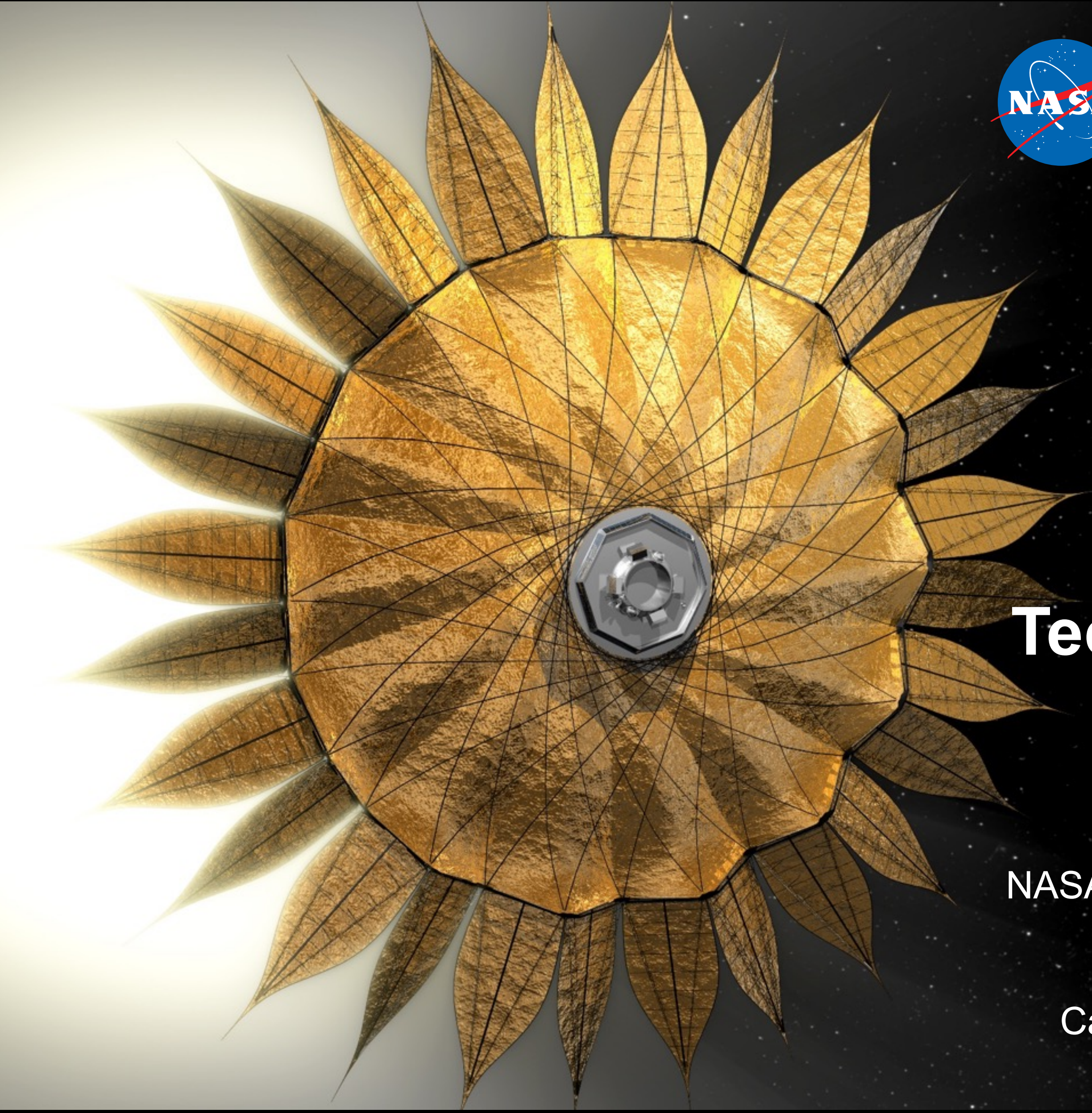


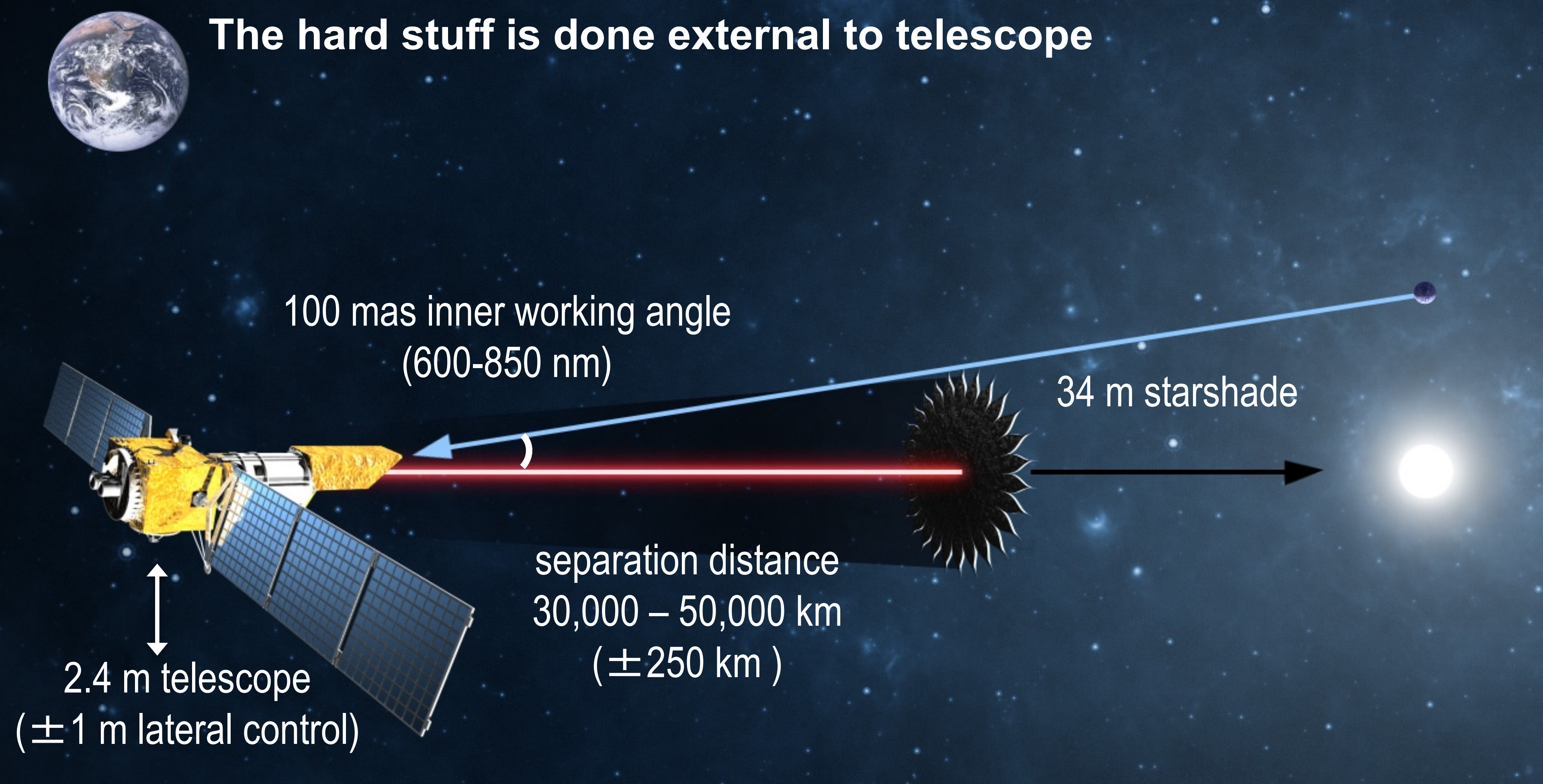
Jet Propulsion Laboratory
California Institute of Technology

Update on S5's Starshade Technology Activities

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

Starshade

The hard stuff is done external to telescope

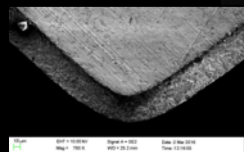


Organization of S5

- 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.
  - All milestones reviewed by external independent panel (ExoTAC)
- S5 includes Science and Industry Partners (SIP) program to solicit fresh ideas and approaches
- See https://exoplanets.nasa.gov/exep/technology/starshade/

