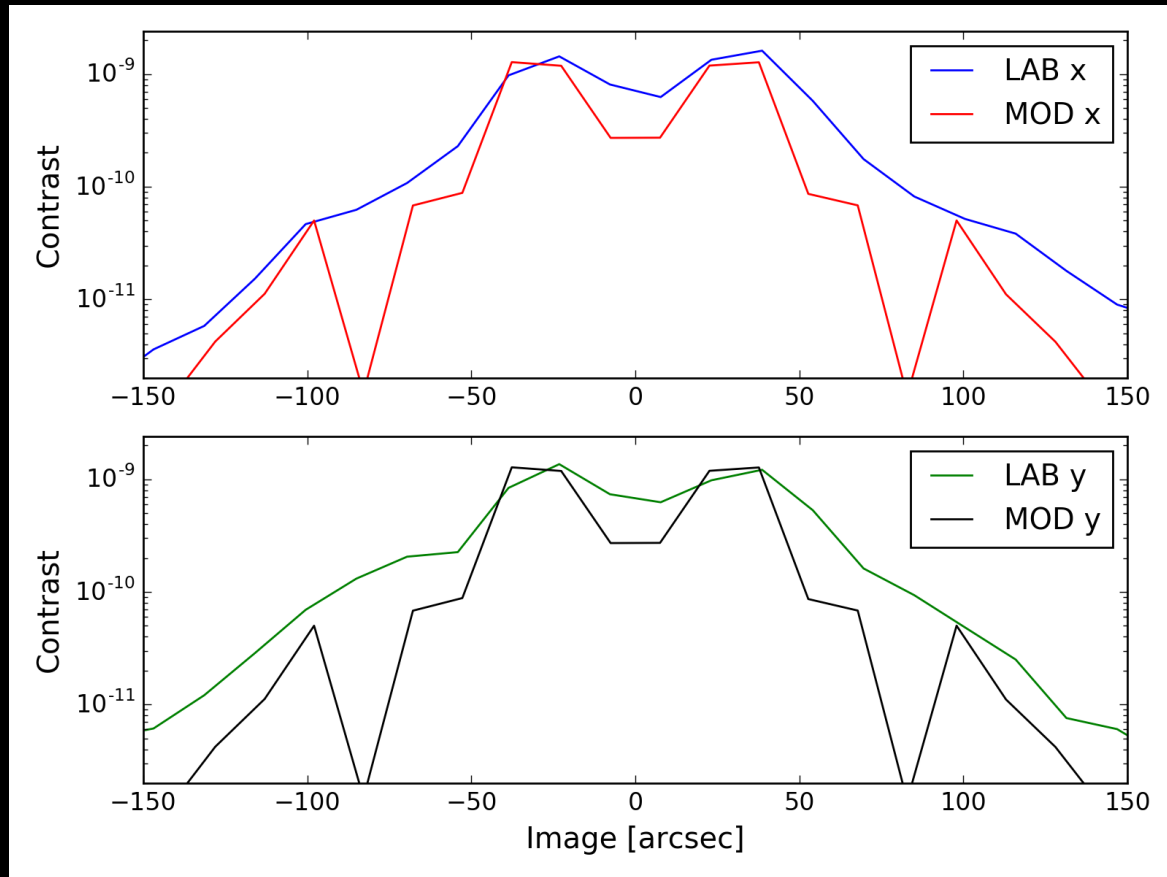
Optical Performance

Testbed Data – Driving toward Model Validation



Optical Performance

Testbed Data – Driving toward Model Validation



Optical Edge Development (Petals)

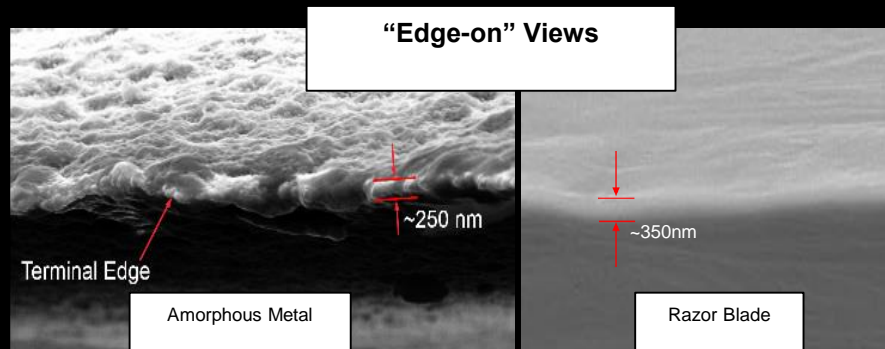
Scattered Sunlight Suppression

Need:

