



Starshade Technology Readiness

Presentation to Astro 2020 NAS Decadal Committee

Ms. Kendra Short, Exoplanet Exploration Program Deputy Manager, JPL

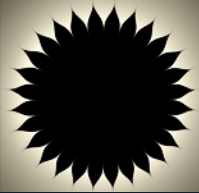
Dr. Phil Willems, Starshade Technology Manager, JPL

November 19, 2019

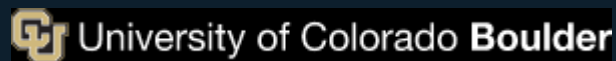
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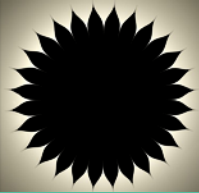


Jet Propulsion Laboratory
California Institute of Technology



Contributors





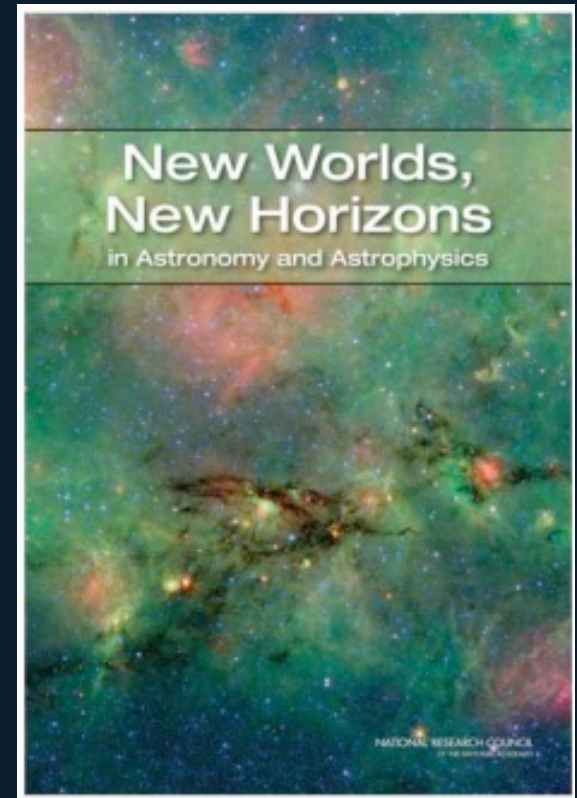
2010 Decadal Called for Technology Investment

Decadal Survey Recommendation:

“Candidate starlight suppression techniques be developed to a level such that mission definition for a space-based planet imaging and spectroscopy mission could start late in the decade.”

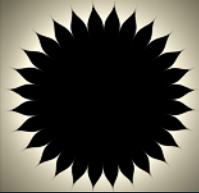
- **APD Response:**

- Strategic Astrophysics Technology (SAT)
 - Competitively selected individual investigator awards to address mid-TRL technologies (3-5)
- In 2016, the starshade was spun off to establish a starshade technology development activity with the goal of advancing starshade technology to TRL 5





Programmatic Context



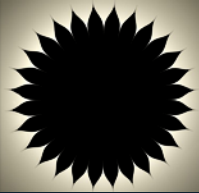
NASA Charters Starshade Technology Activity (March 2016)

Technology Activity Goals:

- “to mature the required techniques to the point at which starshades could be integrated into potential future exoplanet detection and characterization missions”
- *Advance critical capabilities to TRL 5 and close key technology gaps*:*
 - *Starlight suppression*
 - *Formation flying*
 - *Deployment of large-scale, precision structures*

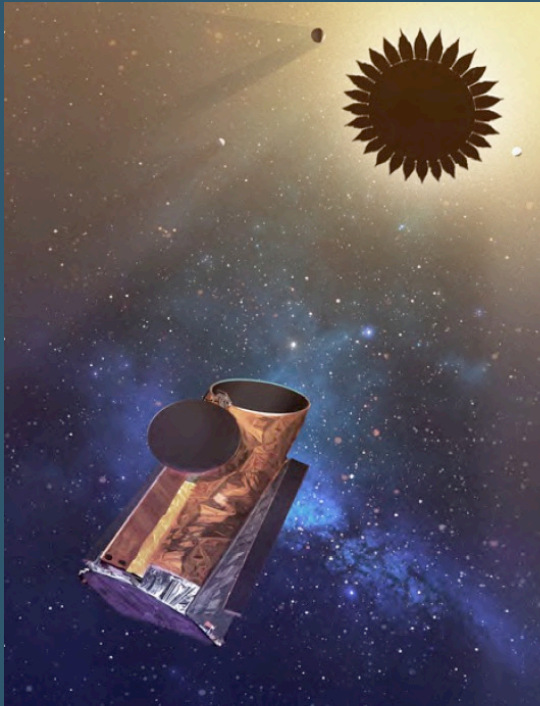


** reference ExEP Technology Plan Appendix*



Reference Mission Concepts for Starshade Technology

Habitable Exoplanet Observatory

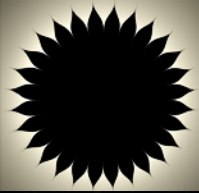


Telescope Diameter:	4 m
Starshade Diameter:	52 m
Separation:	76,600 km
IWA:	70 mas

WFIRST-Rendezvous Probe



Telescope Diameter:	2.4 m
Starshade Diameter:	26 m
Separation:	26,000 km
IWA:	103 mas

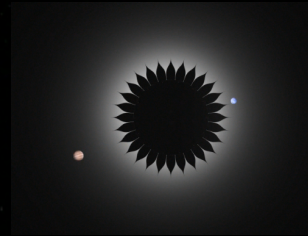


Starshade Technology Gaps

(1) Starlight Suppression

Suppressing diffracted light from on-axis starlight and optical modeling

Suppressing scattered light off petal edges from off-axis Sunlight



(2) Formation Sensing

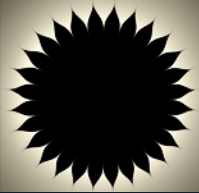
Sensing the lateral offset between the spacecraft



(3) Shape Accuracy and Shape Stability

Fabricating and positioning the petals to high accuracy
Maintaining shape stability over operational conditions





What is Technology Readiness Level 5?

TRL 5

Definition

Component and/or breadboard validation in relevant environment.

Per NPR 7123.1B Appendix E

Exit Criteria

Documented test performance demonstrating agreement with analytical predictions.

Documented definition of scaling requirements.

