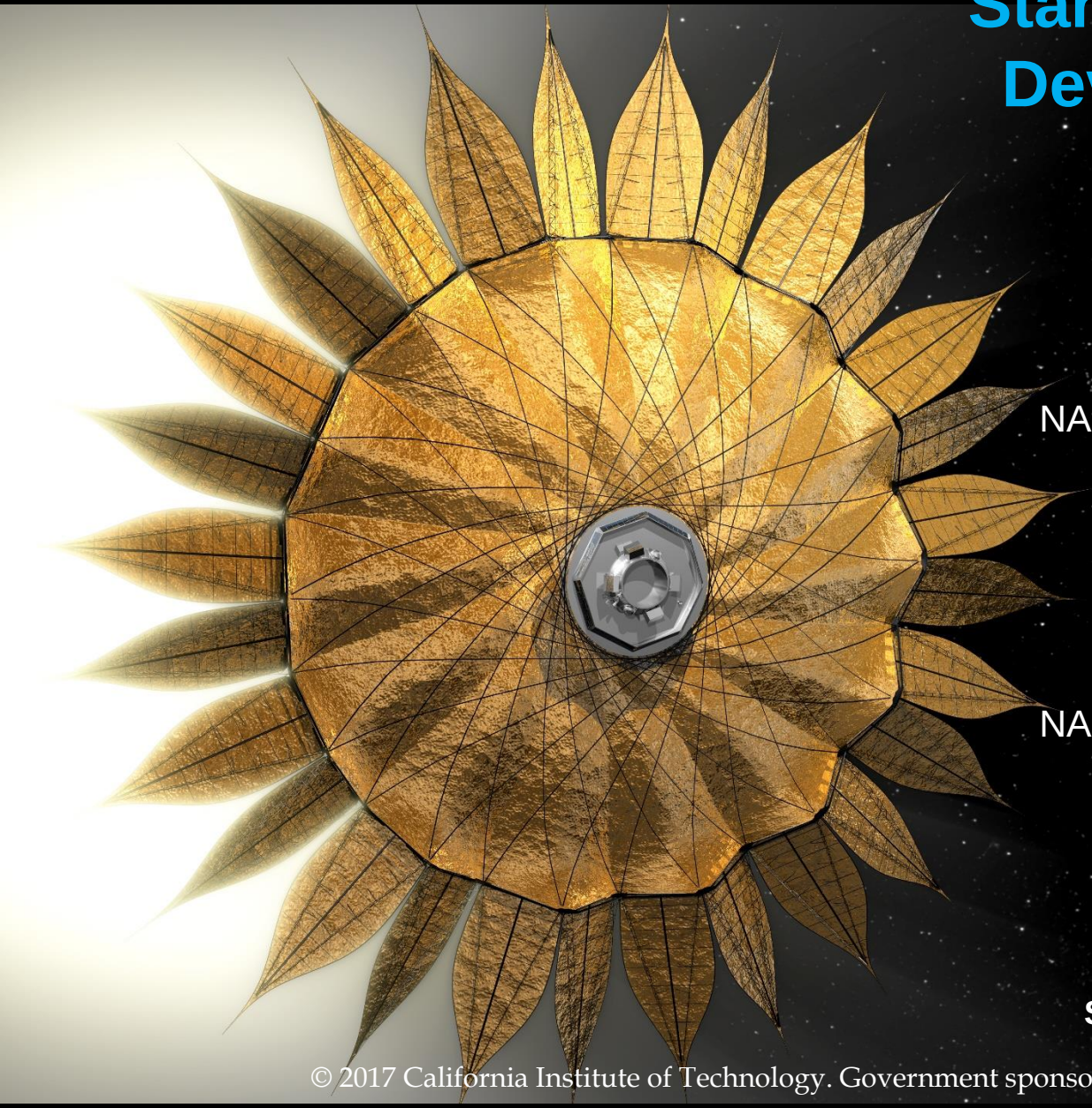
Jet Propulsion Laboratory
California Institute of Technology