- *Petal edges that reduce solar glint magnitude to levels below that of the apparent zodiacal dust*
 - ❖ *Edge radius (μm) * reflectivity (%) < 10 $\mu\text{m}\%$*
- *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)



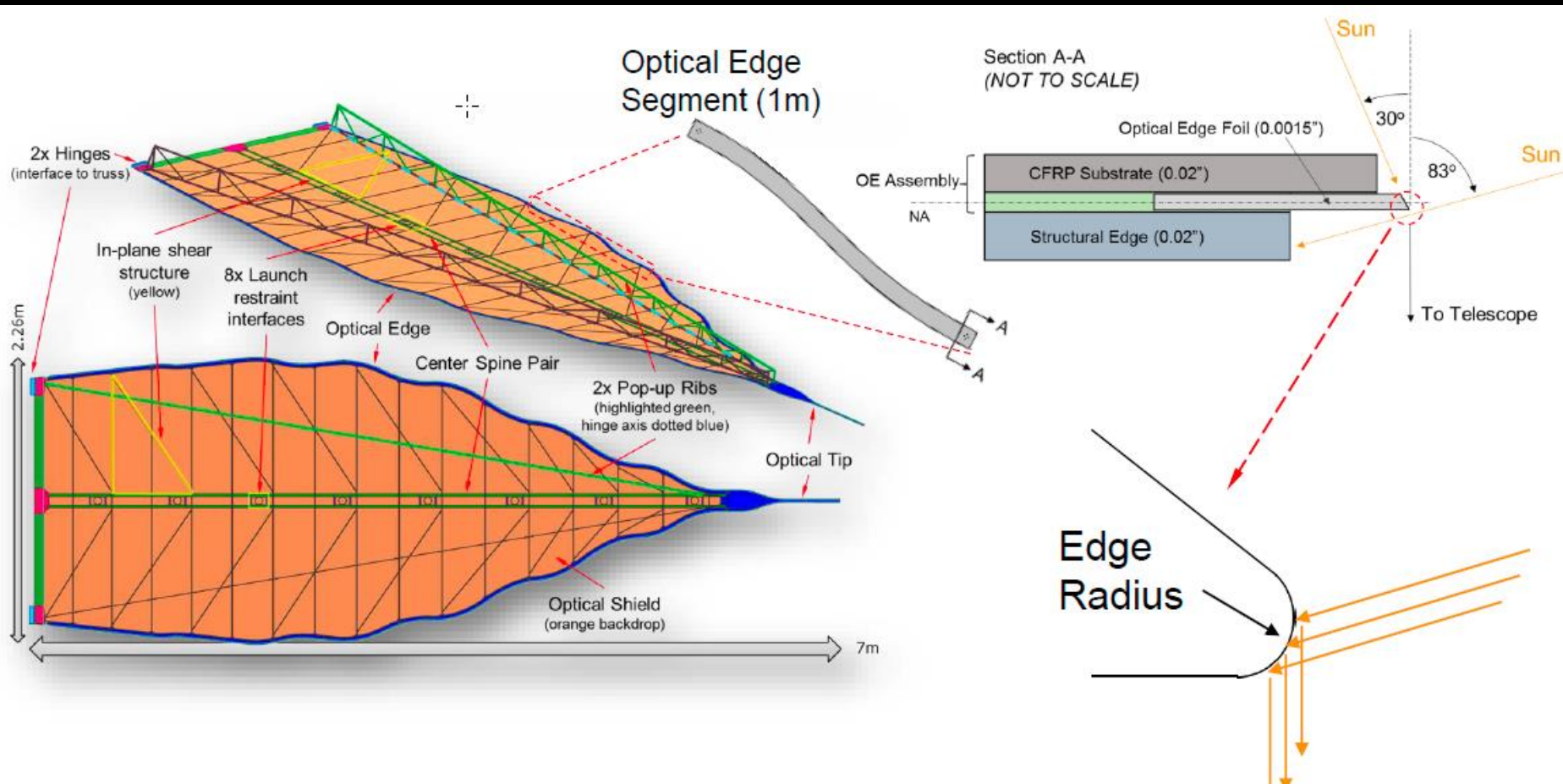
Comparable edge sharpness achieved between etched amorphous metal edges and Gem razor blades