Per NPR 7123.1B Appendix E

Hardware Description

Performance/Function

Demonstrate overall performance in critical areas

Fidelity of Build

Medium fidelity system/component breadboard with realistic support elements

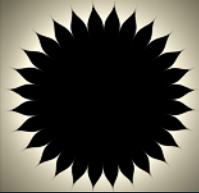
Supporting Analysis

Performance predictions are made for subsequent development phases

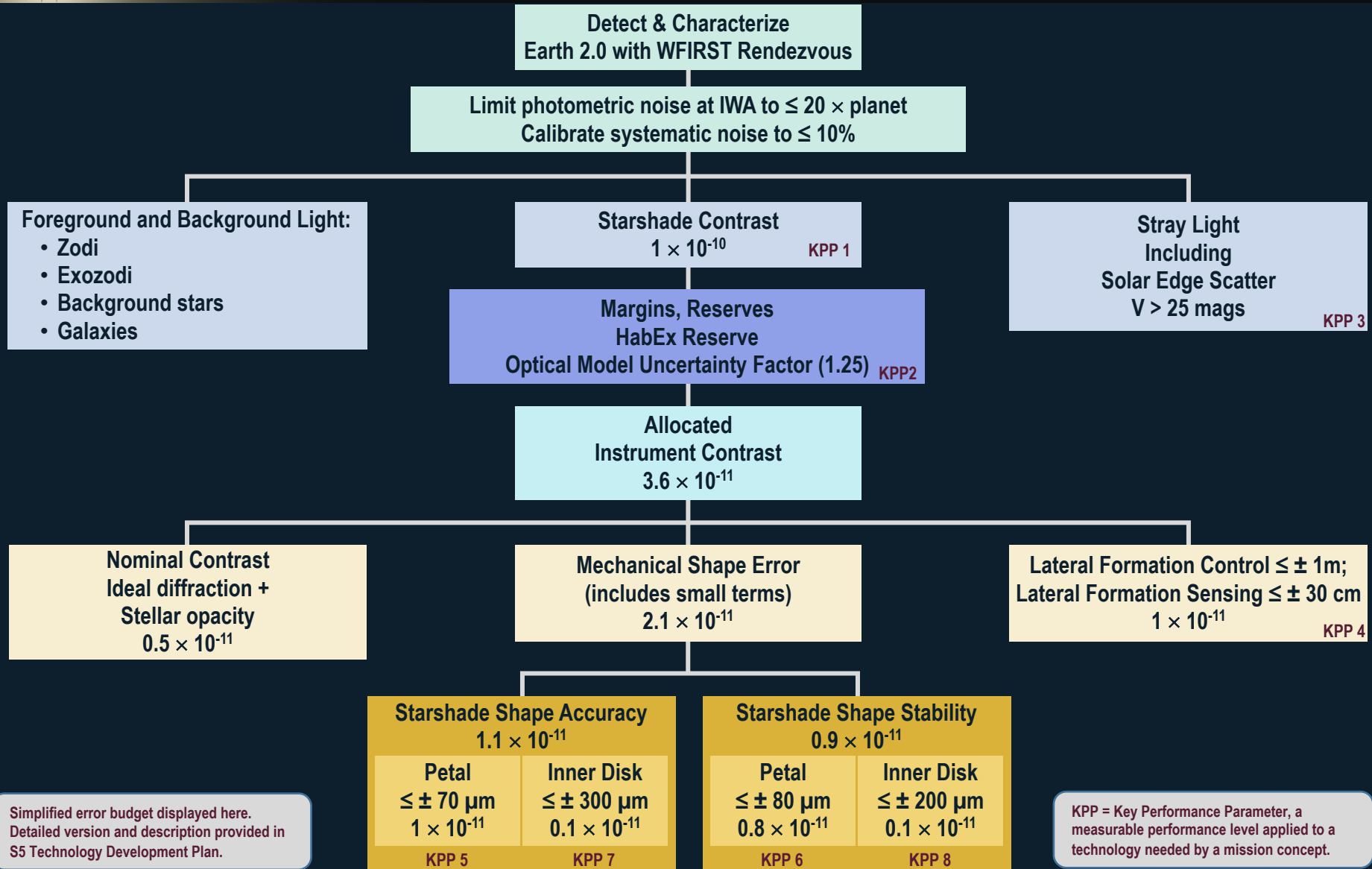
Environment Verification

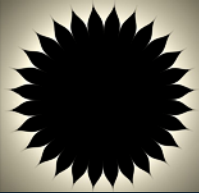
Simulated relevant operational environment.

