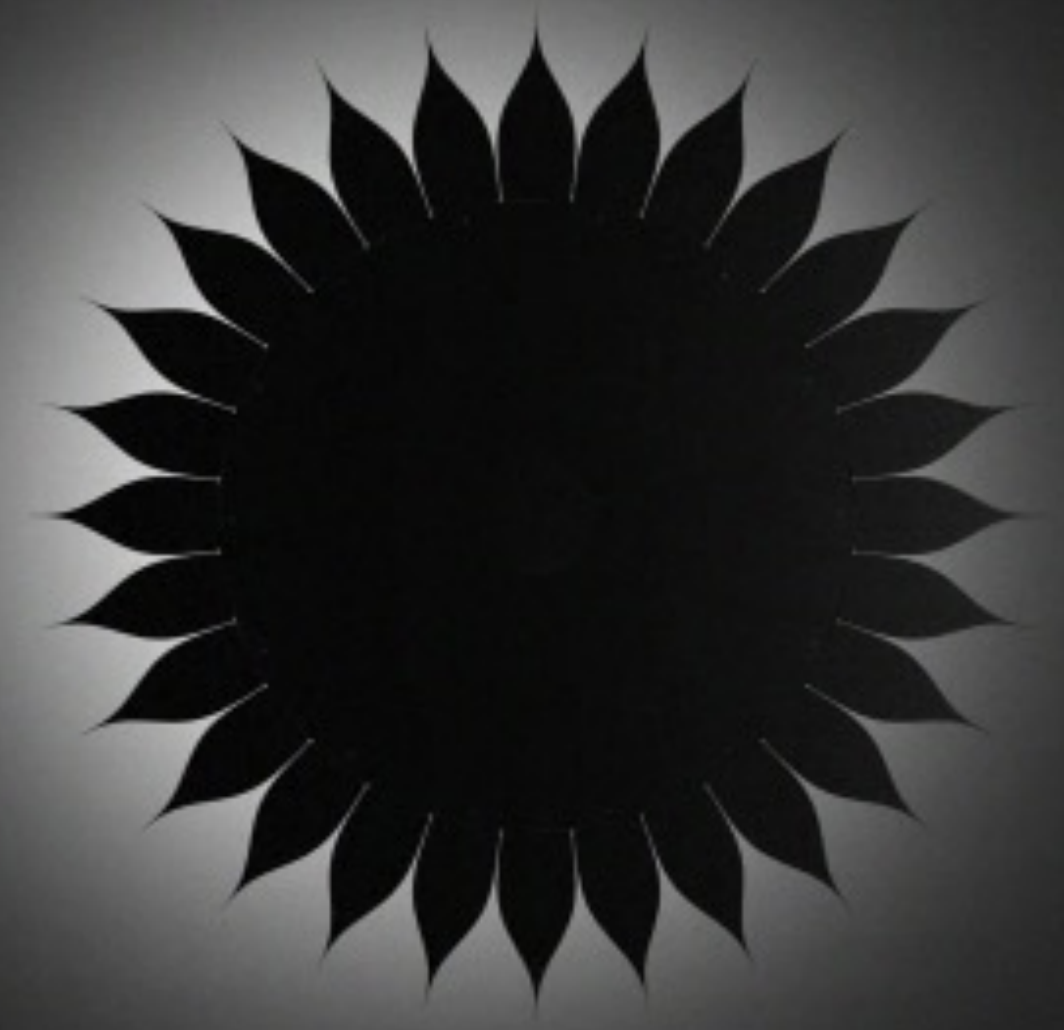
National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Update on Starshade Technology Development: Prospects for a Future Great Observatory



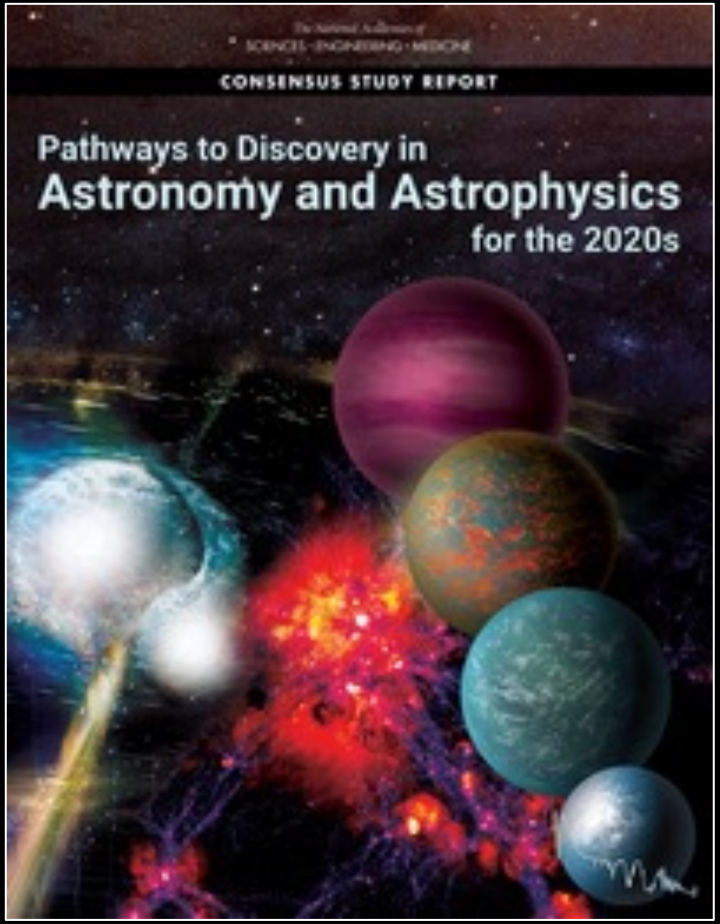
Exoplanet Exploration Program Colloquium

16 November 2022

Case Bradford, Starshade Technology Manager
Jet Propulsion Laboratory
California Institute of Technology

Astrophysics Decadal Report

Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021)

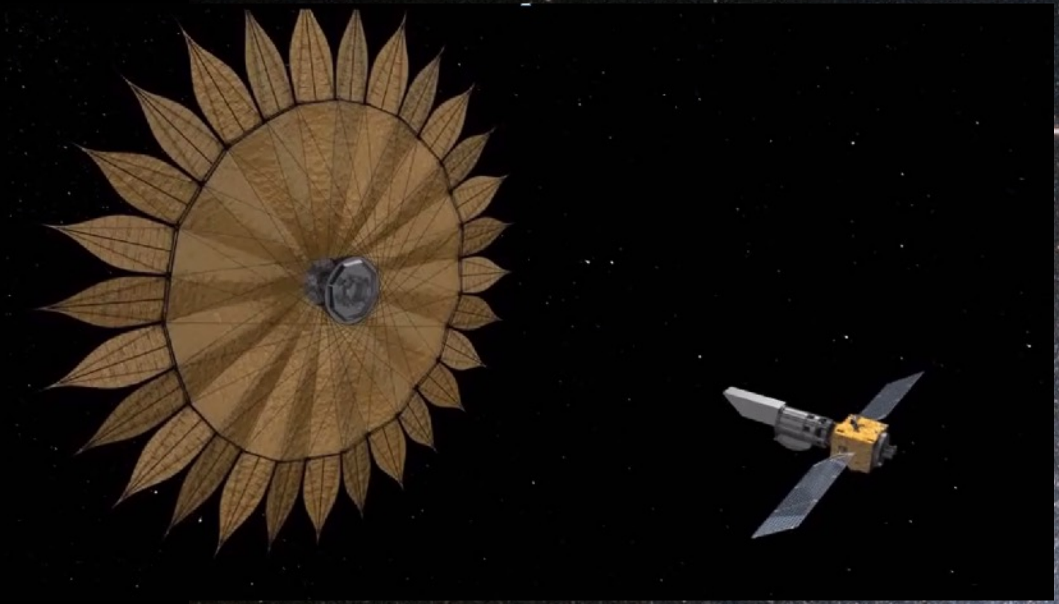


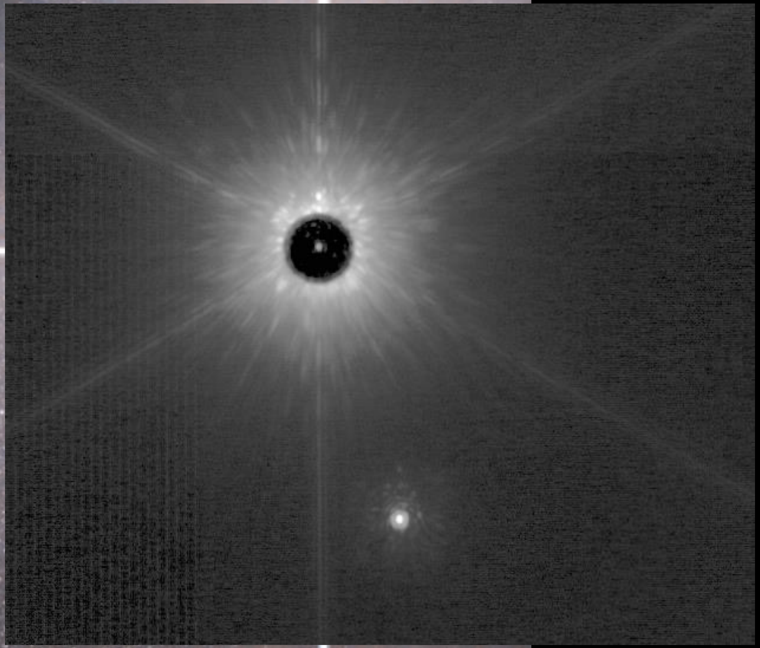
Priority Area: Pathways to Habitable Worlds

Recommendation: *A Great Observatories Mission and Technology Maturation Program*, studying a *Future Large Infrared/Optical/Ultraviolet Telescope Optimized for Observing Habitable Exoplanets and General Astrophysics*

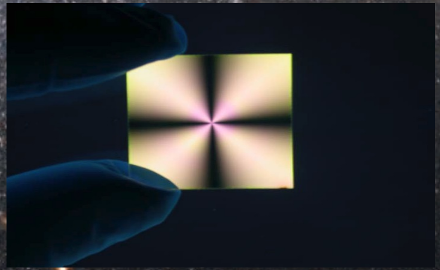
- Capable of observing planets 10 billion times fainter than their star
- UV, visible, and near-IR exoplanet spectroscopic capabilities

External Occulters (Starshades)



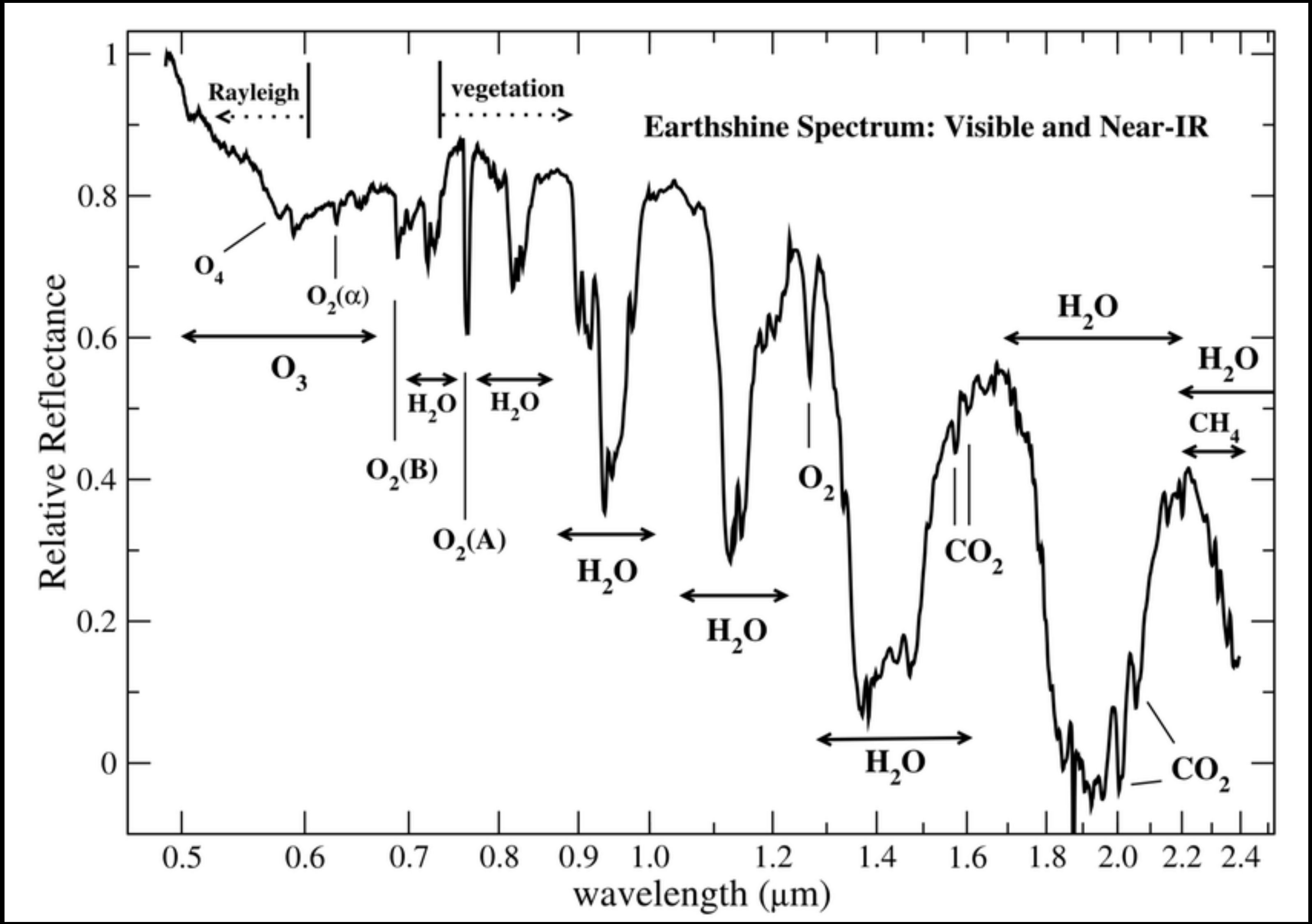


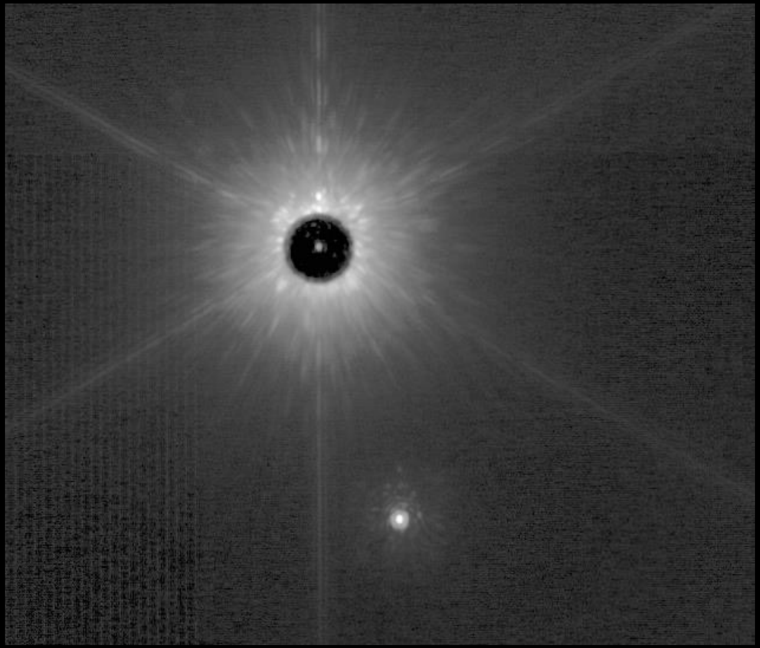
Internal Occulters (Coronagraphs)



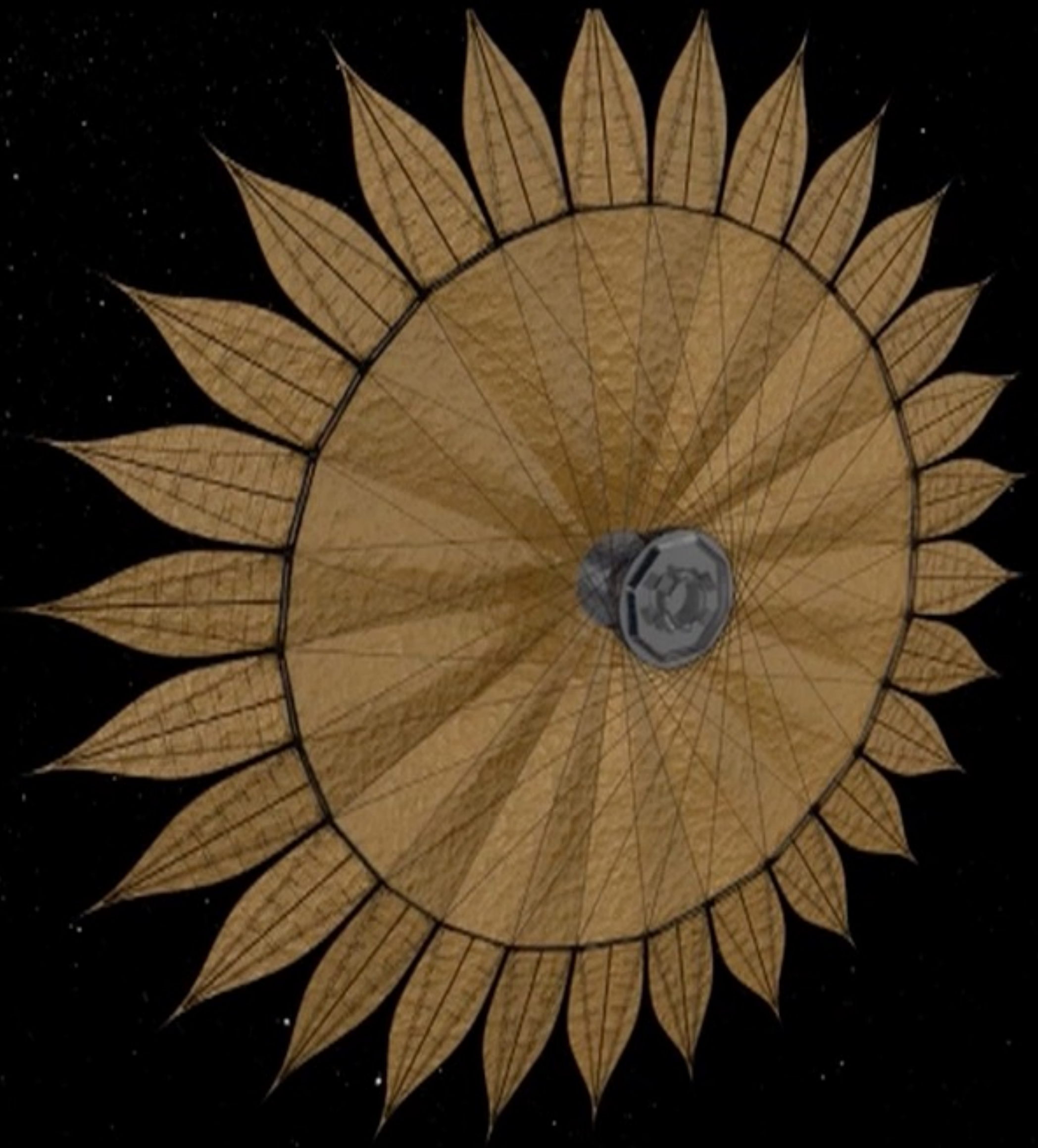
ExEP

Starlight Suppression is the Key Technology in the Search for Biosignatures on Earth-Like Exoplanets