Starshade Technology Development Status



Dr. Nick Siegler
NASA Exoplanets Exploration Program
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Starshade Technology Manager
Jet Propulsion Laboratory
California Institute of Technology

November 16, 2017
SPIE Mirror Technology Workshop

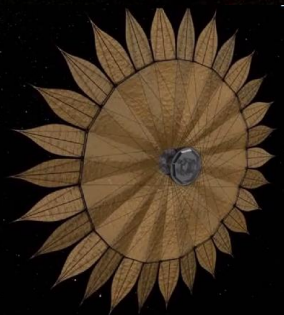
The Need

- NASA needs a mature starlight suppression technology that can
  - Reach the sensitivity levels to directly image exo-Earths in the habitable zone of Sun-like stars
  - Work with large segmented telescopes
  - Achieve high throughput to minimize integration times

- The coronagraph and the starshade are the only two technologies that NASA is prioritizing to suppress starlight to directly image and measure the spectra of Earth-like exoplanets.
  - Will require further technology advancements in starshades and coronagraphs

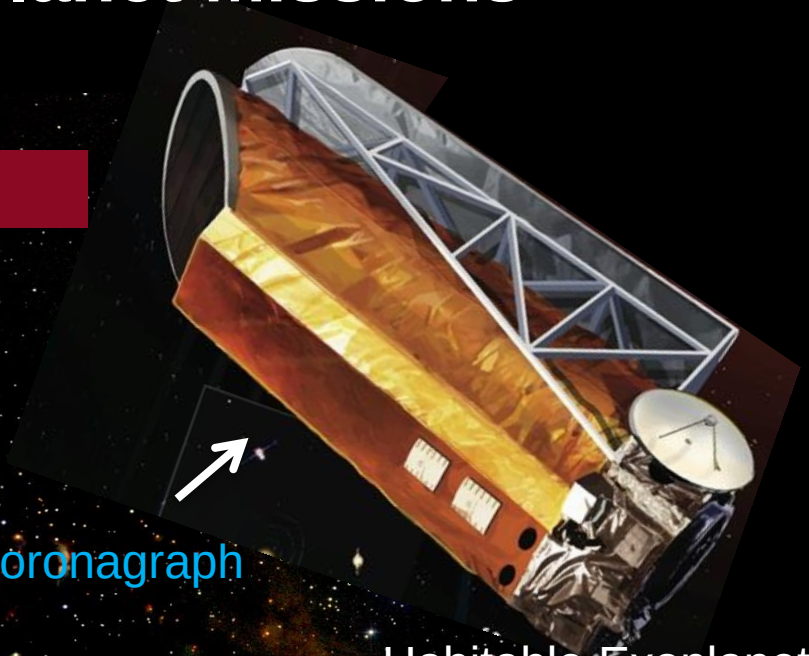
Possible New Worlds Exoplanet Missions