From "JPL Technology Readiness Assessment Guideline" 2016



S5 Error Budget Defines Key Performance

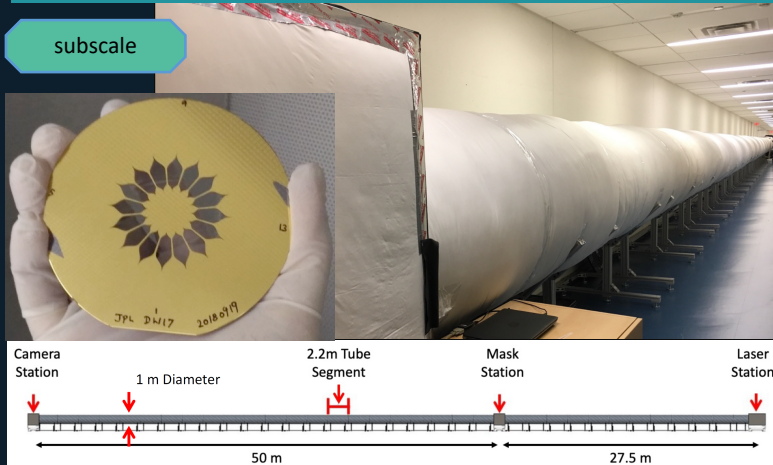




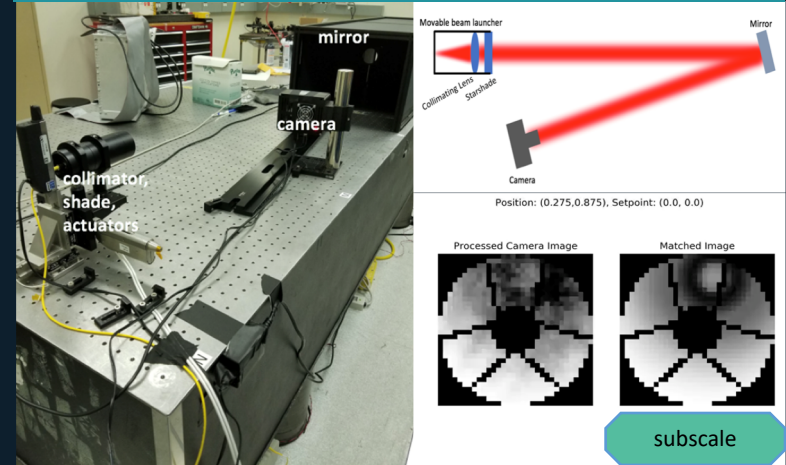
Balanced Use of Scale and Fidelity

Starlight Suppression/Optical Contrast

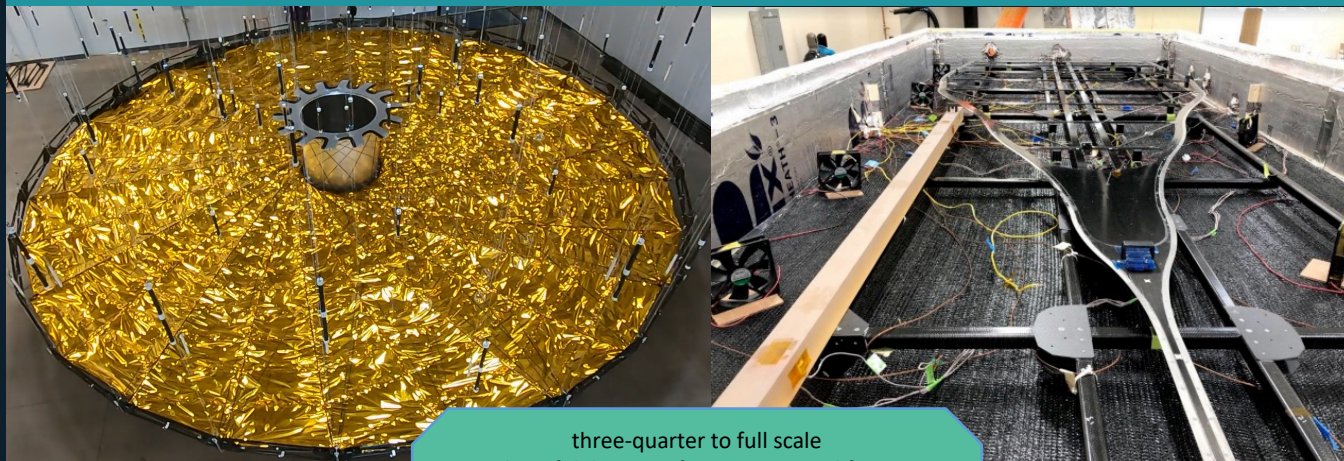
subscale

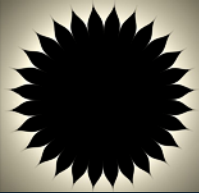


Formation Sensing



Shape Accuracy and Shape Stability





S5 Simulation and Model Validation is Critical

Everything flows from optical performance models

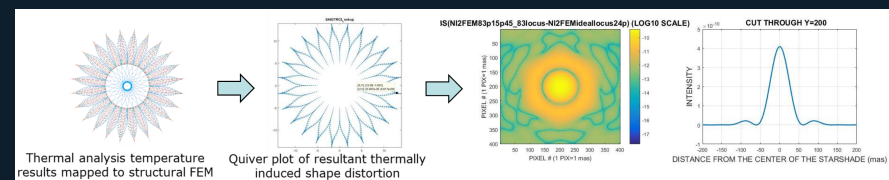
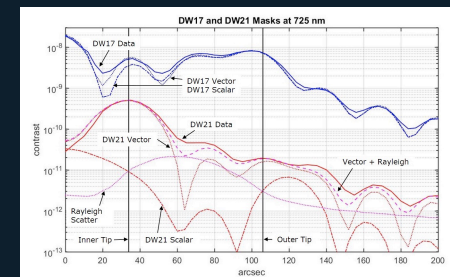
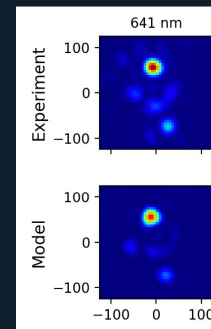
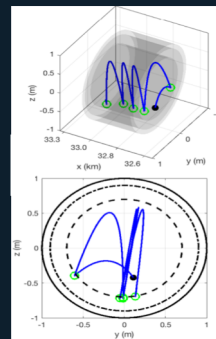
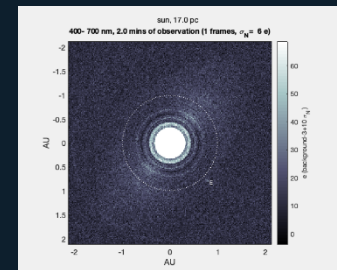
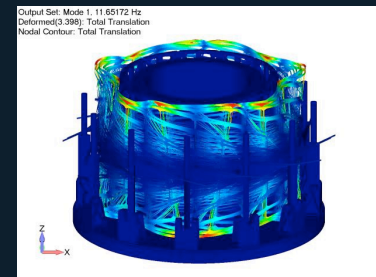
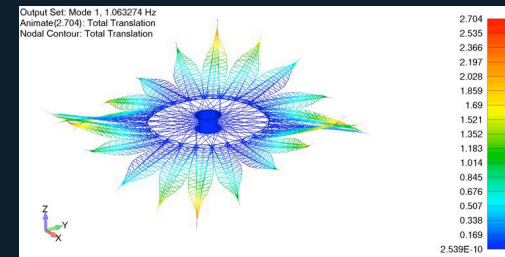
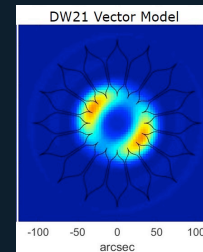
There won't ever be a full-scale system test of a starshade at flight conditions

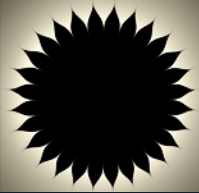
Confidence in our models and requirements through sub-scale testing and validation

Independent analysis and modeling where possible

Diverse collection of analytical tools:

- Optical Model and error analysis tool
- SISTER – optical simulation tool
- Formation control simulation
- Mechanical finite element model
- Thermal model
- Dynamic deployment models
- Stray light /scattered sunlight models





Technology Development Plan and Milestones

Starshade to TRL5 (S5) Technology Development Plan



Starshade to TRL5 (S5) Technology Development Plan

September 13, 2018

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

National Aeronautics and
Space Administration

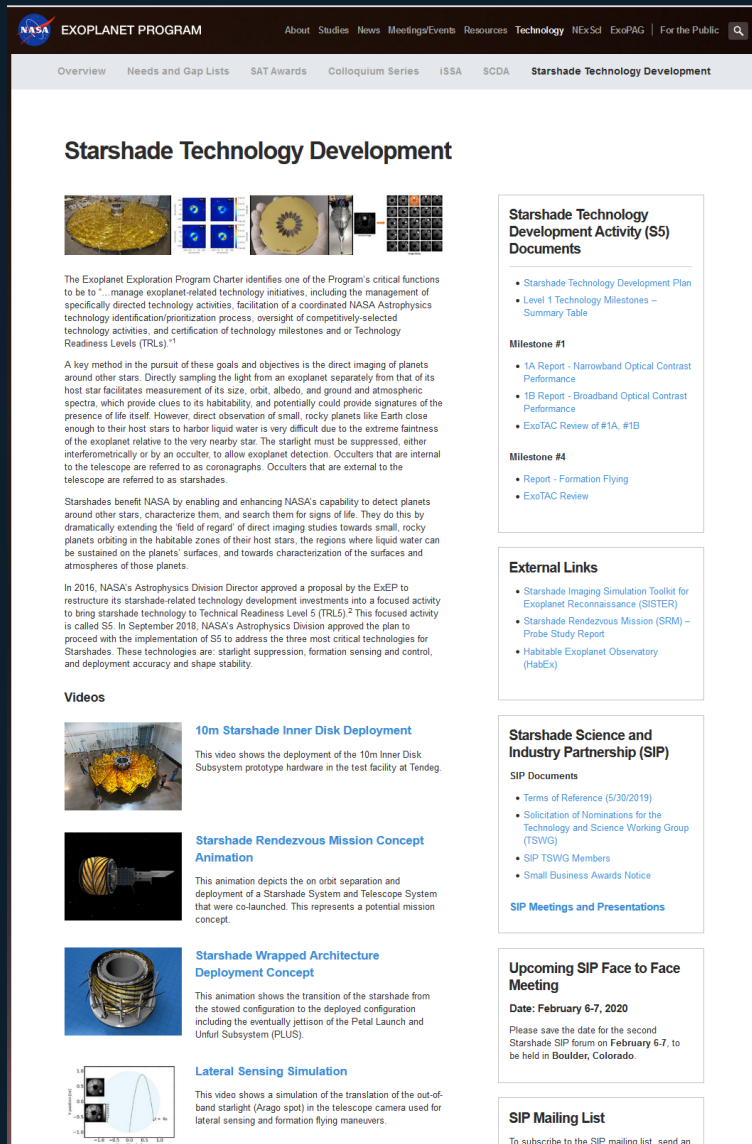
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

<https://exoplanets.nasa.gov/exep/technology/starshade/>

MS	Demonstration	KPP
1A	Optical Contrast – Narrowband	10^{-10}
1B	Optical Contrast – Broadband	10^{-10}
2	Optical Validation - MUF	1.25
3	Scattered Sunlight	Vis Mag > 5
4	Lateral Sensing	± 30 cm
5A	Petal Shape Accuracy – Crit Features	± 70 μ m
6A	Petal Shape Stability – Crit Features	± 80 μ m
7A	Truss Bay Accuracy – Crit Features	± 300 μ m
7C	Inner Disk Accuracy – Crit Features	± 300 μ m
8A	Truss Bay Stability – Crit Features	± 200 μ m
5B	Petal Shape Accuracy – All Features	± 70 μ m
6B	Petal Shape Stability – All Features	± 80 μ m
7B	Truss Bay Accuracy – All Features	± 300 μ m
7D	Inner Disk Accuracy – All Features	± 300 μ m
8B	Truss Bay Stability – All Features	± 200 μ m

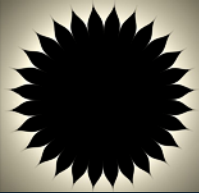
*Independent review and approval of milestone definition and completion by
ExEP's Technology Assessment Committee (ExoTAC)*