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

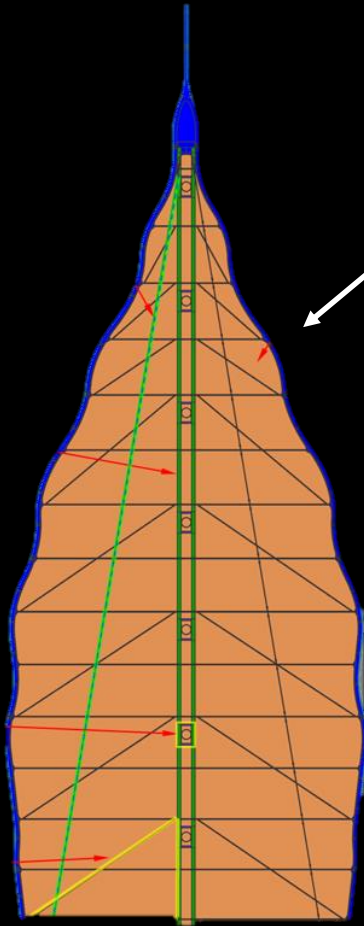
Optical Edge Development

SBIR Award: Tendeg's Petal Optical Edge Integration



Optical Edge Development

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

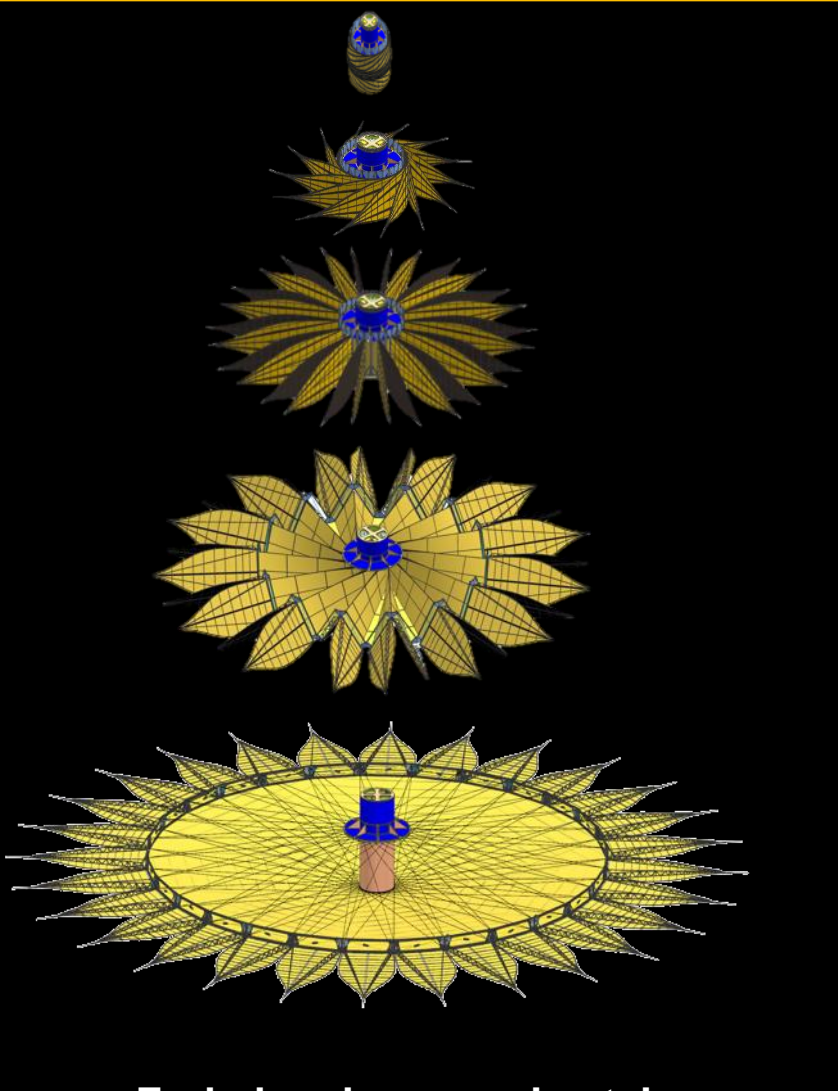


To avoid solar glare and scatter interference petal optical edges must be razor-sharp and exceedingly clean