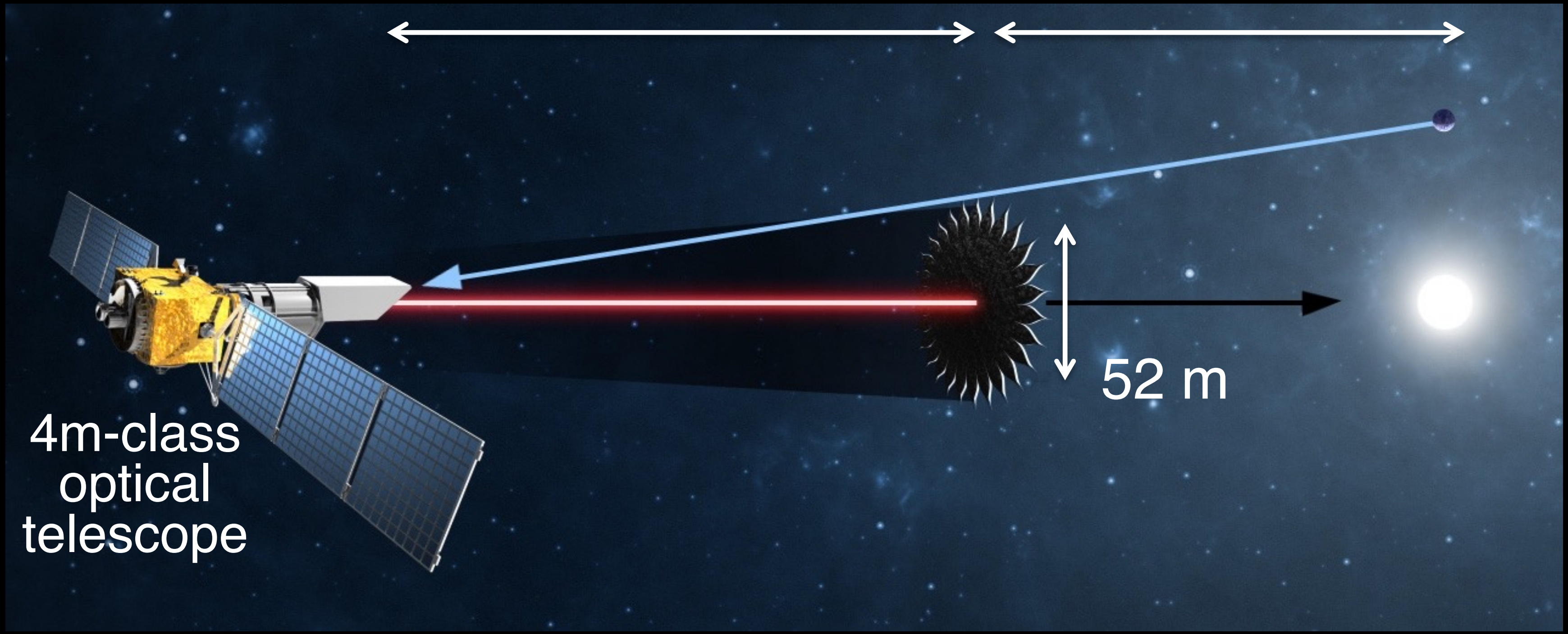
Turnbull, et al., 2006



Studying
Other Worlds
with the Help of a
Starshade

~40,000 km

Light years



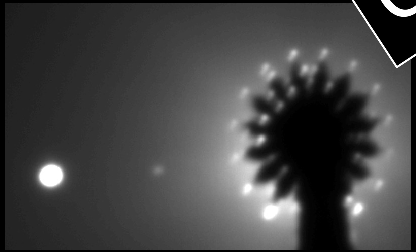
(NOT TO SCALE!)

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

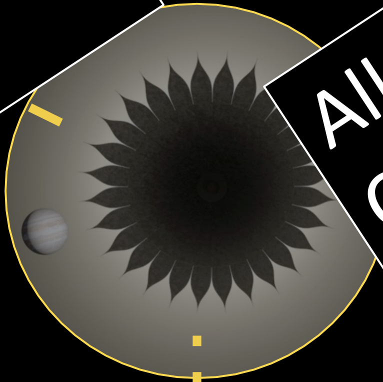
Starshade Technology Gaps

Starlight Suppression



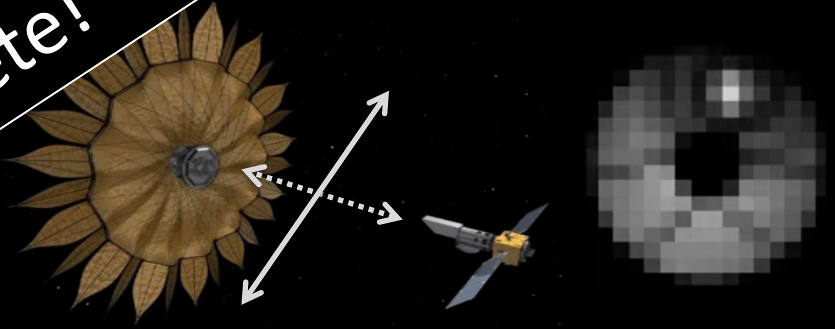


All Milestones Complete!

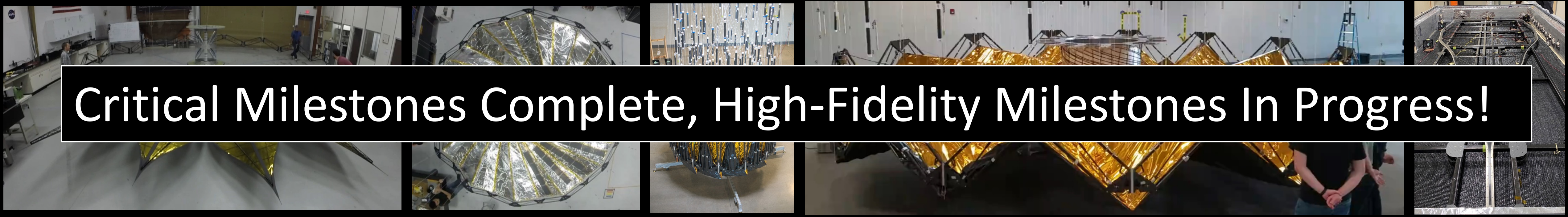


Formation Sensing and Control

All Milestones Complete!



Deployment Accuracy and Shape Stability

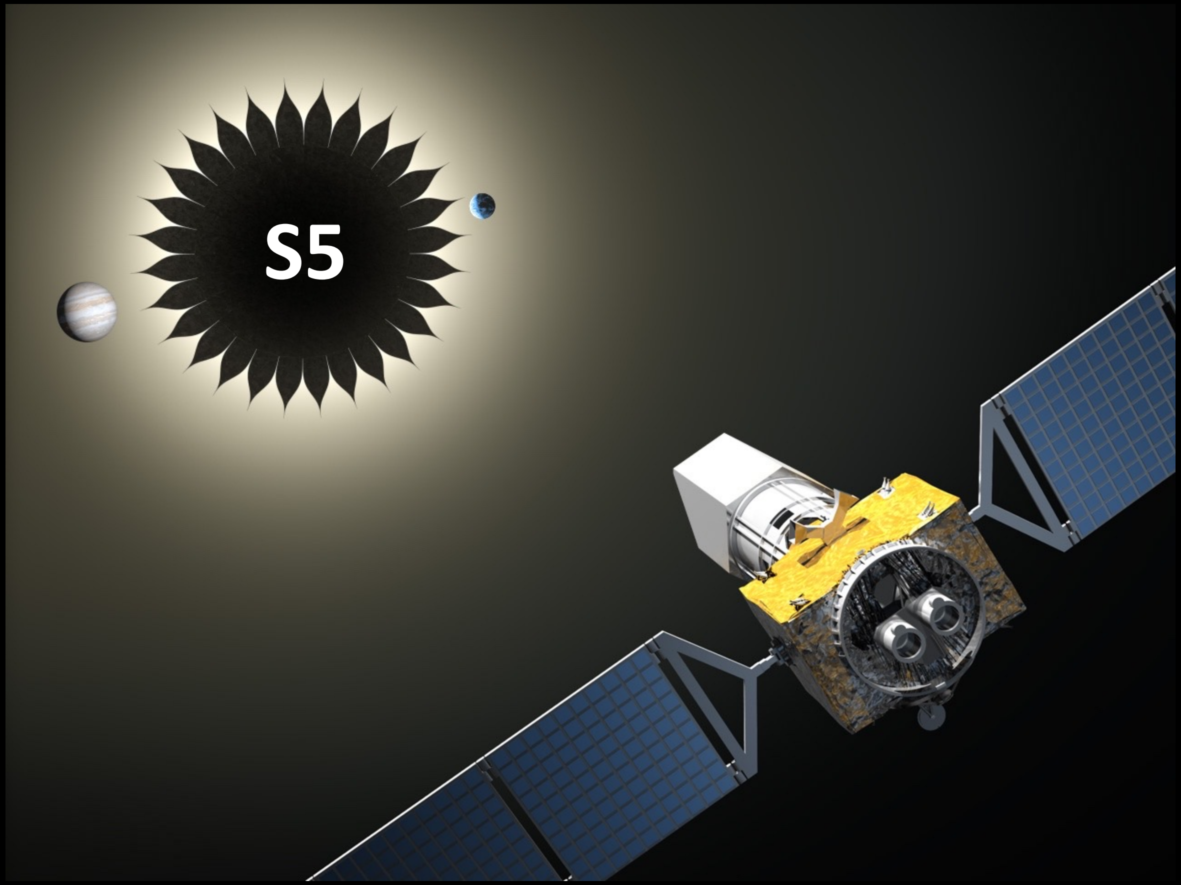


Critical Milestones Complete, High-Fidelity Milestones In Progress!

March 2016: Starshade to TRL5 Activity ("S5")

S5 Activity Goals:

- Develop starshade technology to discover Earth-like planets in habitable zones around Sun-like stars for future space telescope missions.
- Help coordinate community research.
- *Advance the technologies that close the three key technology gaps to TRL 5.*



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

S5: Closing Starshade Technology Gaps

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

Starshade Milestones as of 2016

Gap 1

Starlight Suppression
- Contrast NB 1A
- Contrast BB 1B
- Modeling Validation 2

Scattered Sunlight
- Edges 3

Gap 2

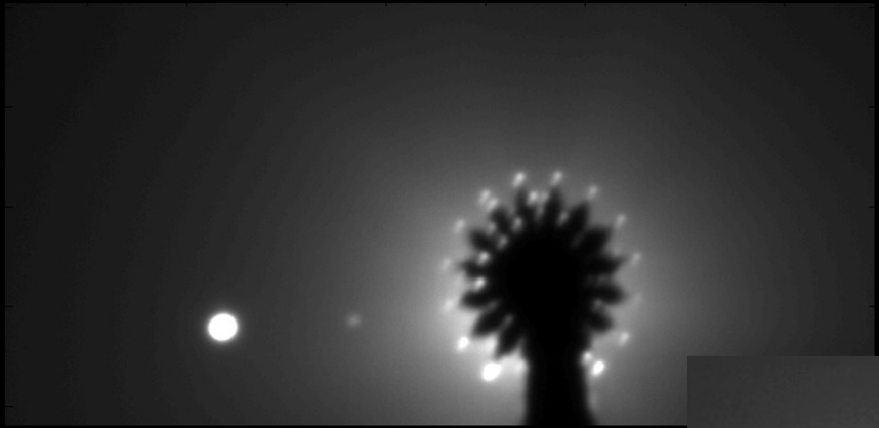
Formation Flying
- Sensing 4

Gap 3

	Critical Features	All Features
Shape Accuracy	Petal 5A; Truss Bay 7A; Inner Disk Deployment 7C	Petal 5B; Truss Bay 7B; Inner Disk 7D
Shape Stability	Petal 6A; Inner Disk (thermal) 8A	Petal 6B; Inner Disk 8B

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Gap 1: Starlight Suppression & Scattered Sunlight



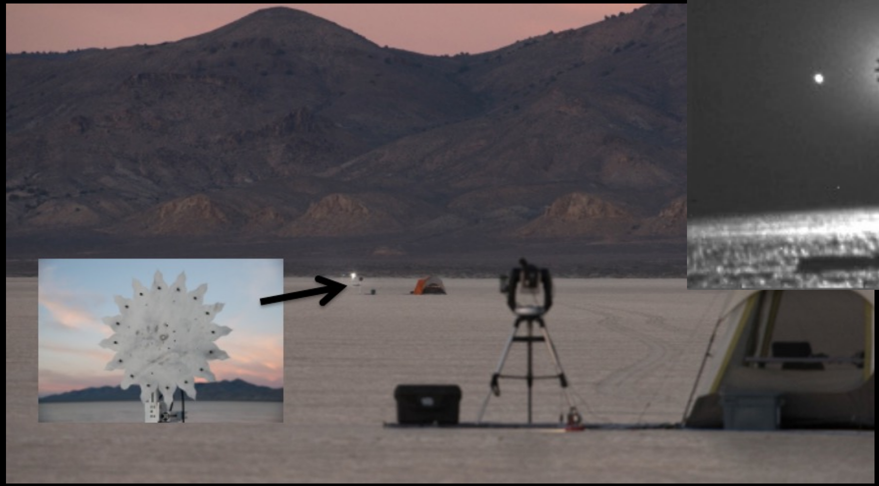
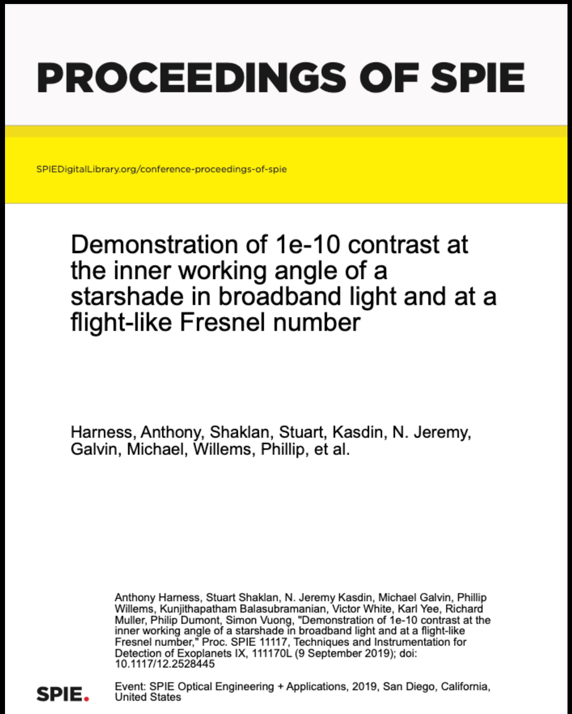


Image credit, desert testing: Northrop Grumman



PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

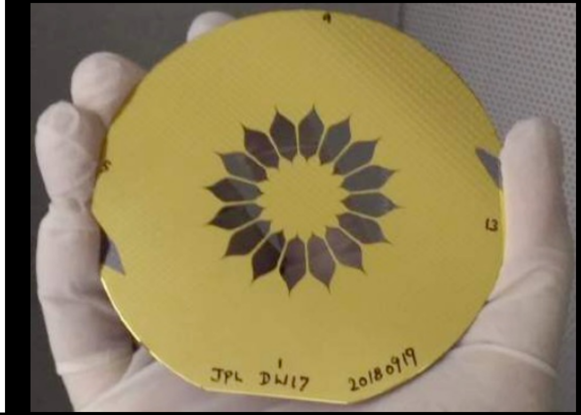
Demonstration of 1e-10 contrast at the inner working angle of a starshade in broadband light and at a flight-like Fresnel number

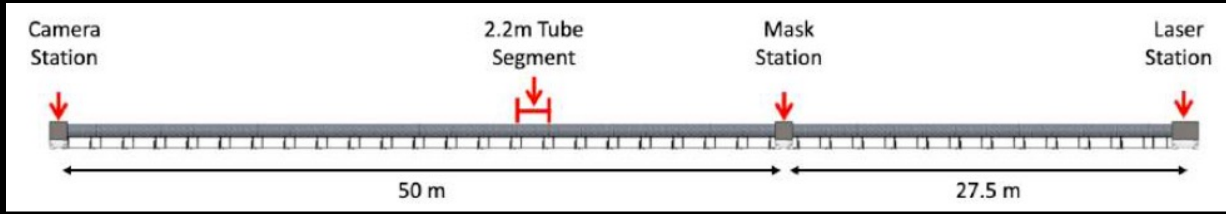
Harness, Anthony, Shaklan, Stuart, Kasdin, N. Jeremy, Galvin, Michael, Willems, Phillip, et al.