Public Dissemination of S5 Results

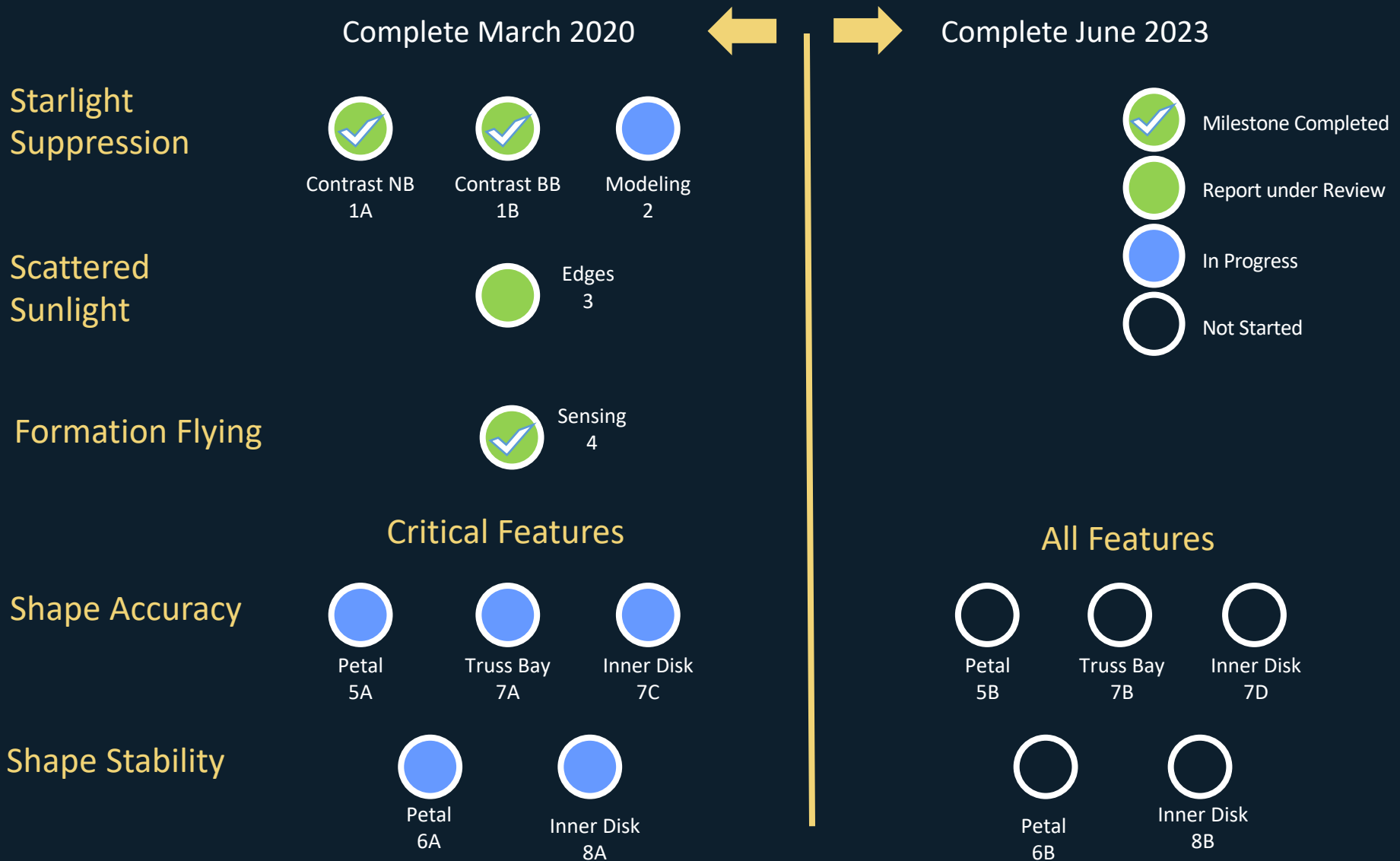


The screenshot shows the NASA Exoplanet Program website with a focus on the Starshade Technology Development section. The page includes a navigation bar with links like 'About', 'Studies', 'News', 'Meetings/Events', 'Resources', 'Technology', 'NExSci', 'ExoPAG', and 'For the Public'. The main content area is titled 'Starshade Technology Development' and features a grid of images showing various stages of starshade development, from conceptual art to physical prototypes. Below the images, there is a detailed text block explaining the Exoplanet Exploration Program Charter's critical functions, the challenges of direct imaging, and the role of starshades. It also mentions the 2016 NASA Astrophysics Division Director's proposal to restructure starshade-related technology development. To the right of the main text, there are several sidebar sections: 'Starshade Technology Development Activity (S5) Documents' listing development plans and milestones, 'Milestone #1' and 'Milestone #4' with specific reports, 'External Links' to simulation toolkits and mission reports, 'Starshade Science and Industry Partnership (SIP)' documents, 'Upcoming SIP Face to Face Meeting' details for February 6-7, 2020, and a 'SIP Mailing List' subscription link. At the bottom, there are 'Videos' including '10m Starshade Inner Disk Deployment', 'Starshade Rendezvous Mission Concept Animation', 'Starshade Wrapped Architecture Deployment Concept', and 'Lateral Sensing Simulation'.

- S5 Starshade Technology web-page
<https://exoplanets.nasa.gov/exep/technology/starshade/>
- Important Resources:
 - S5 Technology Development Plan
 - Milestone Reports and ExoTAC Reviews
 - Starshade Technology Status Reports
 - SIP Forum Presentations (webex and F2F)
 - Links to relevant publications and webpages
 - Starshade graphics, videos and other materials
- Milestone results also published in technical journals and presented at conferences.

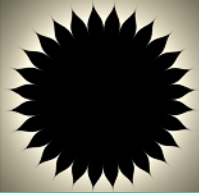


S5 Technology Milestones Scorecard





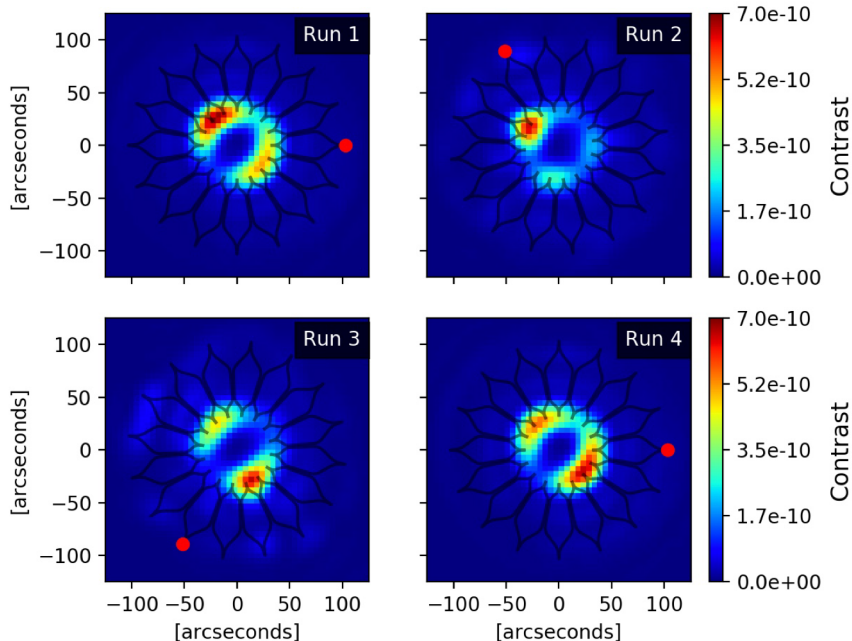
Technology Status



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



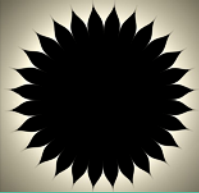
REQUIREMENT MET:

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.



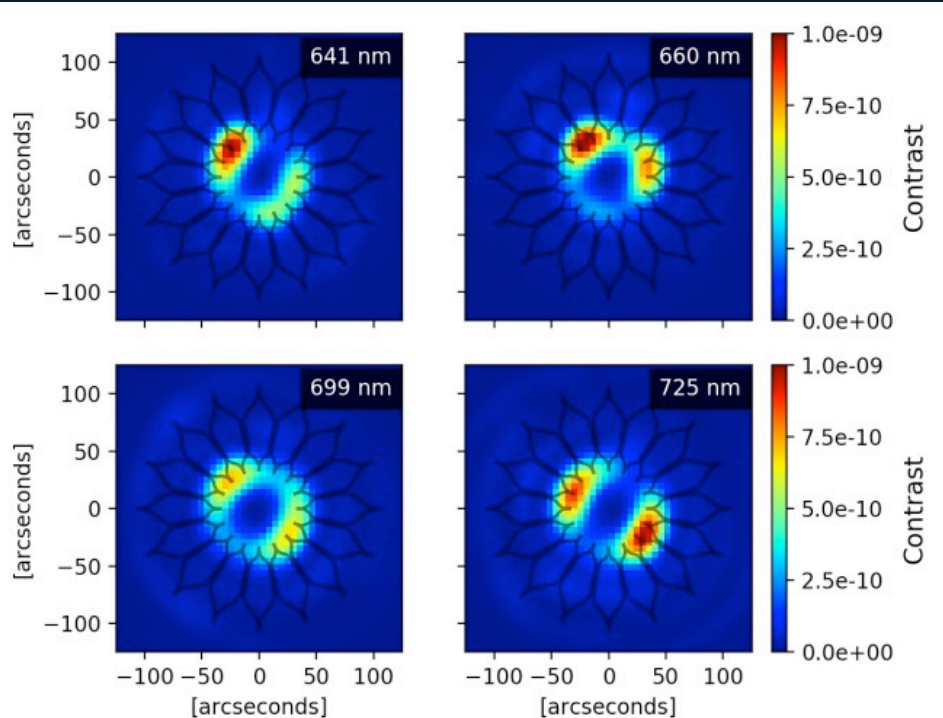
STATUS: Complete



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 $\geq 10\%$ bandpass and Fresnel number ≤ 15 at the longest wavelength.