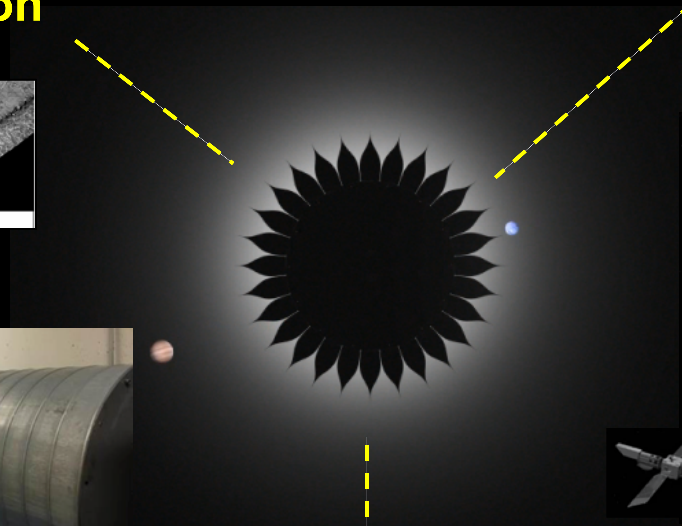
The Three Starshade Technology Gaps

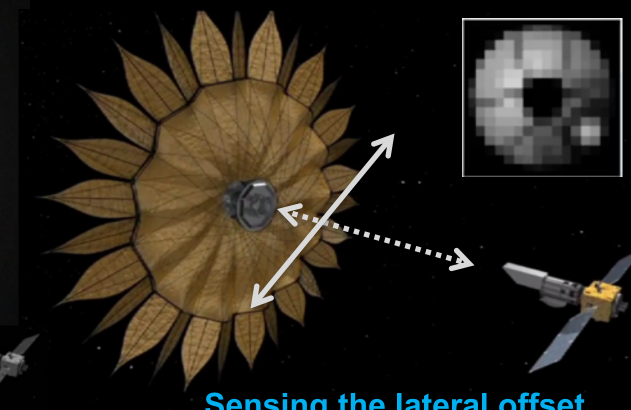
(1) Starlight Suppression

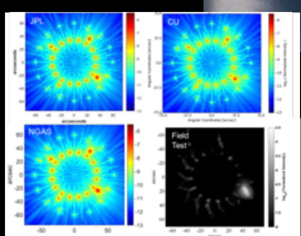
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)

(2) Formation Sensing



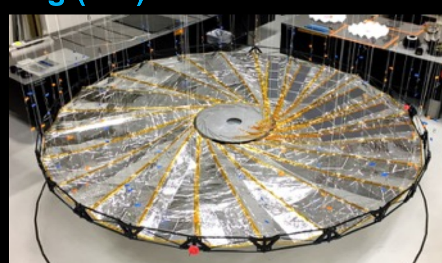


Sensing the lateral offset between the spacecraft (S-3)

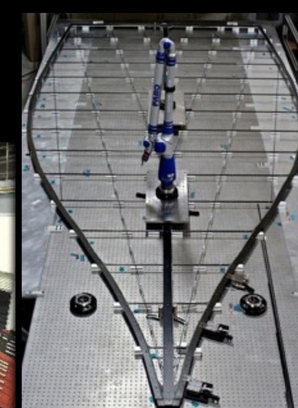


Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(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)

S5 Reference Mission

- S5 Technology Development Plan uses WFIRST Rendezvous and HabEx mission concepts to derive KPPs; these KPPs are not tightly 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 space telescope.
- S5 technology milestones 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; test articles are half-scale for HabEx but still sufficient to demonstrate TRL5

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		

S5 Technology Milestones Scorecard

Complete 2020

Complete 2023

Milestone Completed

Report under Review

In Progress

Not Started

Starlight Suppression

Contrast NB
1A

Contrast BB
1B

Modeling
2

Scattered Sunlight

Edges
3

Formation Flying

Sensing
4

Critical Features

All Features

Shape Accuracy

Petal
5A

Truss Bay
7A

Inner Disk
7C

Petal
5B

Truss Bay
7B

Inner Disk
7D

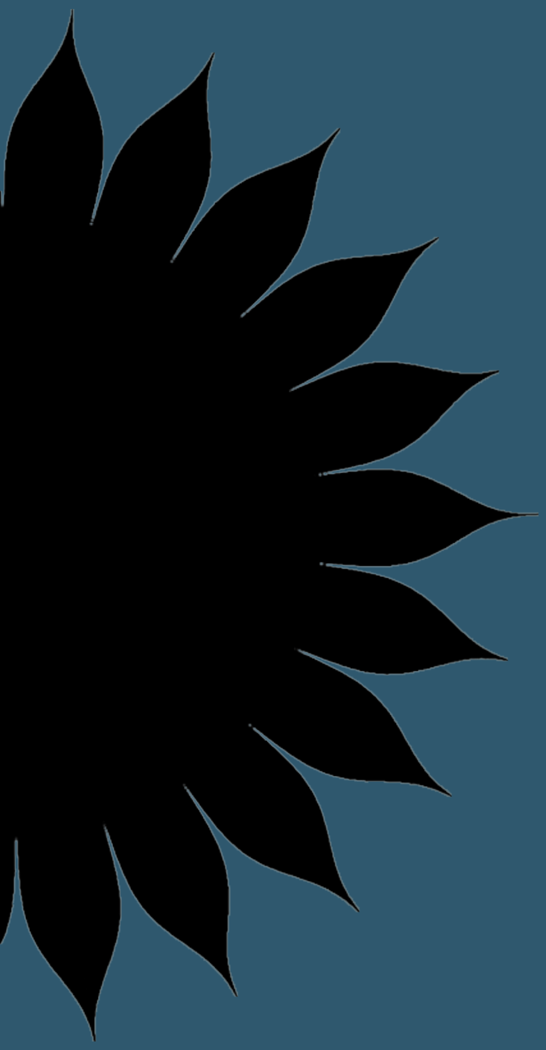
Shape Stability

Petal
6A

Inner Disk
8A

Petal
6B

Inner Disk
8B



Starlight Suppression

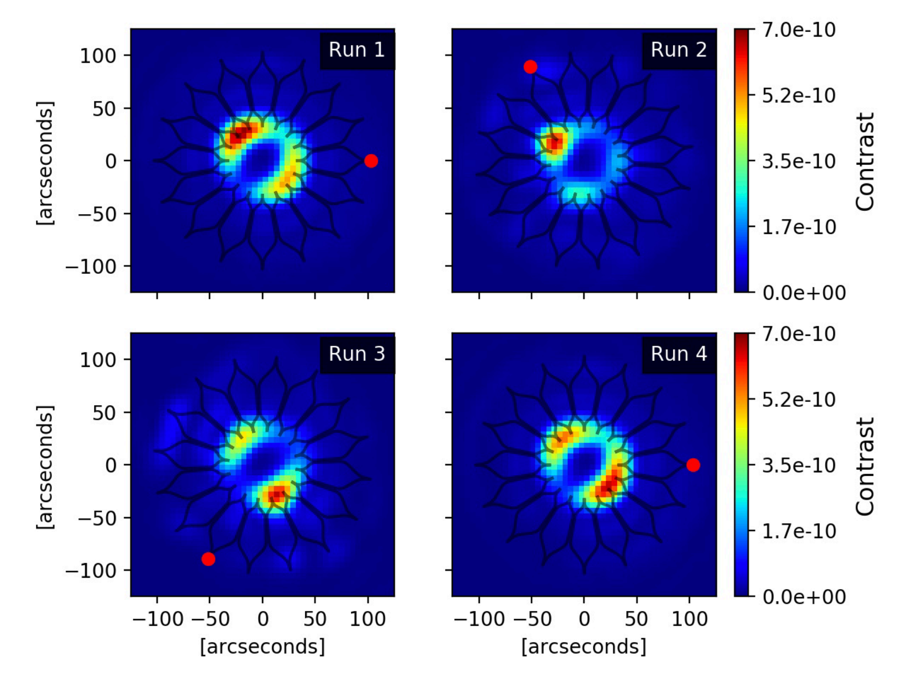
Starlight Suppression Milestones

- 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

Narrowband Contrast Demonstration

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.

KPP 1



REQUIREMENT MET:

Achieved < 10^{-10} contrast at 44% of IWA, best performance to date of a starshade at a flight-like Fresnel number.

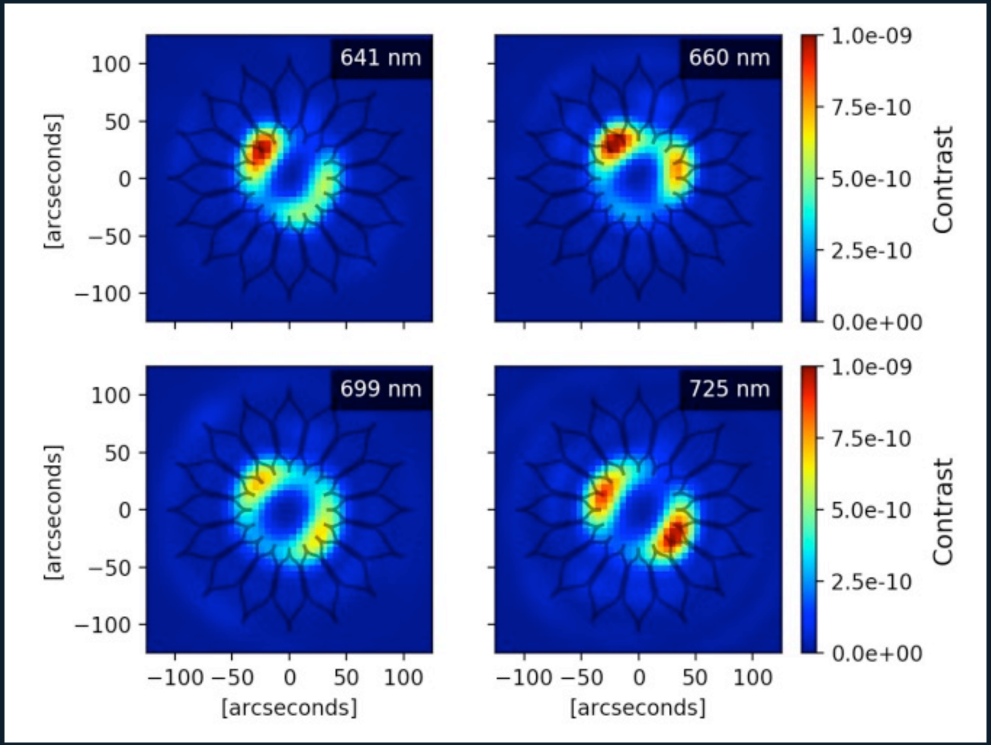
Limits to contrast at small scale are well understood.