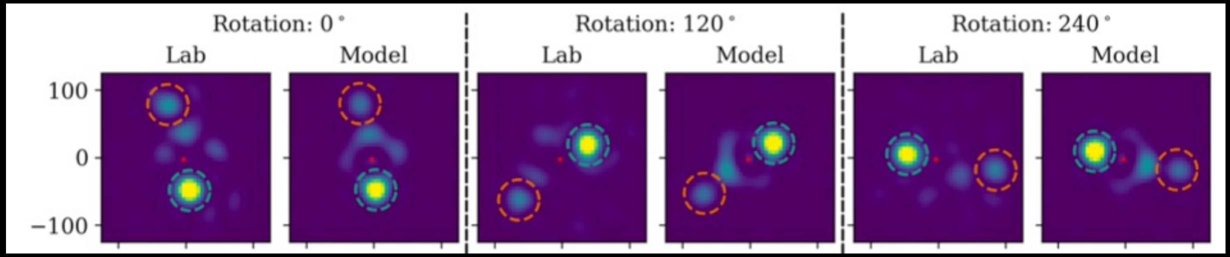
Anthony Harness, Stuart Shaklan, N. Jeremy Kasdin, Michael Galvin, Phillip Willems, Kunjithapatham Balasubramanian, Victor White, Karl Yee, Richard Muller, Philip Dumont, Simon Vuong, "Demonstration of 1e-10 contrast at the inner working angle of a starshade in broadband light and at a flight-like Fresnel number," Proc. SPIE 11117, Techniques and Instrumentation for Detection of Exoplanets IX, 111170L (9 September 2019); doi: 10.1117/12.2528445

SPIE.

Event: SPIE Optical Engineering + Applications, 2019, San Diego, California, United States

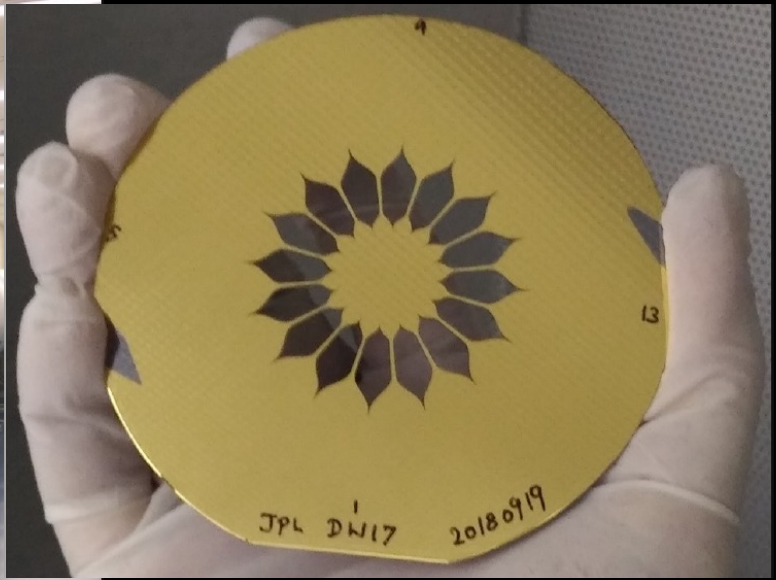


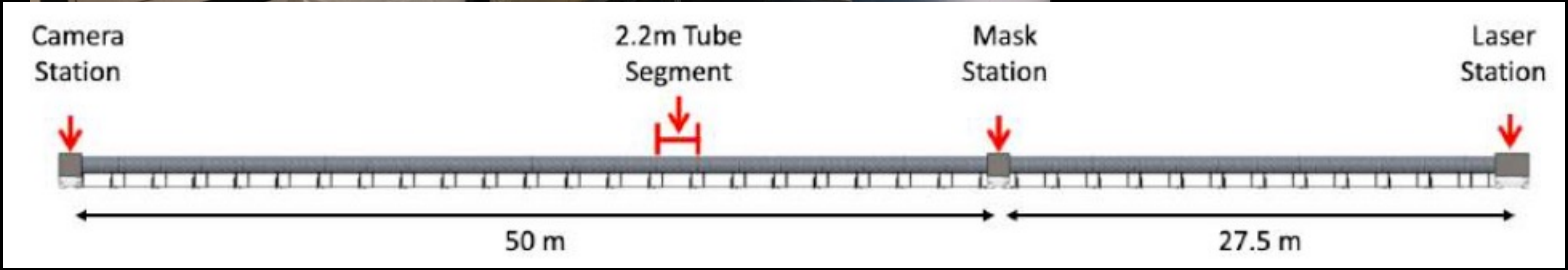




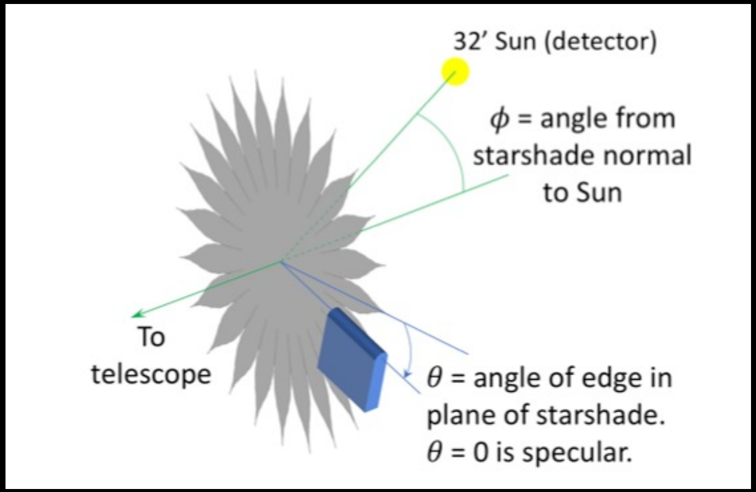
National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology

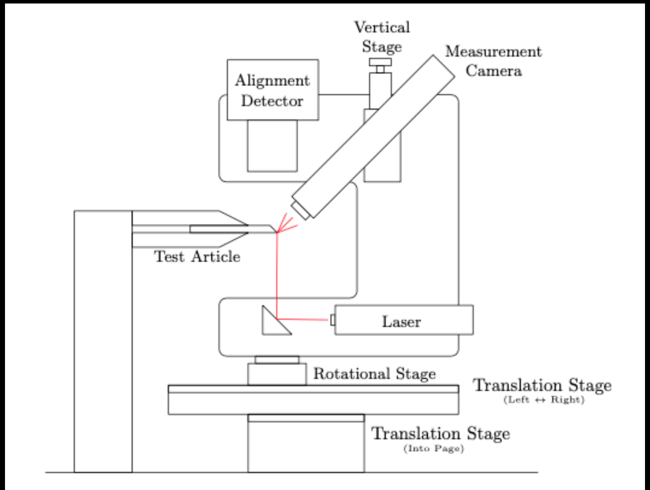
Gap 1: Starlight Suppression & Scattered Sunlight

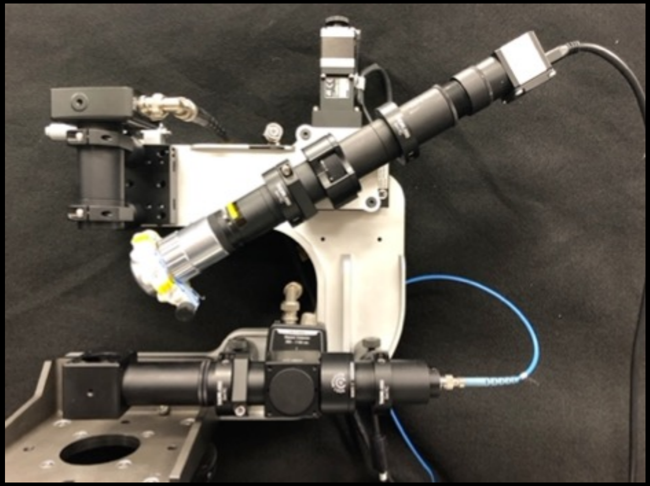


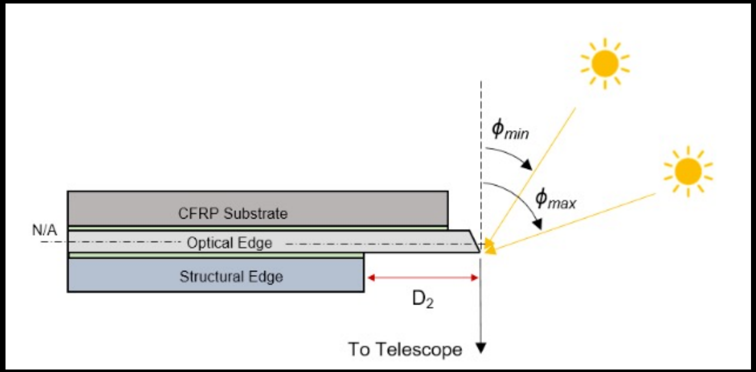


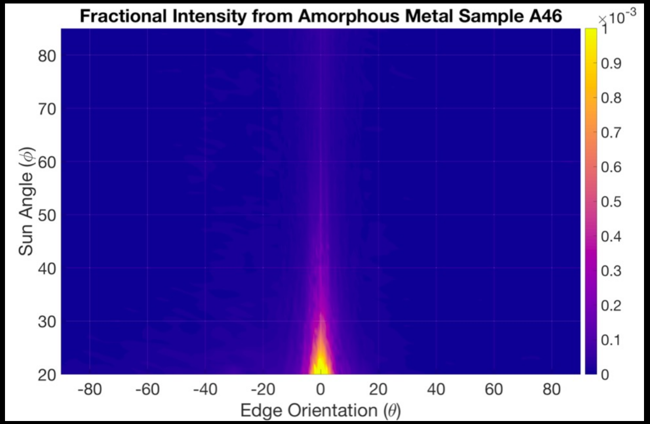
Gap 1: Starlight Suppression & Scattered Sunlight