Pending 2020 Decadal Survey



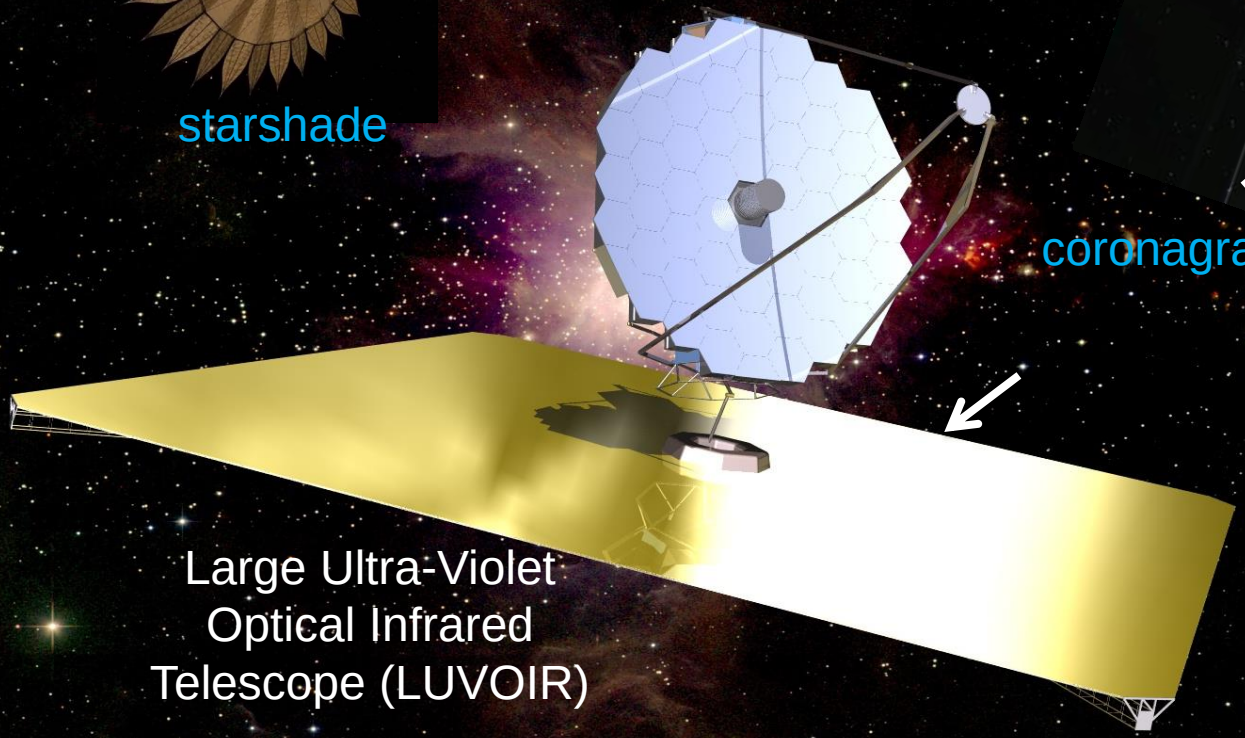
starshade

HabEx starshade is ~ 72 m



coronagraph

Habitable Exoplanet Imaging Mission (HabEx)



Large Ultra-Violet Optical Infrared Telescope (LUVOIR)

NASA Charters Starshade Tech Activity (March 2016)

Objective to get to TRL 5

Goals:

- Develop starshade technology to discover Earth-like planets in habitable zones around Sun-like stars for future space telescope missions

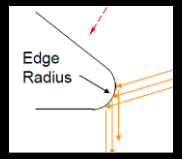
- Advance the technologies that close the three key technology gaps to TRL 5

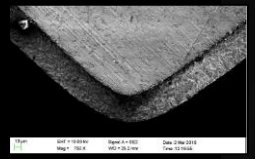
Starshade

The hard stuff is done external to telescope

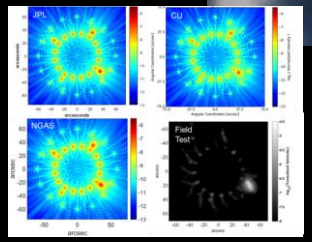
Starshade Technology Gaps

(1) Starlight Suppression



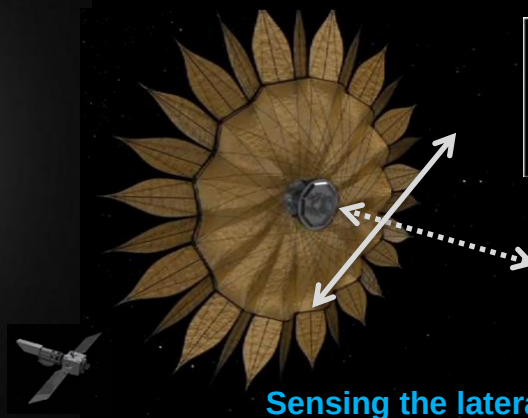


Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



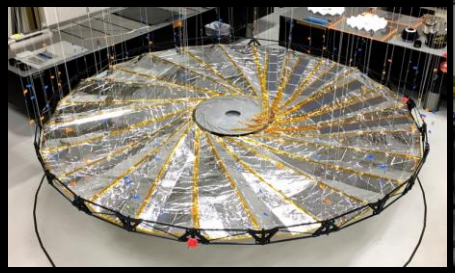
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