STATUS: Complete

Broadband Contrast Demonstration

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 and Fresnel number ≤ 15 at the longest wavelength.

KPP 1

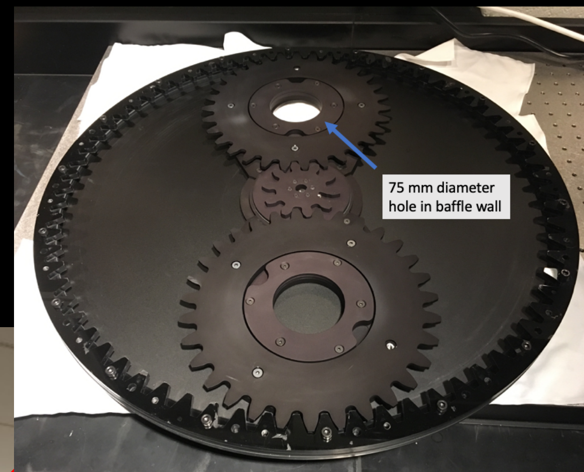


REQUIREMENT MET:
Achieved < 10^{-10} contrast at IWA, for all wavelengths tested.

STATUS: Complete

Upgrades to the Princeton Starshade Testbed

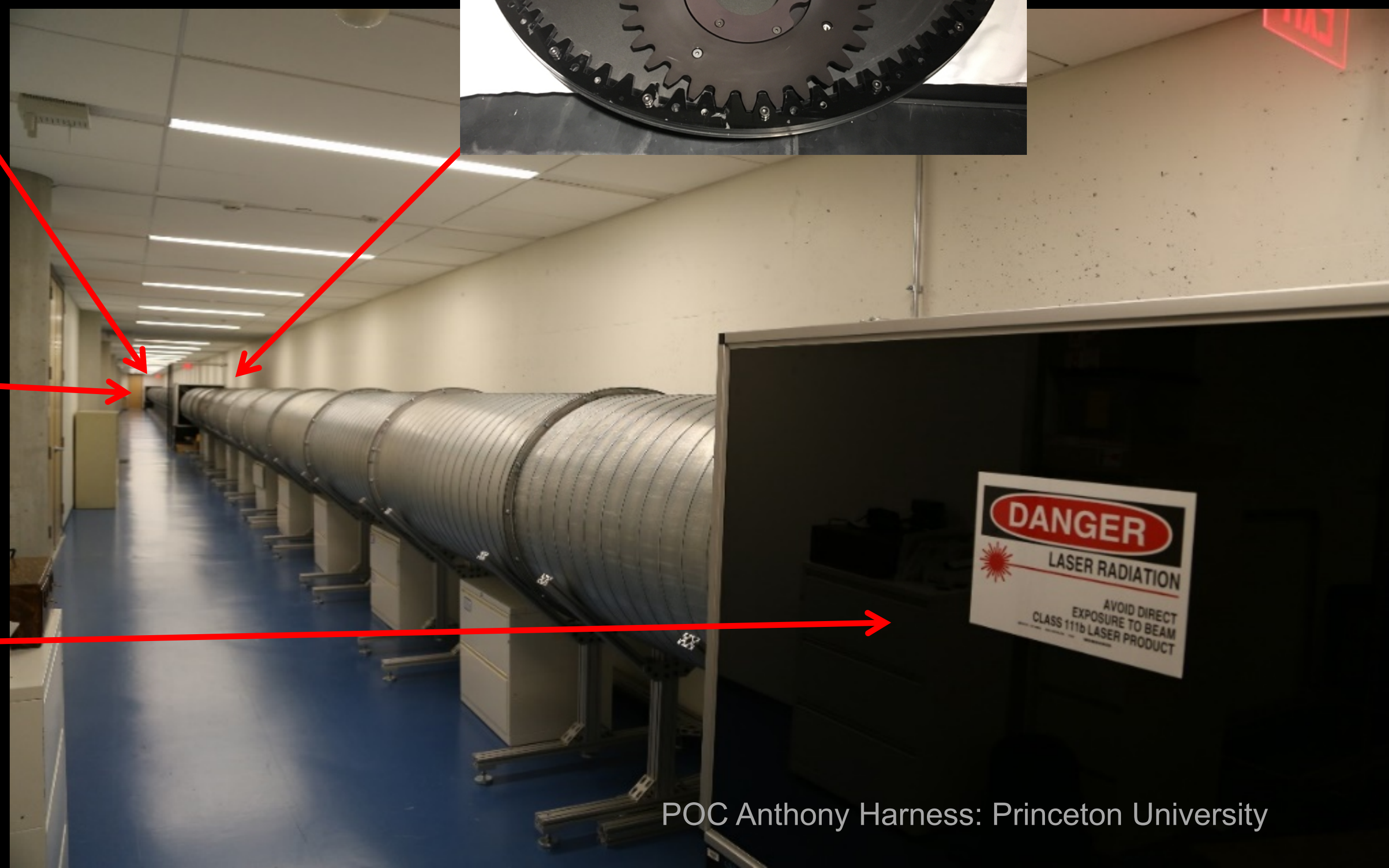
New mask inserter/ rotator



Active control of camera transverse position

Analyzer at camera station

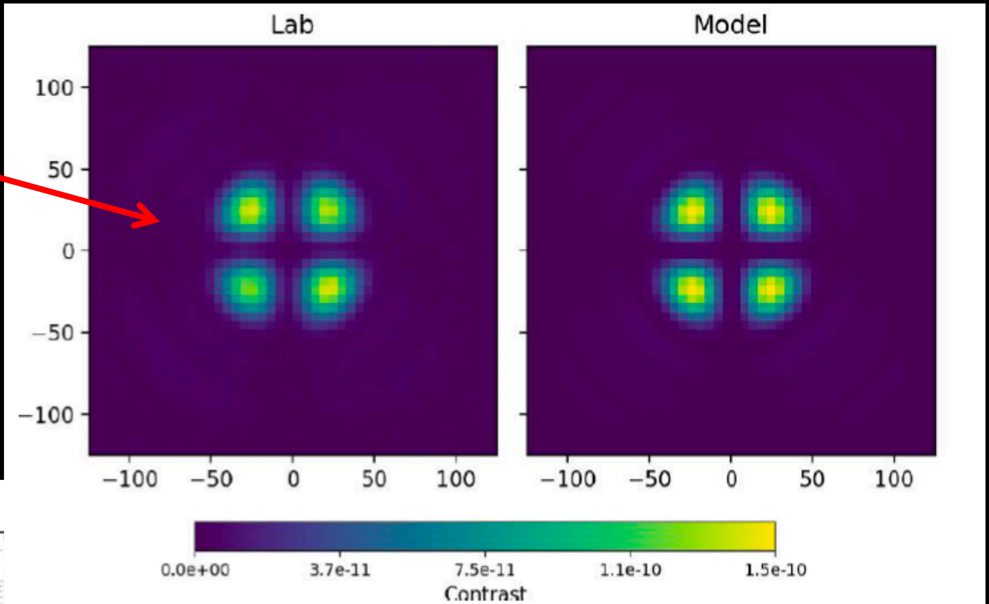
Polarizer at laser station

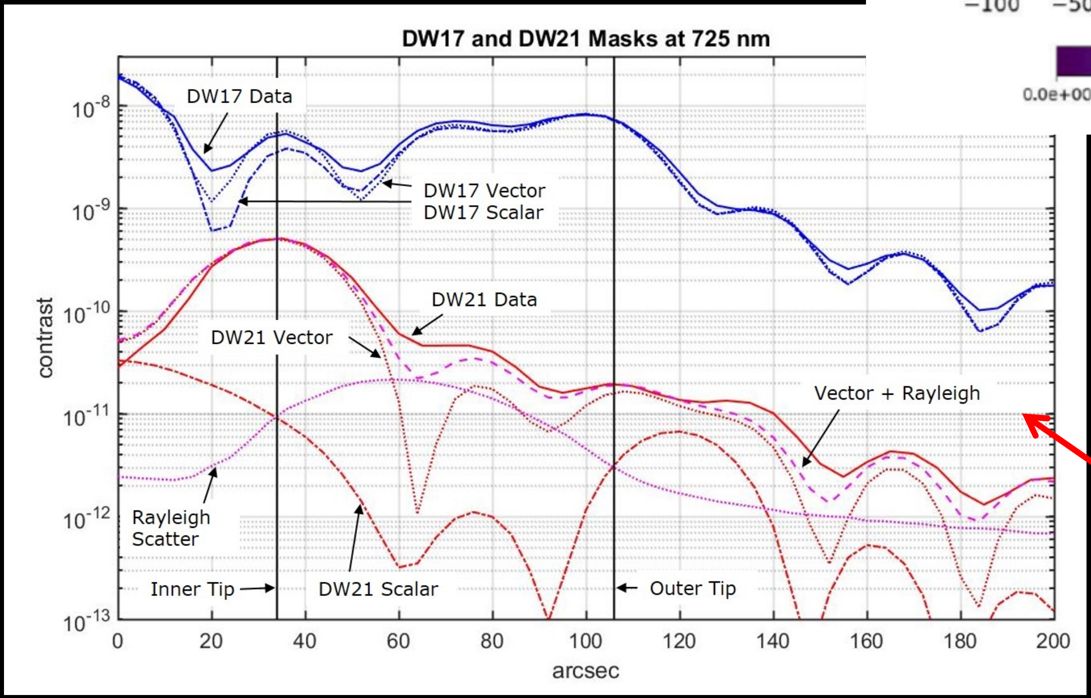


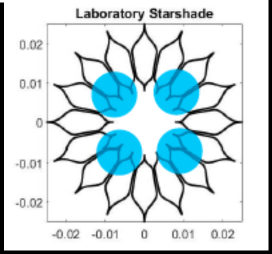
POC Anthony Harness: Princeton University

