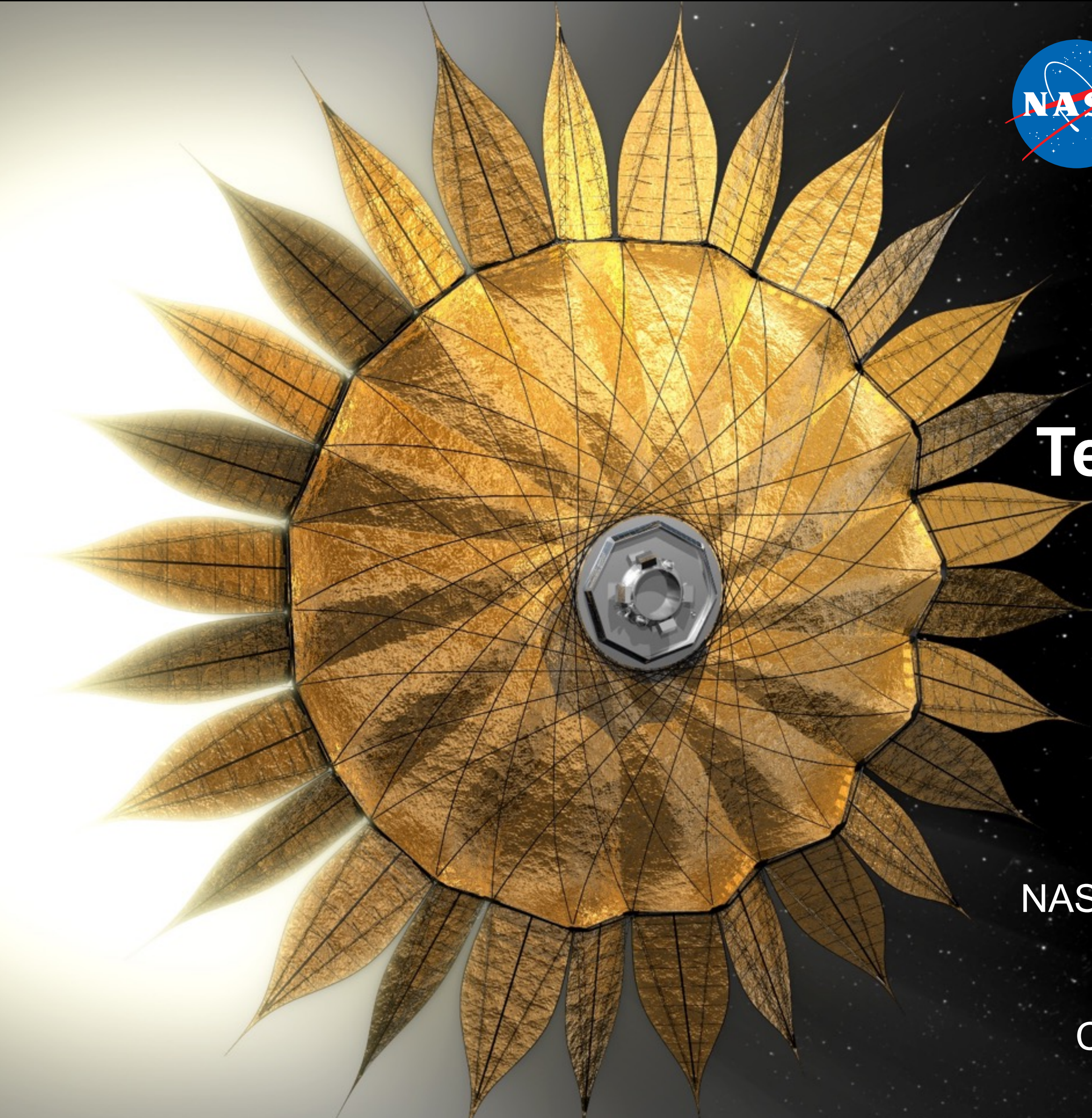


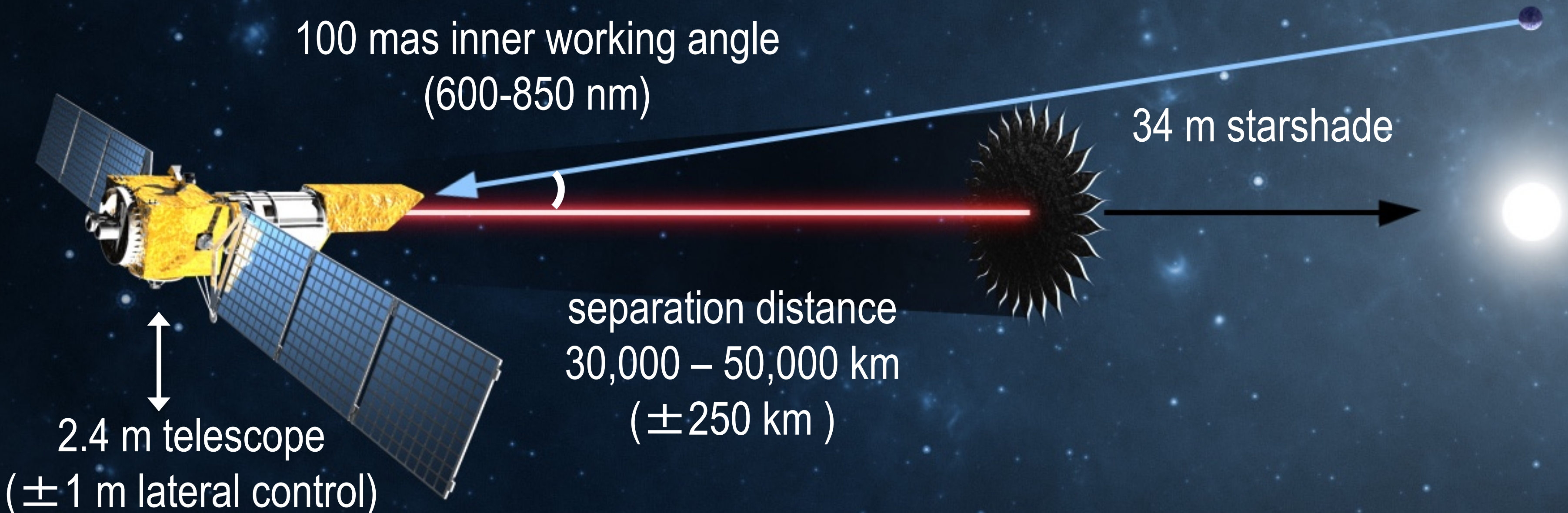
Jet Propulsion Laboratory
California Institute of Technology

Starshade Technology to TRL5 Activity (S5)

Dr. Phil Willems
NASA Exoplanets Exploration Program
S5 Activity Deputy Manager
Jet Propulsion Laboratory
California Institute of Technology

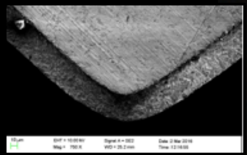
Starshade

The hard stuff is done external to telescope

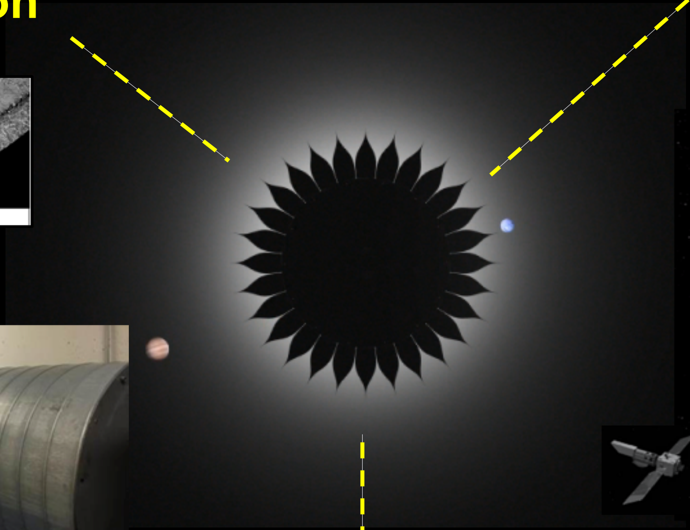


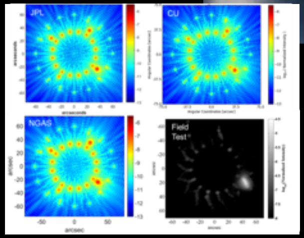
The Three Starshade Technology Gaps

(1) Starlight Suppression



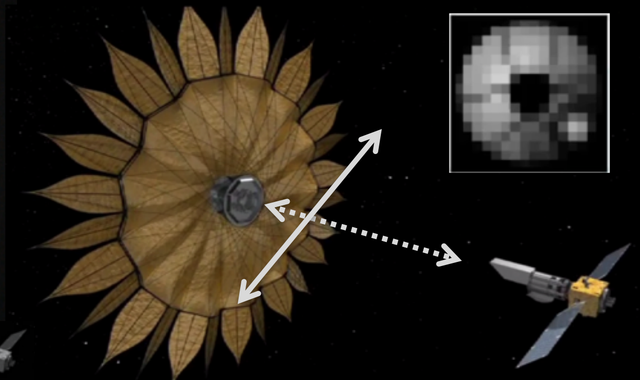
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)





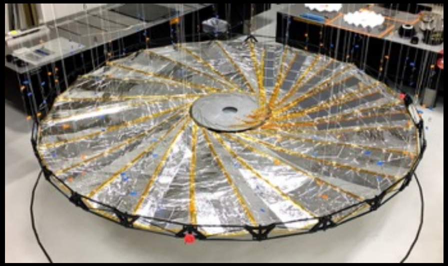
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(2) Formation Sensing

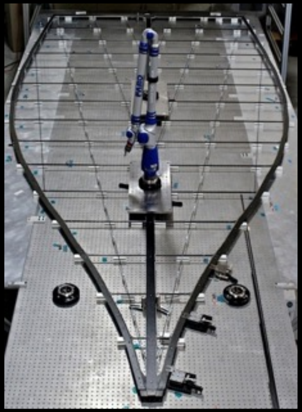


Sensing the lateral offset between the spacecraft (S-3)

(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 S5

- 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
- See https://exoplanets.nasa.gov/exep/technology/starshade/

Starshade to TRL5 (S5) Technology Development Plan

December 6, 2018

Document Owner: Phil Willems
S5 Technology Development Deputy Manager
Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and
Space Administration

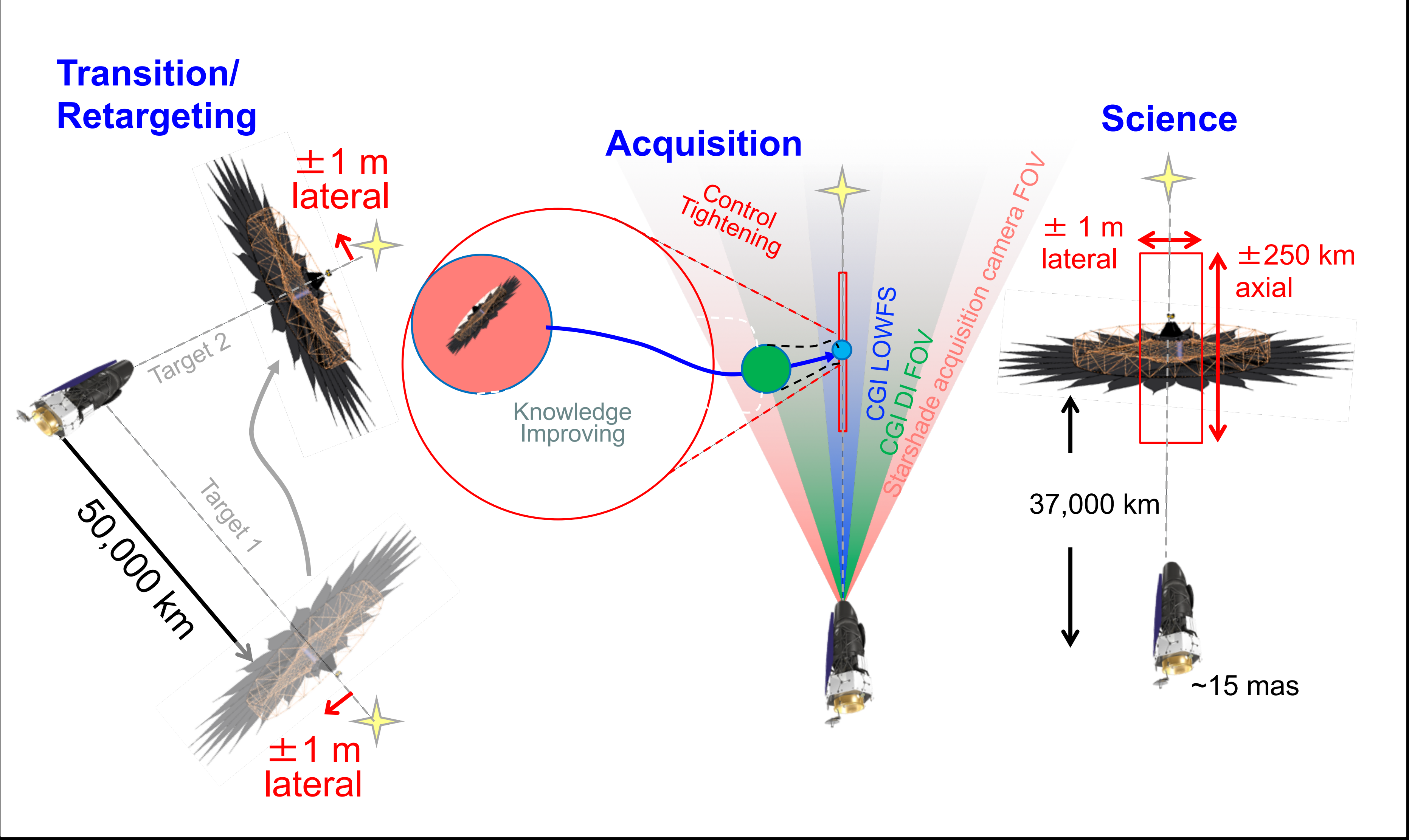
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech. This plan was developed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