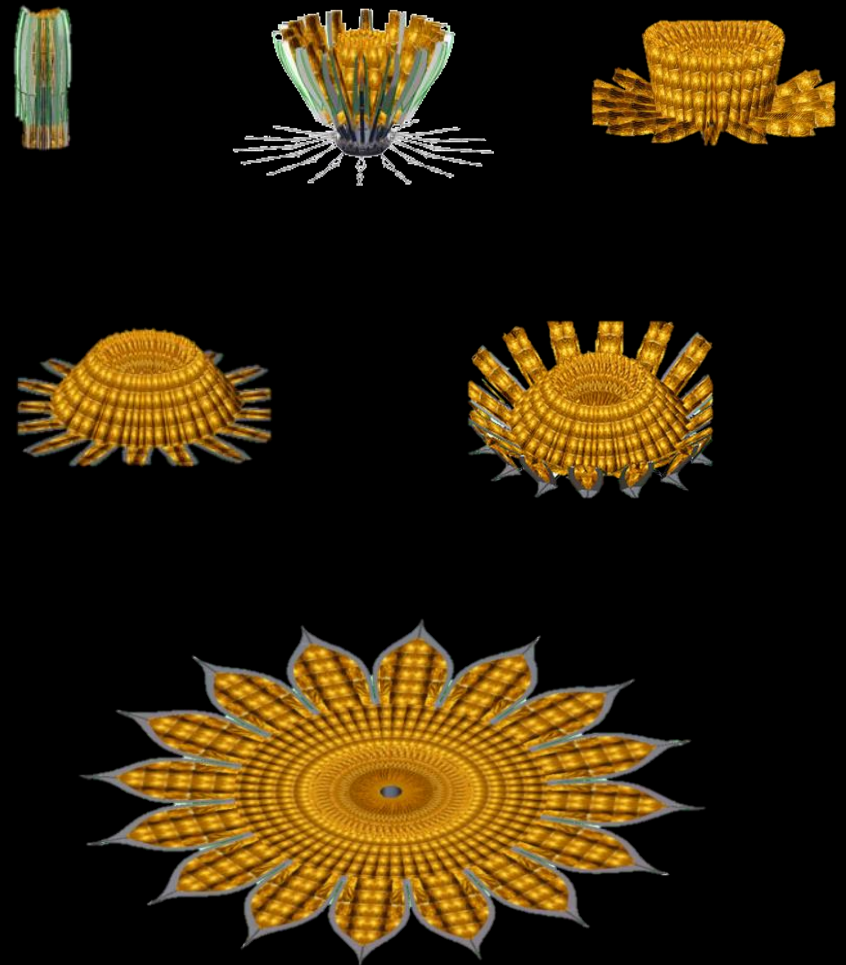
- ❖ *a few 100 μm dust particles on an edge scatters light comparable to the signal of an exoplanet.*

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



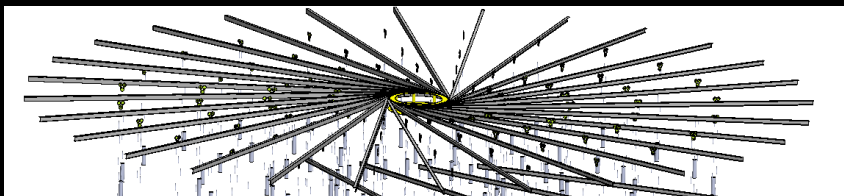
Furled and wrapped petal deployment concept (JPL)