Understanding Vector Diffraction

Viewing starshade between crossed polarizers reveals vector interactions at petal bases







Detailed models show transition to scalar diffraction outside starshade stopband

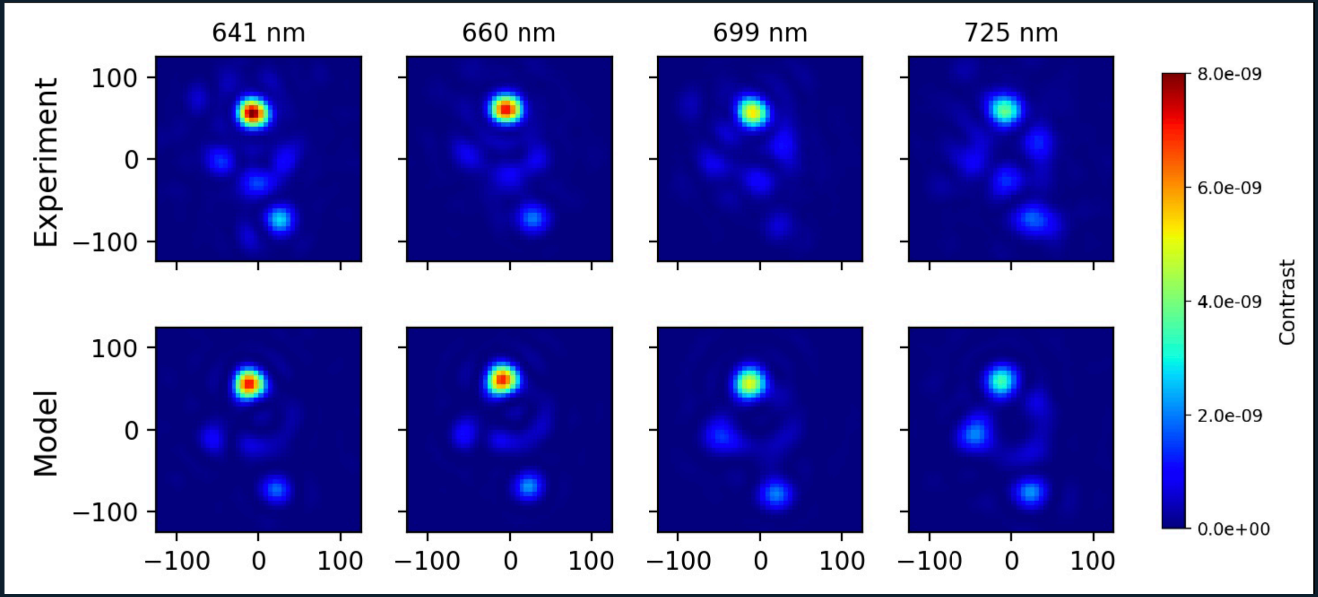
Optical Contrast Model Correlation

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}.

KPP 2

APPROACH:
Test deliberately misshapen masks to verify that contrast varies with shape error as predicted.

STATUS:
Contrast varies with shape as expected in masks tested to date.



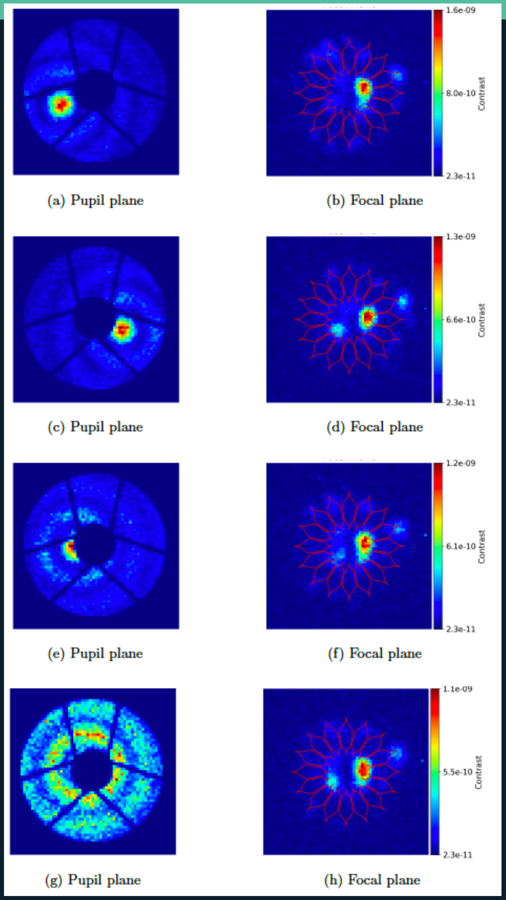
STATUS: Delayed

Formation Flying

Formation Flying

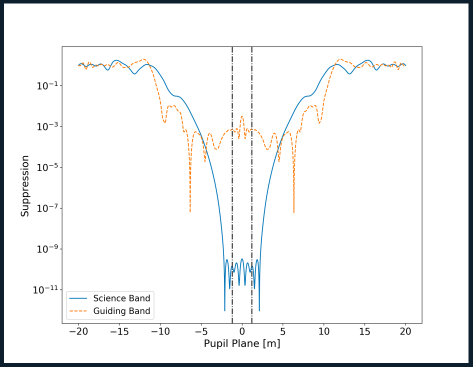
Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral position offset sensitivity to a flight equivalent of 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m.

KPP 4



REQUIREMENT MET:

- Starshade lateral offset measured to 10 cm flight equivalent.
- Formation flying simulation controlled position to $\pm$ 1 m.
- Large margins on stellar magnitude, allowable measurement error.

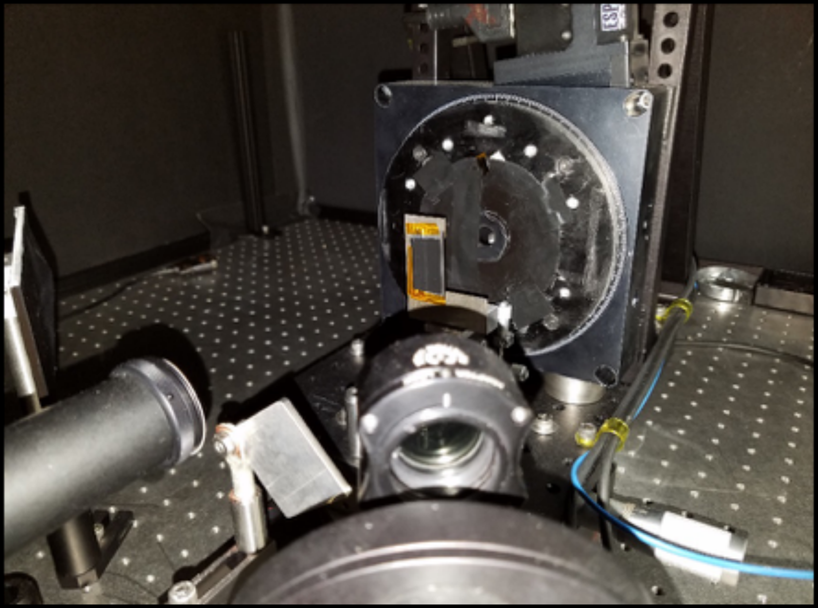


STATUS: Complete, formation flying at TRL 5

Figure credit: Palacios *et al.*

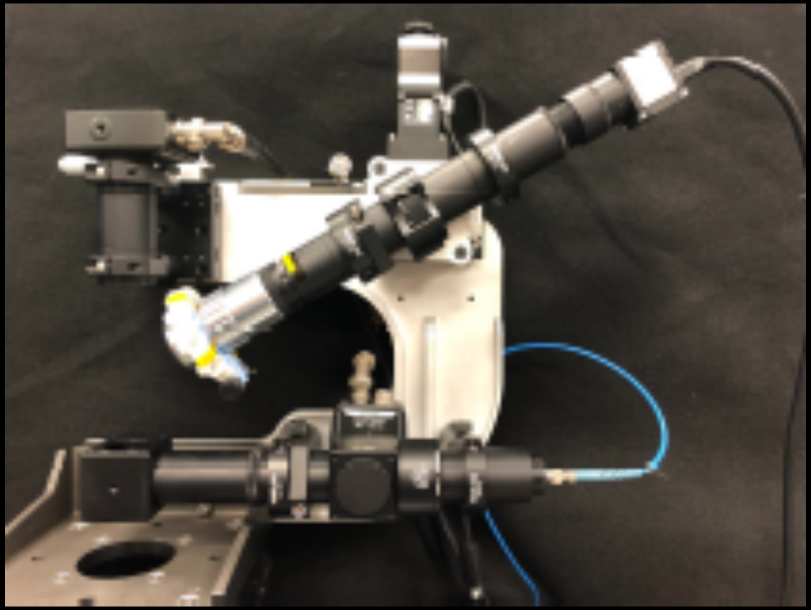
Solar Glint

S5 Scatterometers



Multiple Angle Scatterometer

- Used to measure scatter for full range of sun and edge orientations
- Can test orthogonal polarizations separately
- Can only measure small coupons
- Current upgrade to higher power and wider spectral range