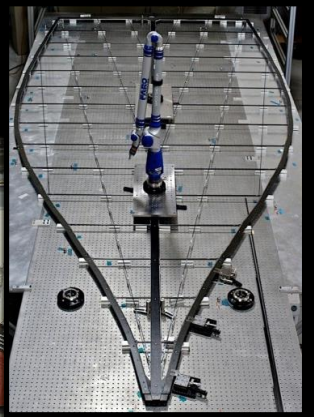
(2) Formation Sensing



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)

Keys to Success

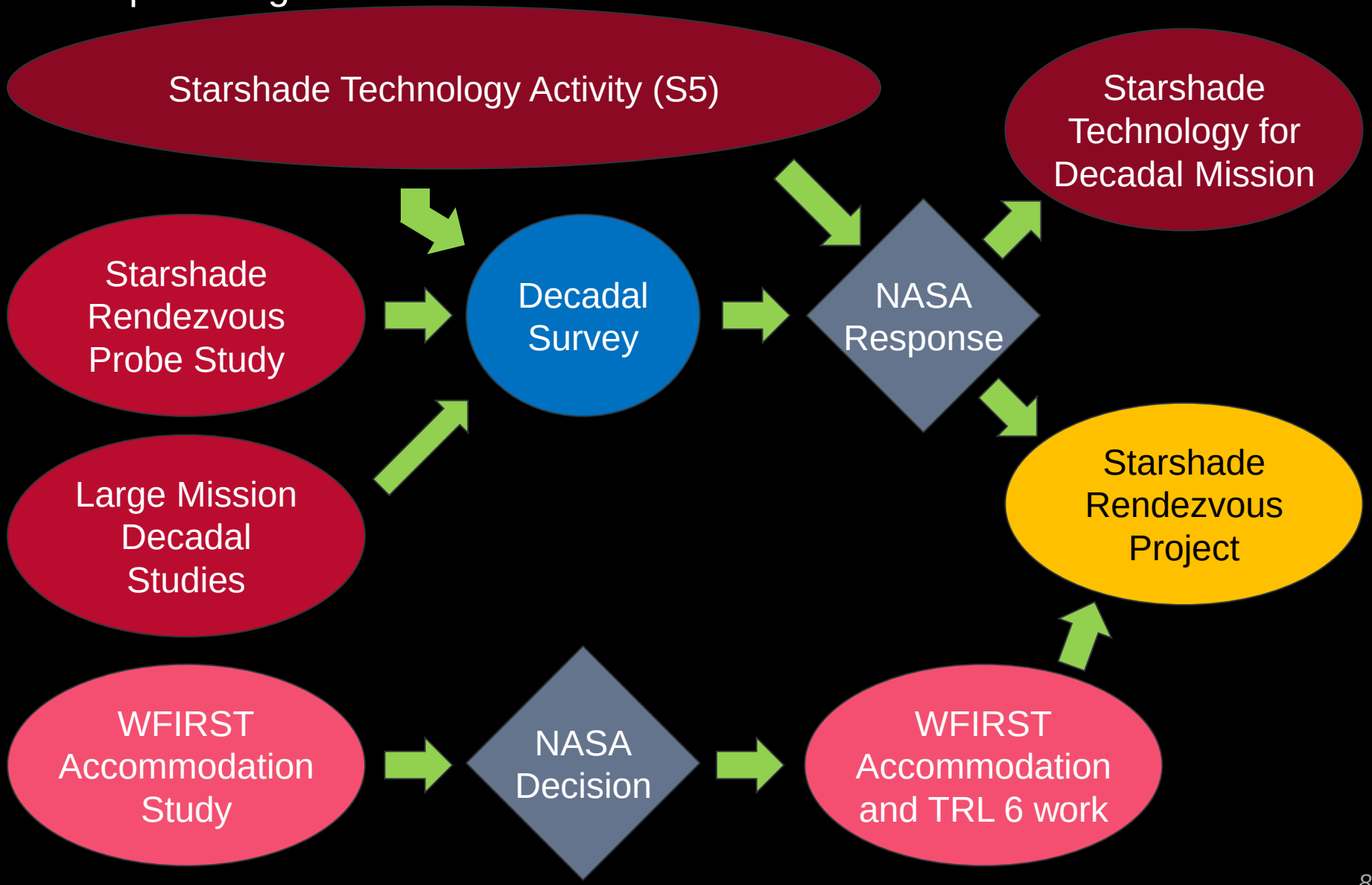
- Must be ready for 2020 Astrophysics Decadal
  - Key technologies need to be sufficiently mature before end of decade to enable a starshade to be considered for possible WFIRST Rendezvous and future large telescope missions
  - Develop and receive approval for a TRL 5 Plan