S5 Reference Mission

- S5 Technology Development Plan uses WFIRST Rendezvous and HabEx mission concepts to derive KPPs; these KPPs are not <u>tightly</u> coupled to concept designs and apply fairly generally to space telescope missions at L2.
- Technology gaps are defined with reference to a starshade operating in formation with a <u>space</u> telescope.
- S5 technology <u>milestones</u> are more strictly defined with respect to WFIRST Rendezvous mission concept:
  - Optical and formation flying milestones apply equally well to HabEx
  - Mechanical milestones are built around test articles appropriate to WFIRST scale; applicability to HabEx still under discussion
- mDOT?

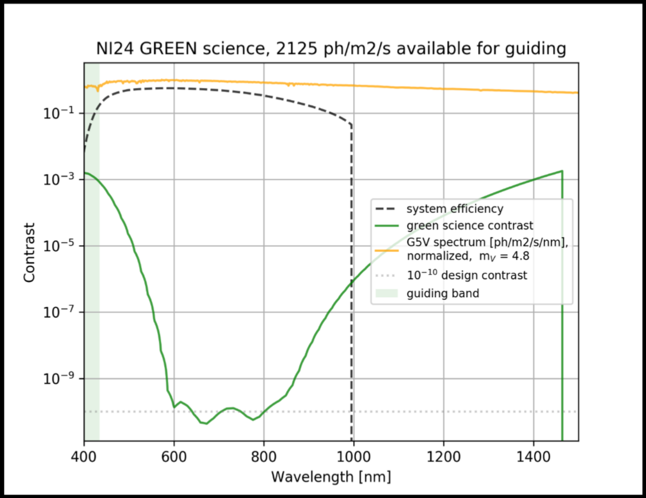
Formation Flying
High Level Operations Concept

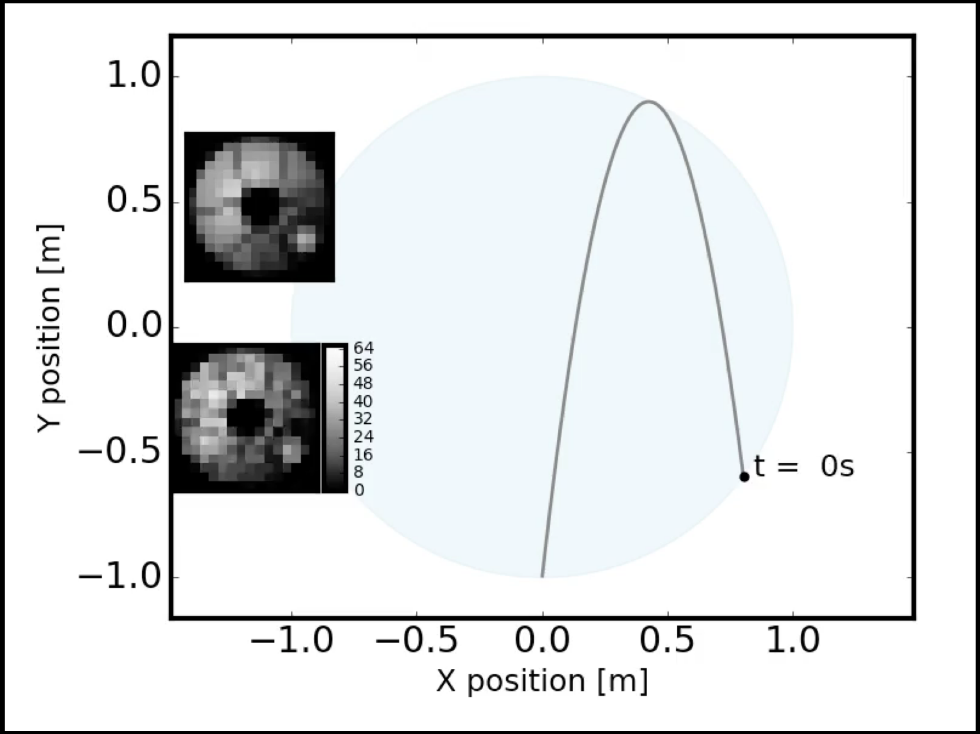


Formation Flying

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



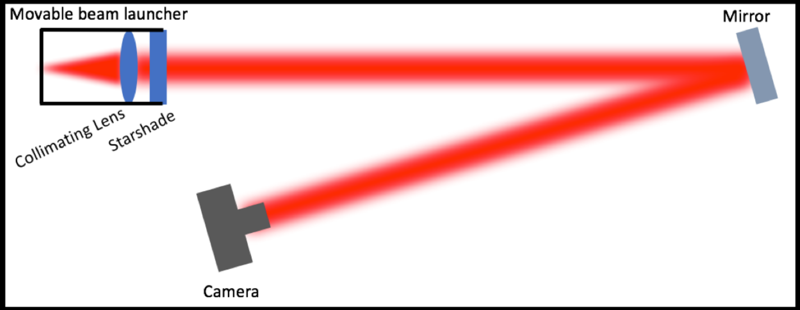


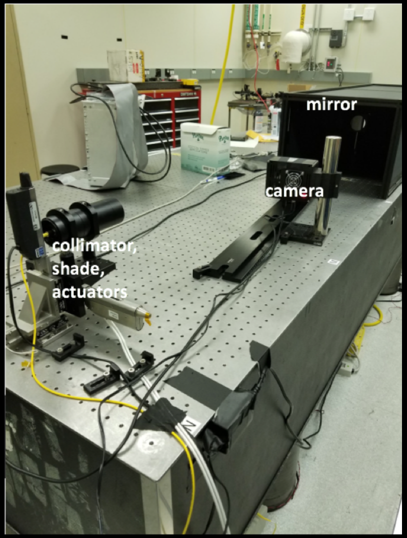
POC: Michael Bottom (JPL)

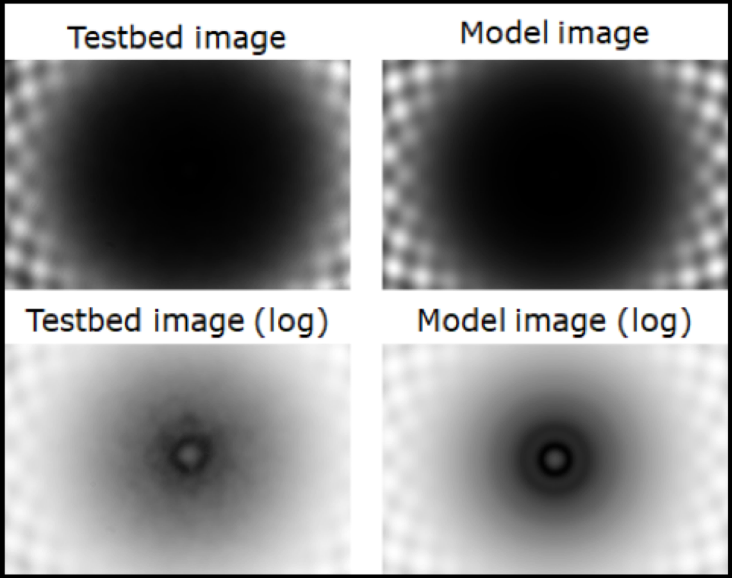
Formation Flying

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.





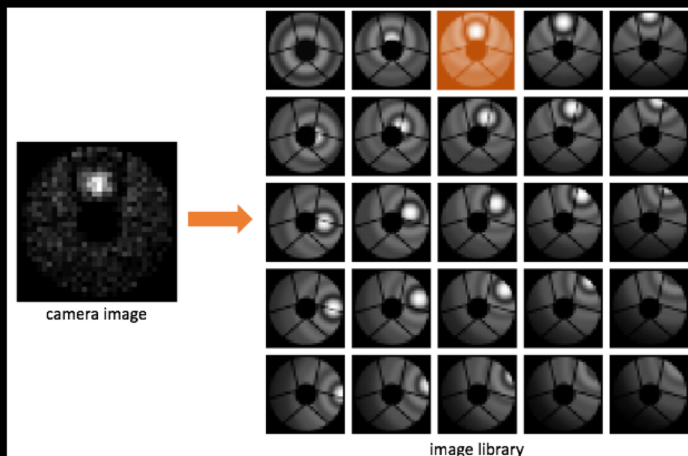


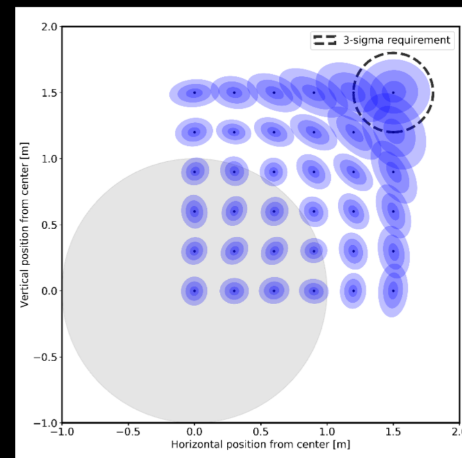
POC: Michael Bottom (JPL)

Formation Flying

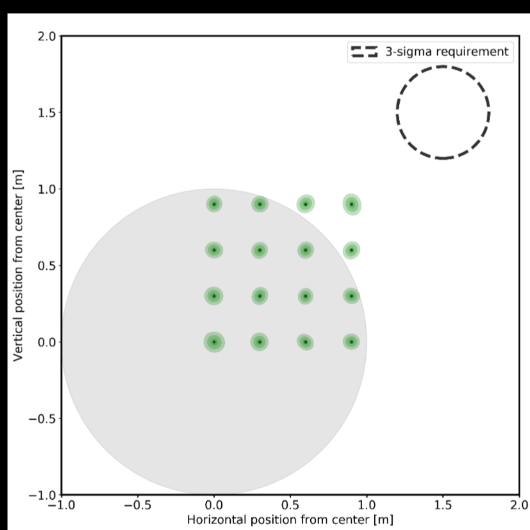
Lateral Offset Sensing

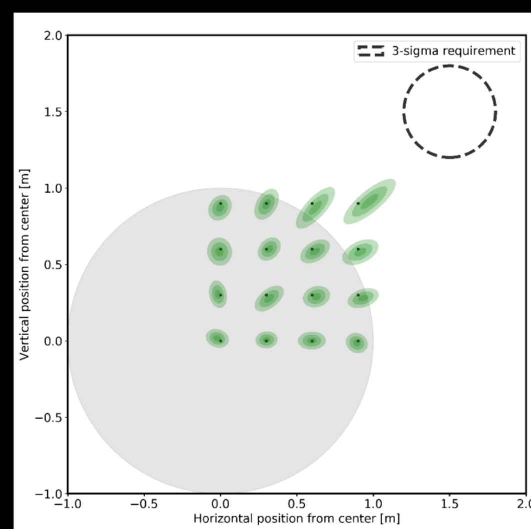
- Pupil image is collected and compared to library of stored offset pupil images to determine direction and distance of lateral offset