Single Angle Scatterometer

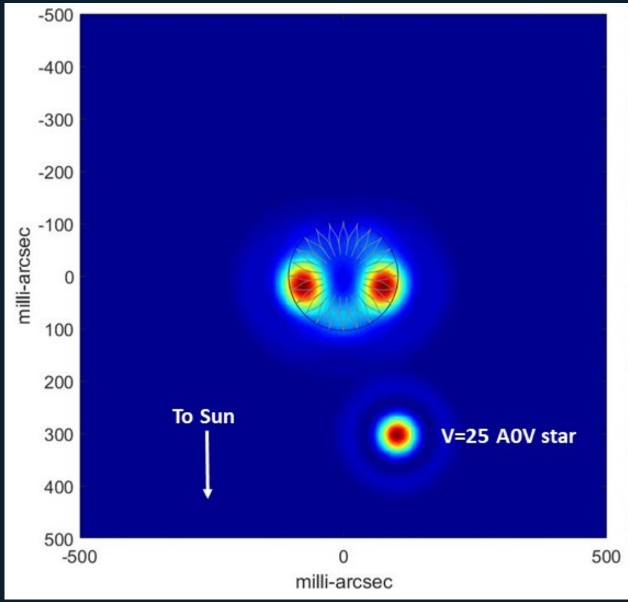
- Measures scatter over full range of of sun angles simultaneously, smaller range of edge angles
- Measures unpolarized light scatter
- Can scan and measure flight scale edge assemblies, on or off petals.

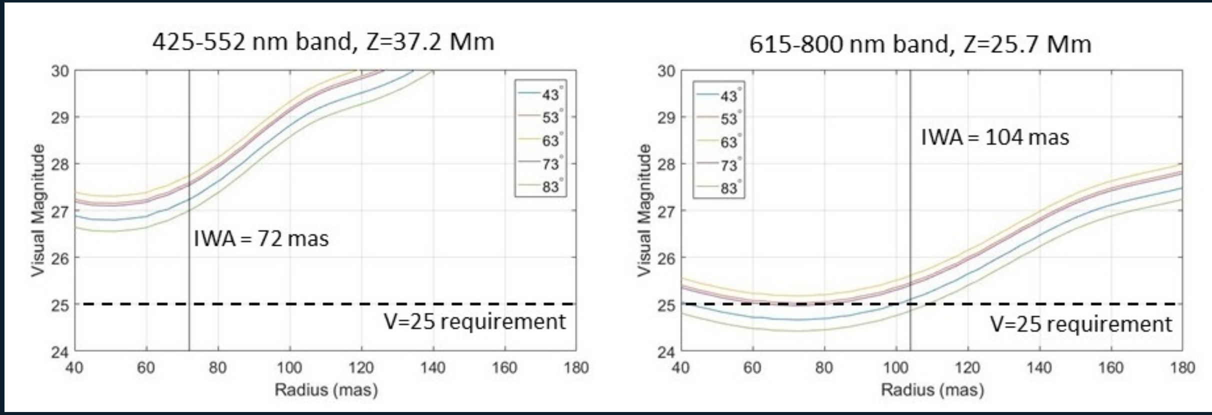
Solar Glint

Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles. KPP 3

RESULTS:

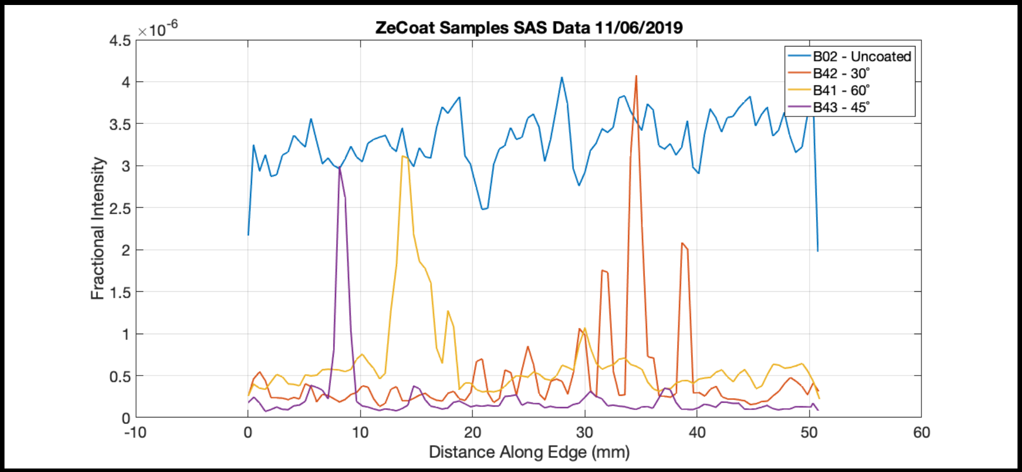
- System model shows scatter lobe dimmer than V = 25 mag for all wavelengths and nearly all sun angles.
- No degradation in scatter performance after exposure to environments.
- Some delamination seen after stow cycles, to be fixed in final petal article





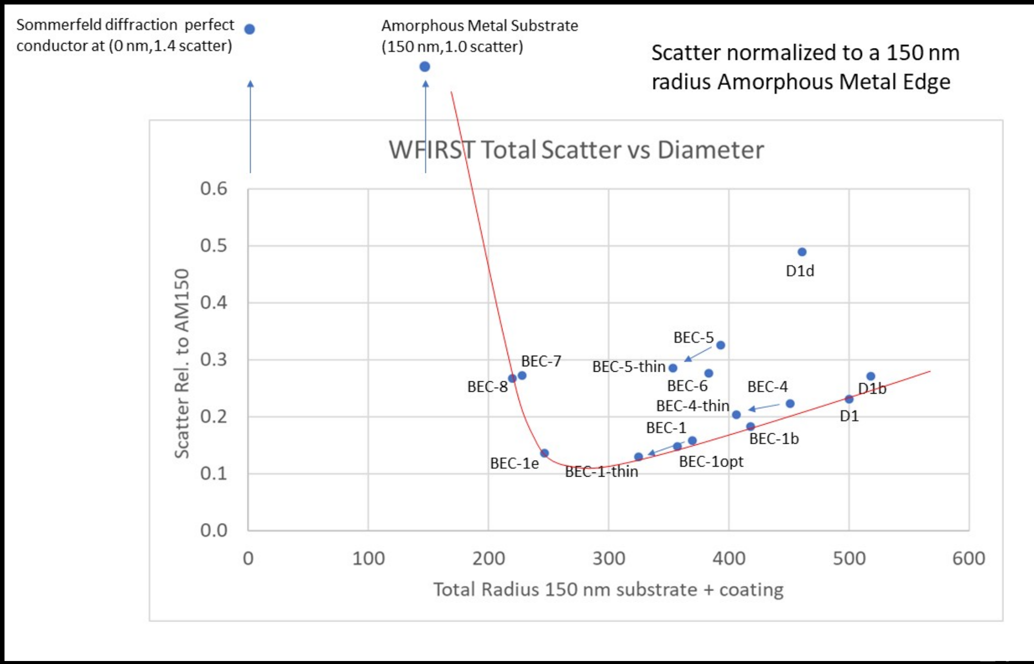
STATUS: Complete

Latest Edge Scatter Work



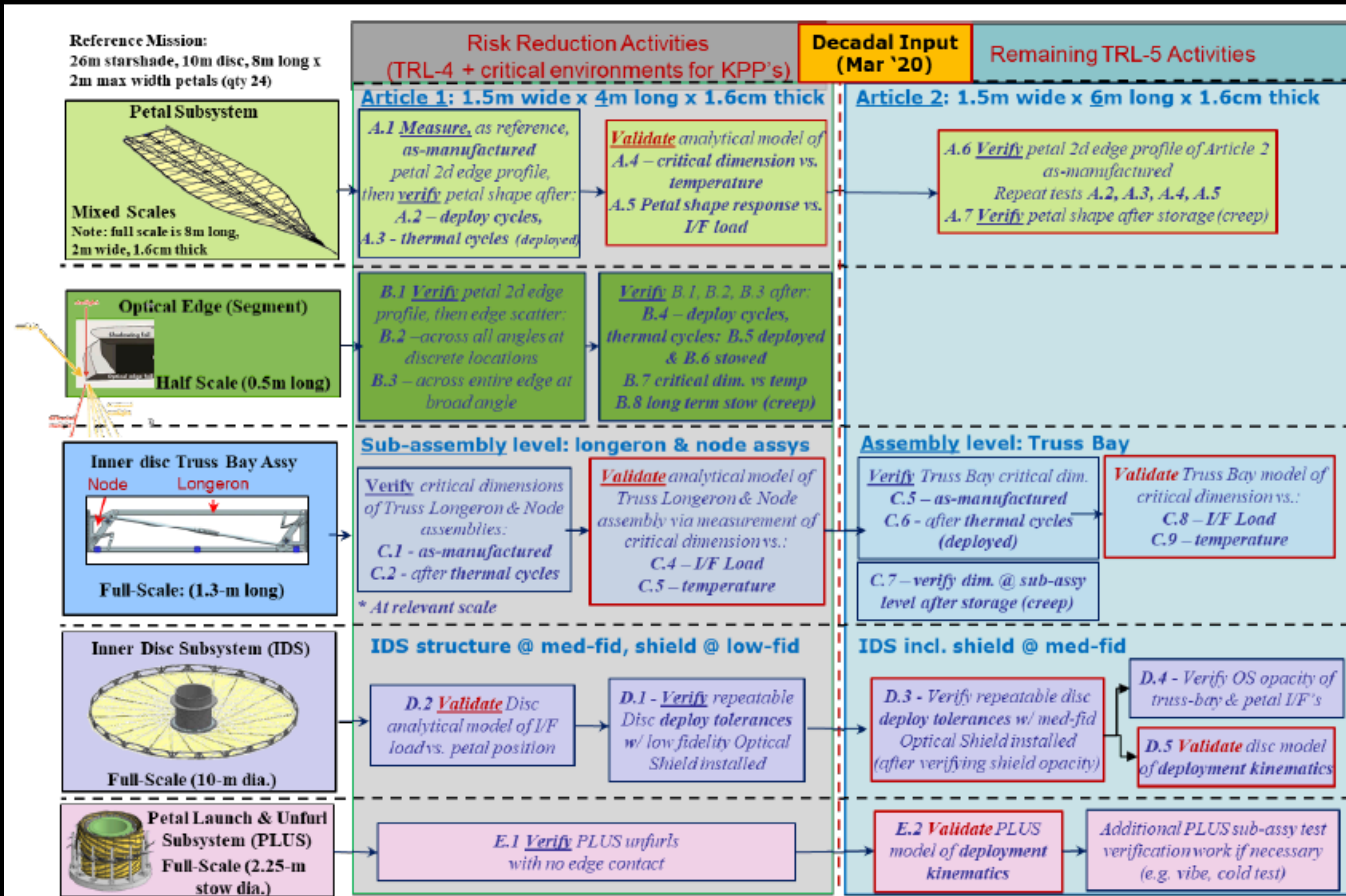
Edge robustness activity spawned.