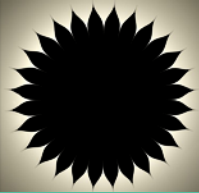
KPP 1



REQUIREMENT MET:

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

STATUS: Complete



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} .

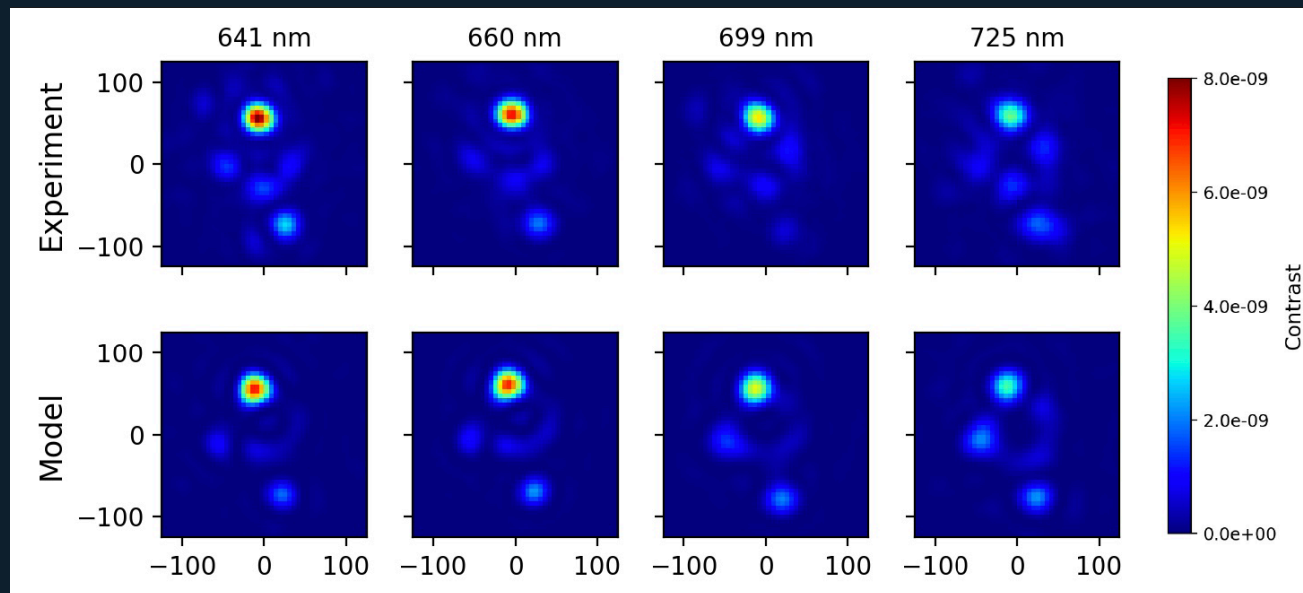
KPP 2

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.



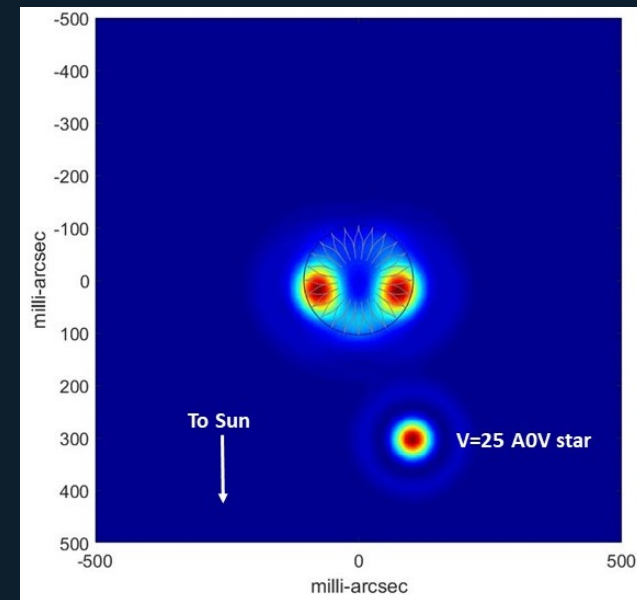
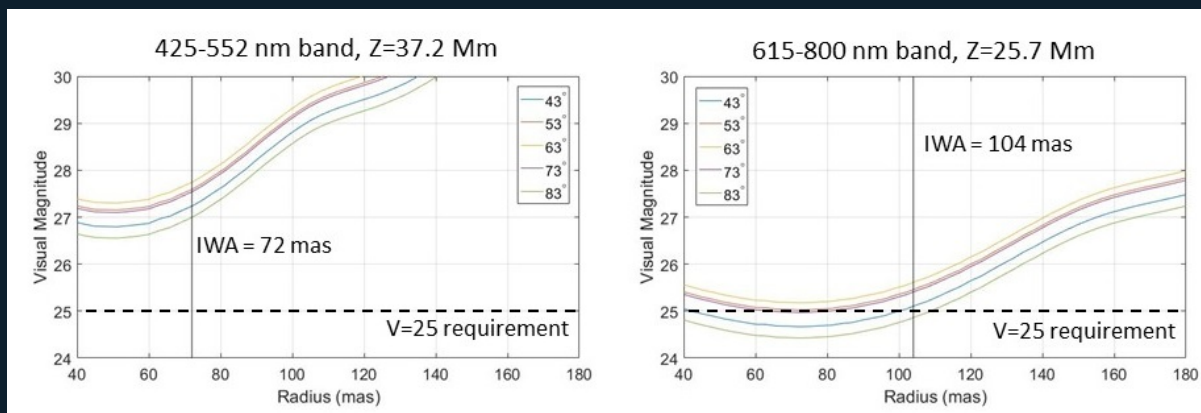
STATUS: In process, complete 3/20

Solar Glint

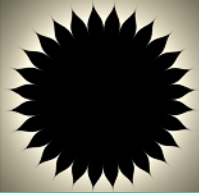
Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles. **KPP 3**

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.



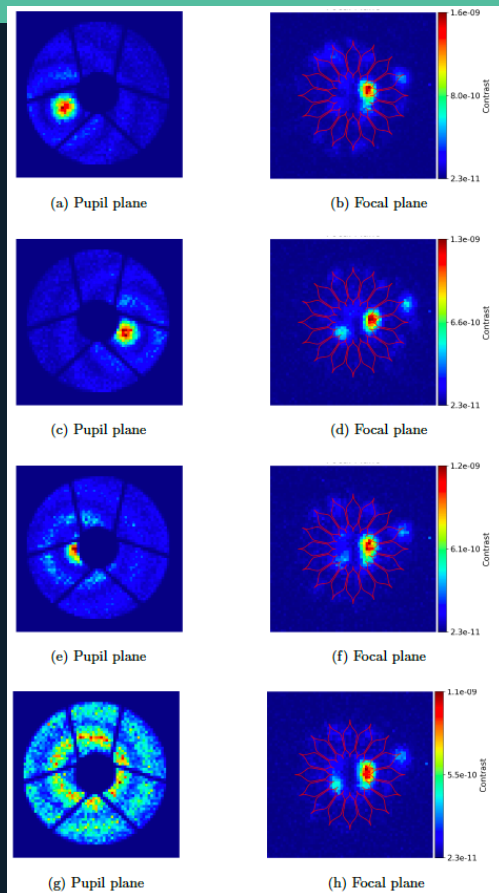
STATUS: In review



Formation Flying

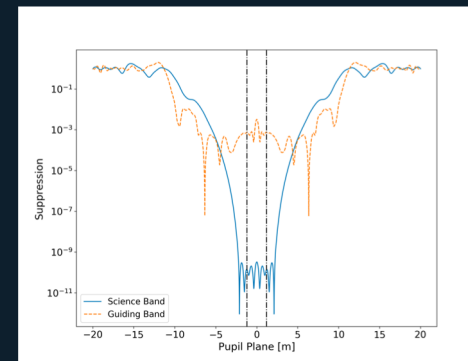
Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral position offset sensitivity to a flight equivalent of 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m.