Optical model





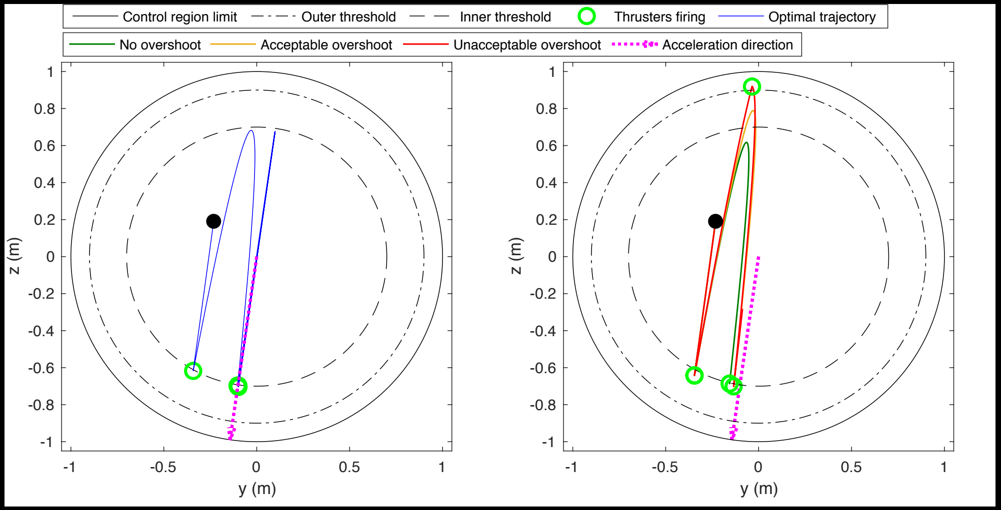
SLATE results

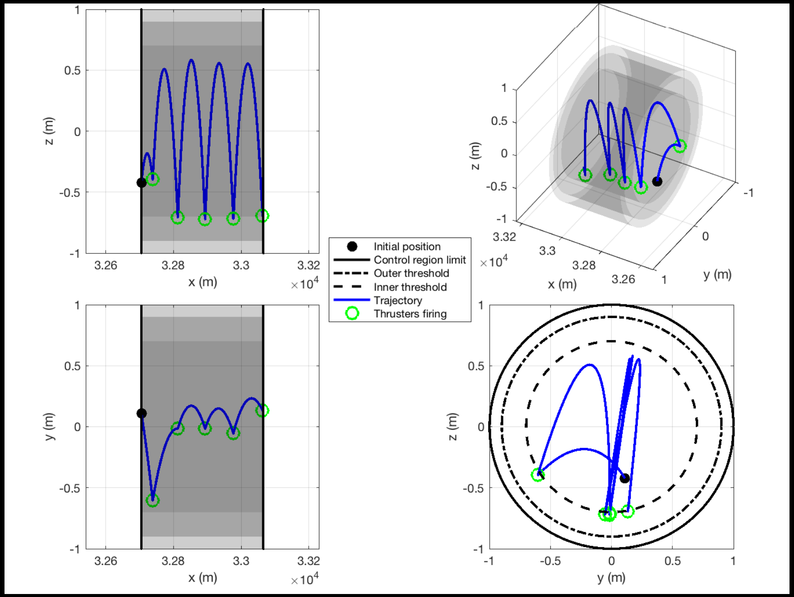
POC: Michael Bottom (JPL)

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.

POC: Thibault Flinois (JPL)

Formation Flying is Now at TRL5

- The ExoTAC reviewed the results described above and declared that the formation flying milestone has been achieved.
  - MILESTONE 4: Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral position offset sensitivity to a flight equivalent of 30cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ±1m.

Overall, the ExoTAC believes that Milestone #4 has been fully met and congratulates the entire team on their excellent efforts to advance the technology readiness levels of the elements in the S5 activity. Precision lateral control over thousands of kilometers is an unprecedented requirement, and essential for starshade operation. Achieving this first of fifteen S5 Milestones serves as a confidence builder for the entire S5 activity.

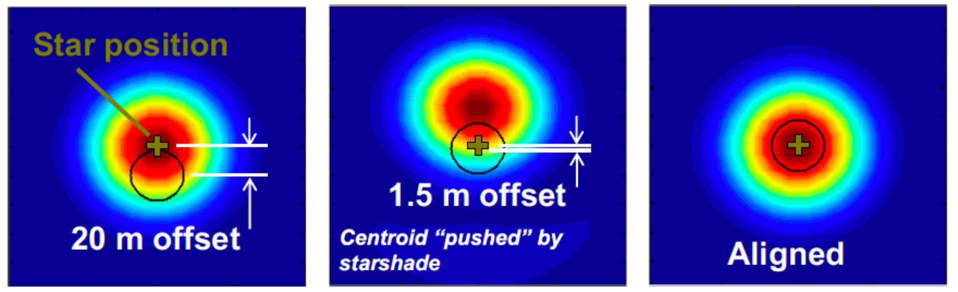
We also note that by virtue of the successful achievement of Milestone #4, the Exoplanet Exploration Program's Technology Gap List item S-3 on "Lateral Formation Sensing" is retired.

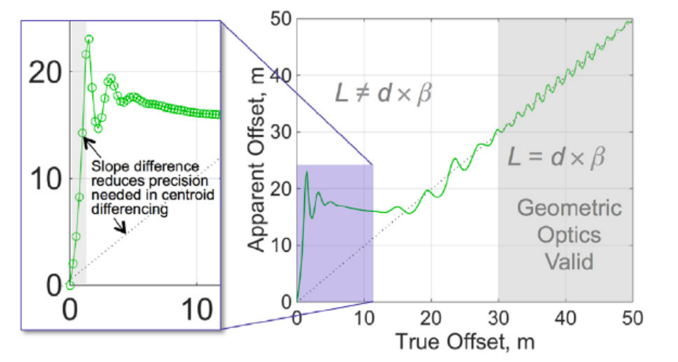
ExoTAC report available at https://exoplanets.nasa.gov/exep/technology/starshade/

Formation Flying
Fine Stationkeeping Acquisition

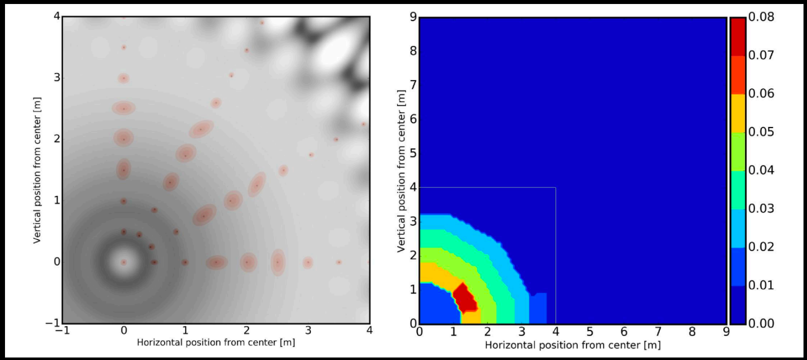
- Two approaches available to get the starshade the last dozen or so meters into alignment:

Focal Plane | **Pupil Plane**





– D. Scharf et al., "Precision formation flying at megameter separations for exoplanet characterization", Acta Astronautica vol. 123, pp. 420-34 (2016).



- M. Bottom et al., "Precise starshade stationkeeping and pointing with a Zernike wavefront sensor", Proc. SPIE vol. 10400, art. no. 1B (2017).

POC: Michael Bottom (JPL)

Optical Performance: Starlight Suppression

Starshade Testbed at Princeton University

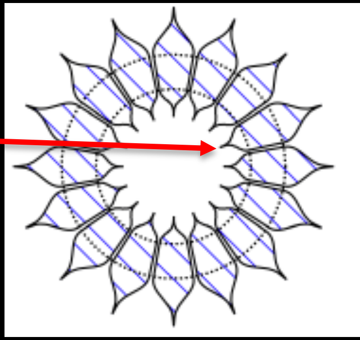
Starlight Suppression Milestones

- MILESTONE 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.
- MILESTONE 1B: Small-scale starshade mask in the Princeton Testbed demonstrates 1×10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning ≥ 10% bandpass at Fresnel number ≤ 15 at the longest wavelength.
- MILESTONE 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}.
- Successful completion of all three milestones brings starlight suppression technology to TRL5

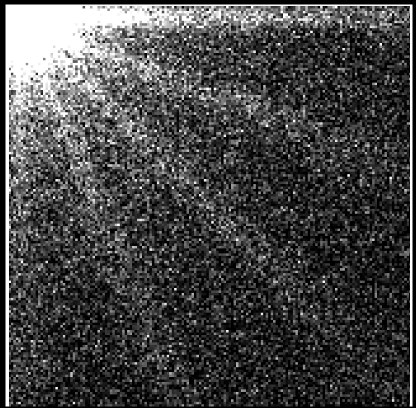
Two Main Complications in Testbed

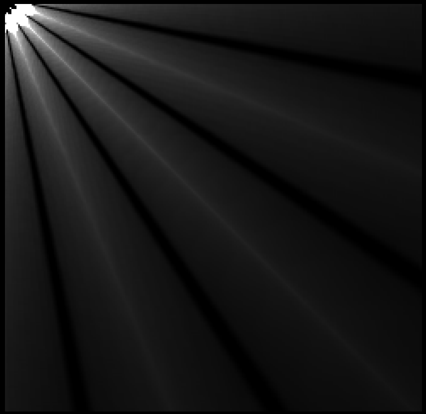
- Vector diffraction (i.e. polarization-dependent effects) become relatively significant as starshade features approach optical wavelength scales

like here!



- Rayleigh scattering by air or dust in testbed adds a background not present in space





Vector Diffraction

Vector Diffraction Code

Meep (MIT Electromagentic Equation Propagation)

- A.F. Oskooi, et al., *Computer Physics Communications*, 181, 687 (2010)