SIP subcontractor ZeCoat is applying black coatings to starshade edges- first results show tenfold reduction in scatter over uncoated edges.



Petal Shape and Position Accuracy & Stability

Mechanical Technology Development



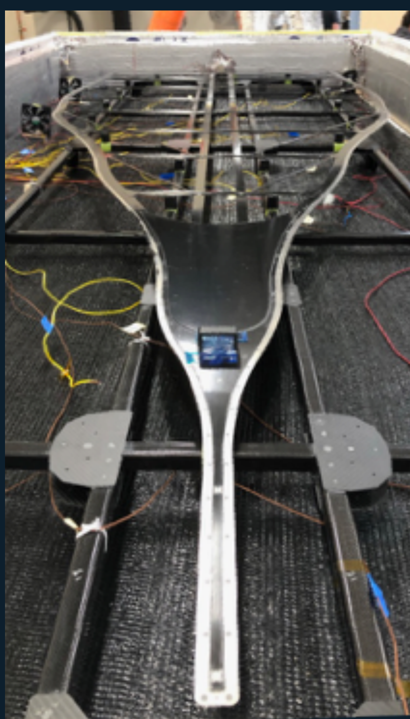
Starshade Shape Accuracy - Petal

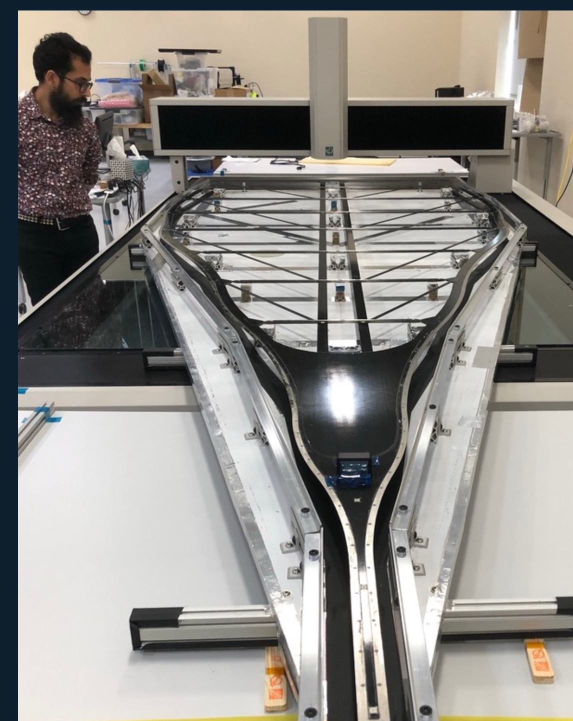
Petal subsystem demonstrates total prelaunch shape stability (manufacture, deploy cycles, thermal cycles deployed, and storage) consistent with a total pre-launch shape accuracy within $\pm$ 70 µm.

KPP 5

RESULTS:

Shape-critical element prototype meets requirement after stow-and-deploy and thermal cycles.





First article milestone passed, TRL 5 by 2023

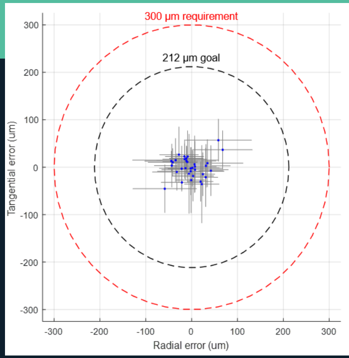
Starshade Shape Accuracy - Inner Disk

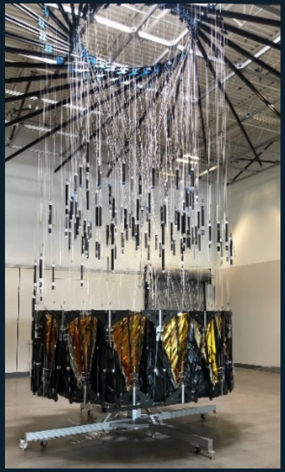
Truss Bay assembly demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within ± 300 µm.

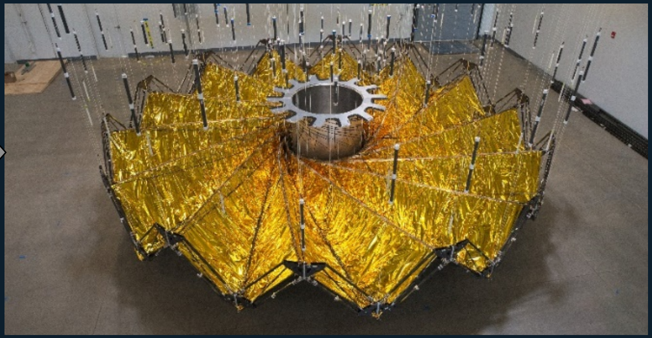
Inner Disk Subsystem with optical shield assembly demonstrates repeatable accuracy consistent with a total prelaunch petal position accuracy within ± 300 µm.

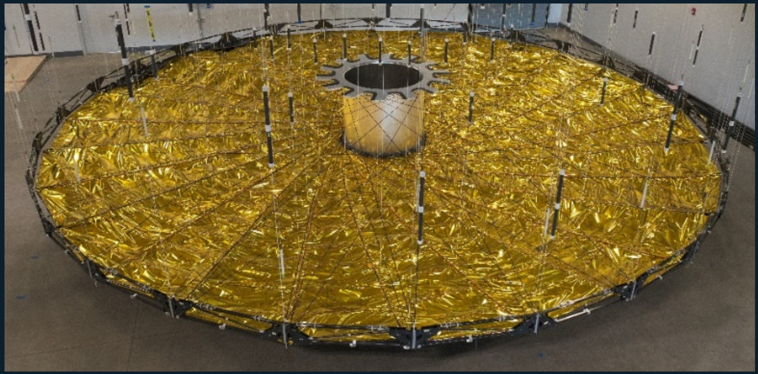
KPP 7

RESULTS:
Shape-critical element prototype meets requirement after stow-and-deploy and thermal cycles.