- Starshade will live and flourish by its model validation
  - Performance models: optical diffraction, light scattering, mechanical, thermal and dynamic deformation
  - Ground based tests must focus on validating performance models and the error budget as well as demonstrations of meeting requirements that are derived from reasonable error budgets

- Independent reviews of the technology plan and technical progress

Ongoing Starshade Activities

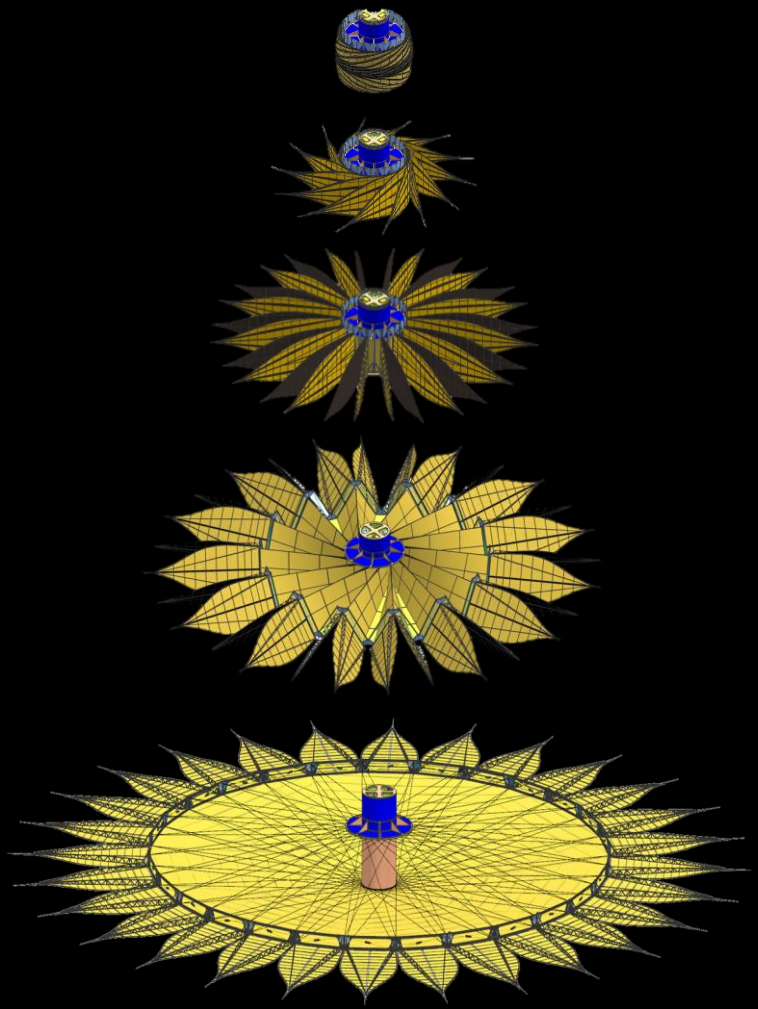
Steps to Flight



Recent Starshade Technology Activities and Future Plans

Mechanical Deployment Trade Study

Wrapped versus Folded petal deployment

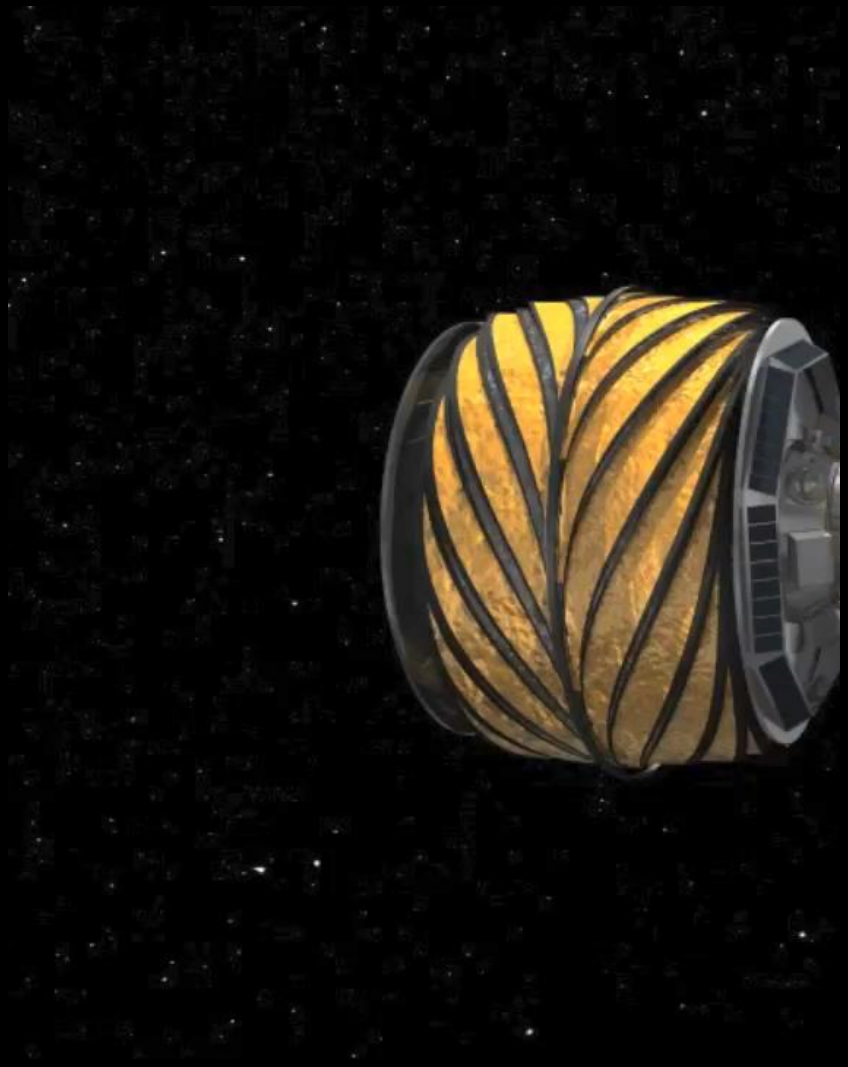


Wrapped petal deployment concept (NASA JPL)

Folded petal deployment concept (Northrop Grumman)