- Finite-Difference Time-Domain solver of Maxwell's equations

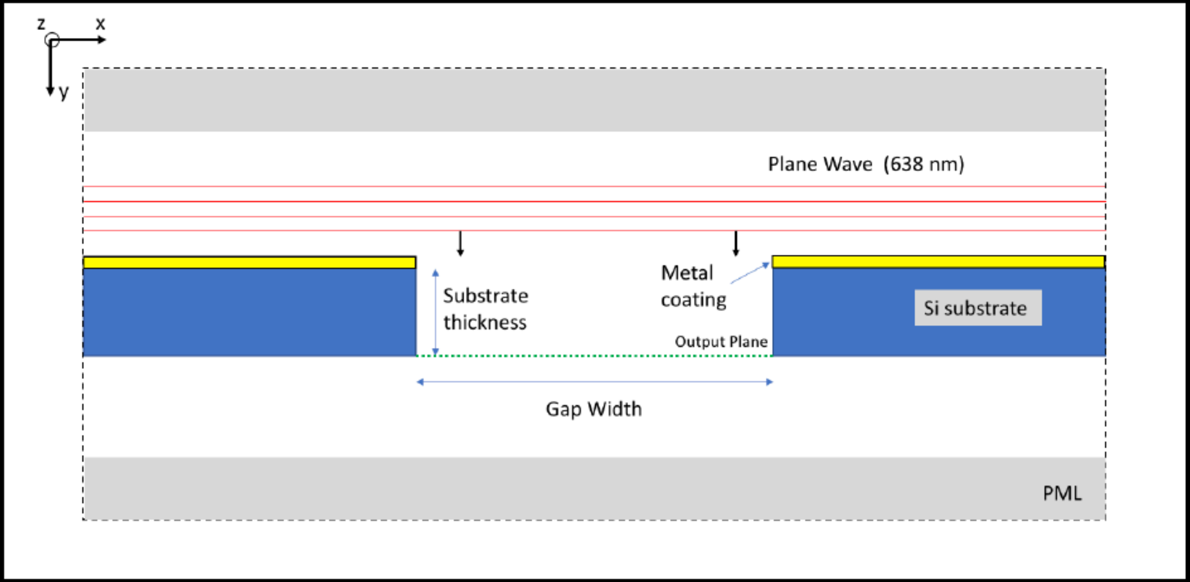
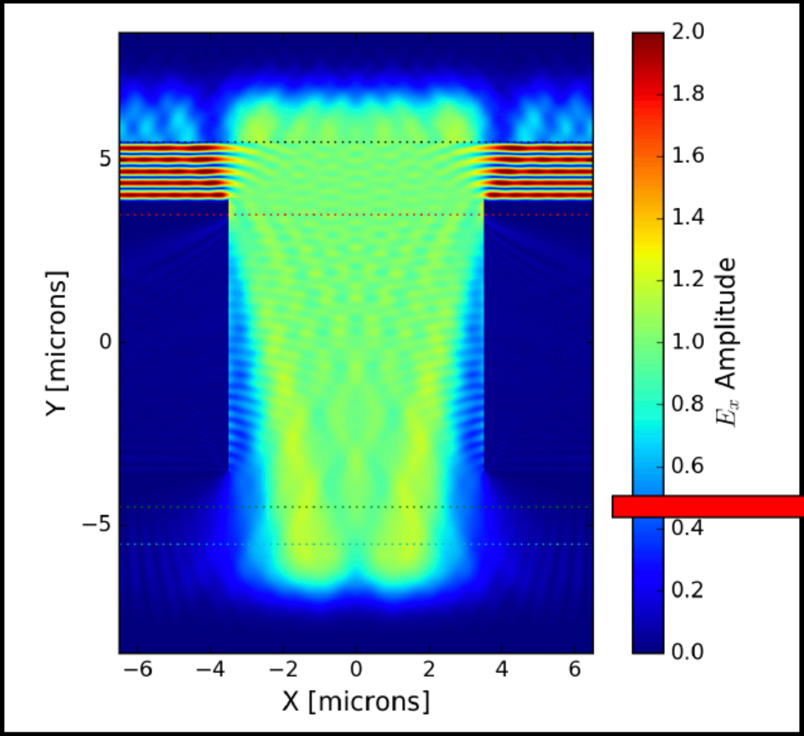
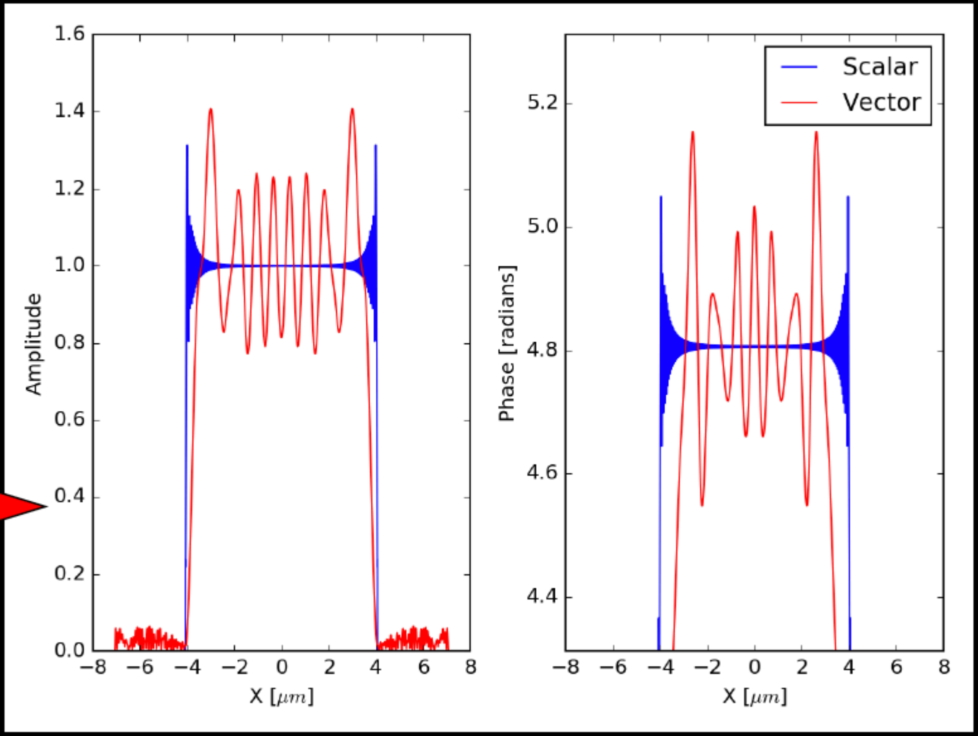


Image courtesy of Anthony Harness

Vector Diffraction

Meep Output





- Gap width = 8 µm
- ’p’ polarization

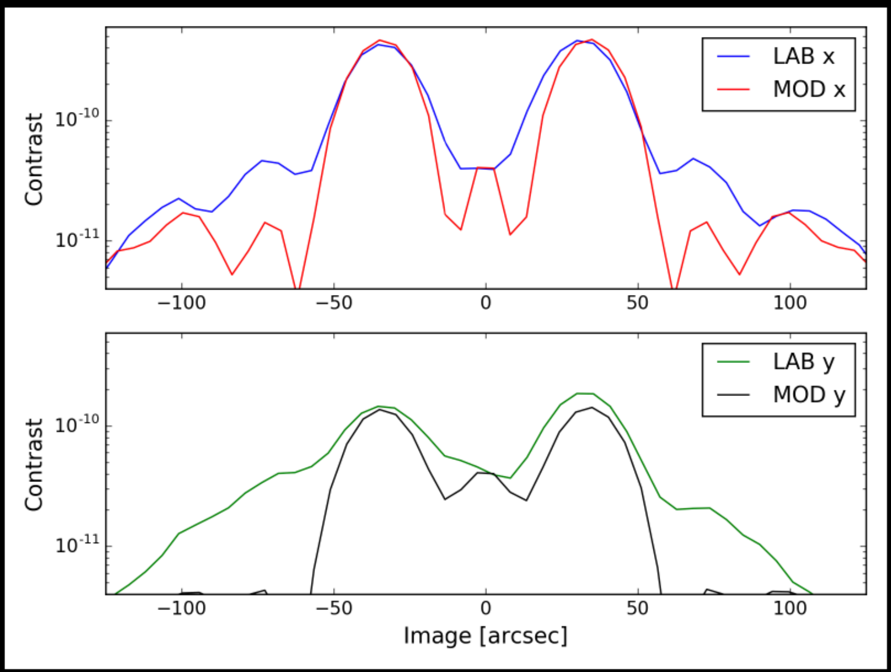
Image courtesy of Anthony Harness

Princeton Testbed Results: Contrast

DW17 - Contrast

Experiment: 4.3×10^{-11}
Vector Model: 1.5×10^{-11}

Thickness
Mask: 2 µm
Model: 0.9 µm



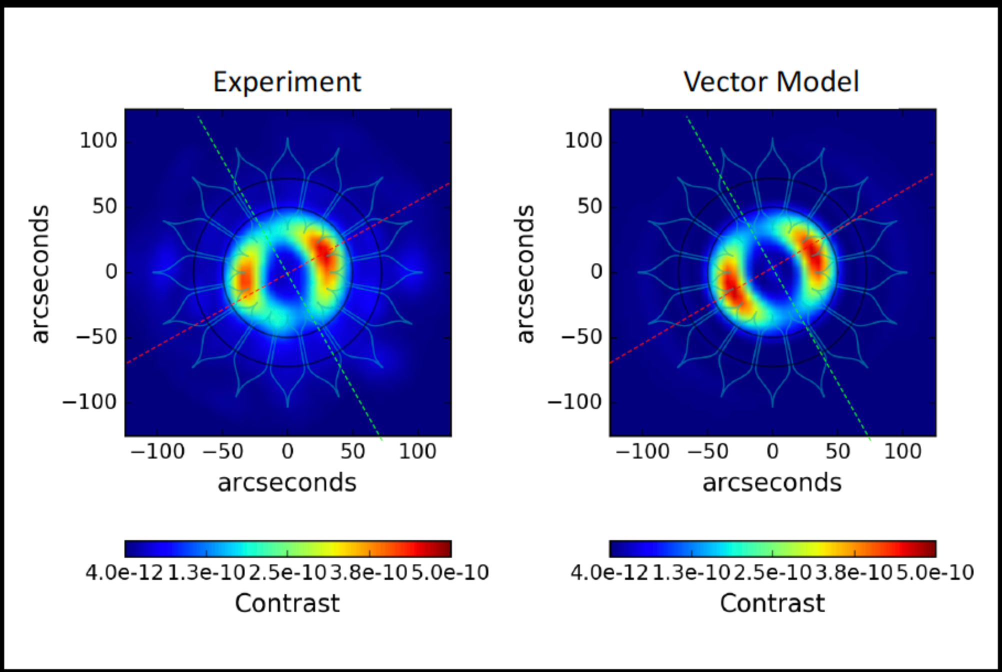
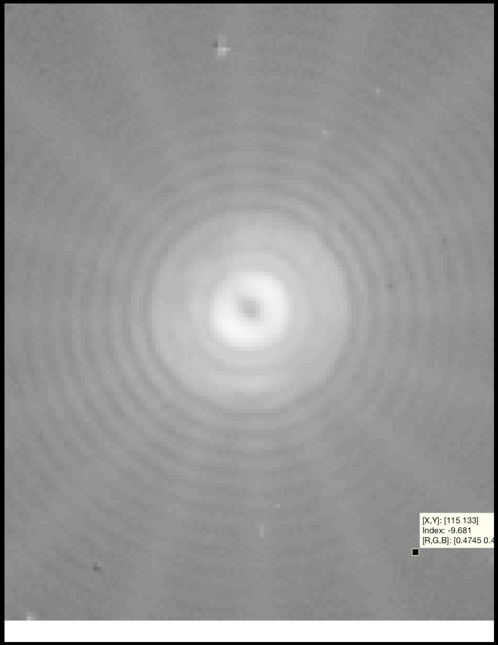
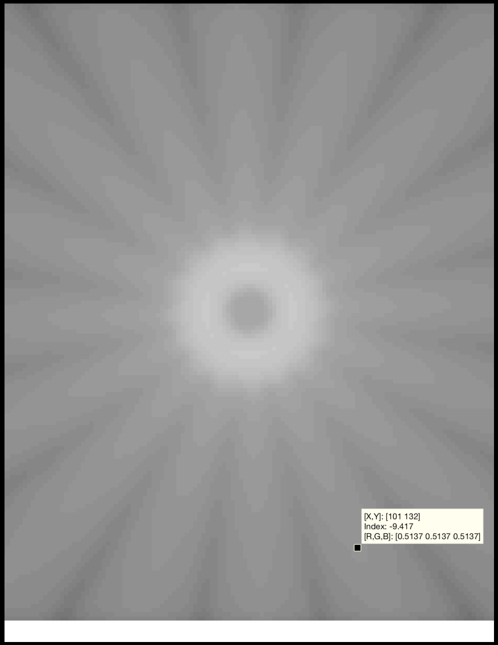


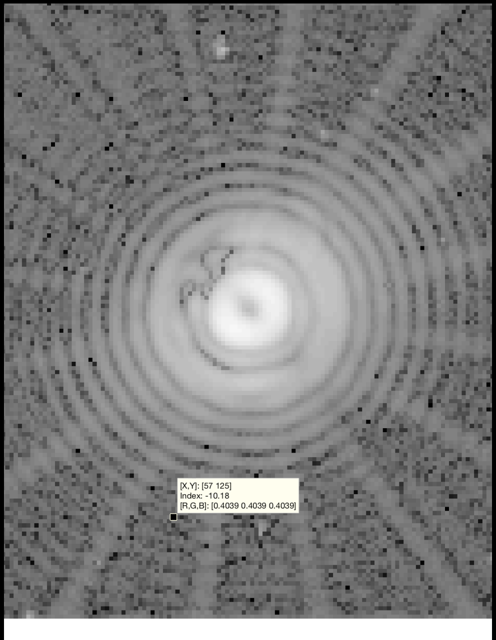
Image courtesy of Anthony Harness

Rayleigh Scattering

- Rayleigh scattering by air molecules limits measurable contrast to the ~1e-11 level at the IWA.
  - Could be reduced 64x by filling the testbed with helium