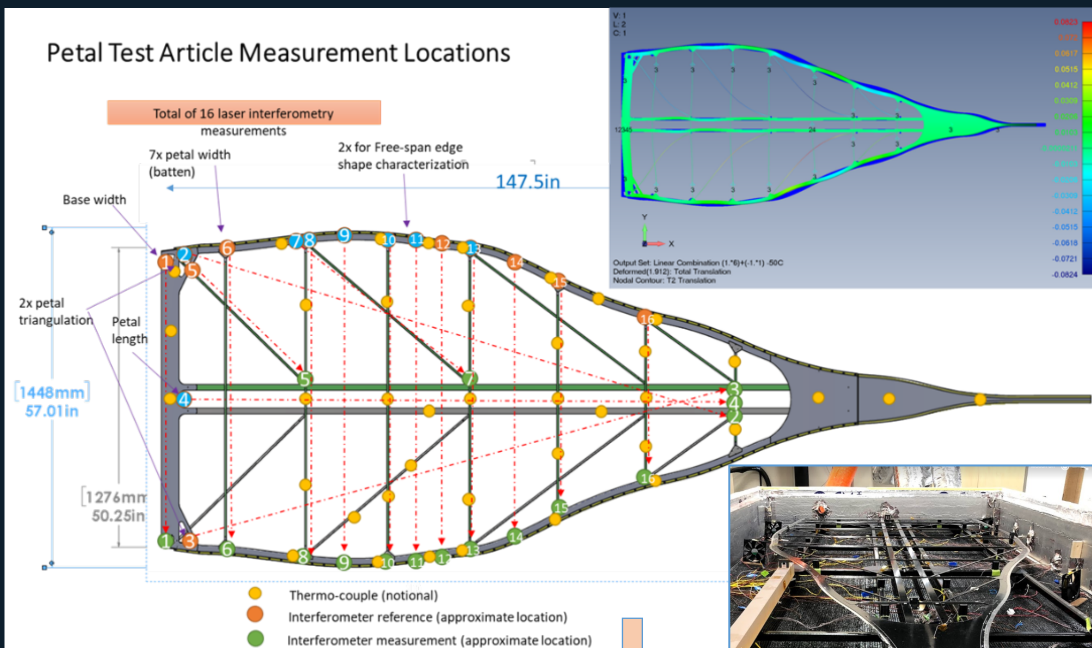




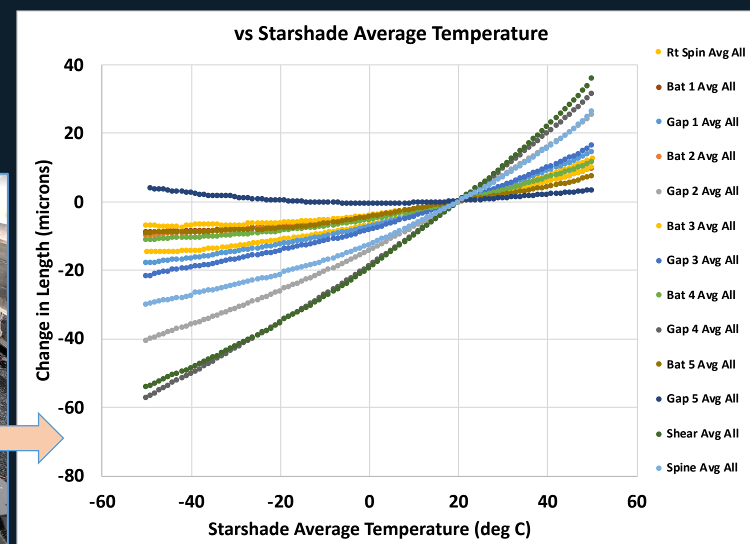
First article milestones passed, TRL 5 by 2023

Starshade Shape Stability - Petal

Petal subsystem demonstrates on-orbit length thermal stability within ±80 µm by analysis using a validated model of critical dimension vs. temperature. **KPP 6**



RESULTS:
Prototype with shape-critical elements meets requirement with large margin.



First article milestone still in review, TRL 5 by 2023

Starshade Shape Stability - Inner Disk

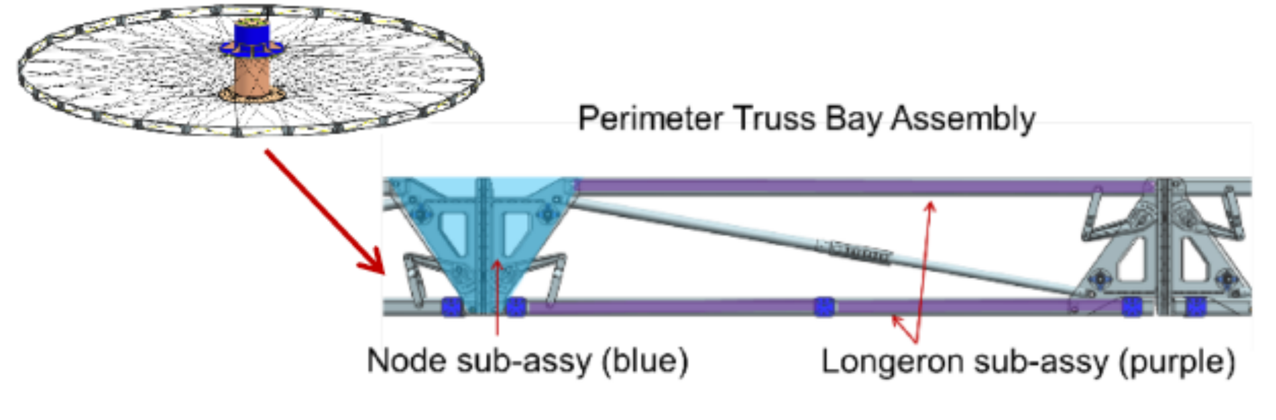
Truss Bay assembly demonstrates on-orbit thermal stability within $\pm$ 200 µm by analysis using a validated model of critical dimension vs. temperature. **KPP 8**

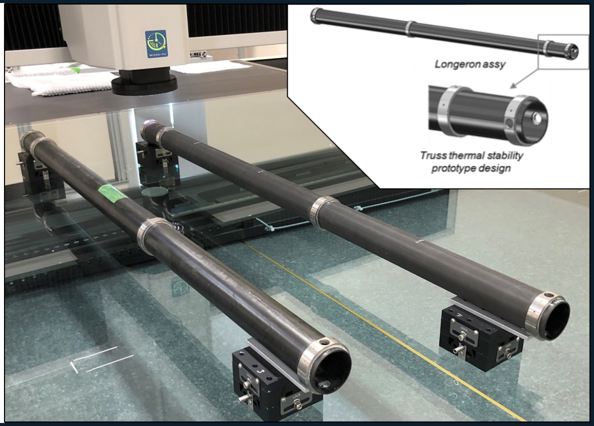
APPROACH:

- Initial tests validate on-orbit finite element models of longeron and node subassemblies
- Final TRL 5 test validates model at truss bay assembly level.

RESULTS:

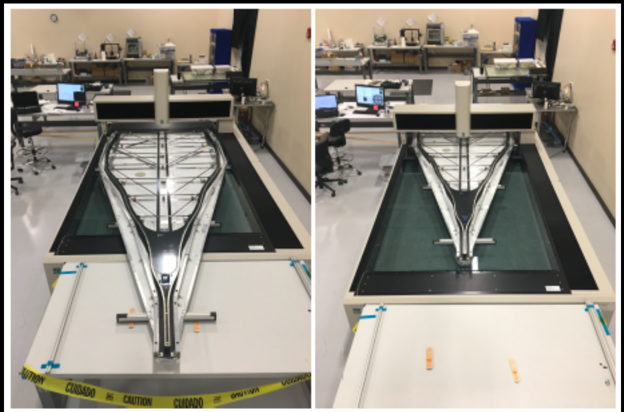
Longerons and nodes meeting requirements with margin.



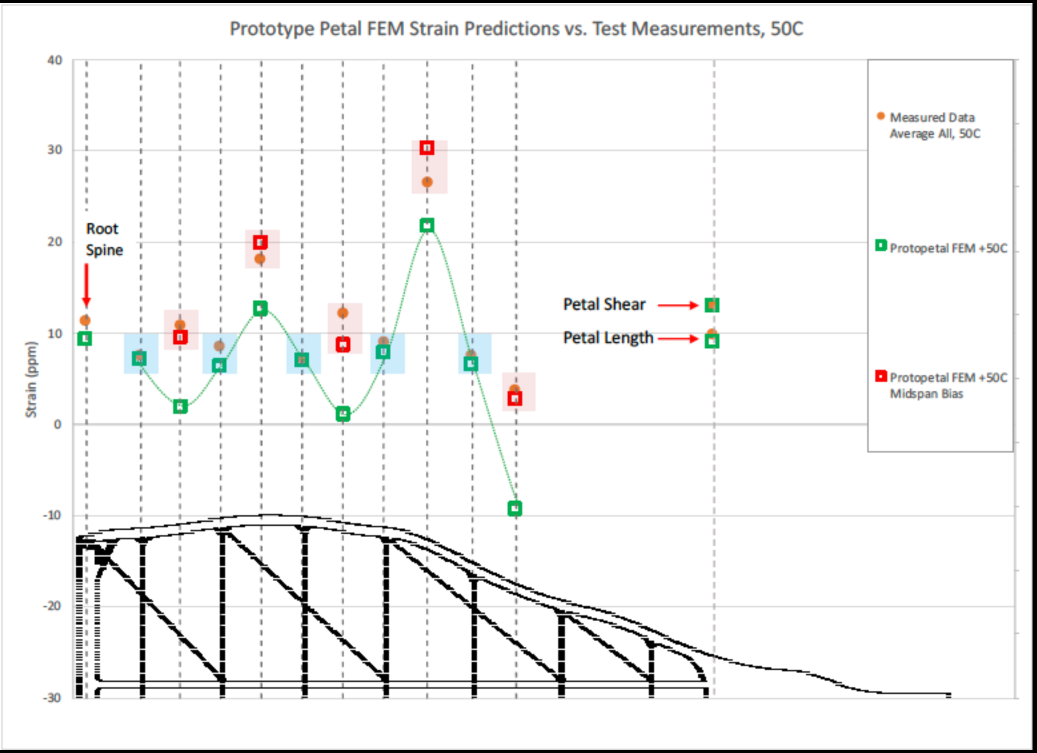


First article milestone passed, TRL 5 by 2023

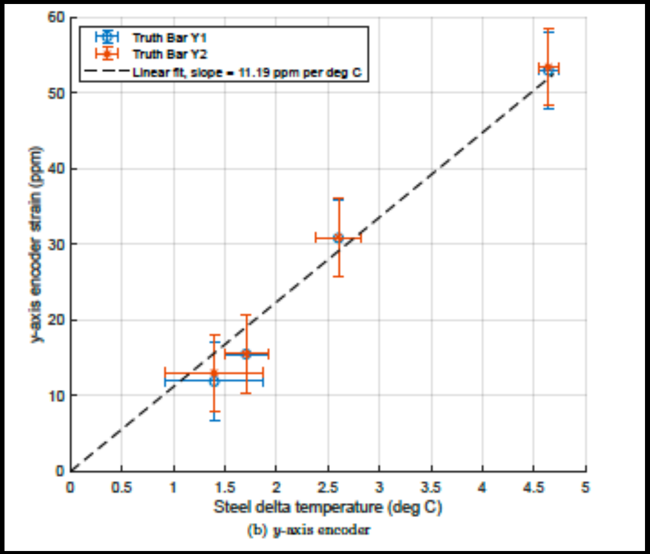
Recent Developments



Unexpected bowing measured at petal midspans in thermal deformation tests; refinements to FEM suggest these are real and caused by thermal stresses at bondlines. Requirements still met.