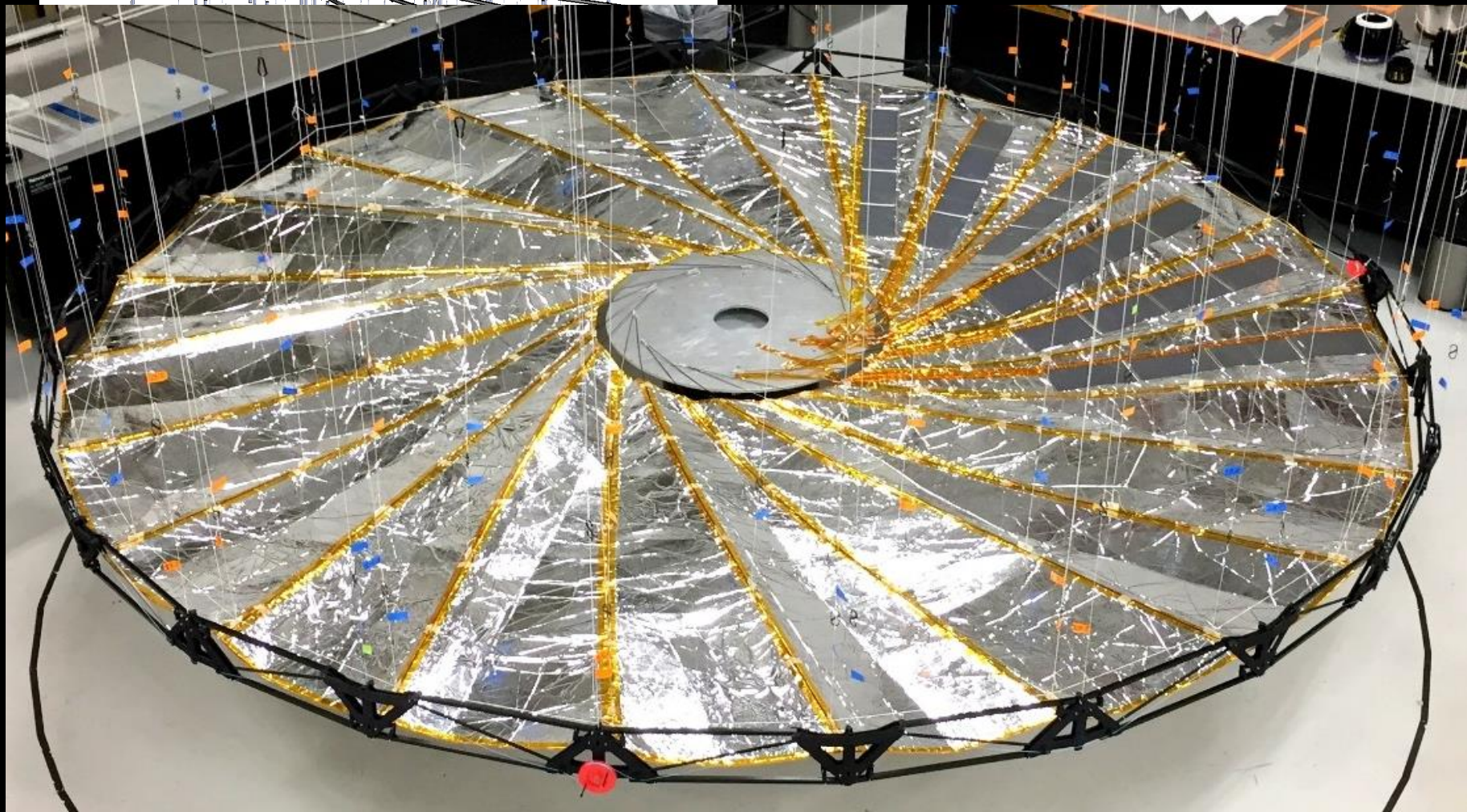
Boom supported and folded petal deployment concept (Northrop Grumman)

Optical Shield Testbed Gravity Offloading

SBIR Award: Rocco / Tendeg

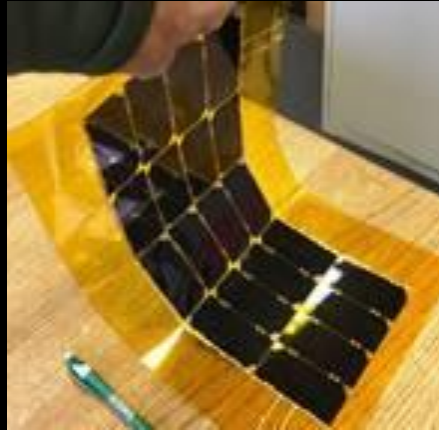


Rocco and Tendeg are made up of experts in composite materials, space mechanisms, and deployable structures