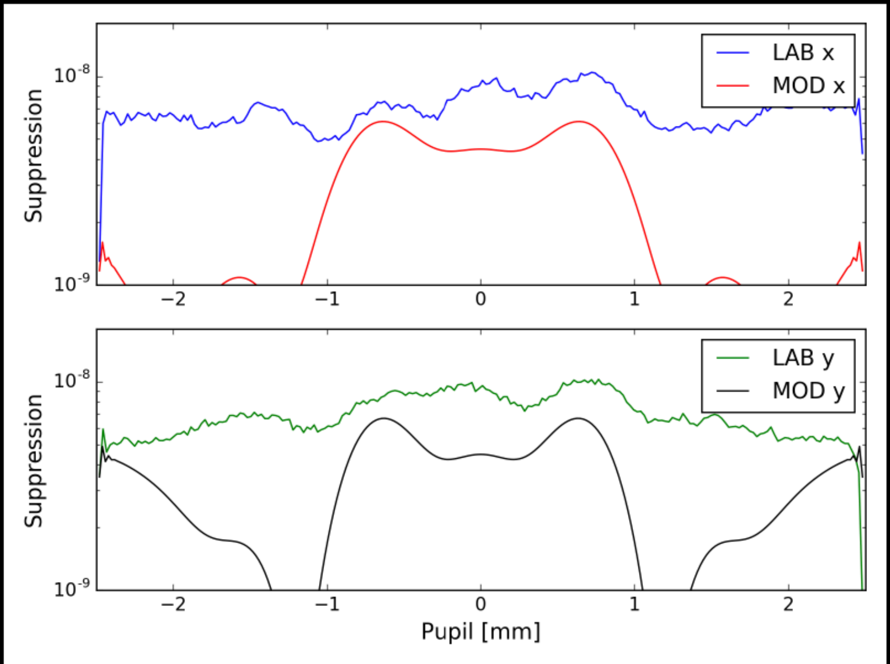
Princeton Testbed Results: Suppression

DW17 - Suppression

Experiment: 6.6×10^{-9}
Vector Model: 2.2×10^{-9}

Rayleigh scatter: $\sim 5.5 \times 10^{-9}$

Thickness
Mask: 2 µm
Model: 0.9 µm



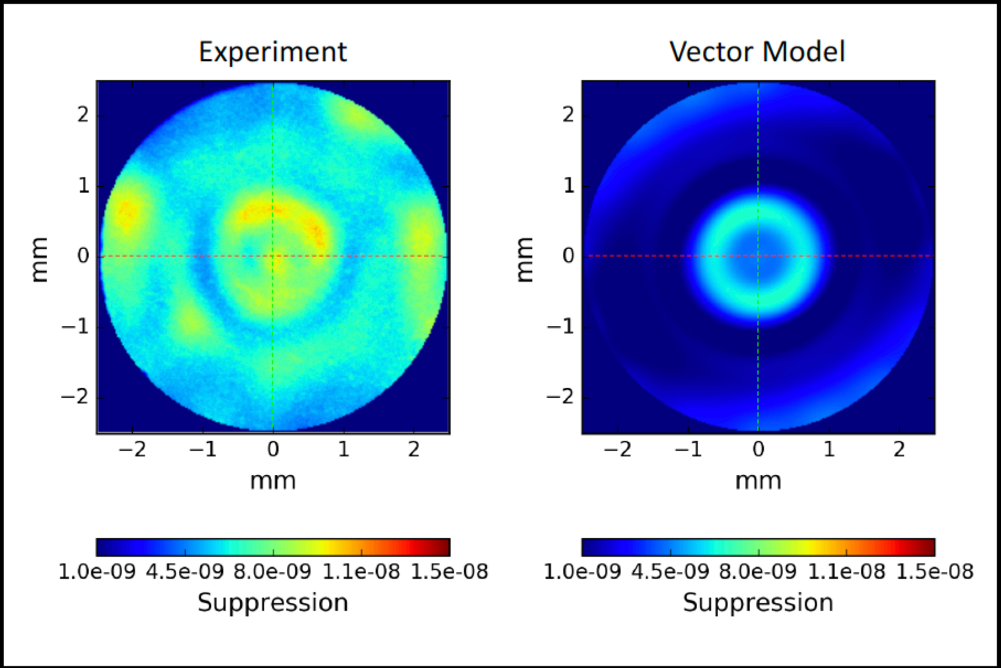


Image courtesy of Anthony Harness

Optical Edge Development (Petals)

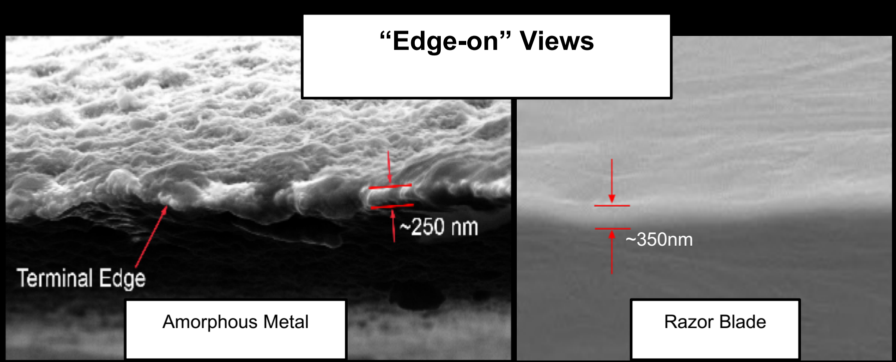
Scattered Sunlight Suppression

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

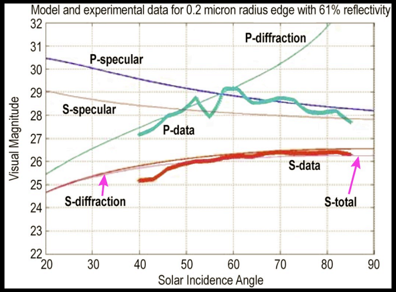
Ultra-black surface coatings can potentially relax requirement on edge sharpness

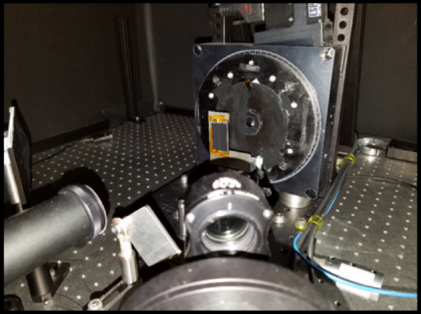
Optical Edge/Solar Glint Milestone

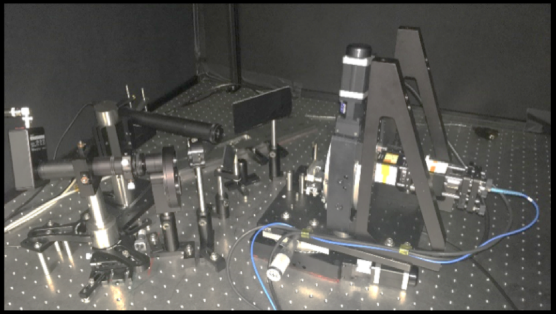
- MILESTONE 3: Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles. (11/1/2019)

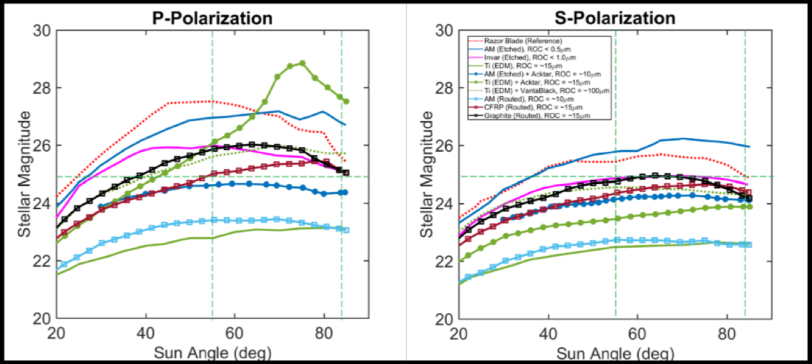
Scatterometer Results

- Multiple-angle scatterometer facility in place at JPL, capable of measuring scattering from small test edge coupons over a range of scattering angles, edge angles, and polarizations.
  - For best edges, data agree with diffraction-dominated performance
  - Results to date show:
    - ‘sharp and dark’ not yet achievable in practice
    - ‘sharp and shiny’ better than ‘blunt and dark’





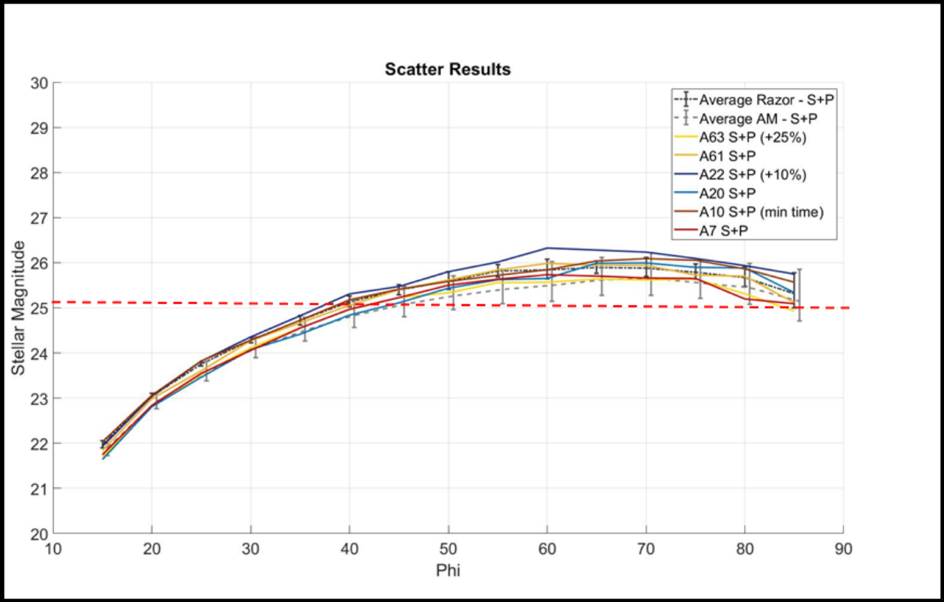


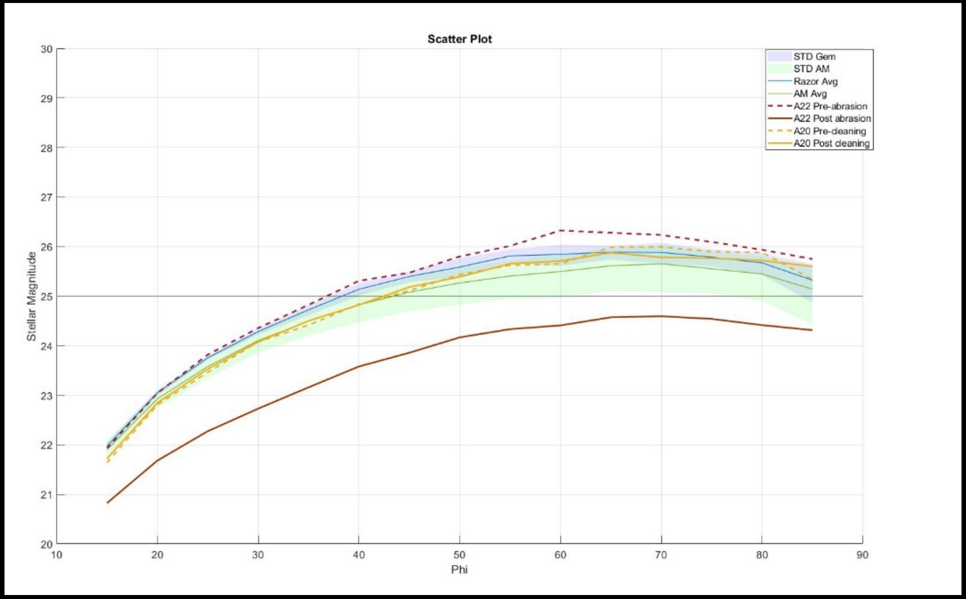


- Fixed-angle scatterometer now in construction for characterization of meter-scale flight-like prototype petal edge prototypes before/after stressing environments