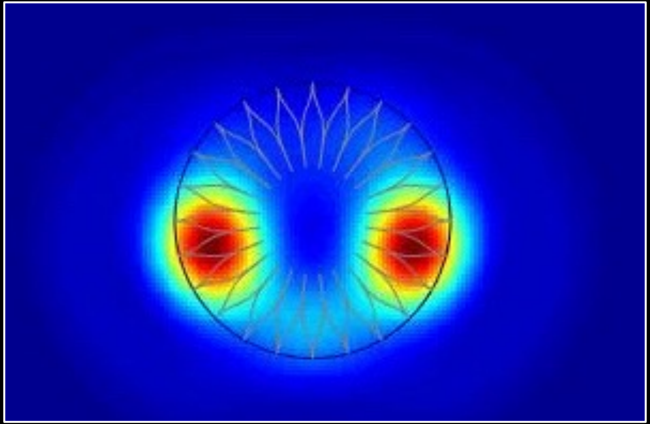




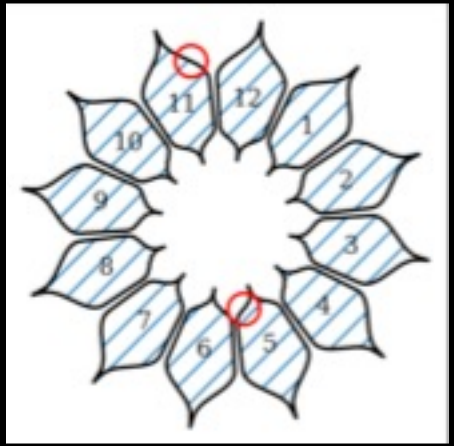


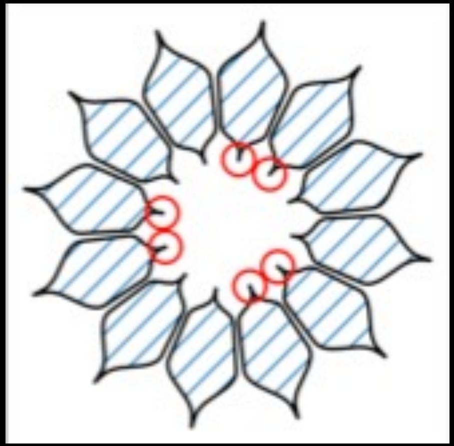


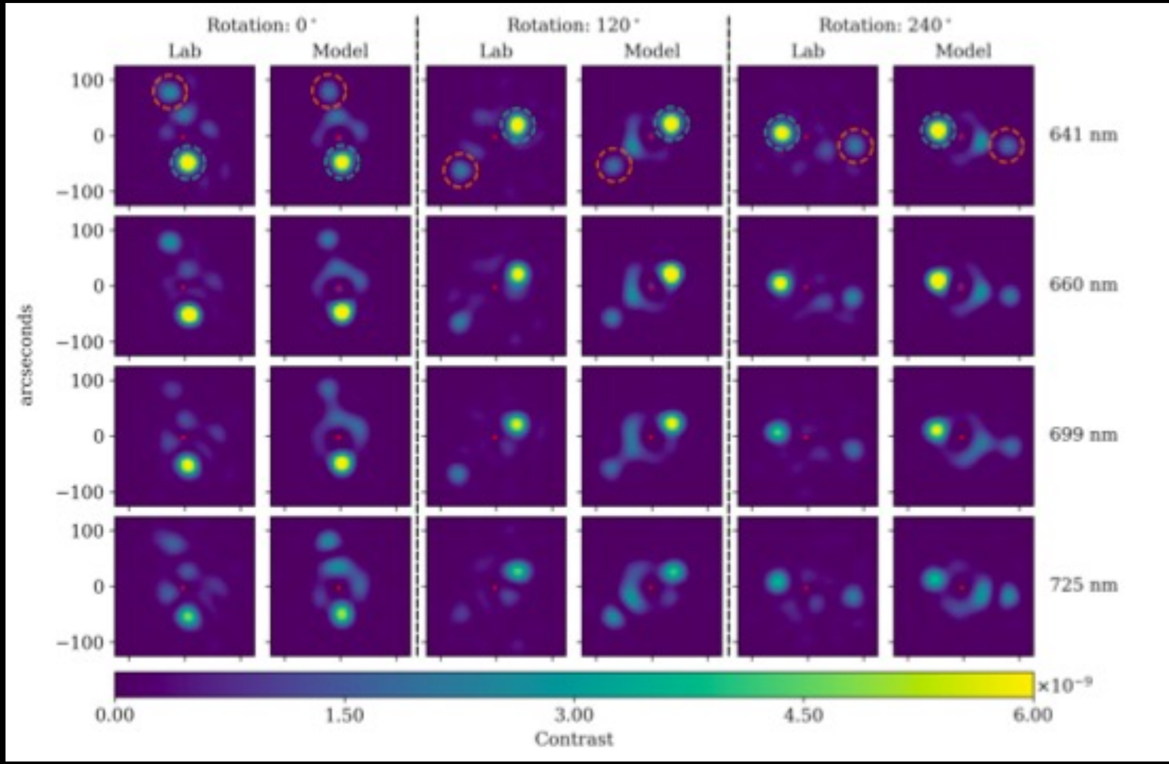


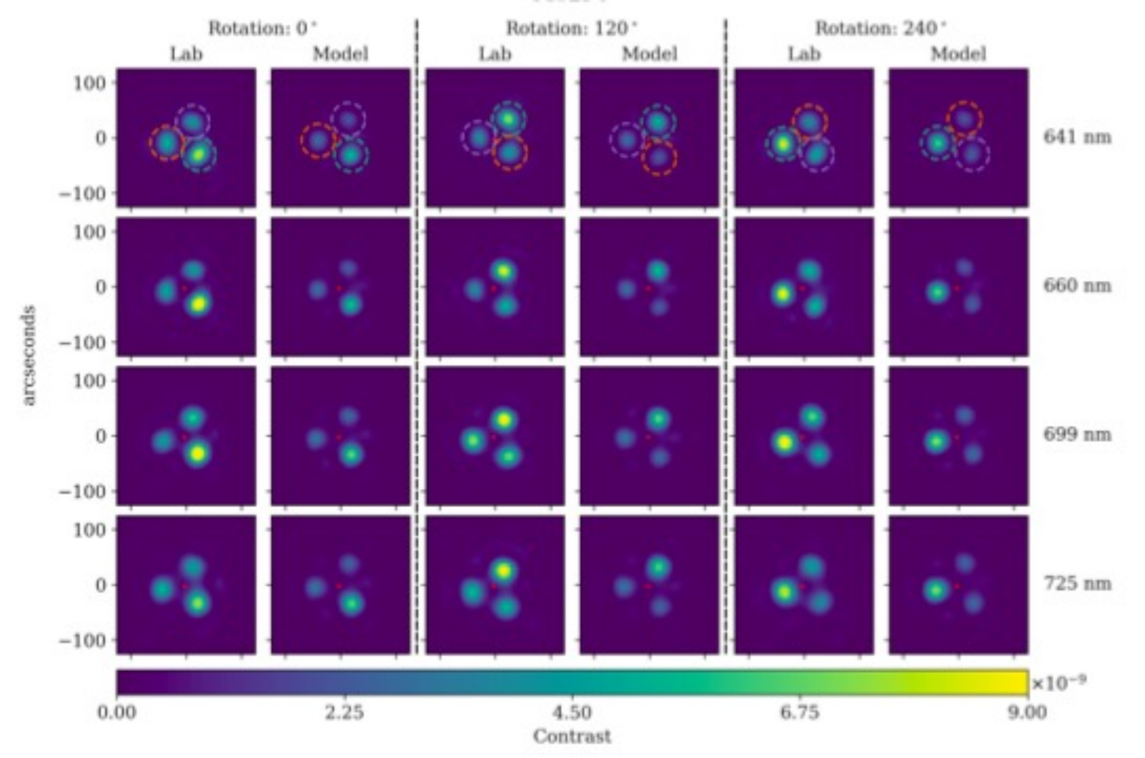


Gap 1: Starlight Suppression & Scattered Sunlight



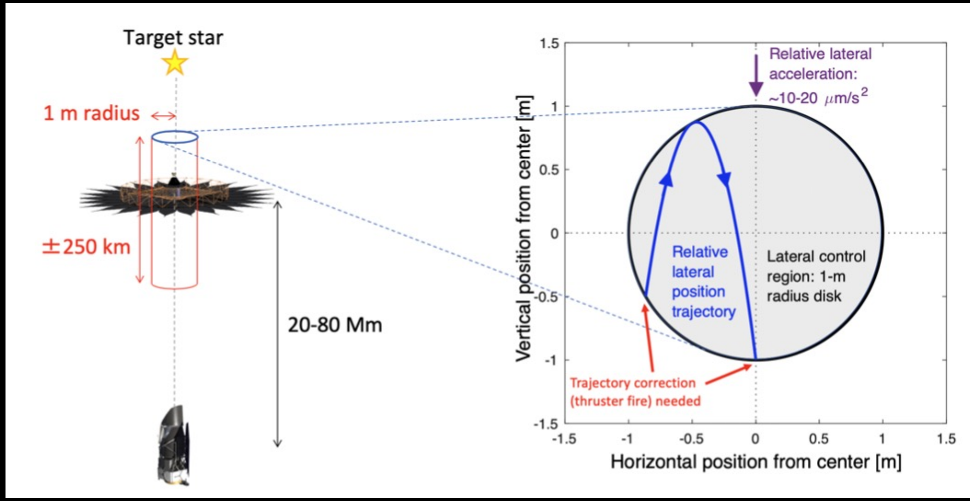


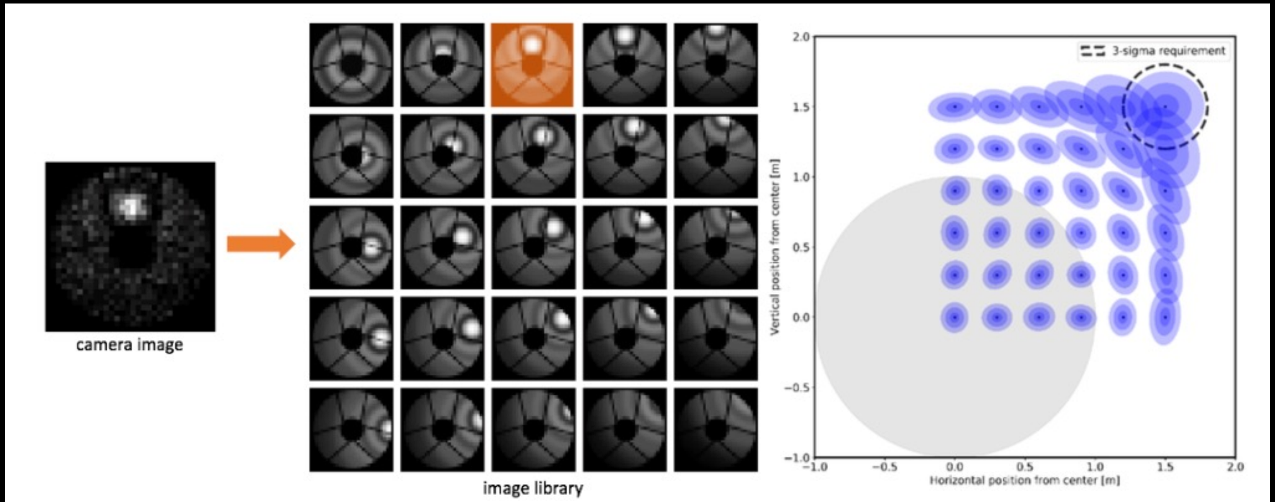


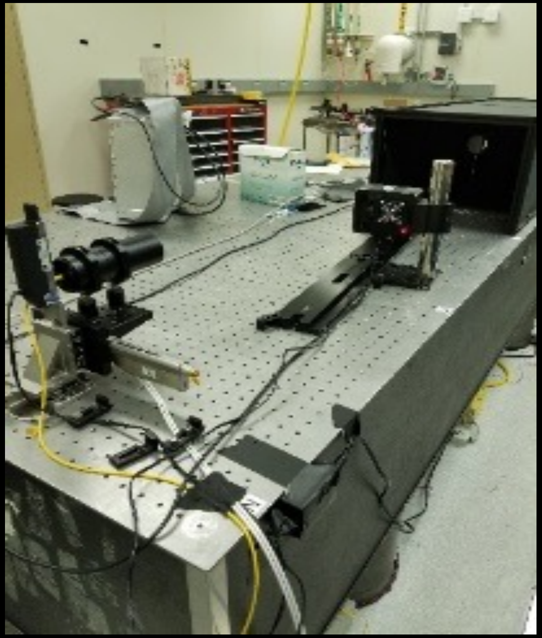


National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Gap 2: Formation Sensing and Control



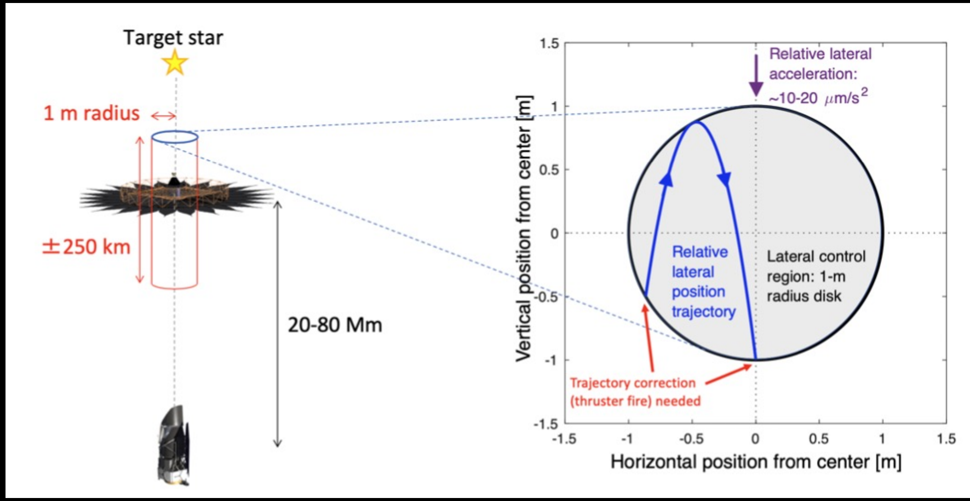


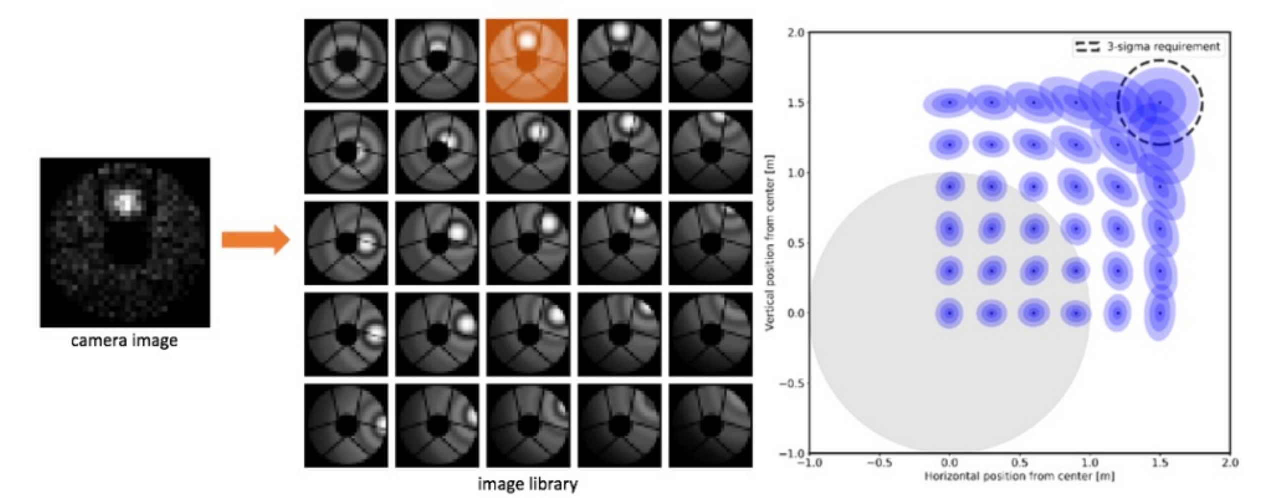


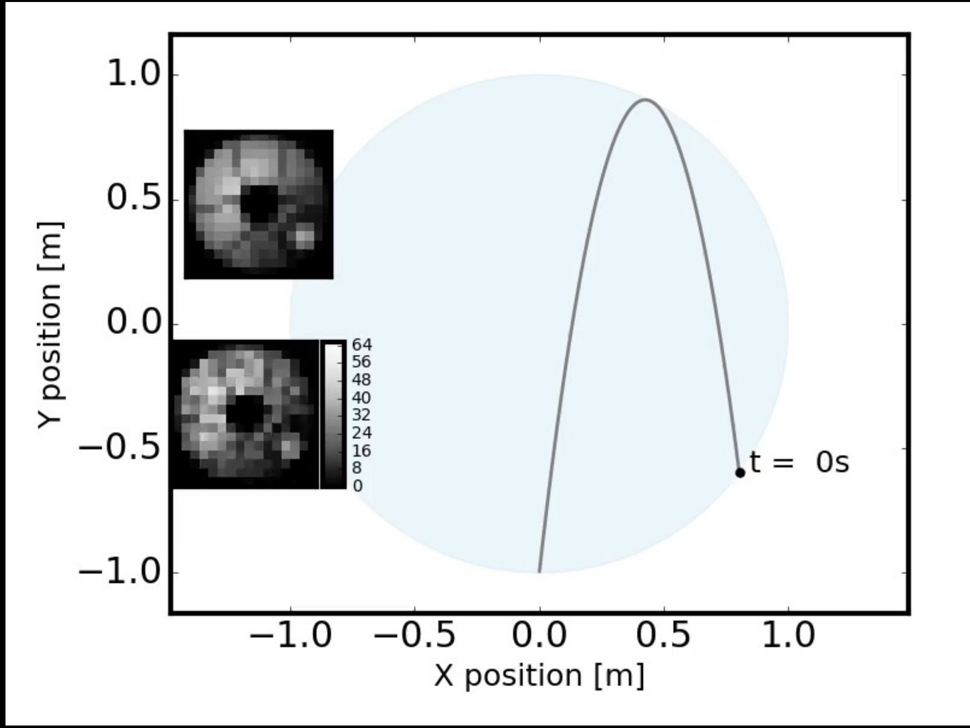
National Aeronautics and Space Administration

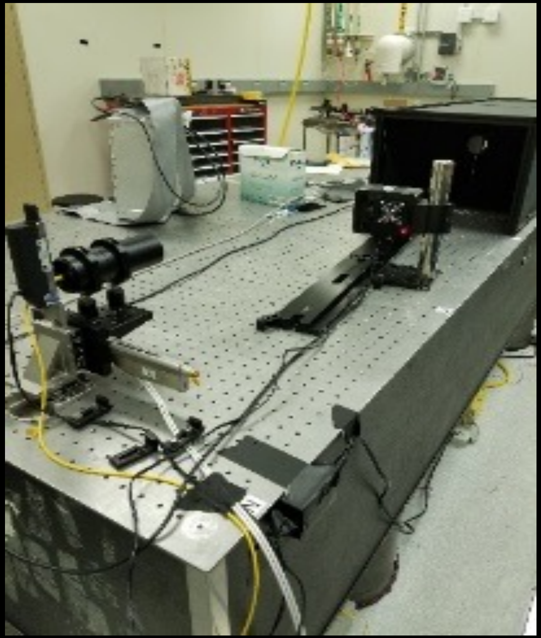
Jet Propulsion Laboratory
California Institute of Technology

Gap 2: Formation Sensing and Control



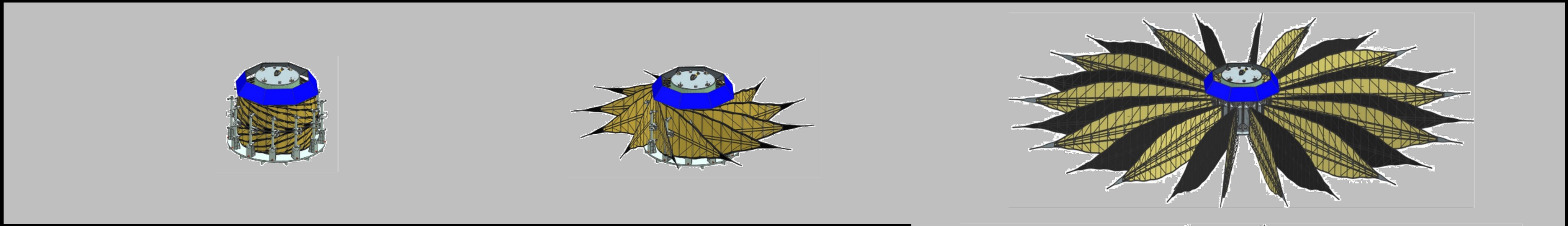


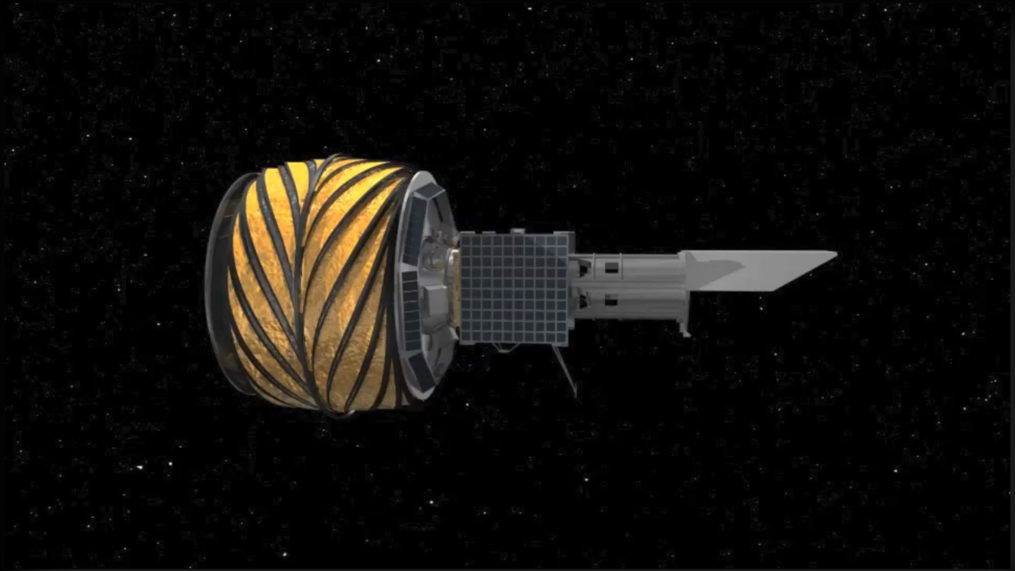


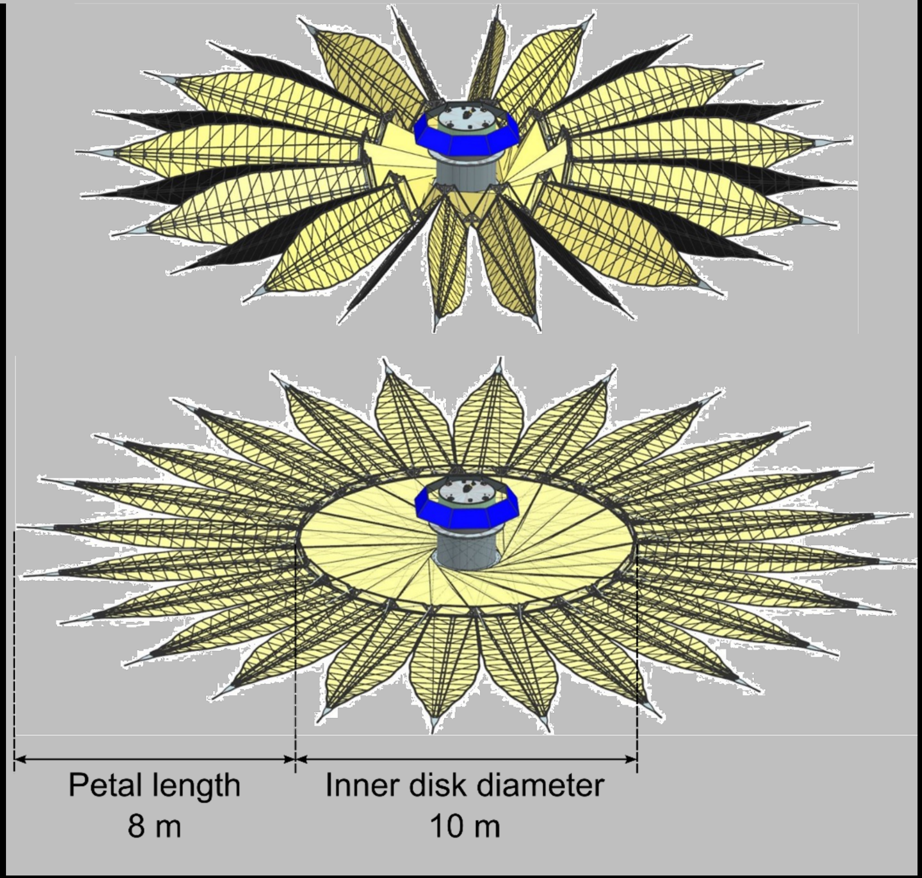


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

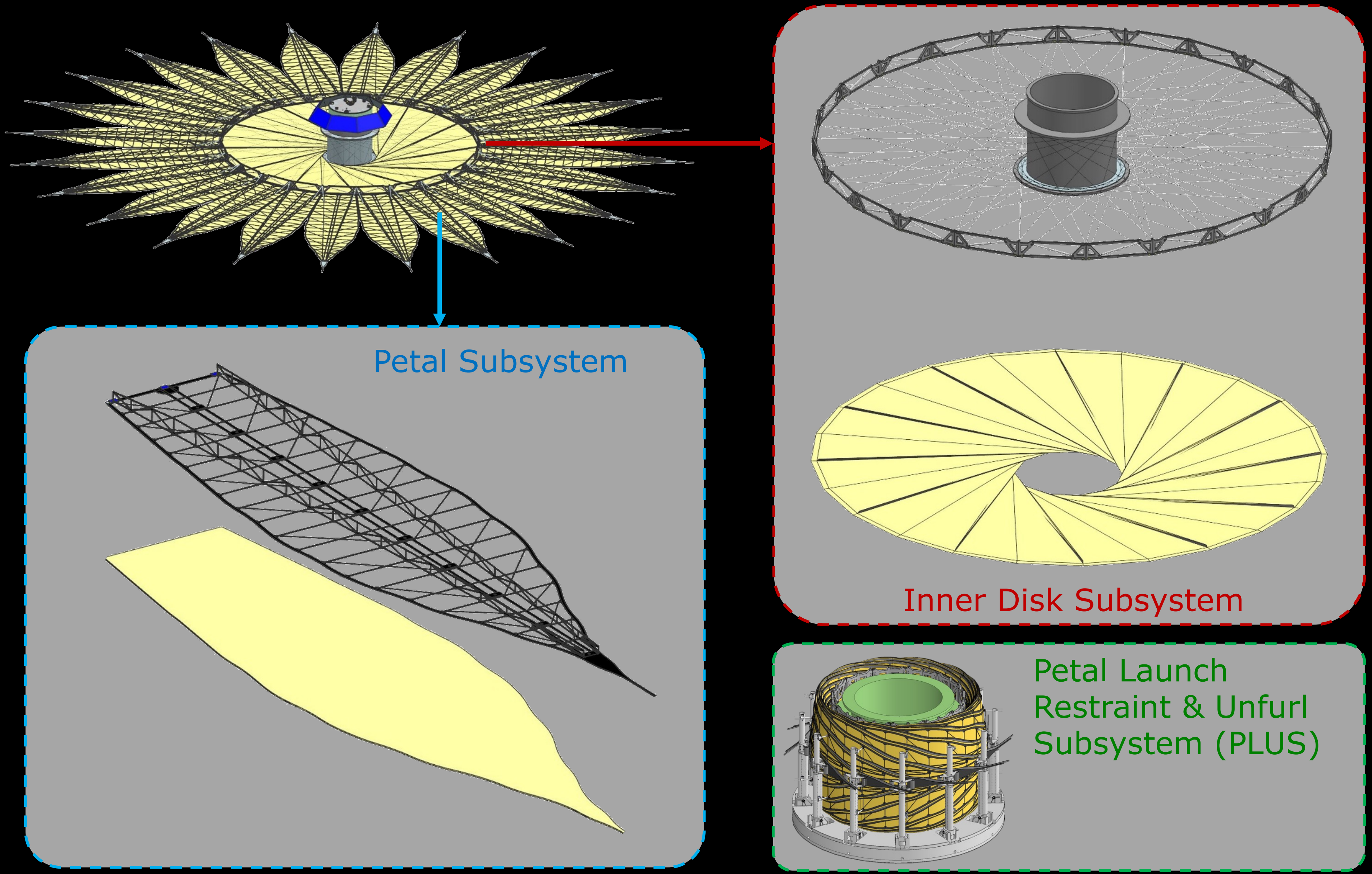
Gap 3: Deployment Accuracy and Shape Stability