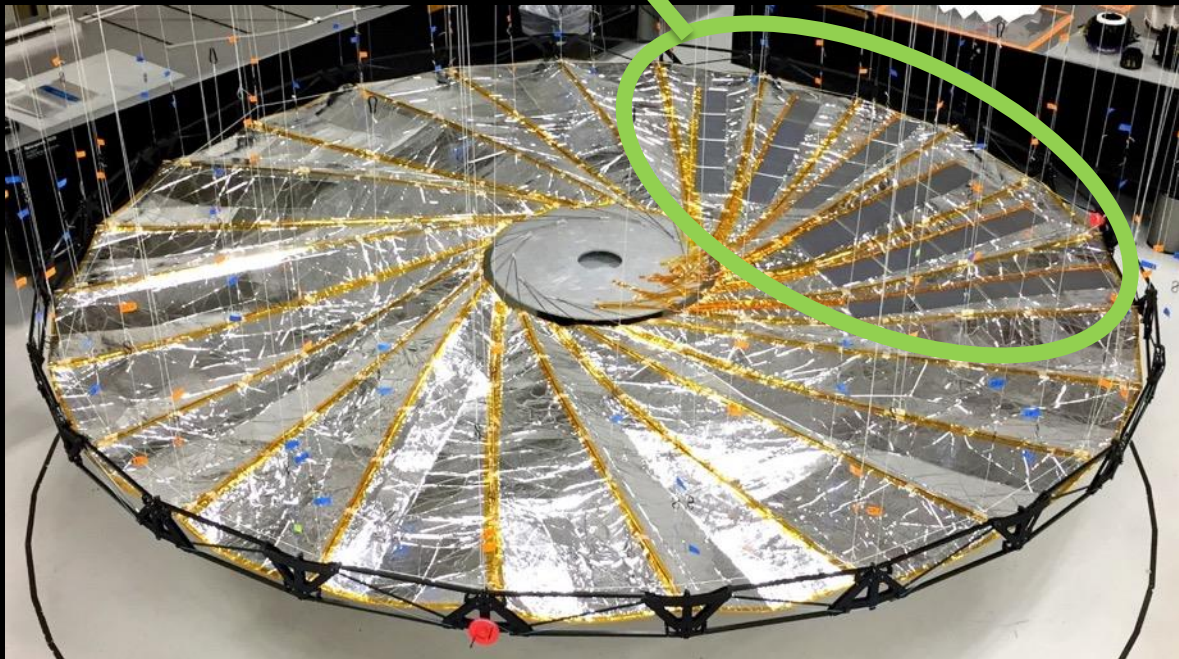


Optical Shield Solar Arrays

SBIR Award: Tendeg's Solar Array Integration

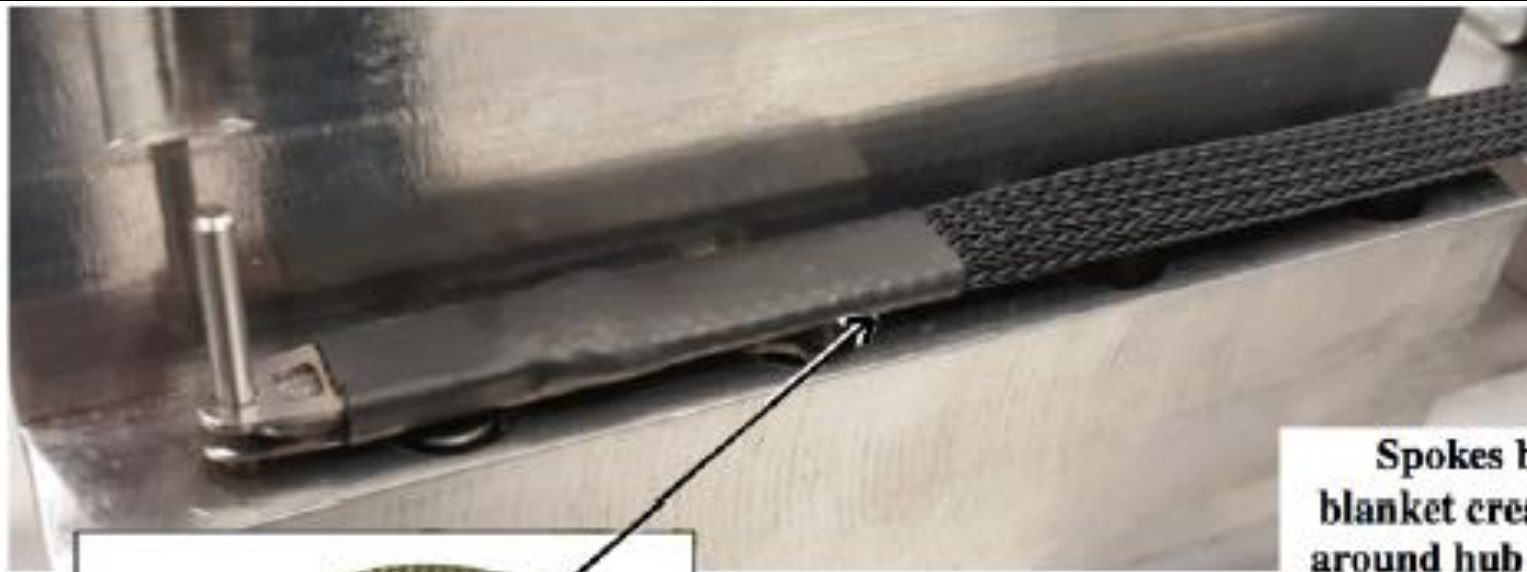


thin photovoltaic



Inner Disk and Optical Shield Deployment