KPP 4

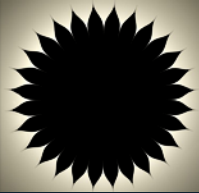


REQUIREMENT MET:

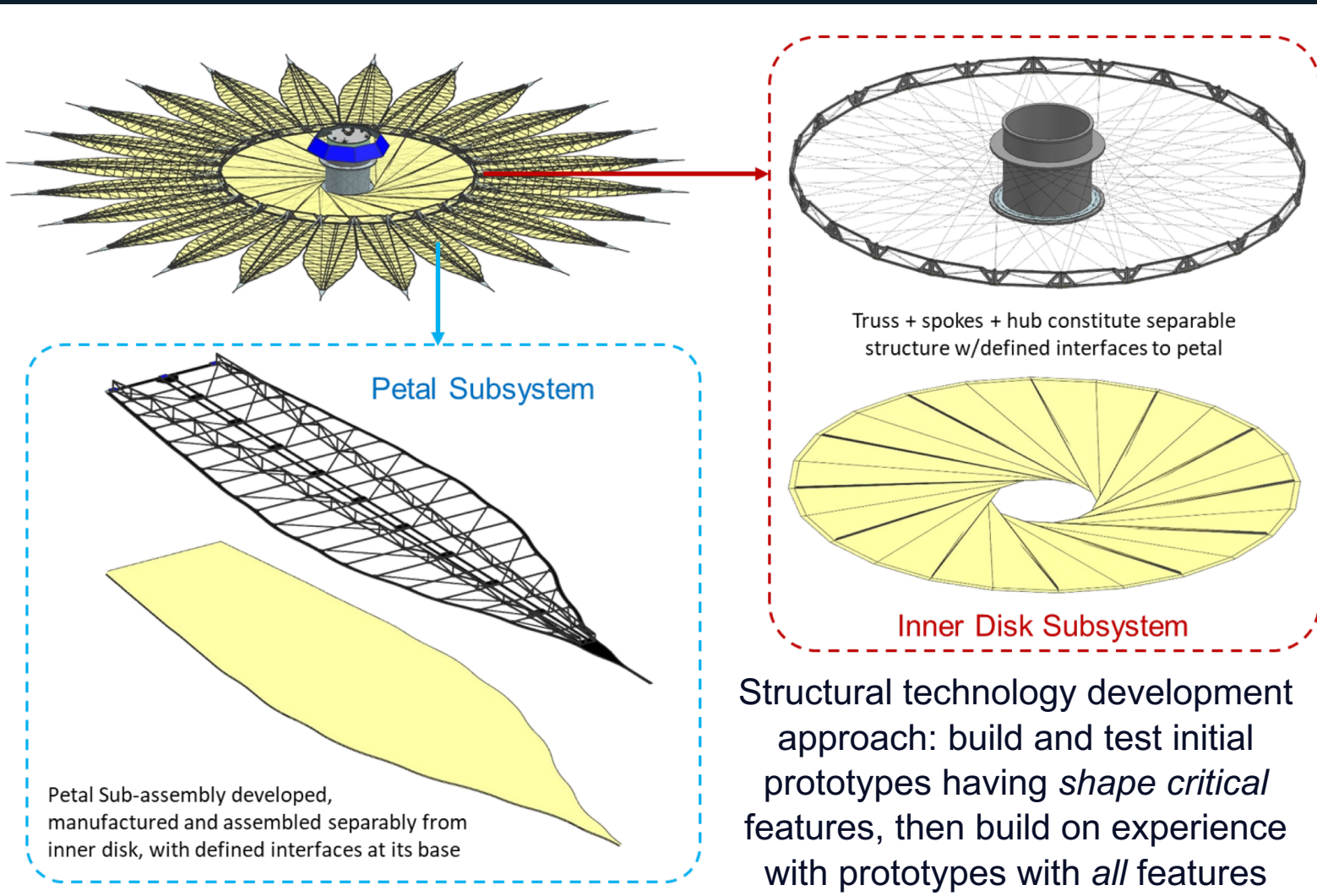
- Starshade lateral offset measured to 10 cm flight equivalent.
- Formation flying simulation controlled position to ± 1 m.
- Large margins on stellar magnitude, allowable measurement error.

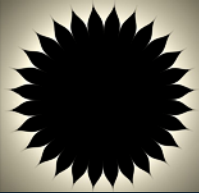


STATUS: Complete, formation flying at TRL 5



Starshade Structural Subsystems

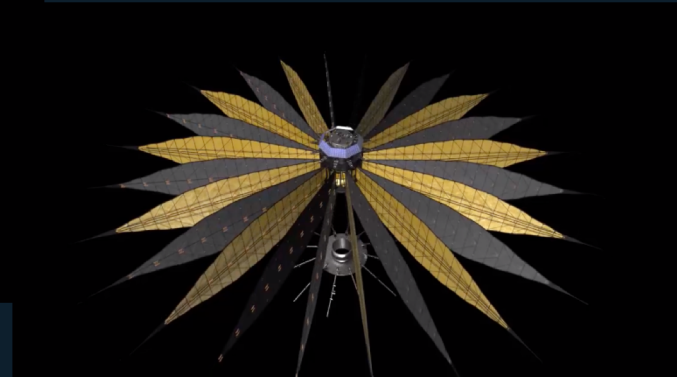




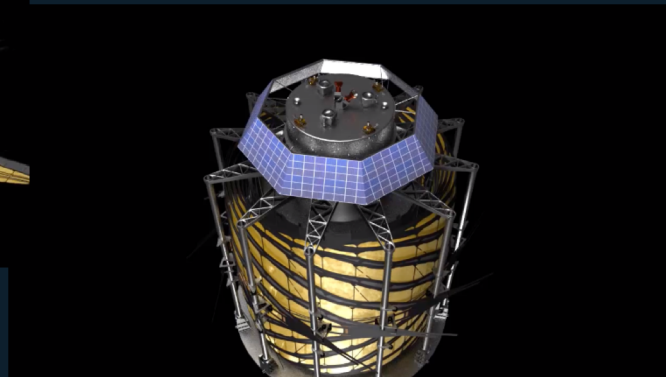
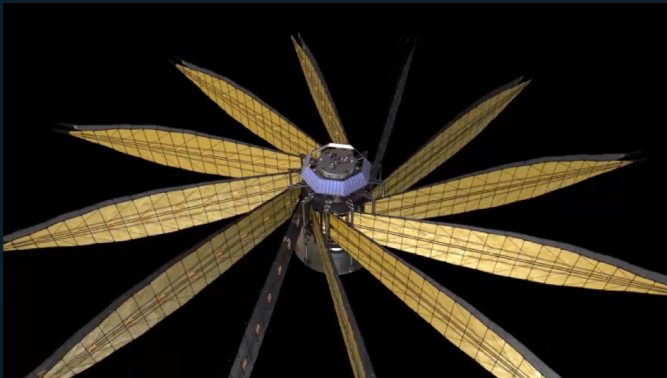
Stowing and Deployment