Scatterometer Results

Latest amorphous metal edge coupons continue to meet scatter requirements

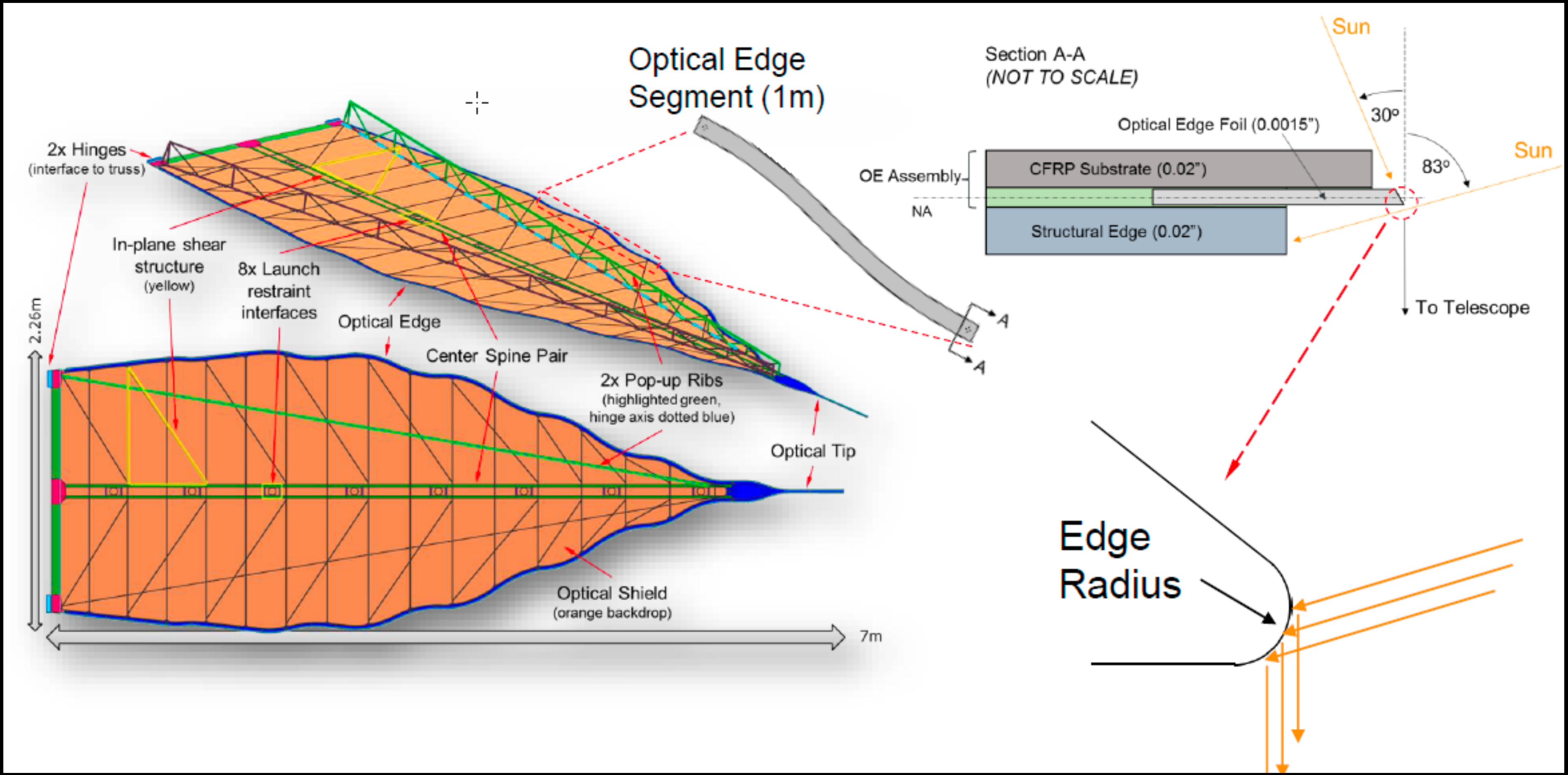




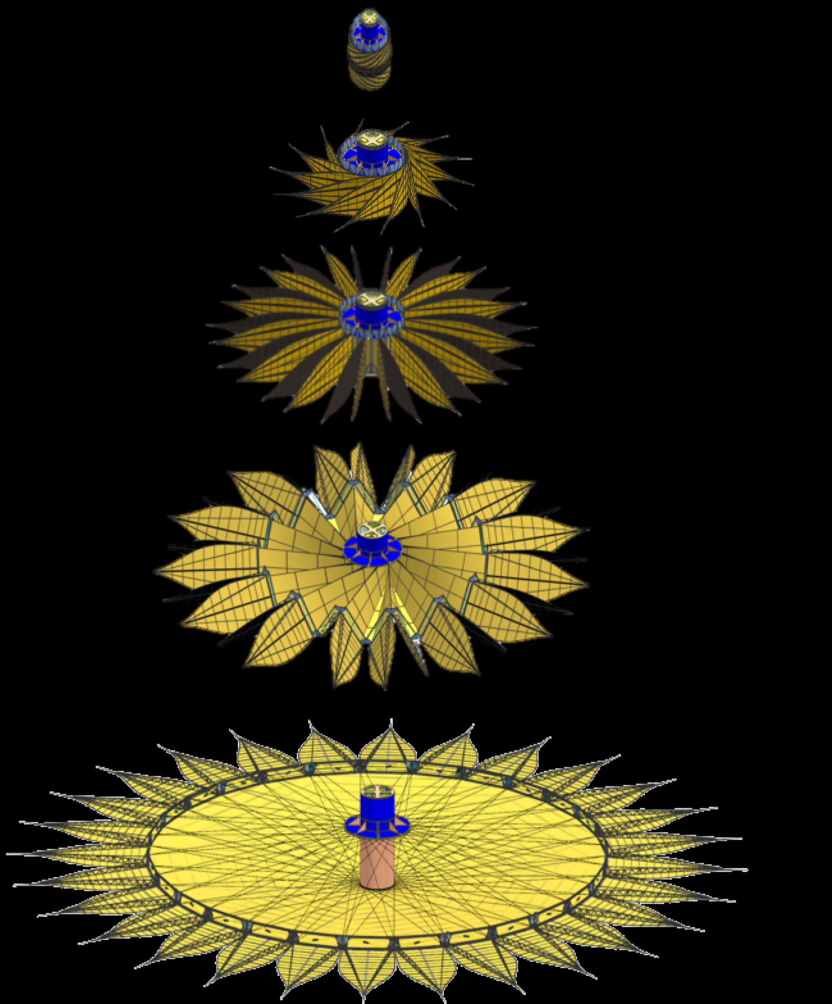
Test of impact of 'exaggerated abrasion' on scatter performance does show an effect: cleaning okay, scraping not so much

Optical Edge Development

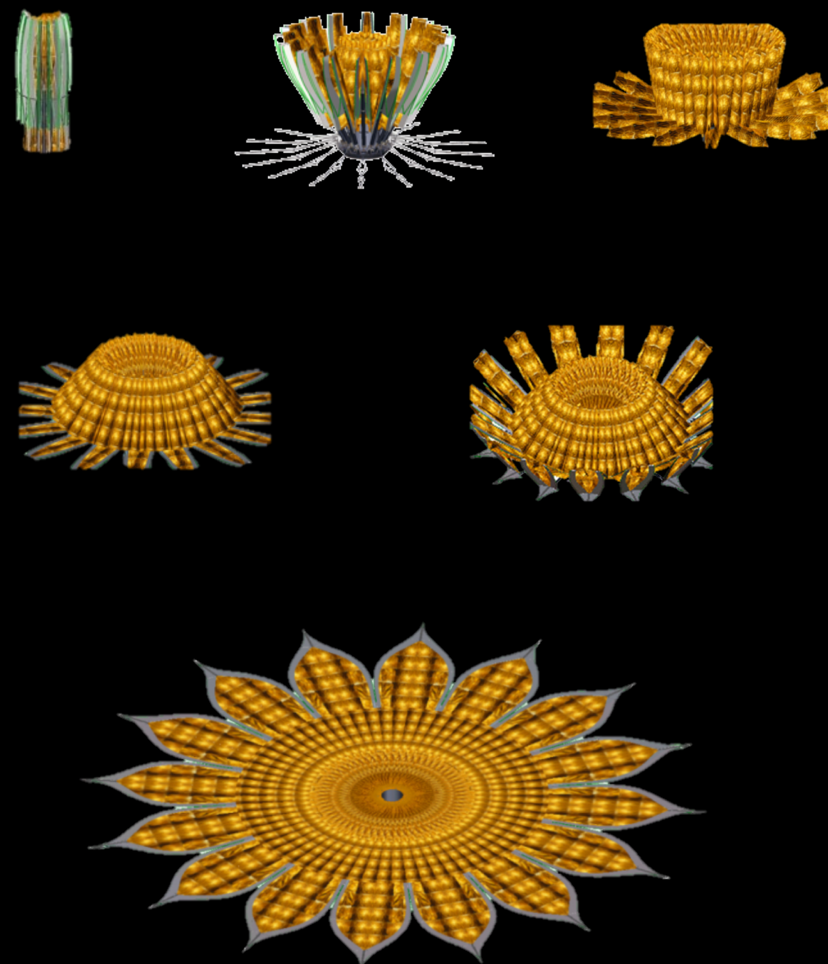
SBIR Award: Tendeg's Petal Optical Edge Integration



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

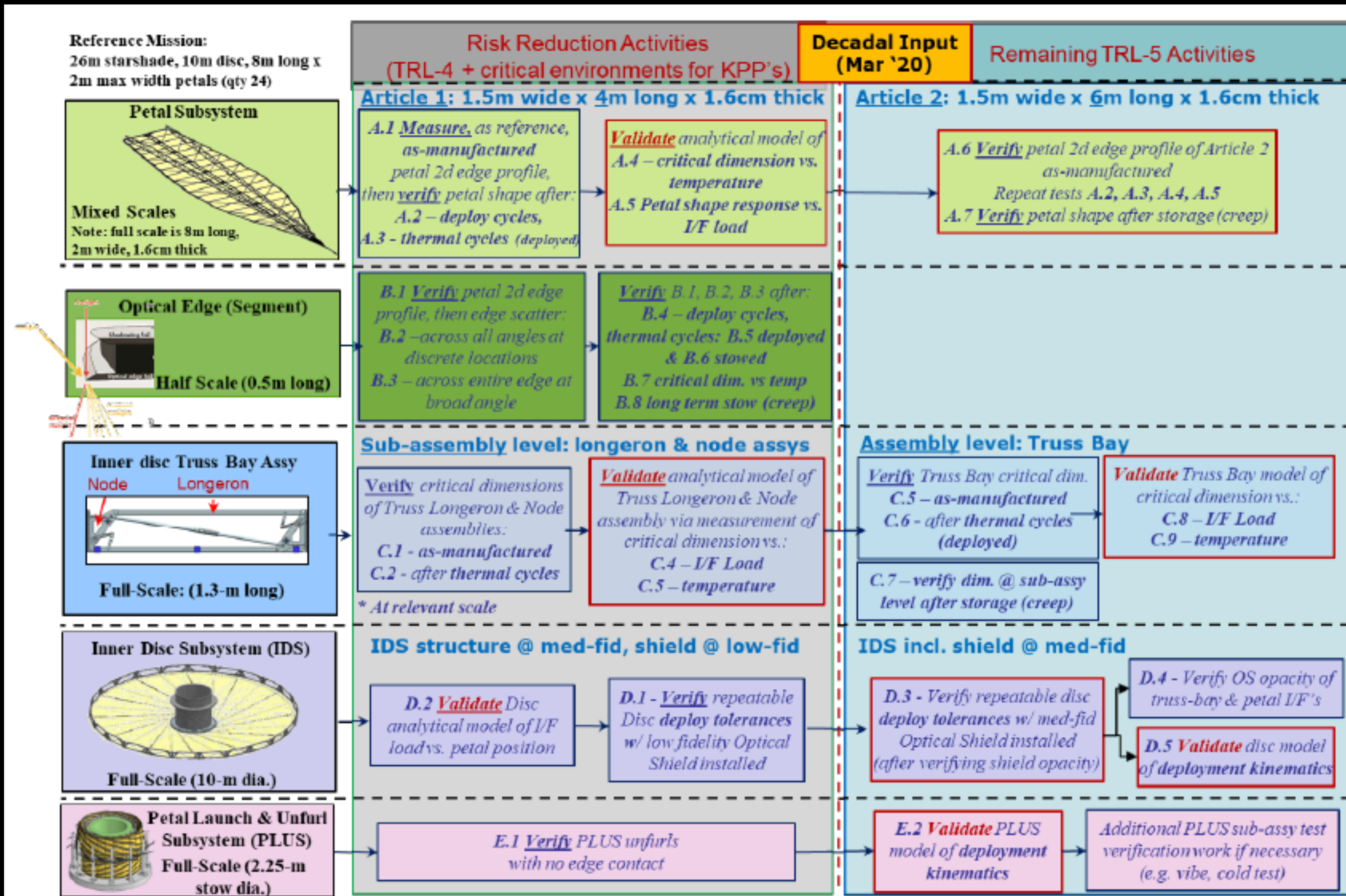


Furled and wrapped petal deployment concept (JPL)