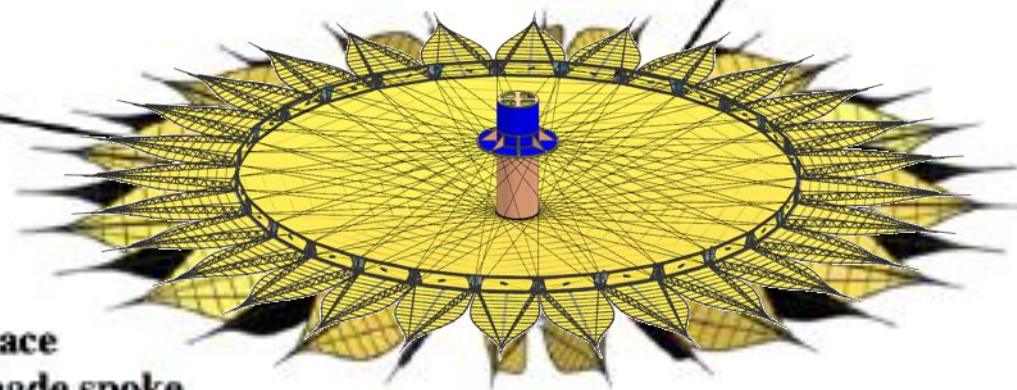
SBIR Award: Rocco's Dimensionally-Stable Structural Spoke



Spokes bend over blanket creases and furl around hub with blanket

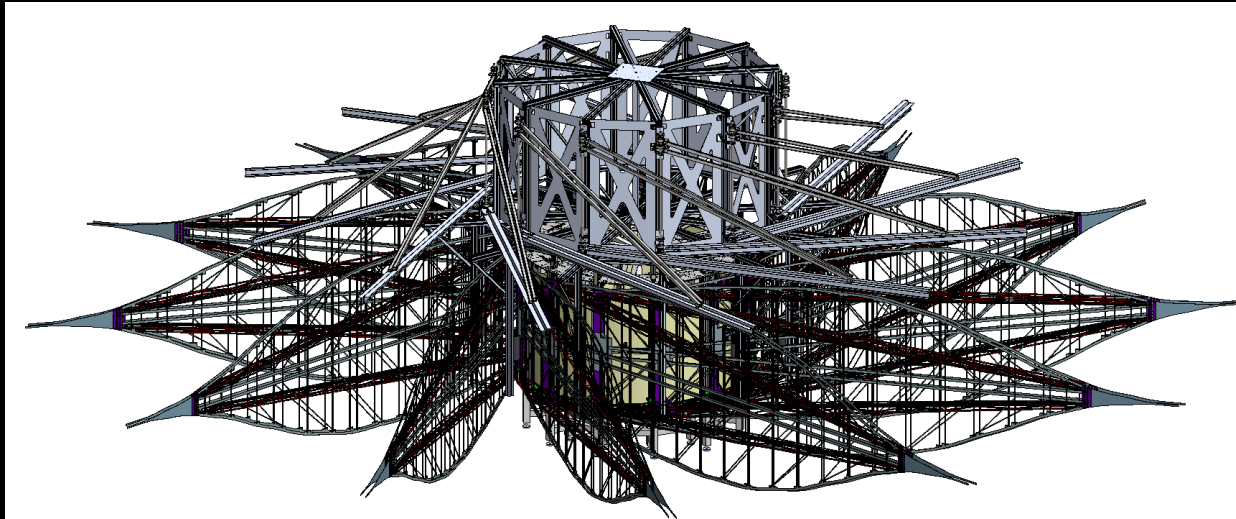
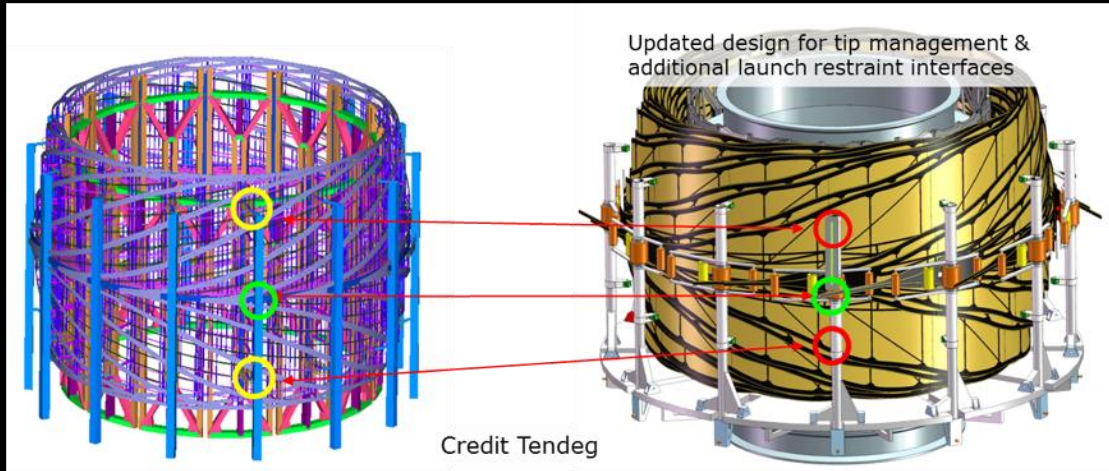