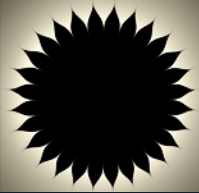


Stowing the inner disk

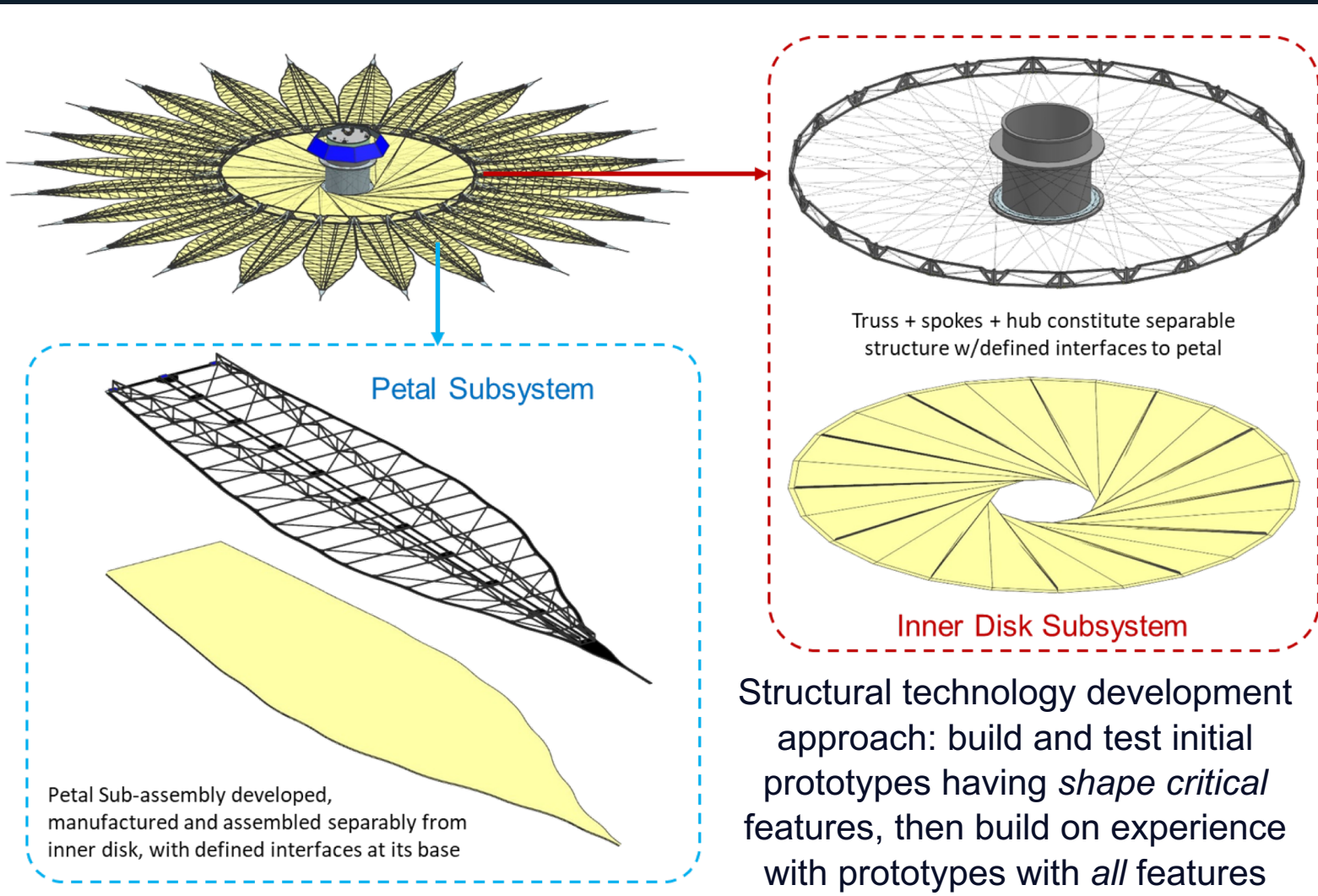


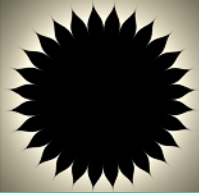
Stowing the petals





Starshade Structural Subsystems





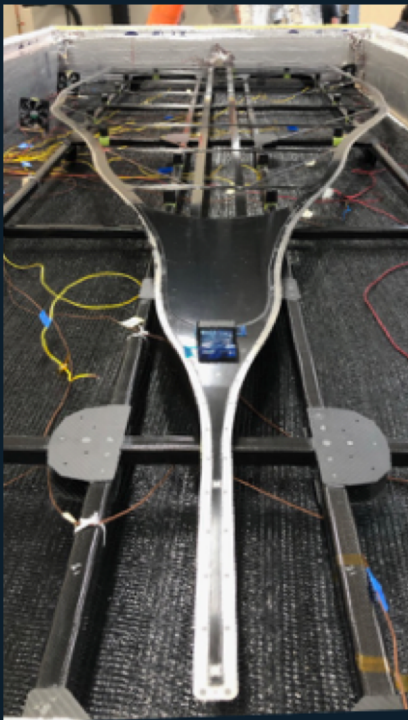
Starshade Shape Accuracy - Petal

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

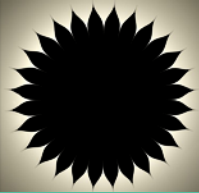
KPP 5

RESULTS:

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



First article 12/2019, TRL 5 by 6/2023



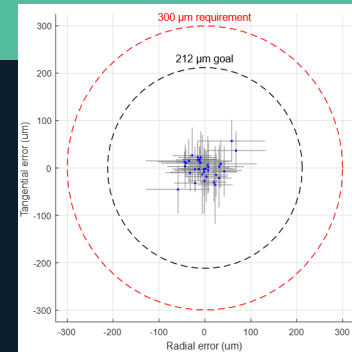
Starshade Shape Accuracy - Inner Disk

Truss Bay assembly demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within $\pm 300 \mu\text{m}$.

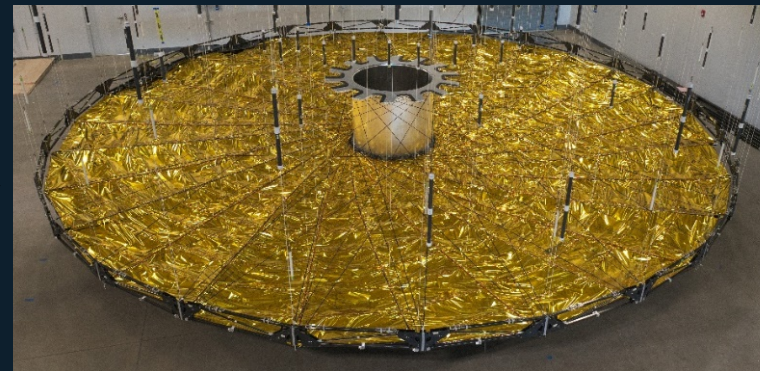
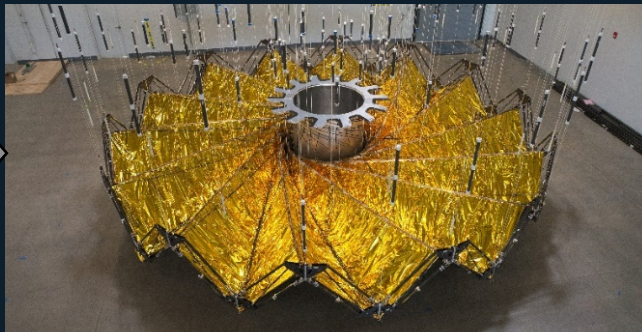
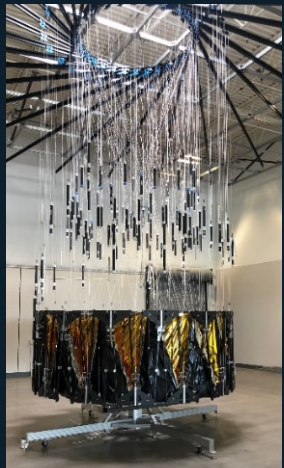
Inner Disk Subsystem with optical shield assembly demonstrates repeatable accuracy consistent with a total prelaunch petal position accuracy within $\pm 300 \mu\text{m}$.

RESULTS:

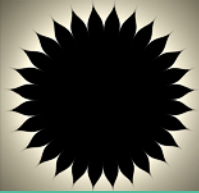
Shape-critical element prototype meets requirement after stow-and-deploy and thermal cycles.