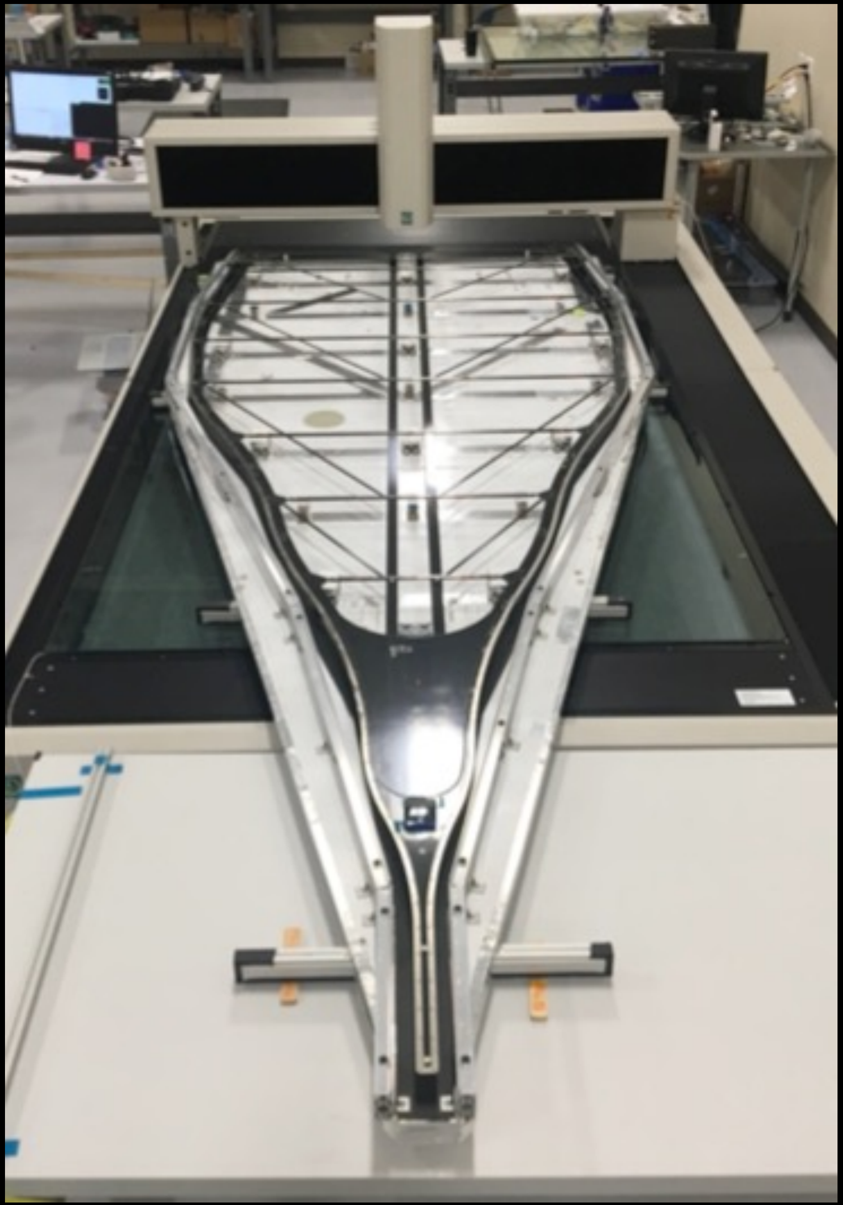


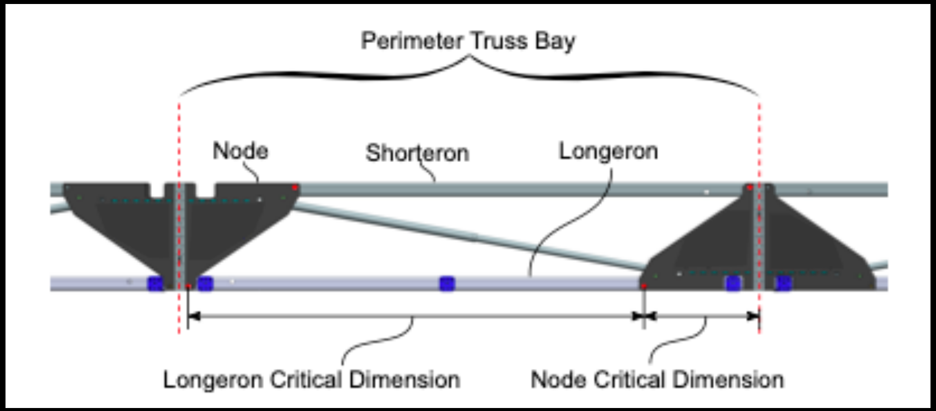
Gap 3: Deployment Accuracy and Shape Stability

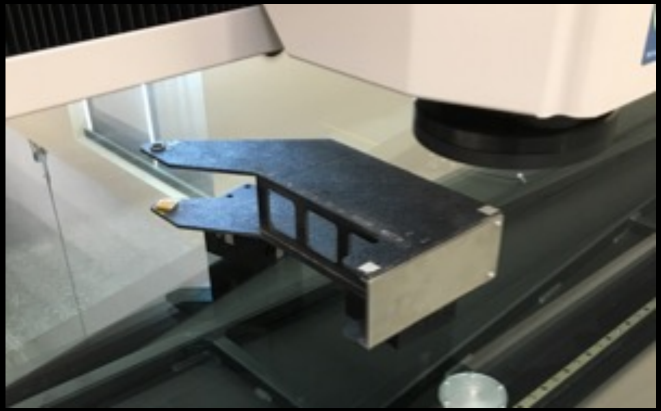


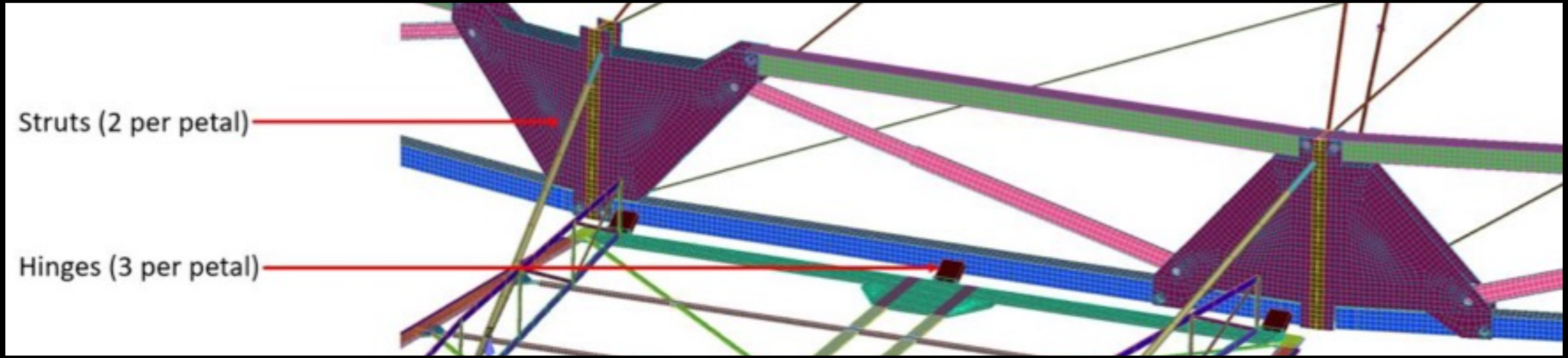
National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology

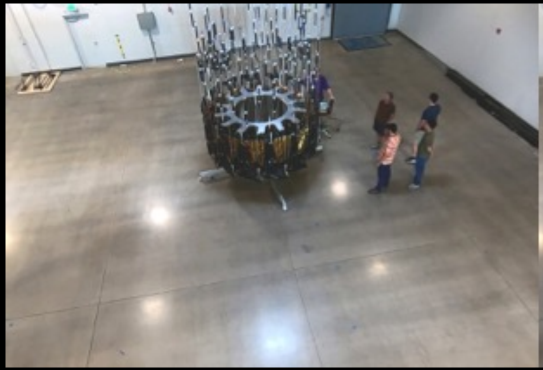
Gap 3: Deployment Accuracy and Shape Stability











Pre-S5 starshade activities

Starshade Deployment
Technology Demo

August 2013

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology

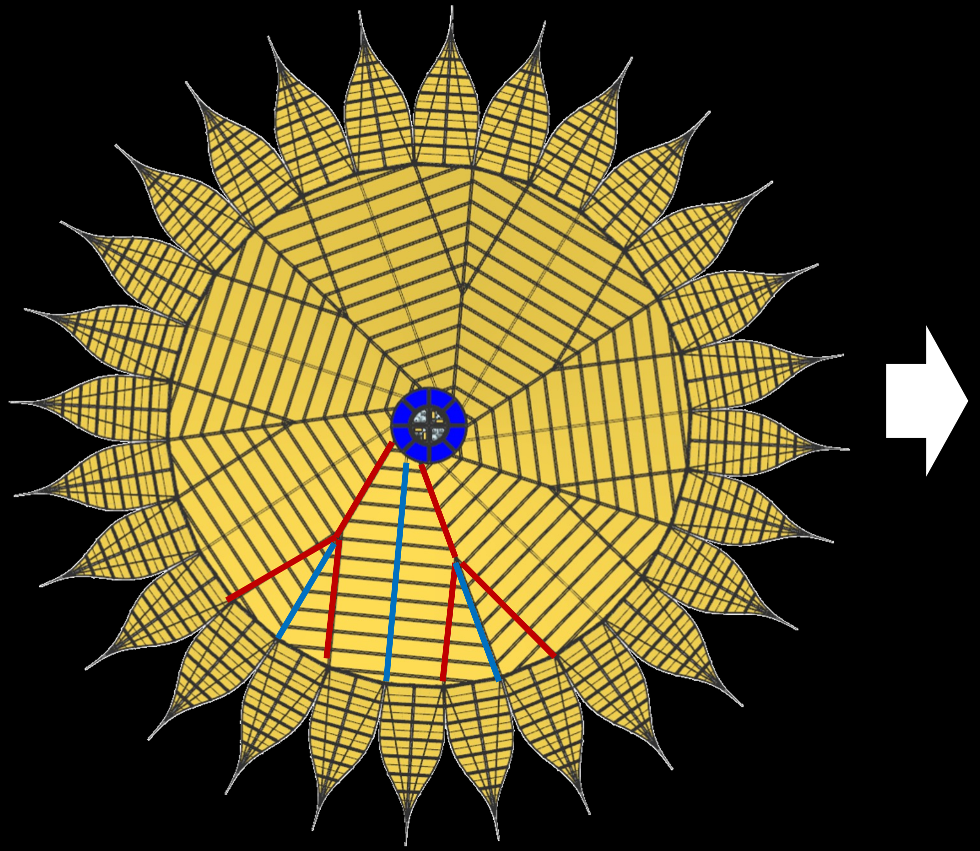
JPL Starshade Laboratory

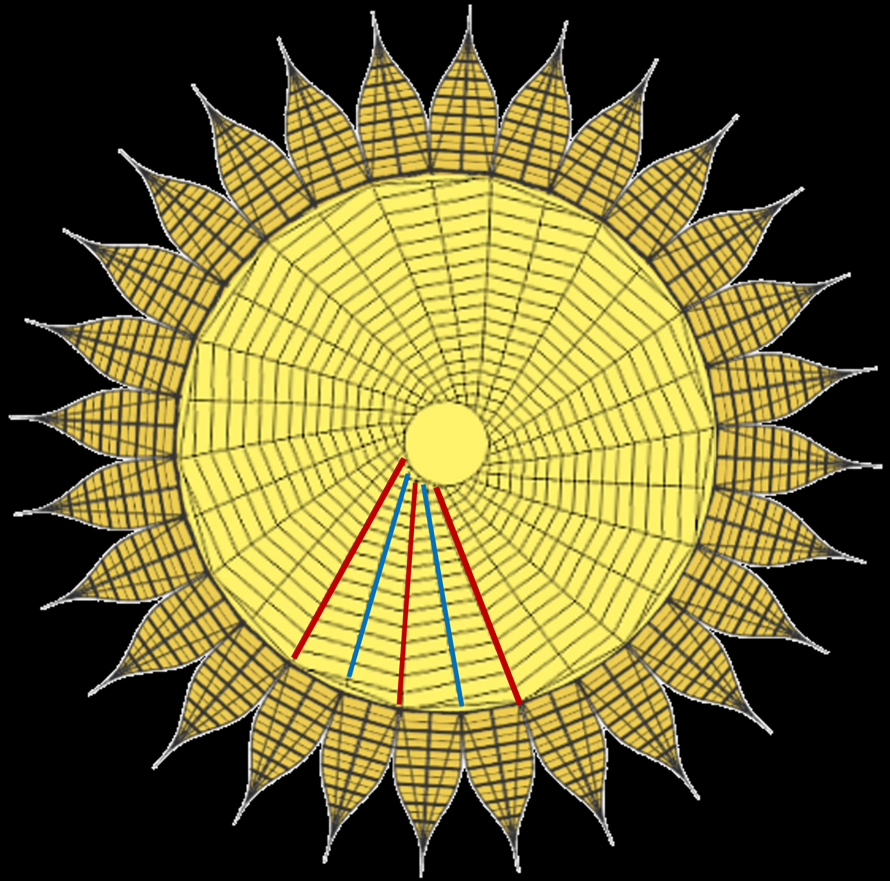
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology

Starshade Inner Disk: Perimeter Truss

Origami-Inspired Deployable Design





Original Design- Heptagon (7-agon)

- Larger and fewer "panels"
- Fewer fold lines at center of disk
- Stows to smaller radial annulus

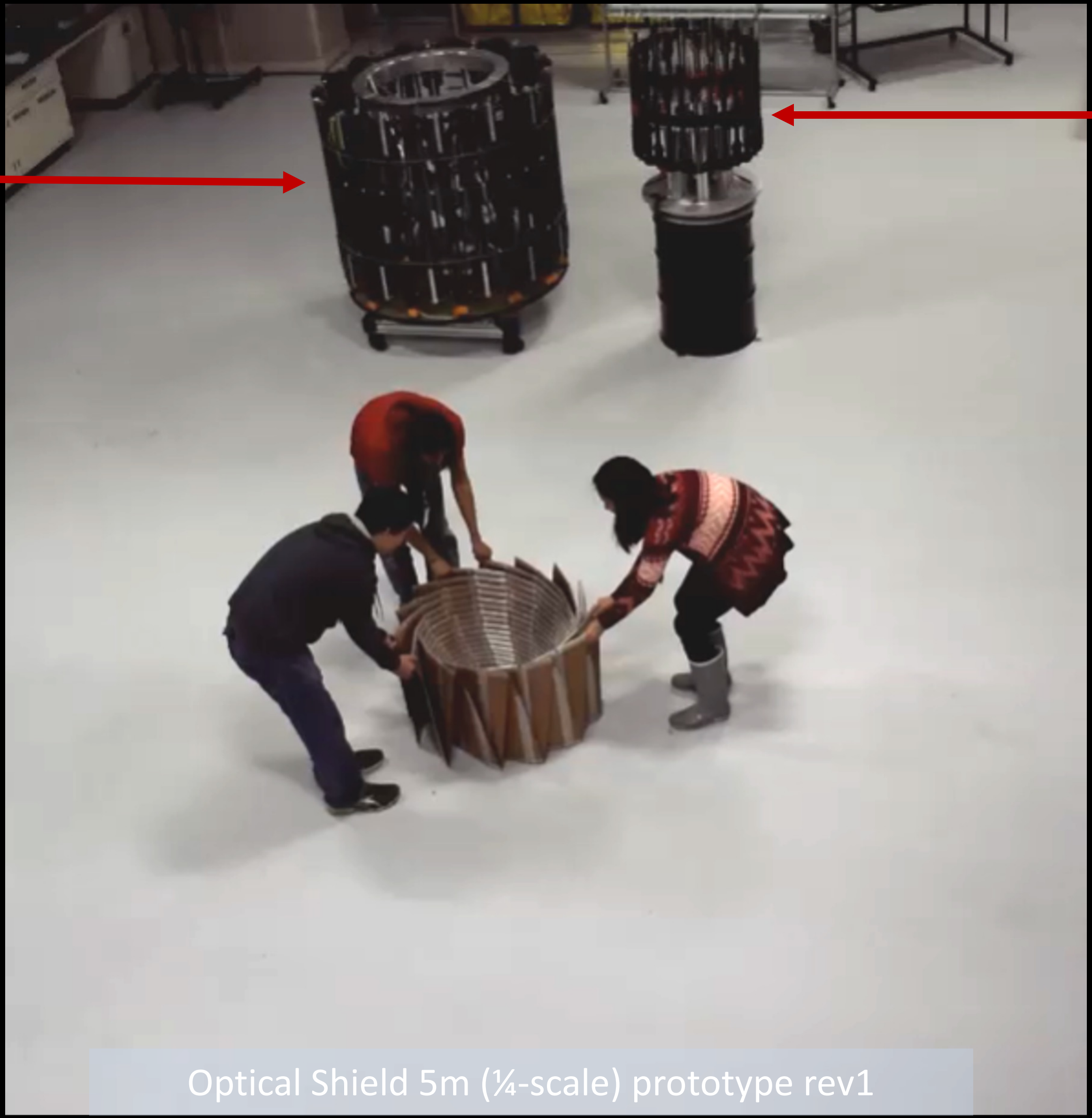
Current Design- Tetra-decagon (14-agon)