Boom supported and folded petal deployment concept (Northrop Grumman)

Mechanical Technology Development



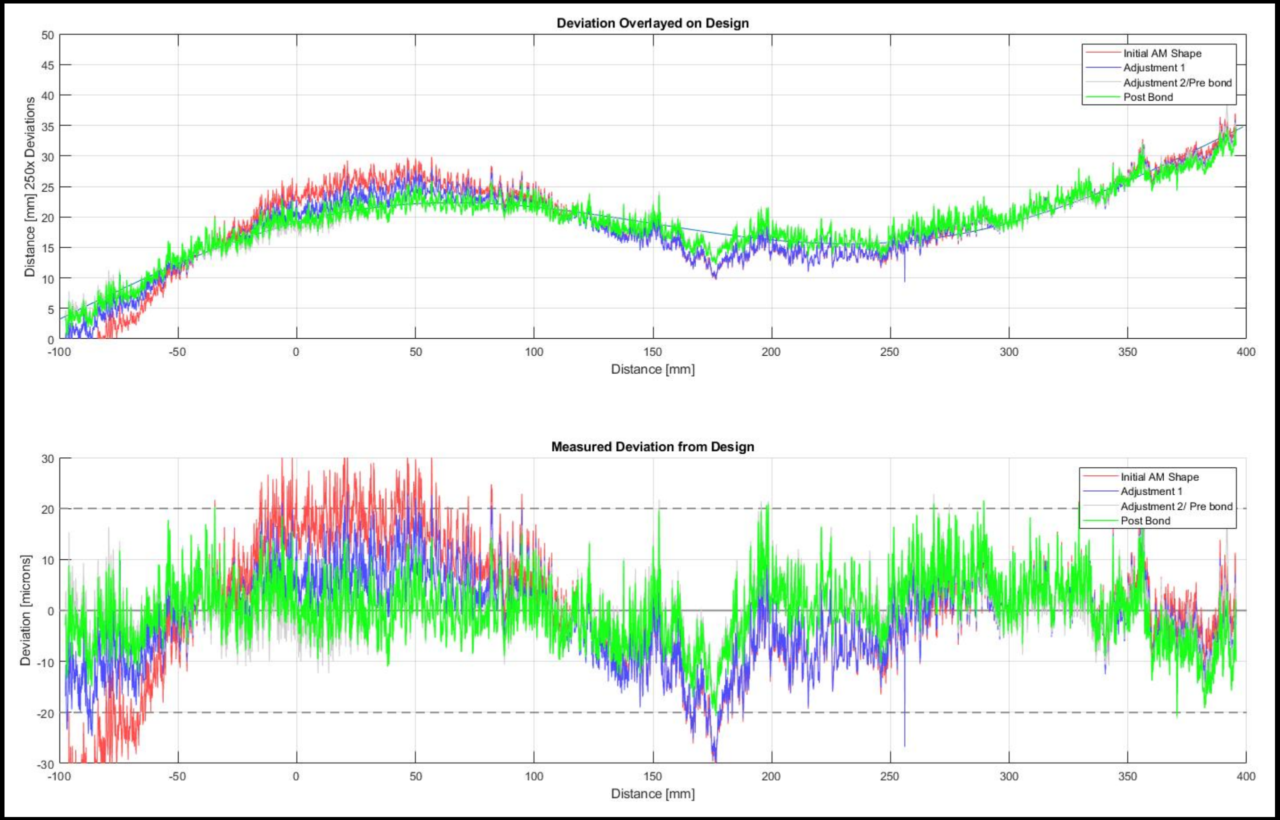
Petal Shape Milestones

- MILESTONE 5A: Petal subsystem with shape critical features demonstrates shape stability after deploy cycles (deployed) consistent with a total pre-launch shape accuracy within $\pm 70\mu m$ (12/20/2019)
- MILESTONE 5B: Petal subsystem with all features demonstrates total pre-launch shape accuracy (manufacture, deploy cycles, thermal cycles deployed, and storage) to within $\pm 70\mu m$ (6/2/2023)
- MILESTONE 6A: Petal subsystem with shape critical features demonstrates on-orbit thermal stability within $\pm 80\mu m$ by analysis using a validated model of critical dimension vs. temperature (12/20/2019)
- MILESTONE 6B: Petal subsystem with all features demonstrates on-orbit thermal stability within $\pm 80\mu m$ by analysis using a validated model of critical dimension vs. temperature (6/2/2023)

Recent Petal Progress

First petal article built

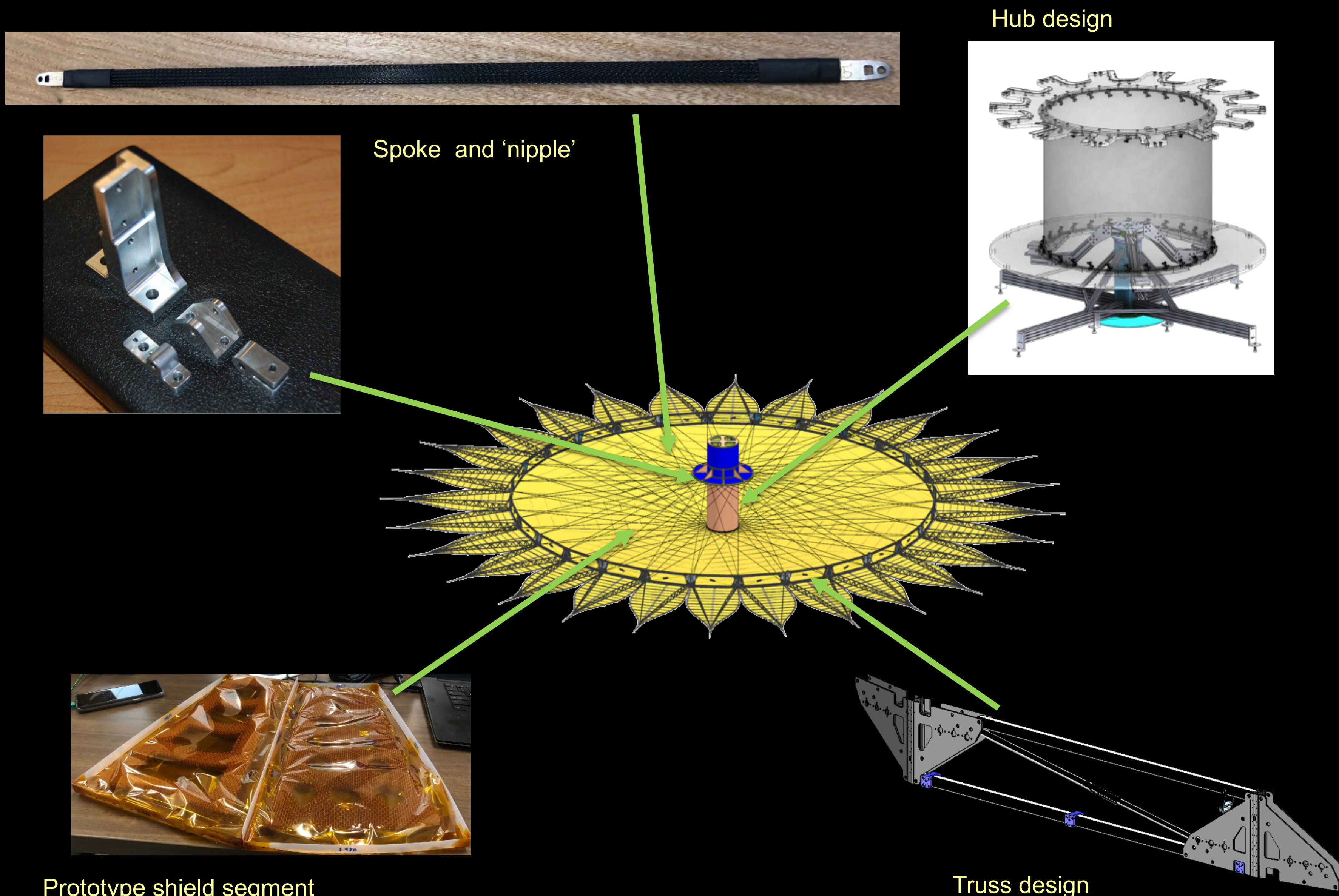
First flight-like edge segment meets shape spec, and small deviations can be corrected before bonding



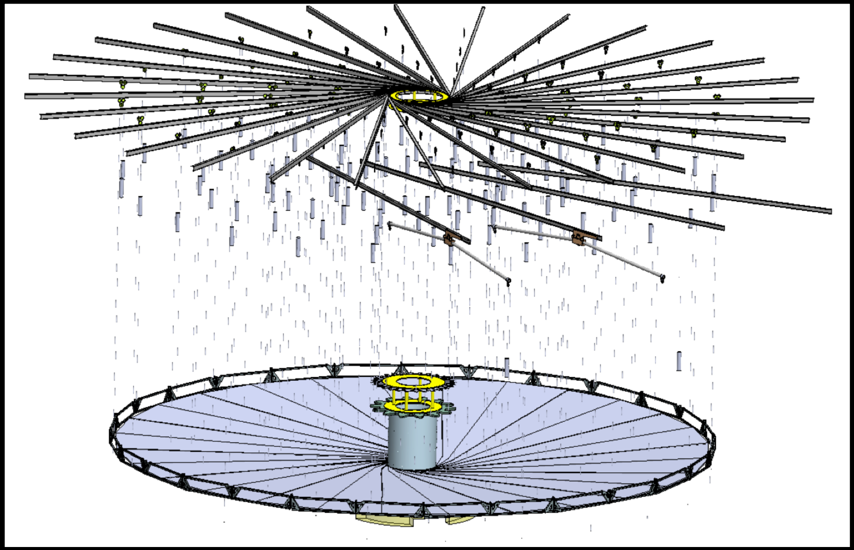
Petal Position Milestones

- MILESTONE 7A: Truss bay longeron and node subassemblies demonstrate dimensional stability with thermal cycles (deployed) consistent with total pre-launch petal position accuracy within $\pm 300\mu m$ (12/20/2019)
- MILESTONE 7B: Truss bay assembly demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with total pre-launch petal position accuracy within $\pm 300\mu m$ (6/2/2023)
- MILESTONE 7C: Inner disk subsystem with optical shield assembly that includes deployment critical features demonstrates repeatable accuracy consistent with total pre-launch petal position accuracy within $\pm 300\mu m$ (12/20/2019)
- MILESTONE 7D: Inner disk subsystem with optical shield assembly that includes all features demonstrates repeatable accuracy consistent with total pre-launch petal position accuracy within $\pm 300\mu m$ (6/2/2023)
- MILESTONE 8A: Truss bay longeron and node subassemblies demonstrate on-orbit thermal stability $\pm 200\mu m$ by analysis using a validated model of critical dimension vs. temperature (12/20/2019)
- MILESTONE 8B: Truss bay assembly demonstrates on-orbit thermal stability $\pm\, 200\mu m$ by analysis using a validated model of critical dimension vs. temperature (6/2/2023)