KPP 7

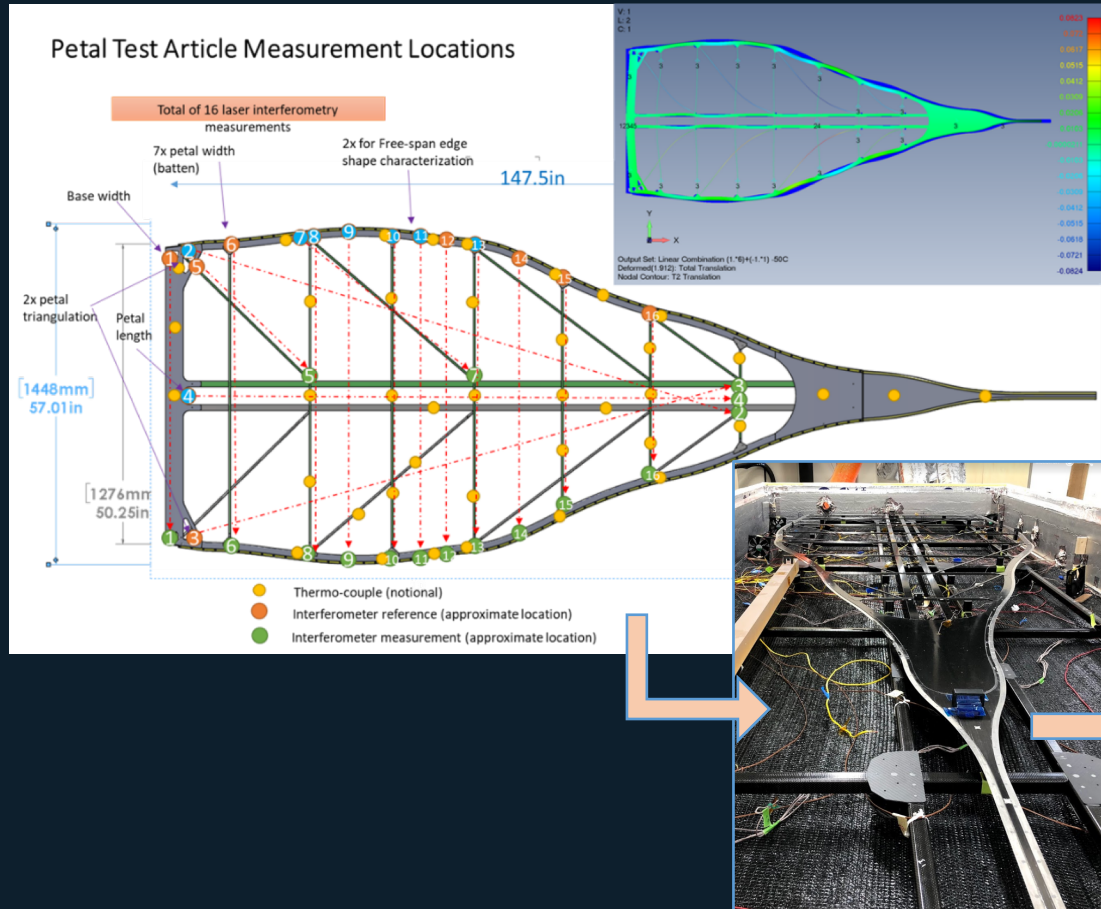


First articles 12/2019, TRL 5 by 6/2023



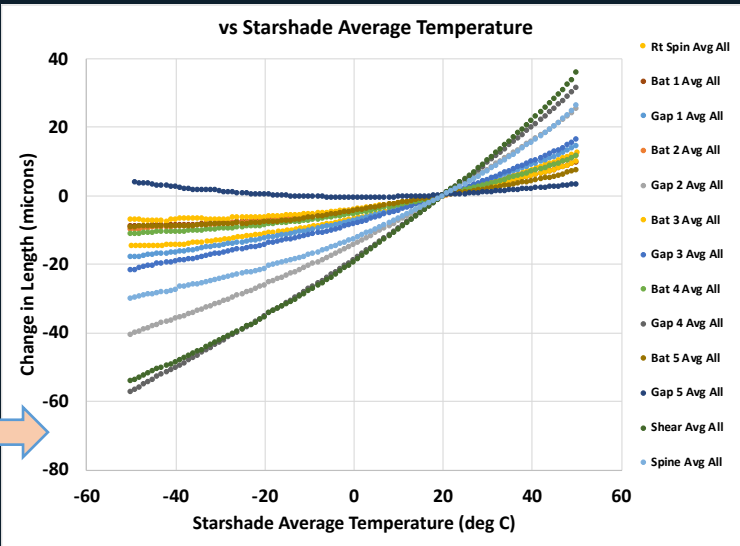
Starshade Shape Stability - Petal

Petal subsystem demonstrates on-orbit length thermal stability within $\pm 80 \mu\text{m}$ by analysis using a validated model of critical dimension vs. temperature. **KPP 6**

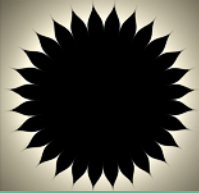


RESULTS:

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



First article 12/2019, TRL 5 by 6/2023



Starshade Shape Stability - Inner Disk

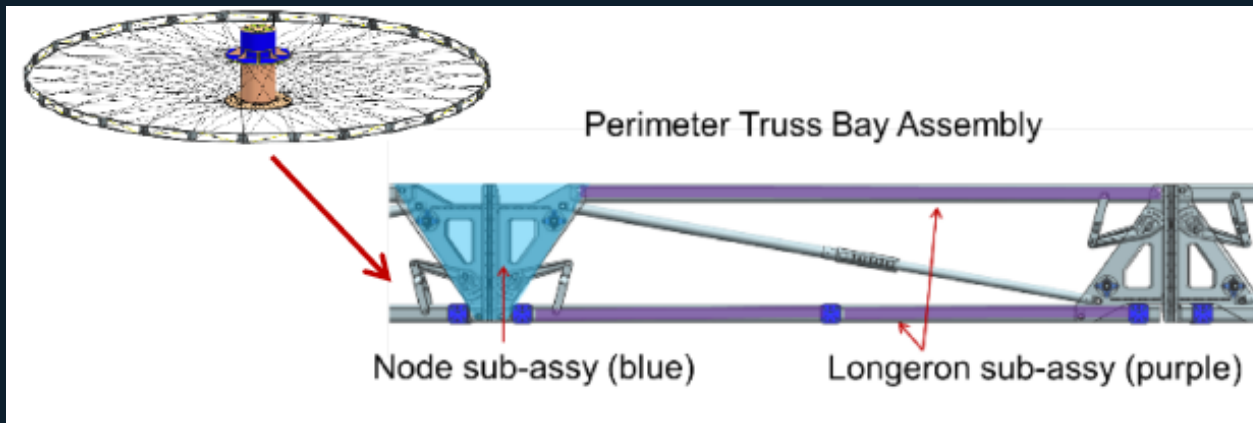
Truss Bay assembly demonstrates on-orbit thermal stability within $\pm 200 \mu\text{m}$ by analysis using a validated model of critical dimension vs. temperature. **KPP 8**

APPROACH:

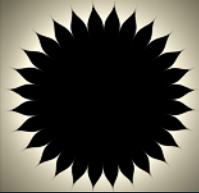
- Initial tests validate on-orbit finite element models of longeron and node subassemblies
- Final TRL 5 test validates model at truss bay assembly level.

RESULTS:

Longerons and nodes meeting requirements with margin.



First articles 12/2019, TRL 5 by 6/2023

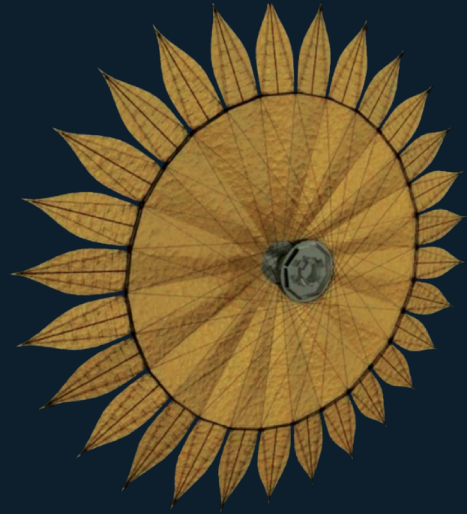


Technology Development Plan and Milestones

MS	Demonstration	KPP	Date	
1A	Optical Contrast – Narrowband	10^{-10}	Jan 2019	
1B	Optical Contrast – Broadband	10^{-10}	Mar 2019	
2	Optical Validation – MUF	1.25	Mar 2020	
3	Scattered Sunlight	Vis Mag > 25	Nov 2019	
4	Lateral Sensing	± 30 cm	Nov 2018	
5A	Petal Shape Accuracy – Crit Features	± 70 μ m	Dec 2019	
6A	Petal Shape Stability – Crit Features	± 80 μ m	Dec 2019	
7A	Truss Bay Accuracy – Crit Features	± 300 μ m	Dec 2019	
7C	Inner Disk Accuracy – Crit Features	± 300 μ m	Dec 2019	
8A	Truss Bay Stability – Crit Features	± 200 μ m	Dec 2019	
5B	Petal Shape Accuracy – All Features	± 70 μ m	Jun 2023	
6B	Petal Shape Stability – All Features	± 80 μ m	Jun 2023	
7B	Truss Bay Accuracy – All Features	± 300 μ m	Jun 2023	
7D	Inner Disk Accuracy – All Features	± 300 μ m	Jun 2023	
8B	Truss Bay Stability – All Features	± 200 μ m	Jun 2023	

- Milestone Completed
- Report under Review
- In Progress
- Not Started

Summary



S5 is successfully developing the enabling technologies for HabEx and Starshade Rendezvous.





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