- Deployment kinematics better match truss
- More panels, but may be able to reduce # of panels radially

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Optical Shield 5m Breadboard 1st Gen

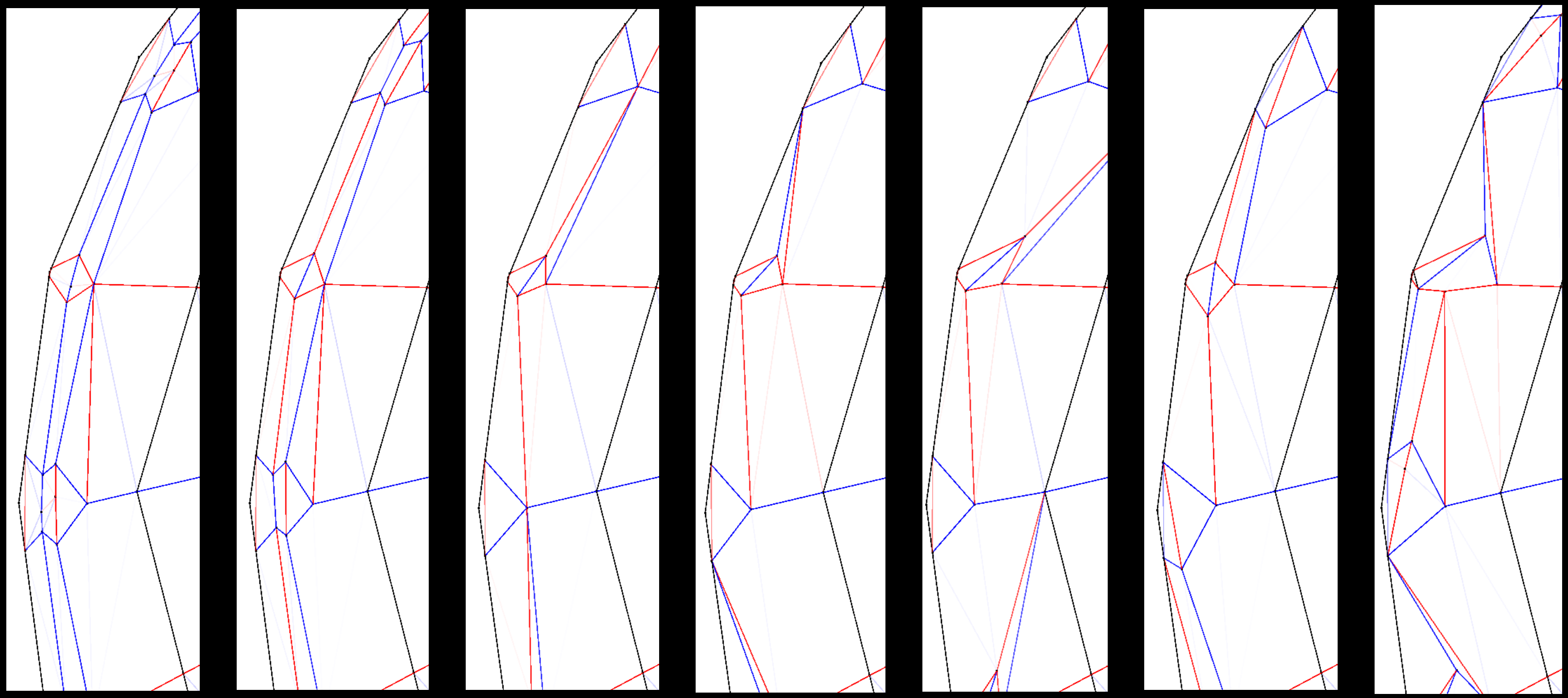
Stowed ½-scale truss (1m diameter)

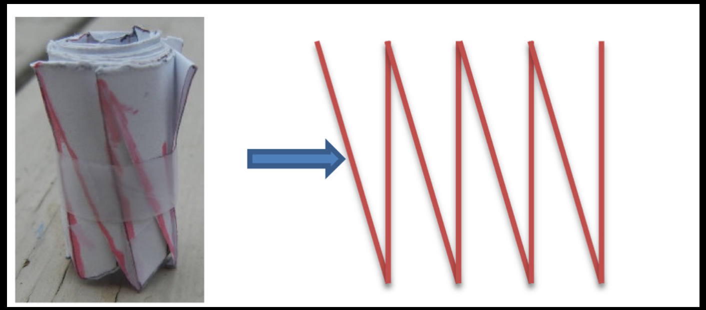


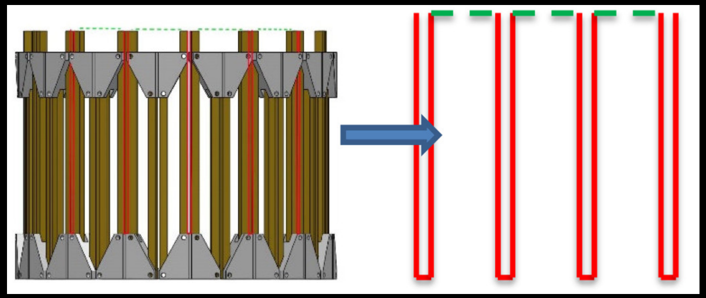
Stowed ¼-scale truss (1.5m diameter)

Matching Truss to Optical Shield

Candidate Patterns



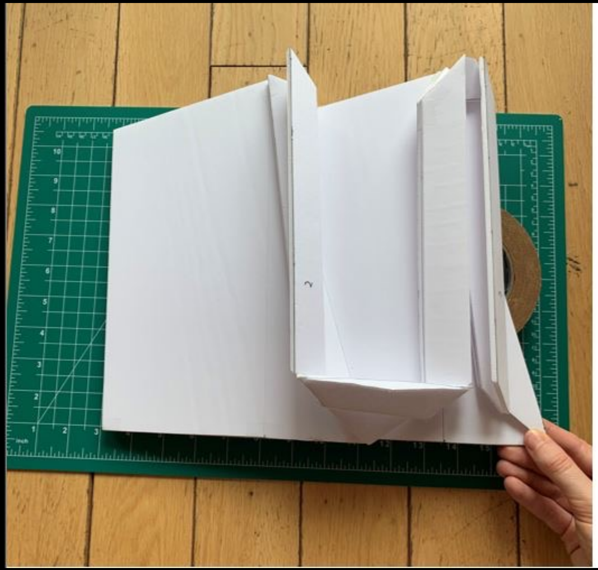


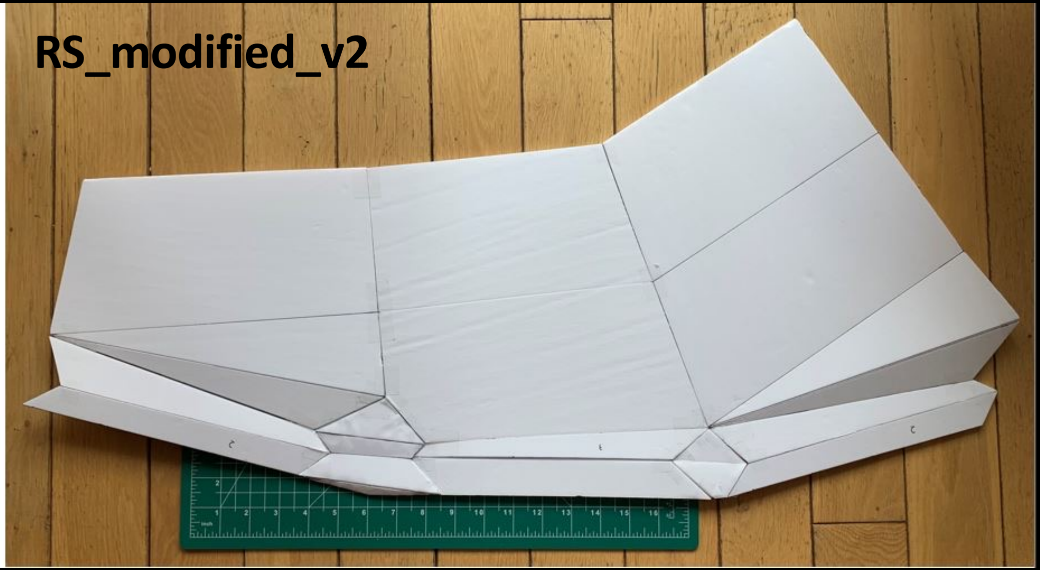


From A. Haraszti 2020-2021 internship

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Matching Truss to Optical Shield





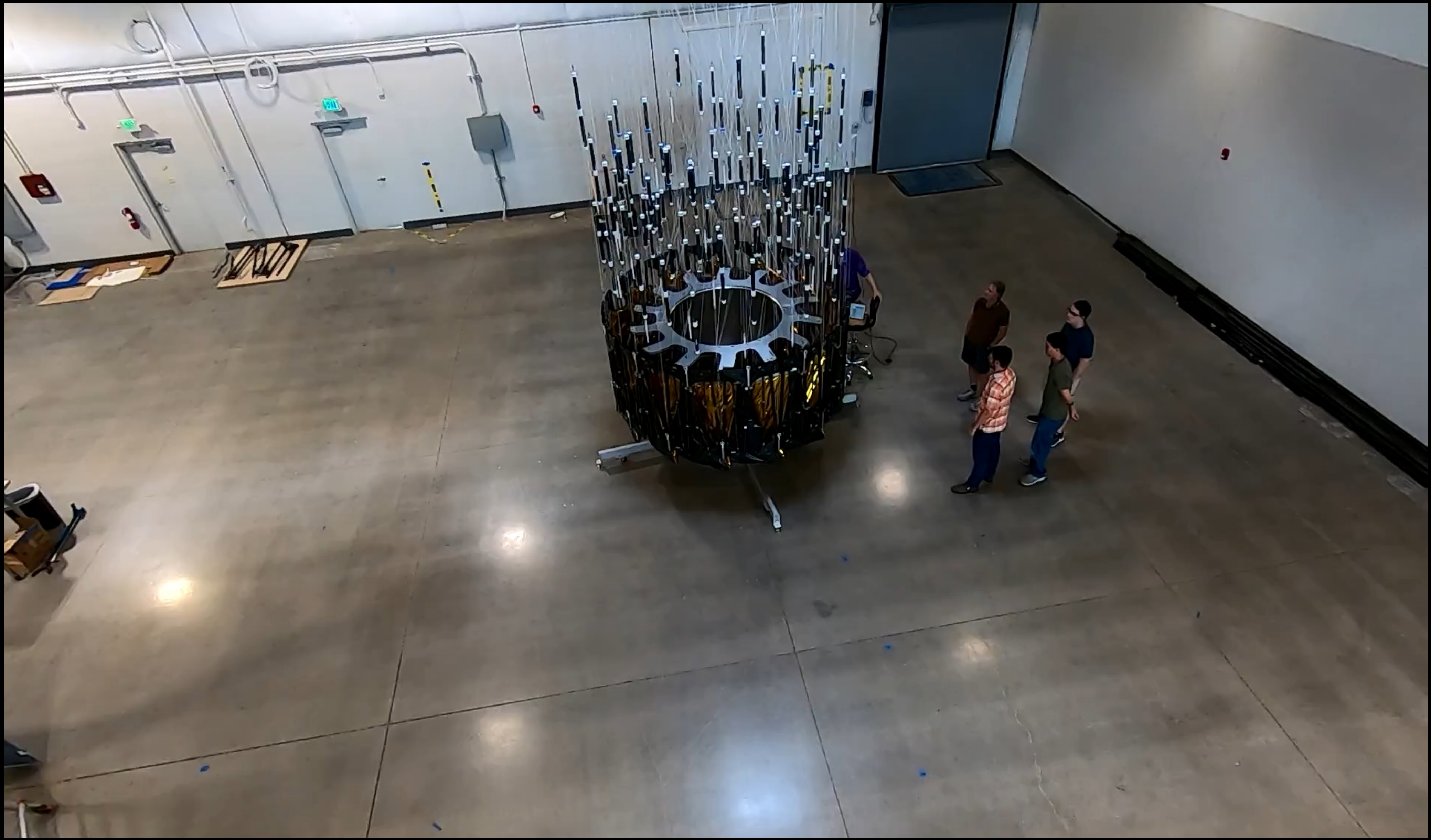
From A. Haraszti 2020-2021 internship

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Starshade Inner Disk

Deployable Inner Disk System and Perimeter Truss at TENDEG facility, Louisville CO

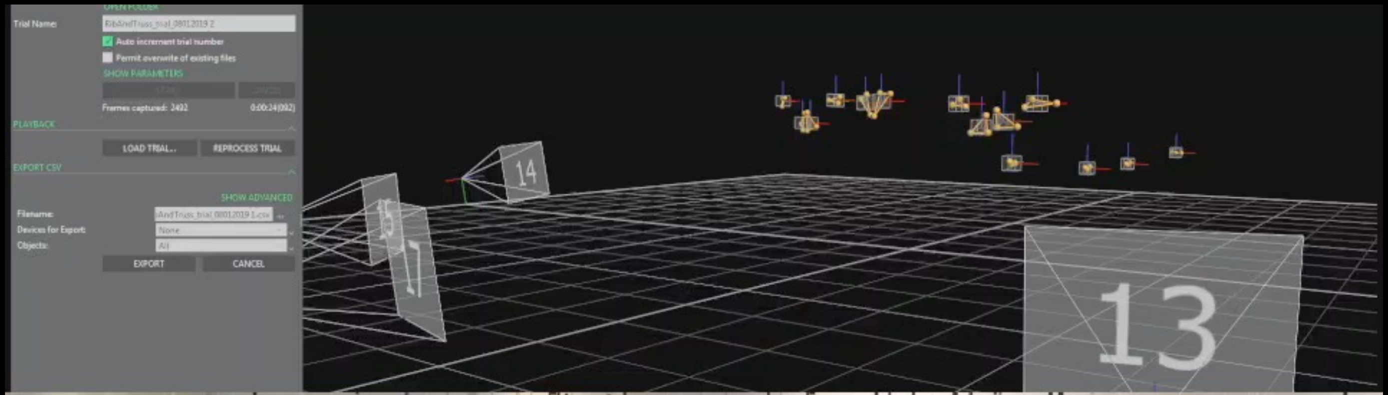
10m Deployment Demo

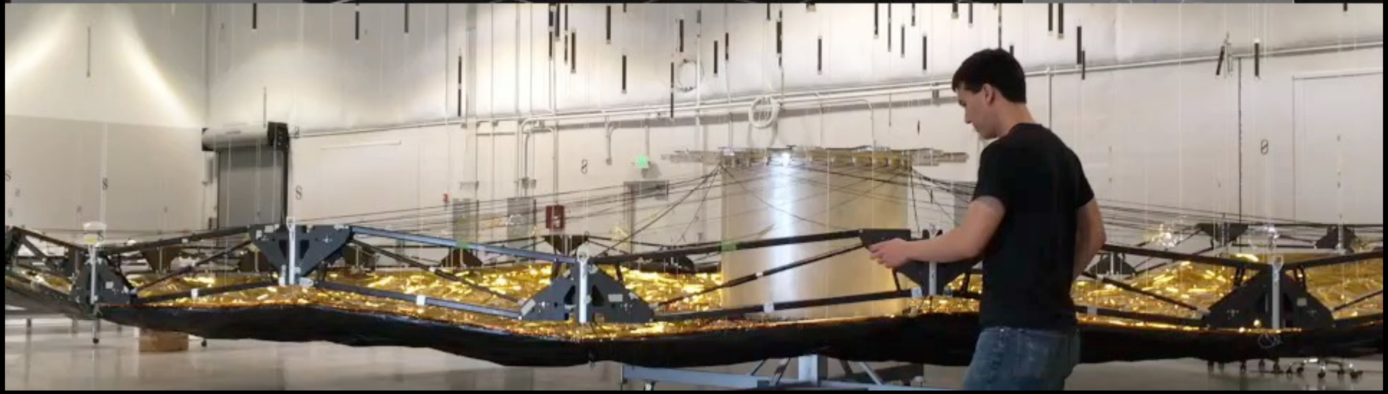


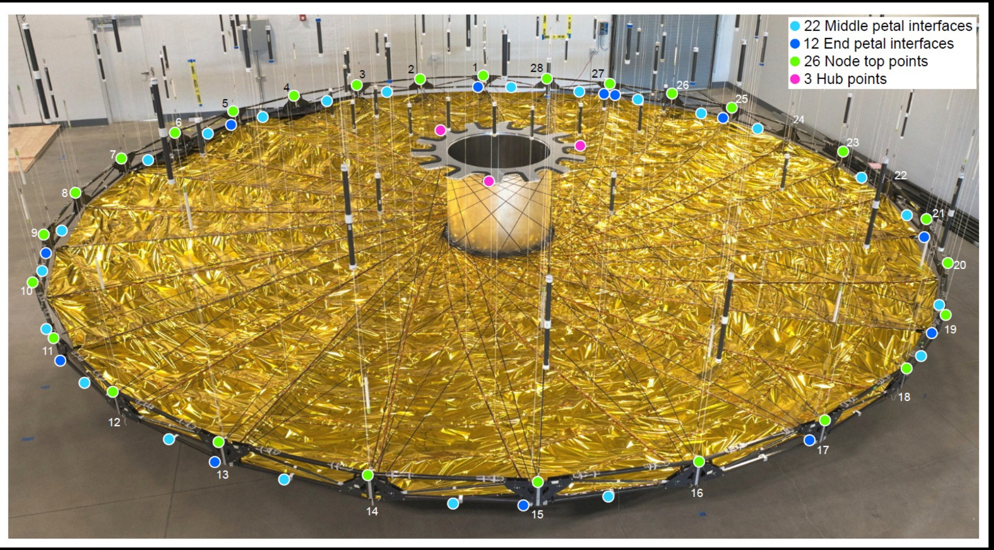
Deployable Inner Disk System and Perimeter Truss at TENDEG facility, Louisville CO