Inner Disk and Optical Shield

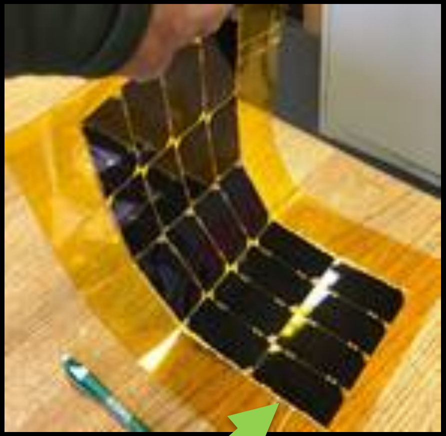


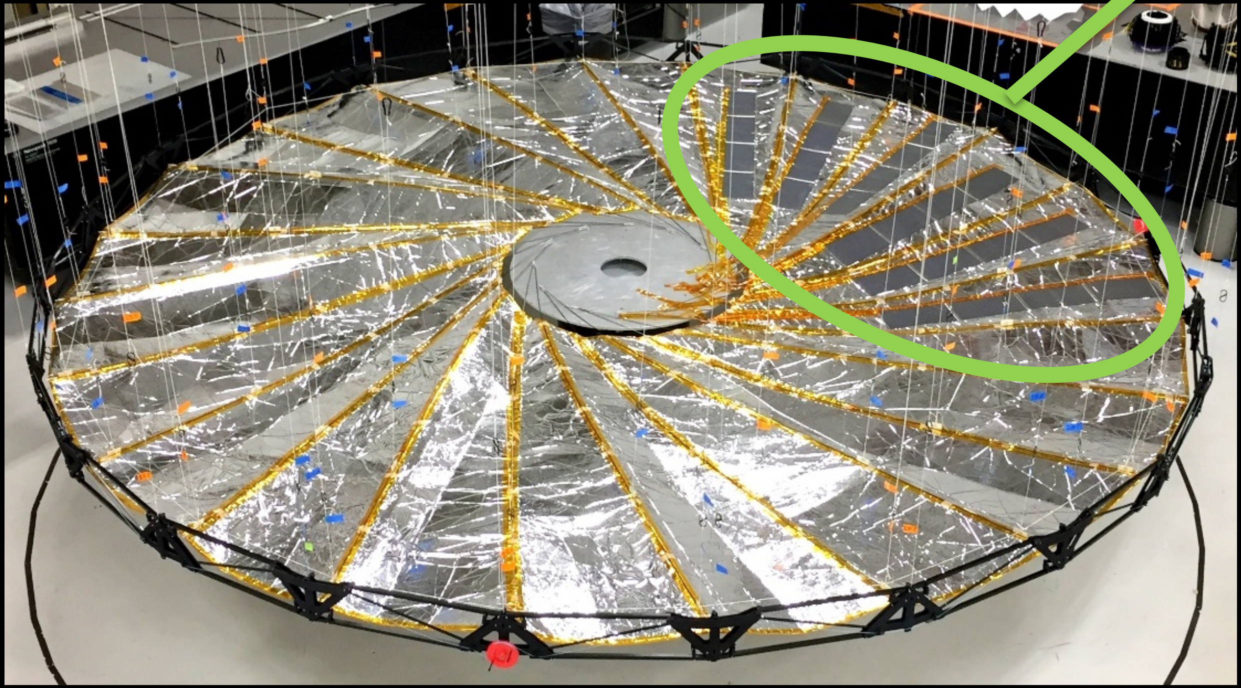
Optical Shield Testbed



Gravity offloading

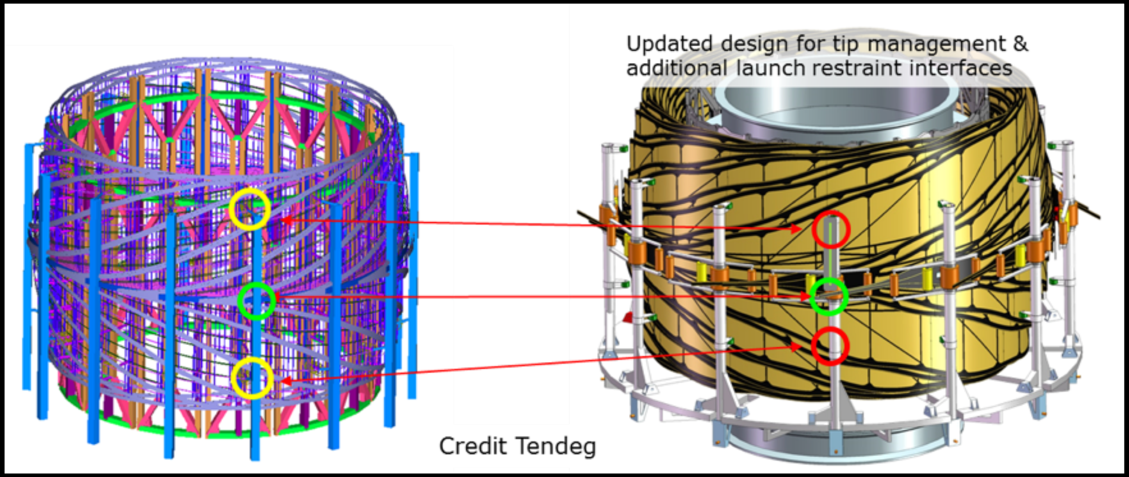
Integrated solar cells

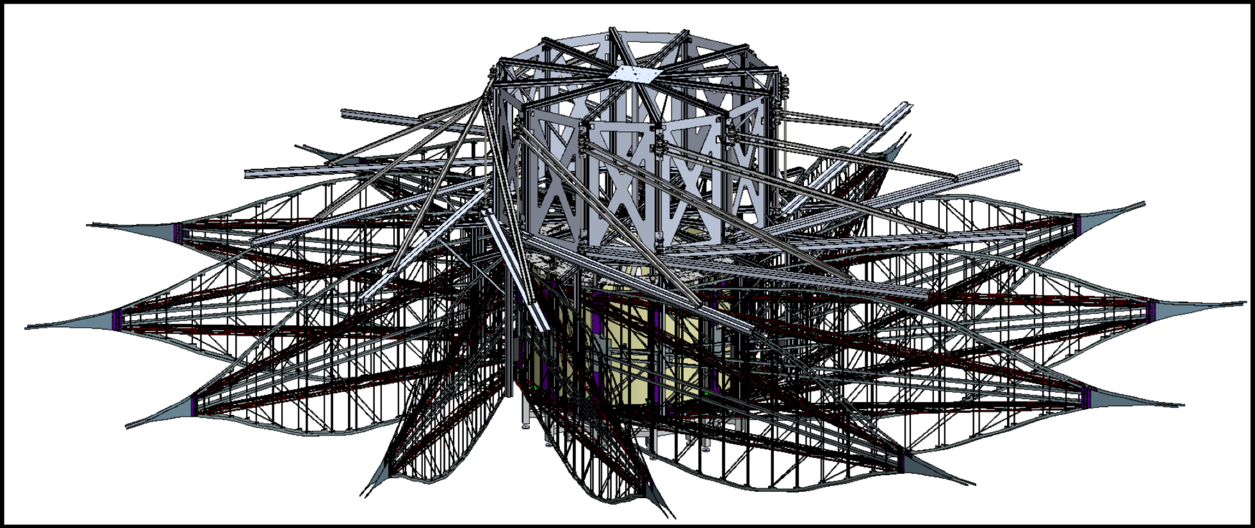




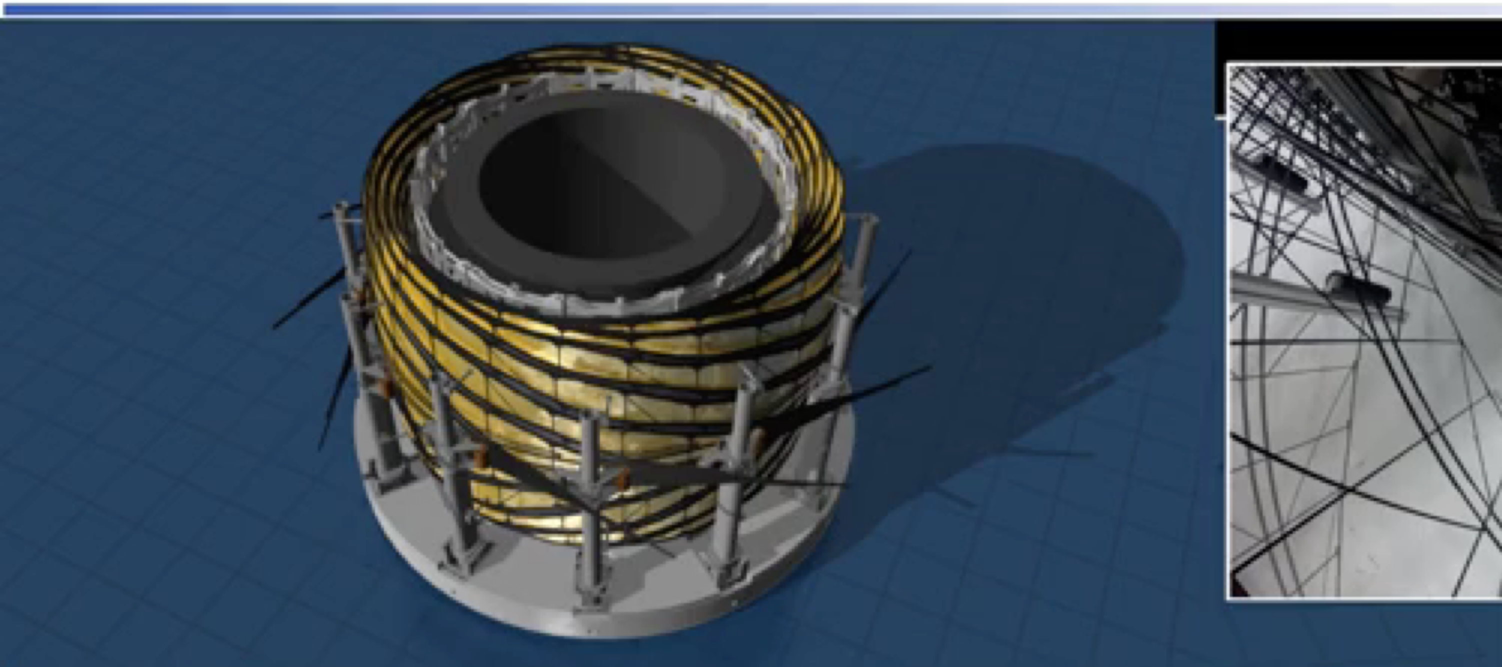
Petal Launch restraint and Unfurler System (PLUS)

The PLUS is not a technology gap, but S5 is developing it as essential engineering in support of the wrapped architecture technology.





PLUS Visualization & Hardware Deployment Overlay

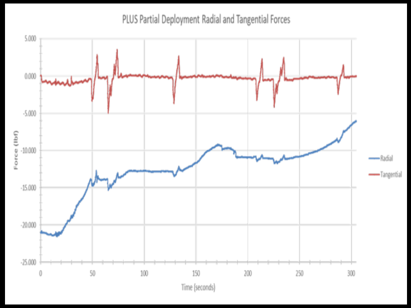


Incipient PLUS testbed deployment with low fidelity petals unfurling hardware (side view and top view)

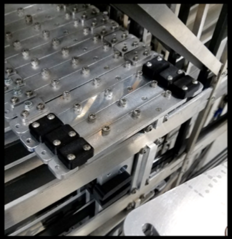
Recent Progress and Plans for PLUS

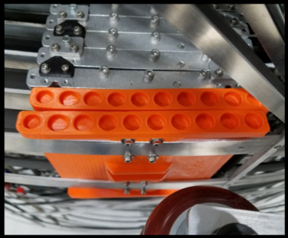
The PLUS is not a technology gap, but S5 is developing it as essential engineering in support of the wrapped architecture technology.

Radial & tangential load cell response for unfurling

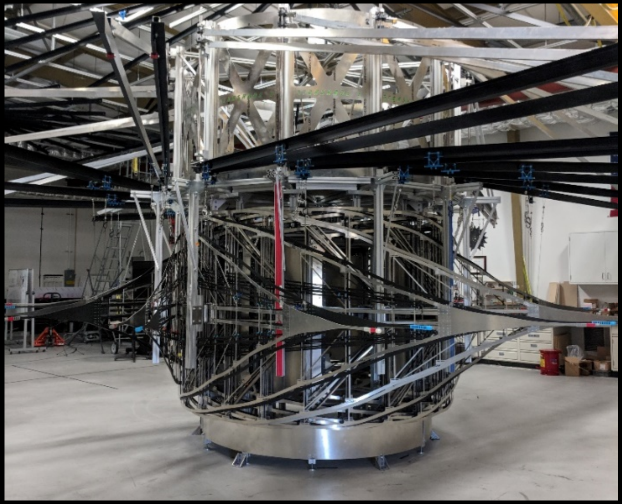


Batten L/R snubber stack





Low fidelity cart designs



New Roller Arm Assy (on 3 arms), per trade study design

PLUS prototype currently being upgraded at JPL, will ship to Tendeg for further upgrade in ~May 2019.

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		