Dimensionally-Stable Structural Space Cable (DS3 Cable) proposed for the Starshade spoke



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 ± 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 ≤ 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 ≤ 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 ± 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m. | 11/14/18 | X | 100 |
| 5A | Petal subsystem with <i>shape critical features</i> demonstrates shape stability after deploy cycles (deployed) consistent with a total pre-launch shape accuracy within ± 70 μm . | 12/20/19 | X | 80 |
| 5B | Petal subsystem with <i>all features</i> demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, and storage) to within ± 70 μm . | 6/2/23 | | |
| 6A | Petal subsystem with <i>shape critical features</i> demonstrates on-orbit thermal stability within ± 80 μm by analysis using a validated model of critical dimension vs. temperature. | 12/20/19 | X | 80 |
| 6B | Petal subsystem <i>all features</i> demonstrates on-orbit thermal stability within ± 80 μm by analysis using a validated model of critical dimension vs. temperature. | 6/2/23 | | |
| 7A | Truss Bay <i>longeron and node subassemblies</i> demonstrate dimensional stability with thermal cycles (deployed) consistent with a total pre-launch petal position accuracy within ± 300 μm . (Note: SBIR funding dependency) | 12/20/19 | X | 80 |
| 7B | Truss Bay <i>assembly</i> demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within ± 300 μm . | 6/2/23 | | |
| 7C | Inner Disk Subsystem with optical shield assembly that includes <i>deployment critical features</i> demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within ± 300 μm . (Note: SBIR funding dependency) | 12/20/19 | X | 80 |
| 7D | Inner Disk Subsystem with optical shield assembly that includes <i>all features</i> demonstrates repeatable accuracy consistent with a total pre-launch petal position accuracy within ± 300 μm . | 6/2/23 | | |
| 8A | Truss Bay <i>longeron and node subassemblies</i> demonstrate on-orbit thermal stability within ± 200 μm by analysis using a validated model of critical dimension vs. temperature. | 12/20/19 | X | 80 |
| 8B | Truss Bay <i>assembly</i> demonstrates on-orbit thermal stability within ± 200 μm by analysis using a validated model of critical dimension vs. temperature. | 6/2/23 | | |

Science and Industry Partnership (SIP) with NASA Starshade Technology Development



ExoPlanet Exploration Program

- Motivation:
 - Continually incorporate new ideas and solutions to S5 starshade technology objectives and challenges
 - Maximize technology readiness for future mission
- Scope:
 - Charter will create open forum for US Persons: Industry, NASA, JPL, partner organizations and individuals.
 - Will include cost-sharing for up to 3 small business (AO Jan 2019)
- Approach:
 - SIP convened in Starshade Forums semiannually through at least 2020
 - First Forum (informational) telecon December 2018
 - Monthly working telecons, coordinated with S5 Technology Development Activity
 - Chair: gary.blackwood@jpl.nasa.gov Science Co-Chair: Renyu.Hu@jpl.nasa.gov
- Will add to Forum:
 - Science and Technology Working Group via AO (Spring 2019). Meet concurrently with SIP in Starshade Forum