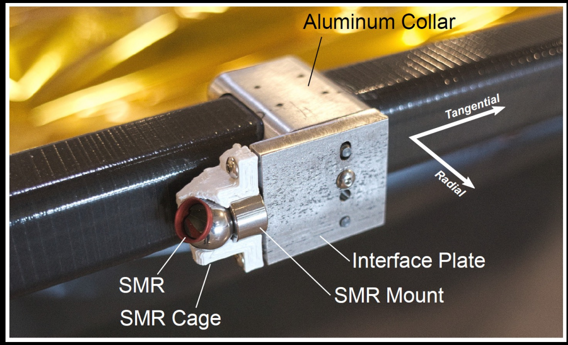
National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Inner Disk Measurement



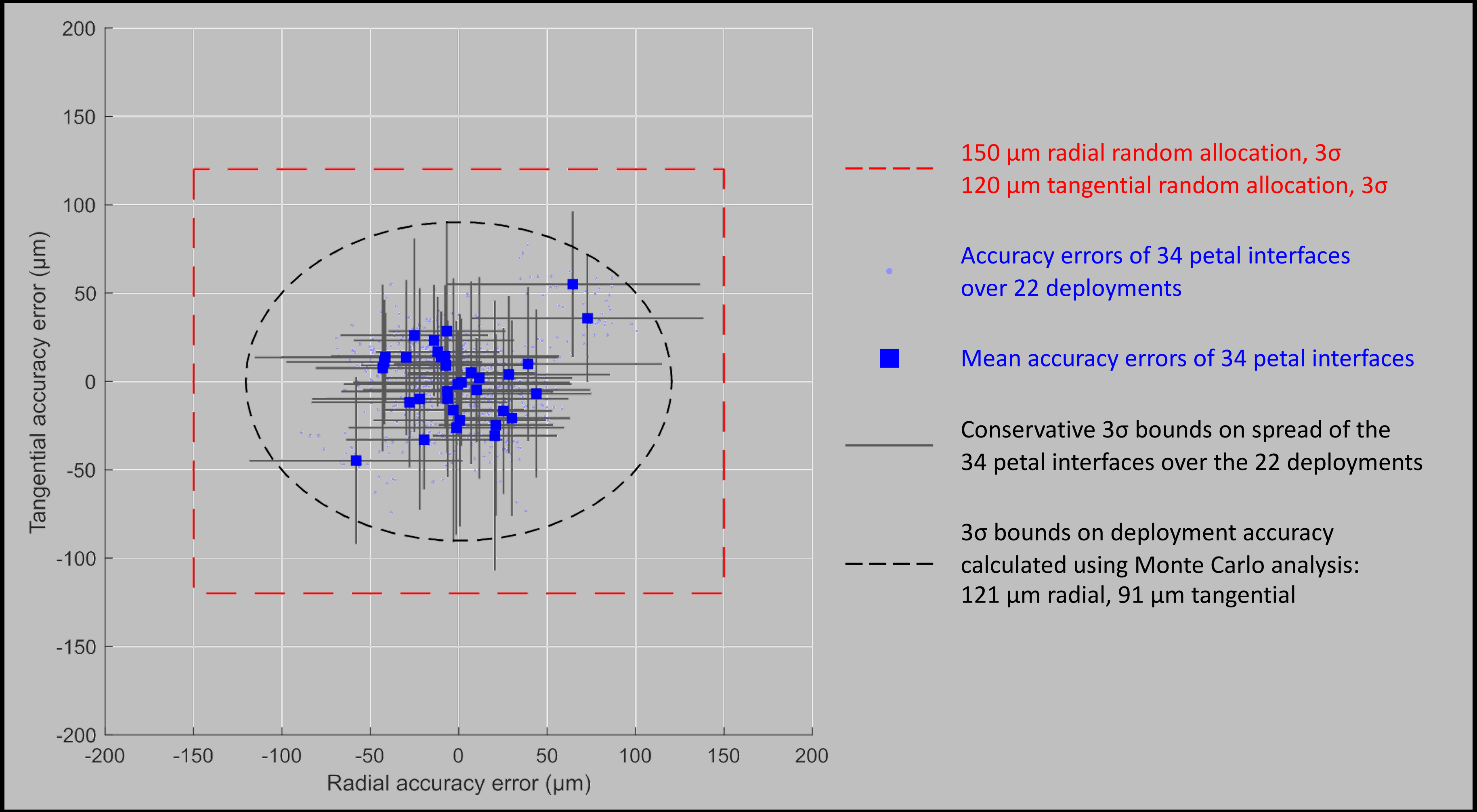






From J. Fulton JPL fellowship / TENDEG

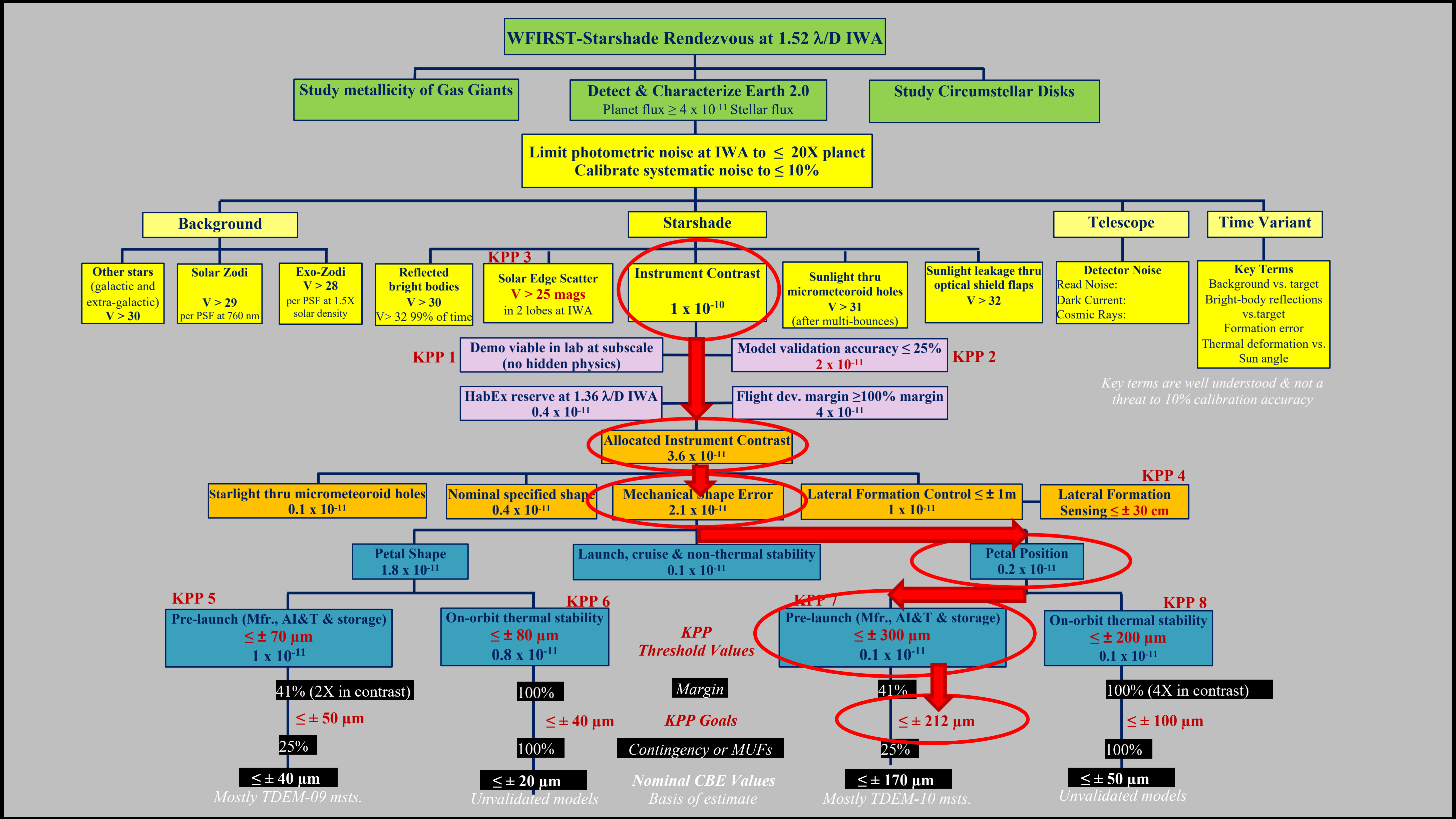
Milestone Example: Deployment Accuracy



Inner Disk Deployment with all CRITICAL features (Milestone 7C): Complete!
Inner Disk Deployment with ALL features (Milestone 7D): In progress for September 2023.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

S5 Error Budget and Allocations



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Evolution and Review of S5 Requirements

Roman (WFIRST) / Starshade Rendezvous Mission

Habitable Exoplanet Observer Mission (HabEx)

ExEP Technology Program

NASA NPR 7123.5 Appendix E

Available Budget Profile

Nominal system design
Interfaces
Relevant environments

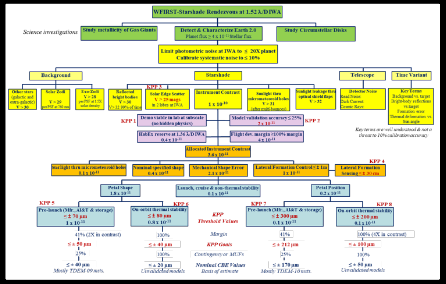
TRL Definitions
Exit Criteria

Milestone dates

Science Objectives
Measurement Thresholds
Calibration
Astrophysical Parameters

Technology Gaps (5)
Key Performance Parameters (8)

Science Performance Error Budget → TRL Definition for Starshade System and Elements → S5 Technology Development Milestones



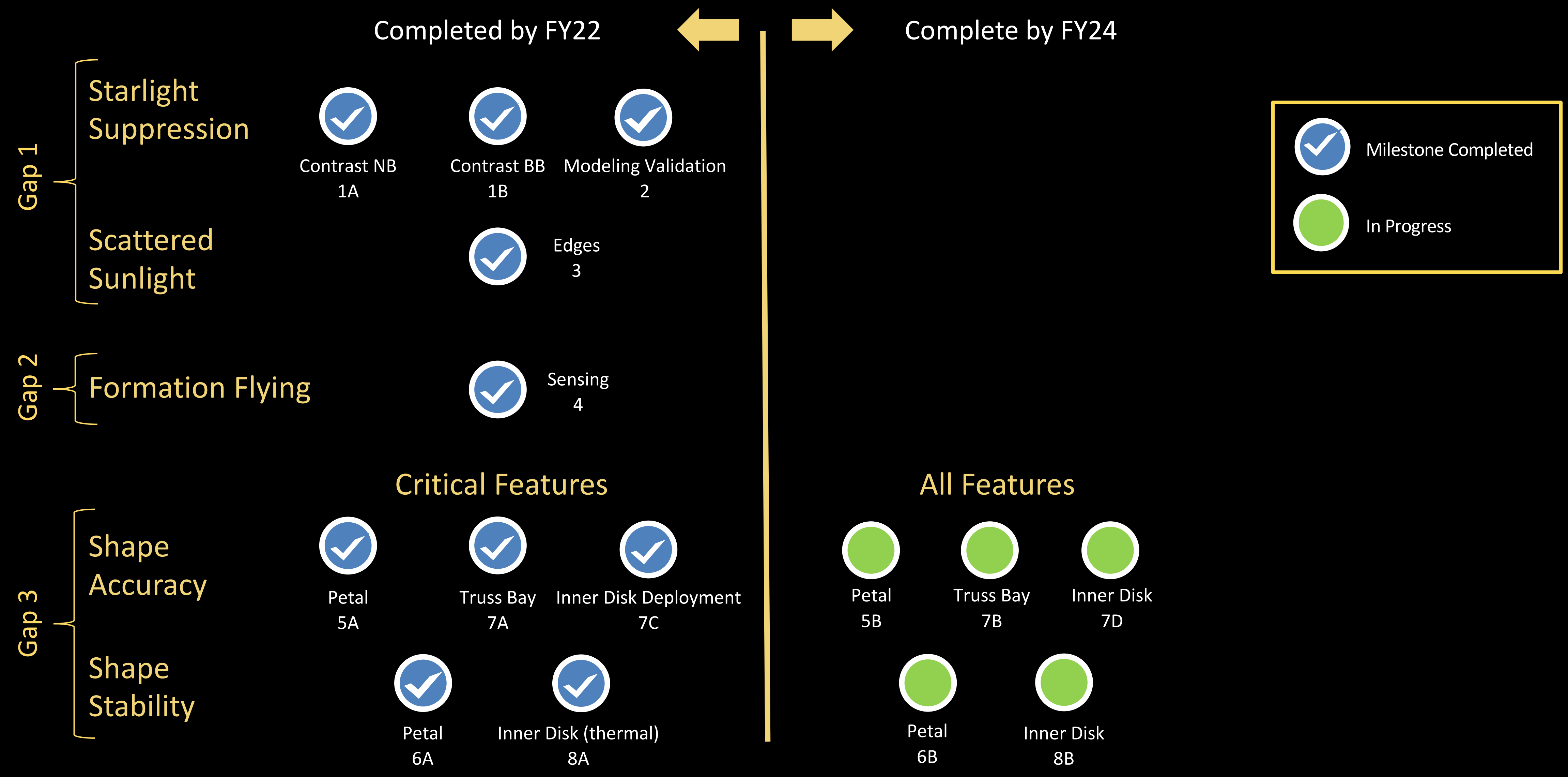
Technology Gap Area	KPP	Fidelity: Form	Fidelity: Fit	Fidelity: Function	Relevant Environments	Verification	Model Validation
Starlight Suppression	Demonstrate flight instrument contrast is viable via subscale lab tests at **≤ 1 x 10^{-10}**	Flight-like shape, etched in silicon	1/500th scale, near-flight Fresnel #	Flight-like diffraction perf.	Space, large telescope distance	Measure image plane contrast at multiple wavelengths covering flight bandpass.	Demonstrates all physics are captured
	Validate contrast senstivity to accuracy of ≤ ± **25%**					Introduce precisely known shape errors, measure contrast at the 10^{-8} to 10^{-9} level, extrapolate to flight contrast.	Validates model used to establish all shape error allocations
Lateral formation sensing & control	Verify sensing accuracy to **≤ ± 30 cm** (1/8th pupil dia.) & corresponding control to **≤ ± 1m**, via simulation	Flight-like shape, copper on glass	1/4000th scale, near-flight Fresenel #	Flight-like diffraction perf.	Space, large telescope distance, ≤ 1 µg gravity gradient	Measure lateral shear in pupil plane of Poisson spot from out of band starlight. Verify control perf. via simulations using a validated sensor model.	Validates prototype lateral sensor algorithms.
Solar Scatter	Verify lobe brightness is dimmer than **25 visual magnitudes**	Medium fidelity optical edge segment.	3/4 scale	Flight-like scatter perf., in-plane shape profile accuracy	Deploy cycles, thermal cycles, dust in lab & launch fairing	Measure scatter at discrete Sun angles & measure in-plane profile, after env. Tests	Validates model of scatter vs. Sun angle at edge coupon level.
Petal Shape	Pre-launch shape accuracy (manufacture, AI&T, storage) **≤ ± 70 µm**	Med. fidelity Petal Subystem, all features & interfaces	3/4 scale	Flight-like	Deploy cycles, thermal cycles, stowed storage, temperature	Measure shape before & after env. tests,	Validates models of: shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
	On-oribt thermal stability **≤ ± 80 µm**					Measure petal critical dimensions in ambient press. "hot box" vs. temperature	
Petal Position	Pre-launch shape accuracy (manufacture, AI&T, storage) **≤ ± 300 µm**	Med. fidility Inner Disk Subsystem, all features & interfaces	Full-scale	Flight-like	0-gravity, space vacuum, stowed storage, temperature	Measure petal position after many quasi-static deployments that min. air drag and imperfect gravity off-loading.	Validates models of: shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
	On-oribt thermal stability **≤ ± 200 µm**					Measure Truss-Bay critical dimensions in ambient press. "hot box" vs. temperature	

MS #	Milestone	Report Completion Date
1A	Small-scale starshade mask in the Princeton Testbed demonstrates 1x10^{-10} instrument contrast at the inner working angle in narrow band visible light and Fresnel number ≤ 15.	1/28/2019
1B	Small-scale starshade mask in the Princeton Testbed demonstrates 1x10^{-10} instrument contrast at the inner working angle at multiple wavelengths spanning ≥ 10% bandpass at Fresnel number ≤ 15 at the longest wavelength.	3/30/2019
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}.	1/15/2020
3	Optical edge segments demonstrate scatter performance consistent with solar glint [illegible] magnitude 25 after relevant thermal and deploy cycles.	