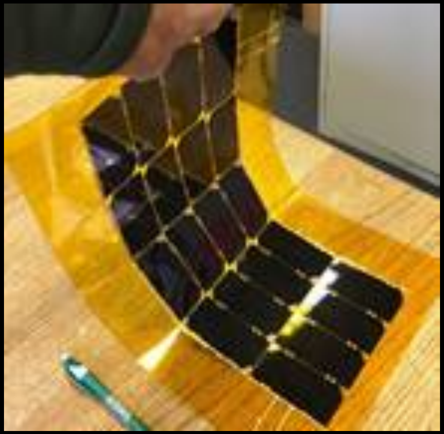


Themal dependence found in MicroVu metrology system



Inner Disk at Tendeg

Integrated solar cells

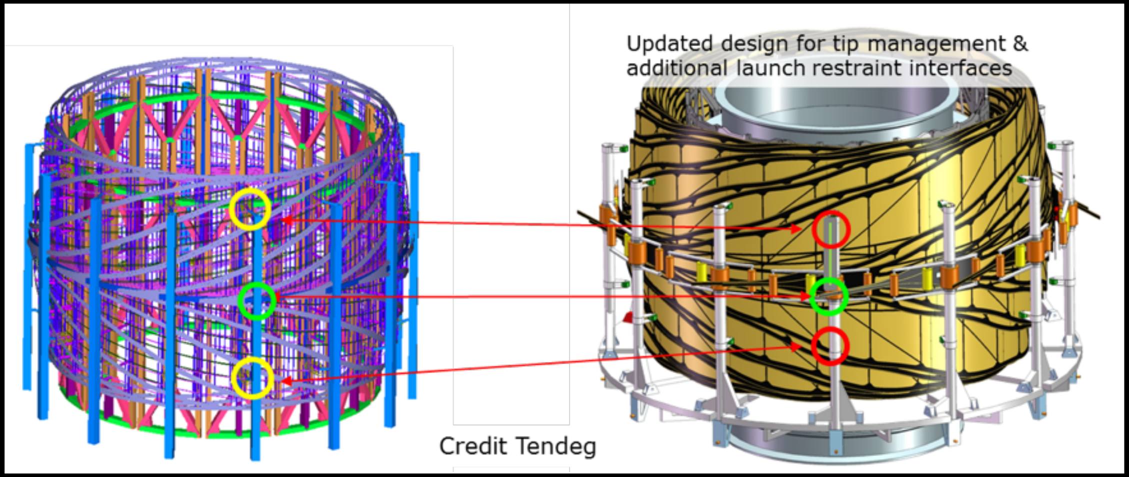


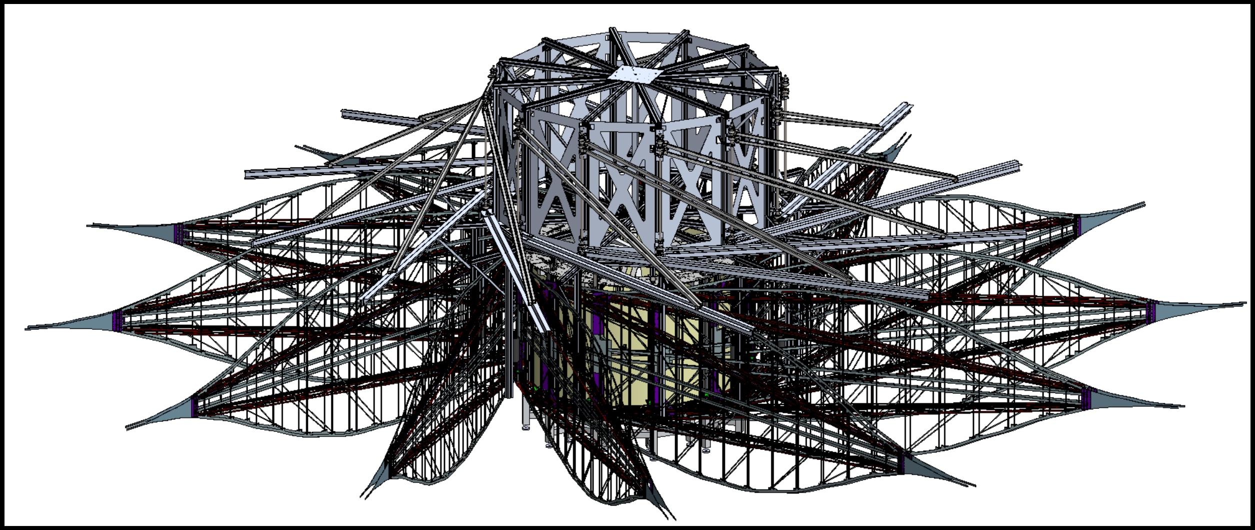
Gravity offloading

(a) Deployed (b) Stowed

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.

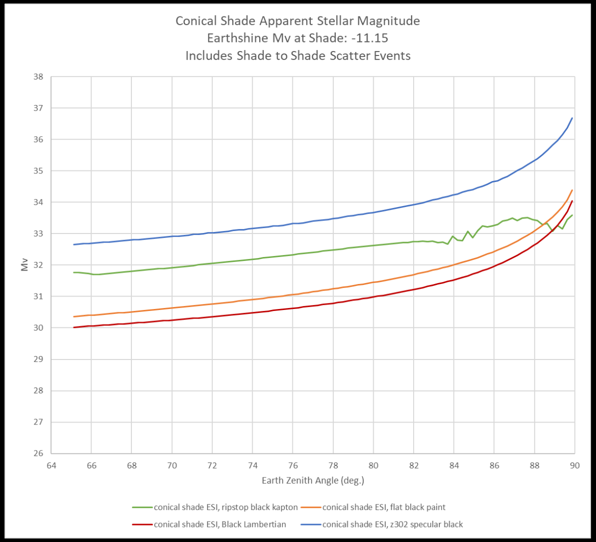




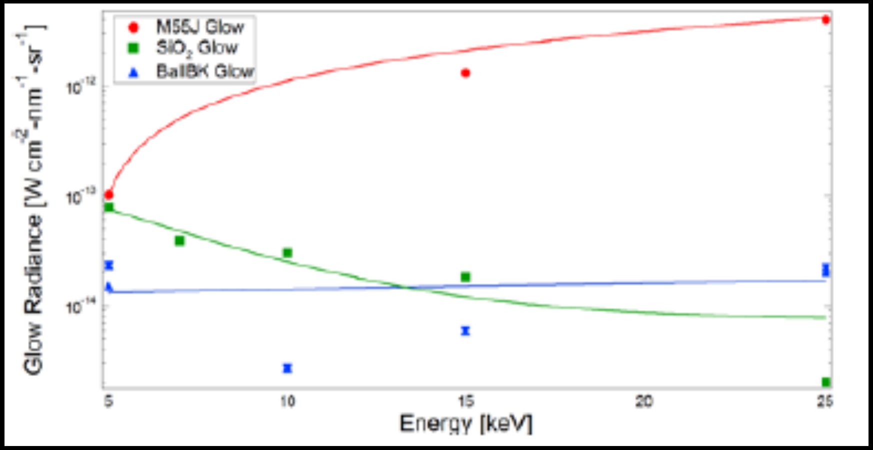
Straylight Studies

S5 is also investigating various sources of stray light from starshades :

- Secondary reflections of sunlight through micrometeoroid holes and from petal to petal
- Reflected light from bright astronomical sources (Earth, moon, Jupiter…)
- Fluorescence of starshade materials in L2 radiation environment
- Starshade thermal emission

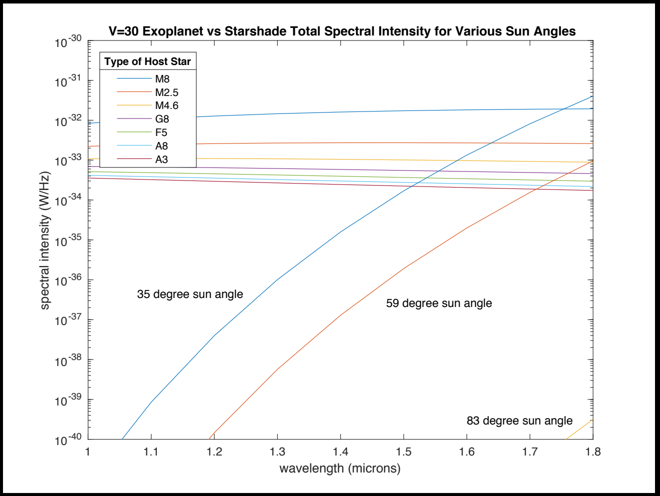


Earthshine magnitudes for various black surfaces



Electron-induced fluorescence in various materials (Dennison et al, 2012)

Starshade thermal emission vs exoplanet fluxes



The End