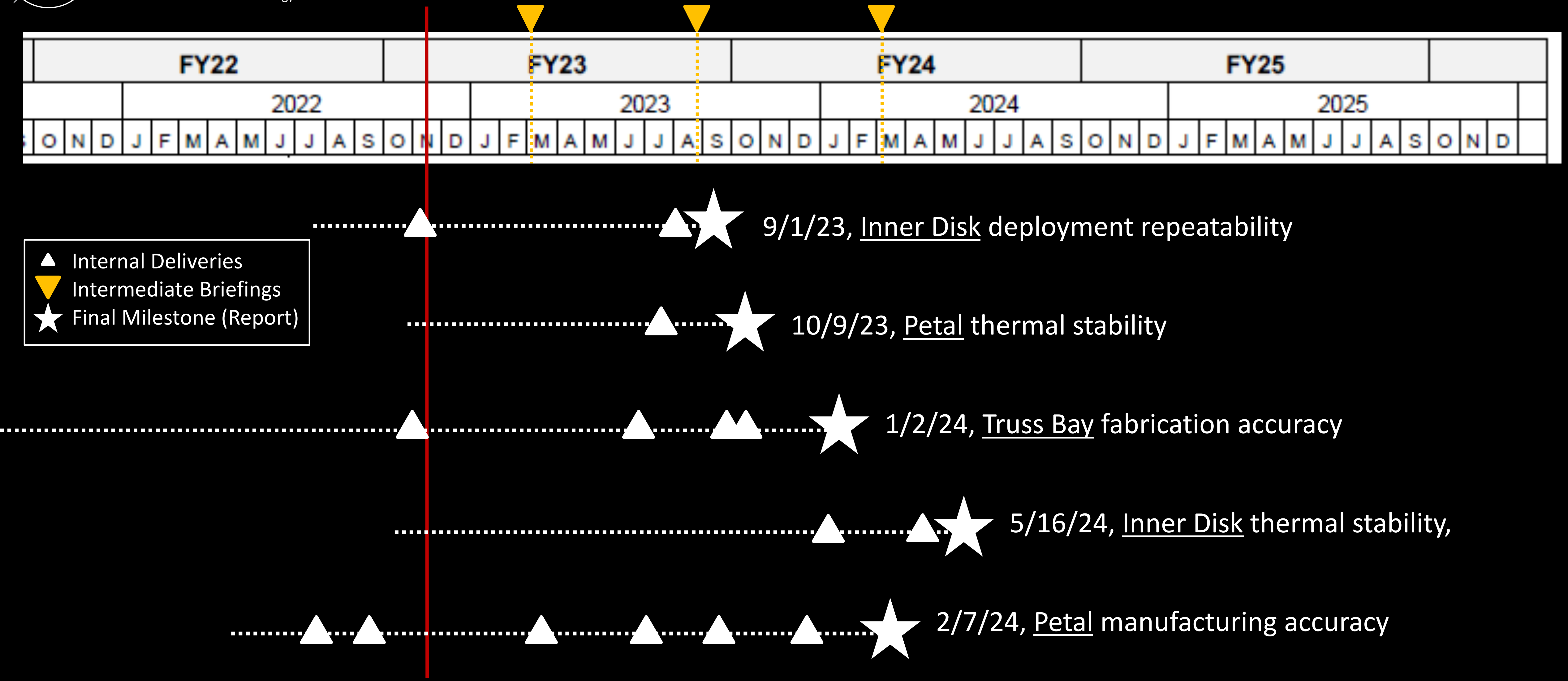
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

S5: Closing Starshade Technology Gaps

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

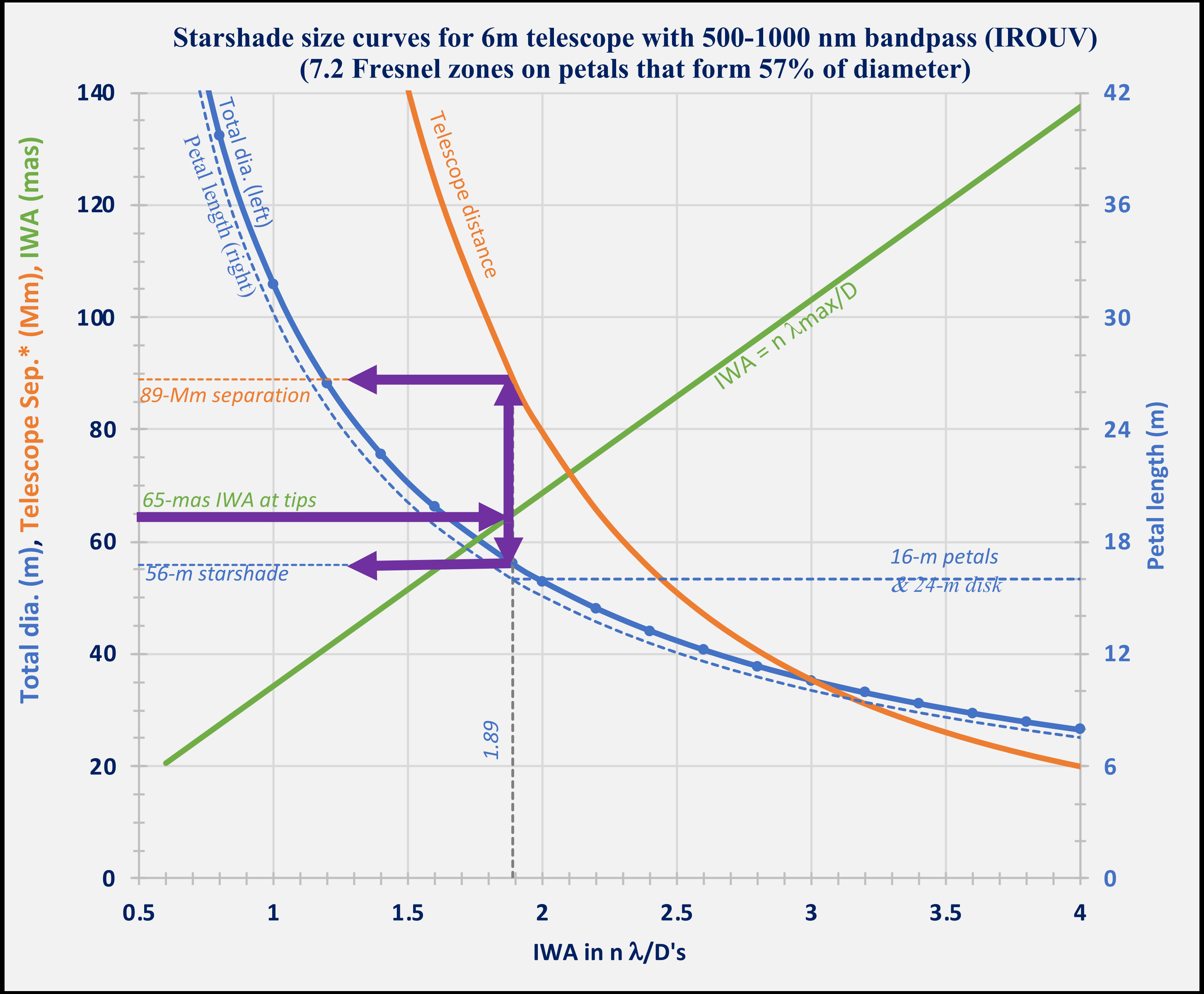


Mechanical Milestone Path to TRL5



Each of these milestones is a conclusion of a previous activity. We are repeating design/fabrication/analysis for a higher-fidelity full-featured version of a component that has already been demonstrated with critical features.

Path towards future flagships



S5 requirements were developed for HabEx mission. (For context: 52m starshade, 16m petals on a 20m inner disk. 70mas IWA at tips over 300-1000nm.)

How does S5 translate to IROUV?

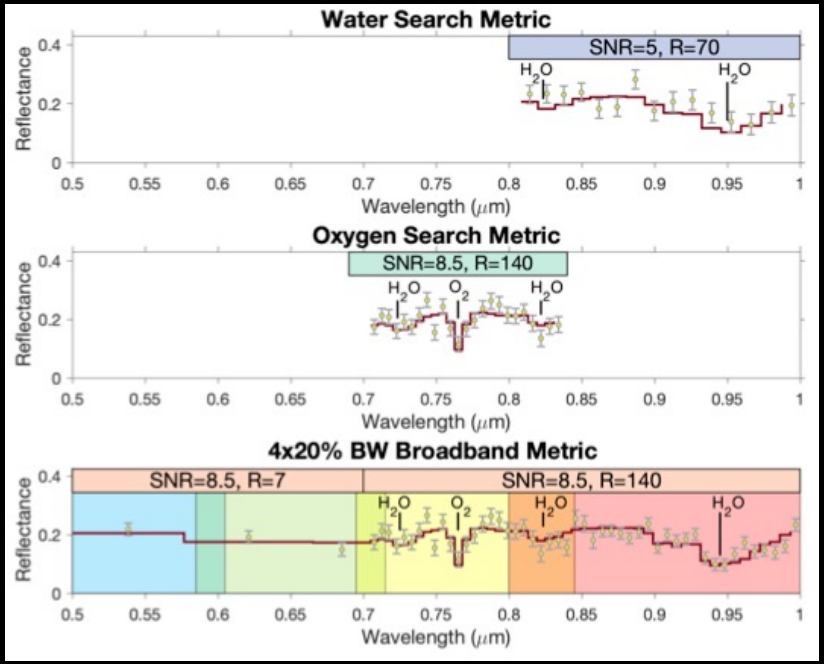
What size starshade would be appropriate for IROUV?

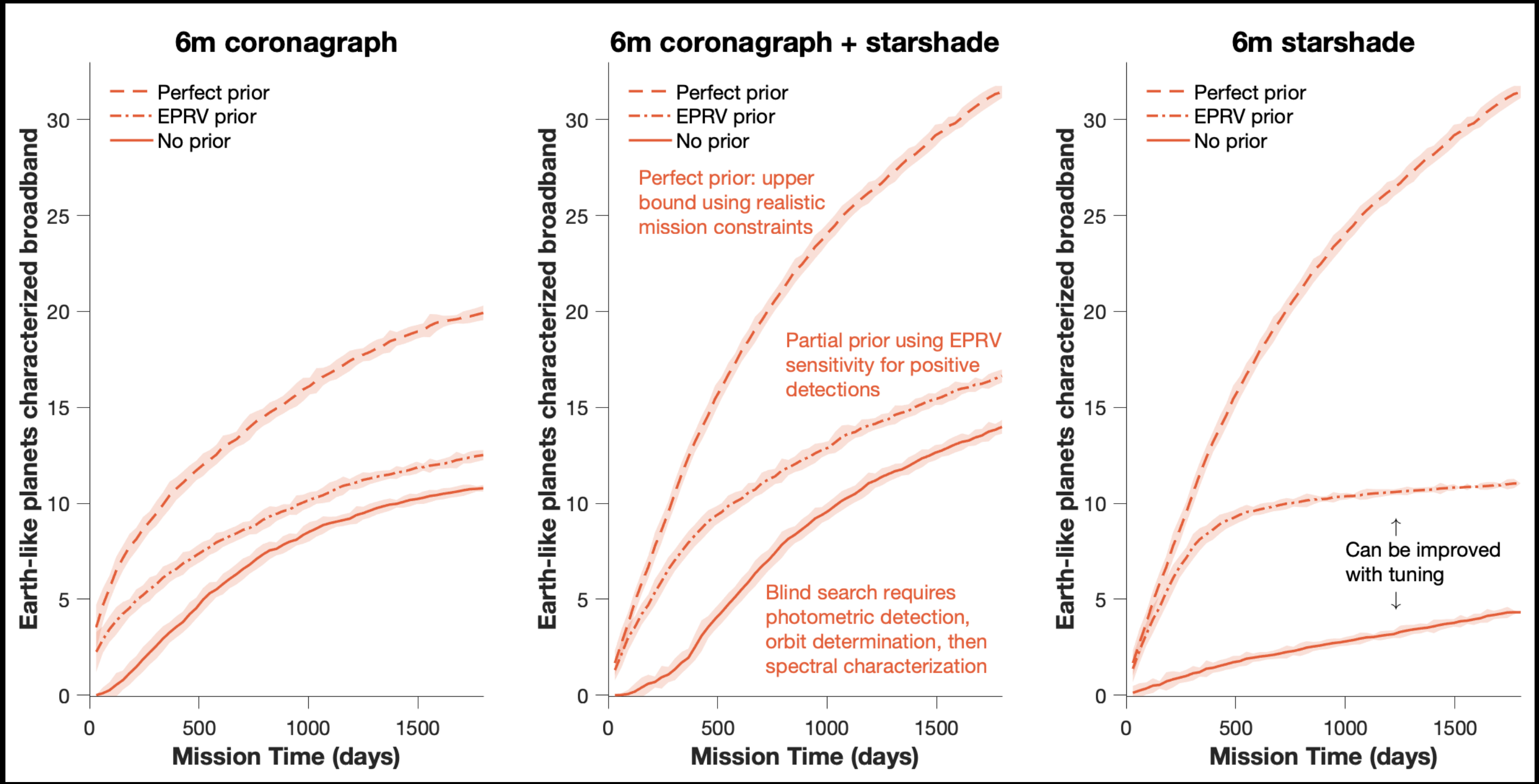
For a 6m telescope, depending on assumptions, we would get excellent results for starshades in the range of 56-70m.

One point design shown in parametric design space at left: 56m starshade with 16m petals, 24m inner disk. 65mas IWA at tips over 500-1000nm.

*Pre-decisional, for planning and discussion purposes only

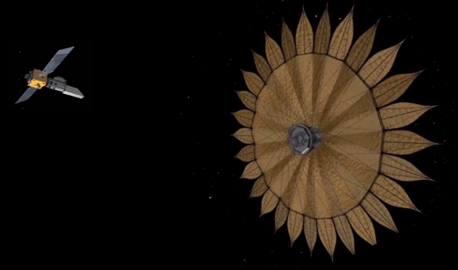
Starshade Utility





Morgan, et al., "An exploration of expected number of exoplanets for a 6m class direct imaging observatory"

Starshades: Advantages and Disadvantages



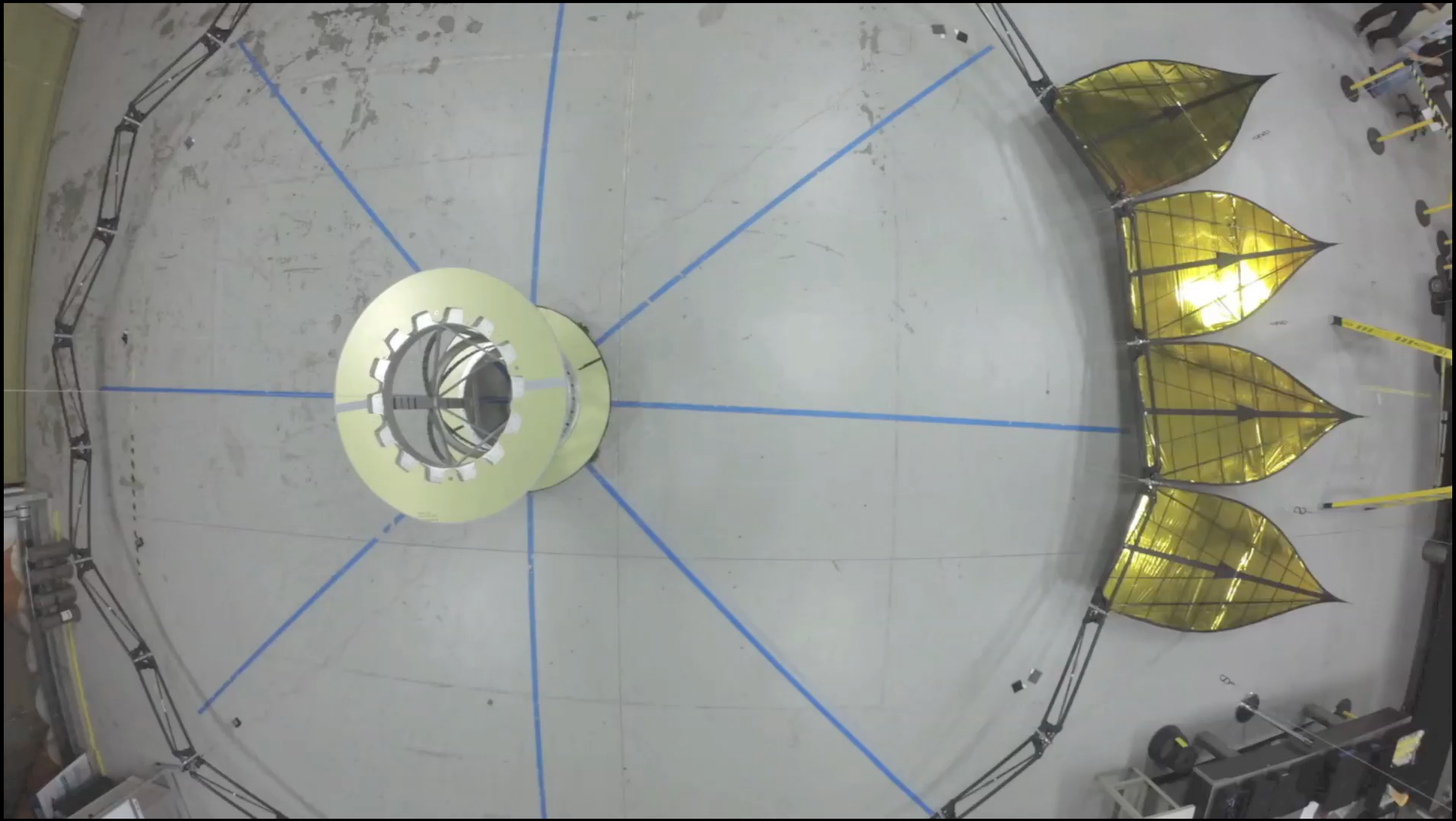
- Require two spacecrafts aligned to line-of-sight
- Relatively long times between observations (~ *few days to weeks)*
- Limited targets due to limited propellant and time for starshade movements
- Not possible to conduct a full-scale end-to-end optical testing on the ground
  - *Relies on ground sub-scale lab and field tests with validated high-fidelity models*

- The starshade does all the starlight suppression before the light enters the telescope, hence:
  - *does not require advanced telescope stability*
  - *wavefront sensing and correction is unnecessary*
  - *doesn't care what type of telescope (segmented, on-axis; aperture shape)*
  - *starshade will not drive the requirements of the telescope (i.e. enables cheaper telescope)*
- Better IWA: ~ 1.5 λ/D vs ~ 3-4 λ/D (emulating a larger telescope)
- High throughput: ~ 40-50% (emulating a larger telescope)
- Larger FOV, limited by detector size rather than DM (can capture simultaneous multi-planet systems and debris disks)
- Capable of operating in the UV

Takeaways

- Starshades have closed the Starlight Suppression and Formation Flying milestones, and are in progress towards closing the final Mechanical milestones; a TRL5 review is underway for IROUV.
- Starshades have demonstrated 1e-10 contrast, exceeding expected IROUV requirements.
- Starshades can cover UV to NIR (200nm to +1300nm).
- Starshades have high multispectral photon throughput, and support spectroscopy past 800nm.
- Exoplanet yields are being investigated for starshade-only and starshade+coronagraph missions.
- S5 starshade architecture and progress to date is broadly compatible with the planned IROUV mission, for all three technology gaps (part of S5 activity closeout).

Questions?



Questions?