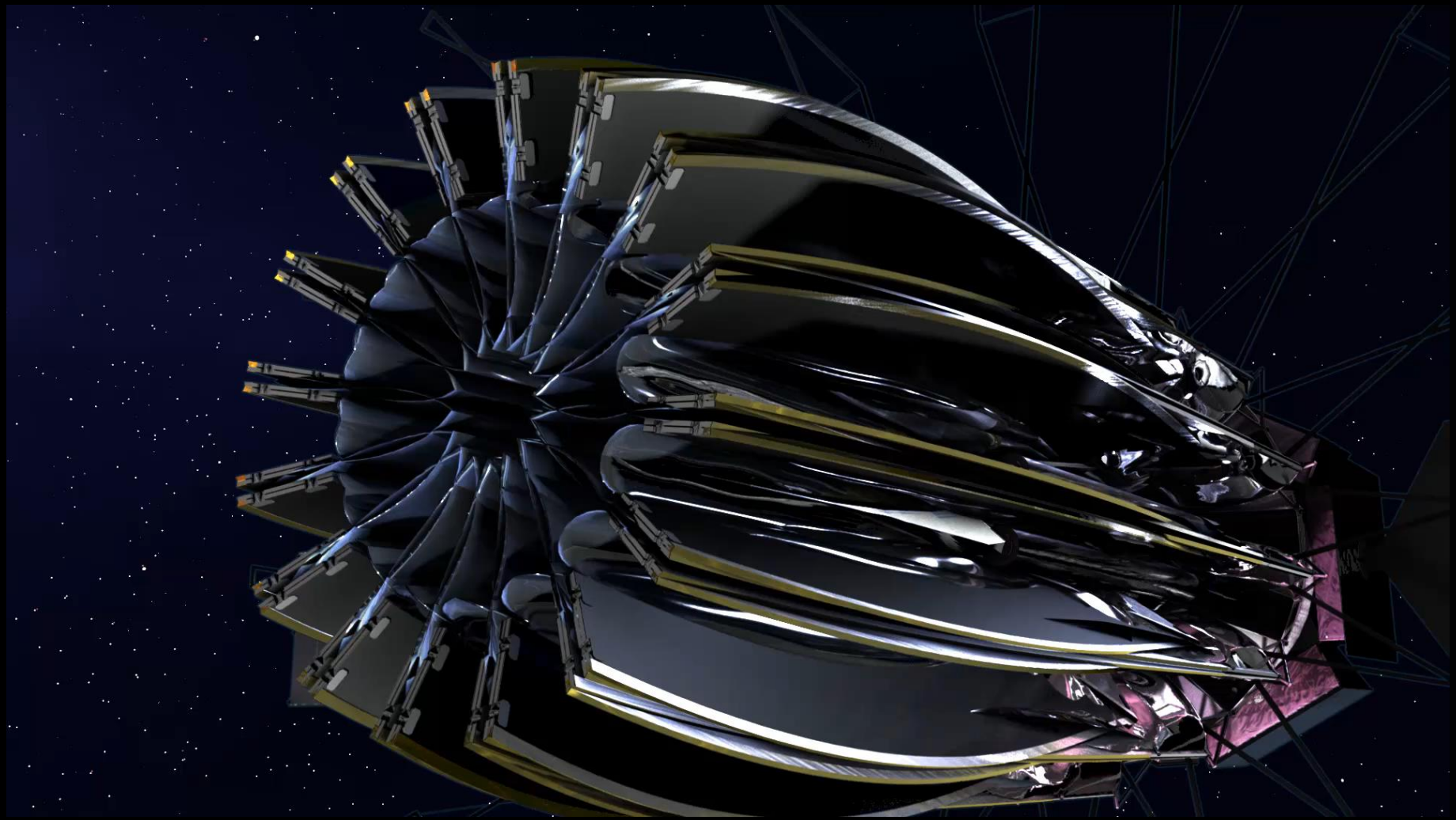
Wrapped Petal Deployment Architecture

NASA's Jet Propulsion Laboratory



Folded Petal Deployment Architecture

Northrup Grumman Aerospace Systems



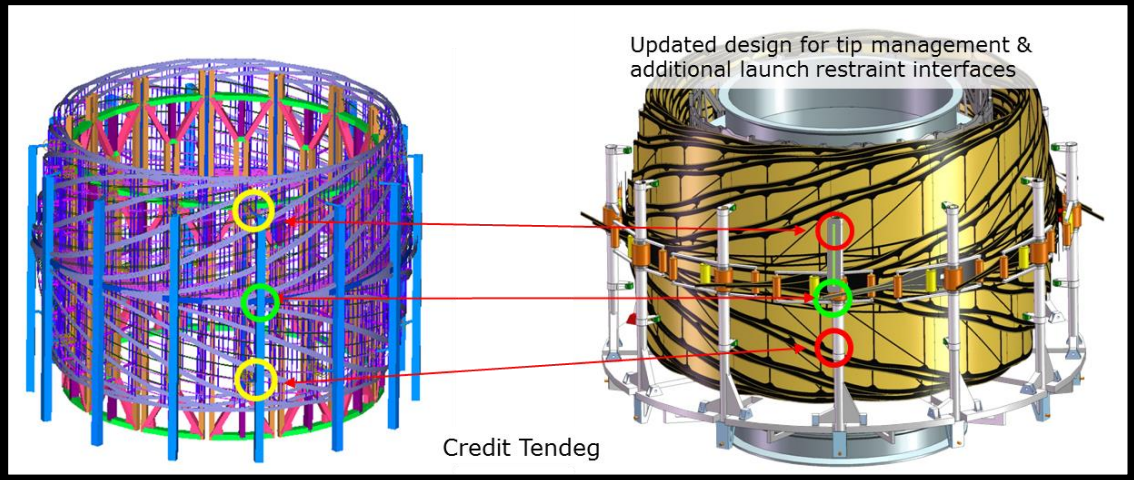
Mechanical Deployment Approaches

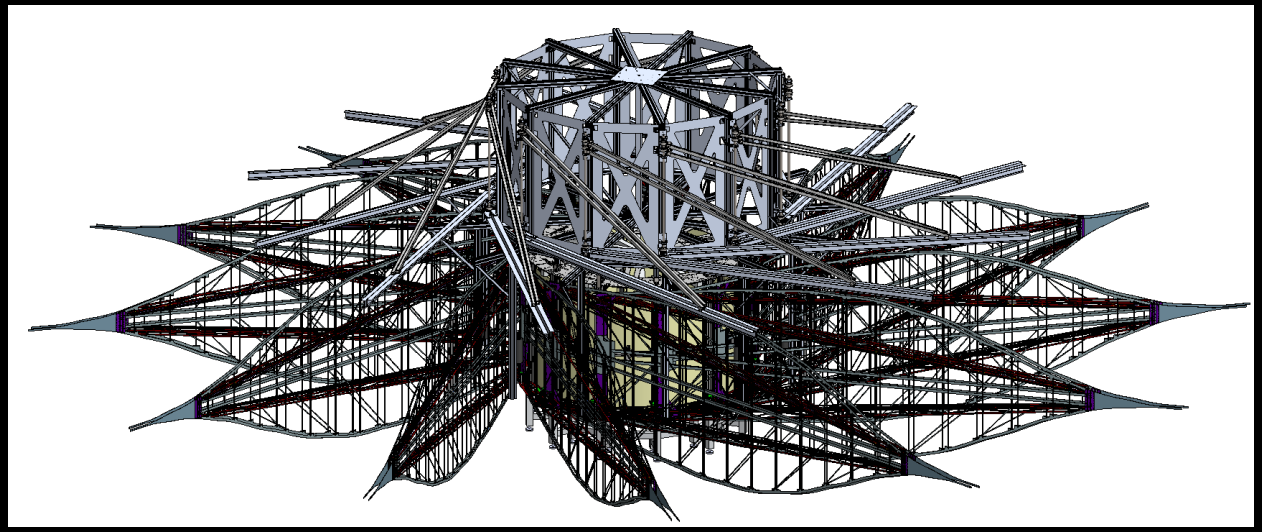
Trade Study Underway

- **Determine the best path forward on the starshade mechanical architecture for reaching TRL 5**
  - Started in late September 2017, expected completion by end of March 2017
  - Examining two architectures with different stowage options: folded and wrapped petals that are deployed using actuators or mainly stored strain energy
- **Independent Trade Evaluation Team (TET) will establish the trade criteria and evaluate trade options**
- **S5 manager will consolidate inputs and provide package to ExEP Manager, who will recommend direction to NASA HQ.**

Petal Unfurler 2.0

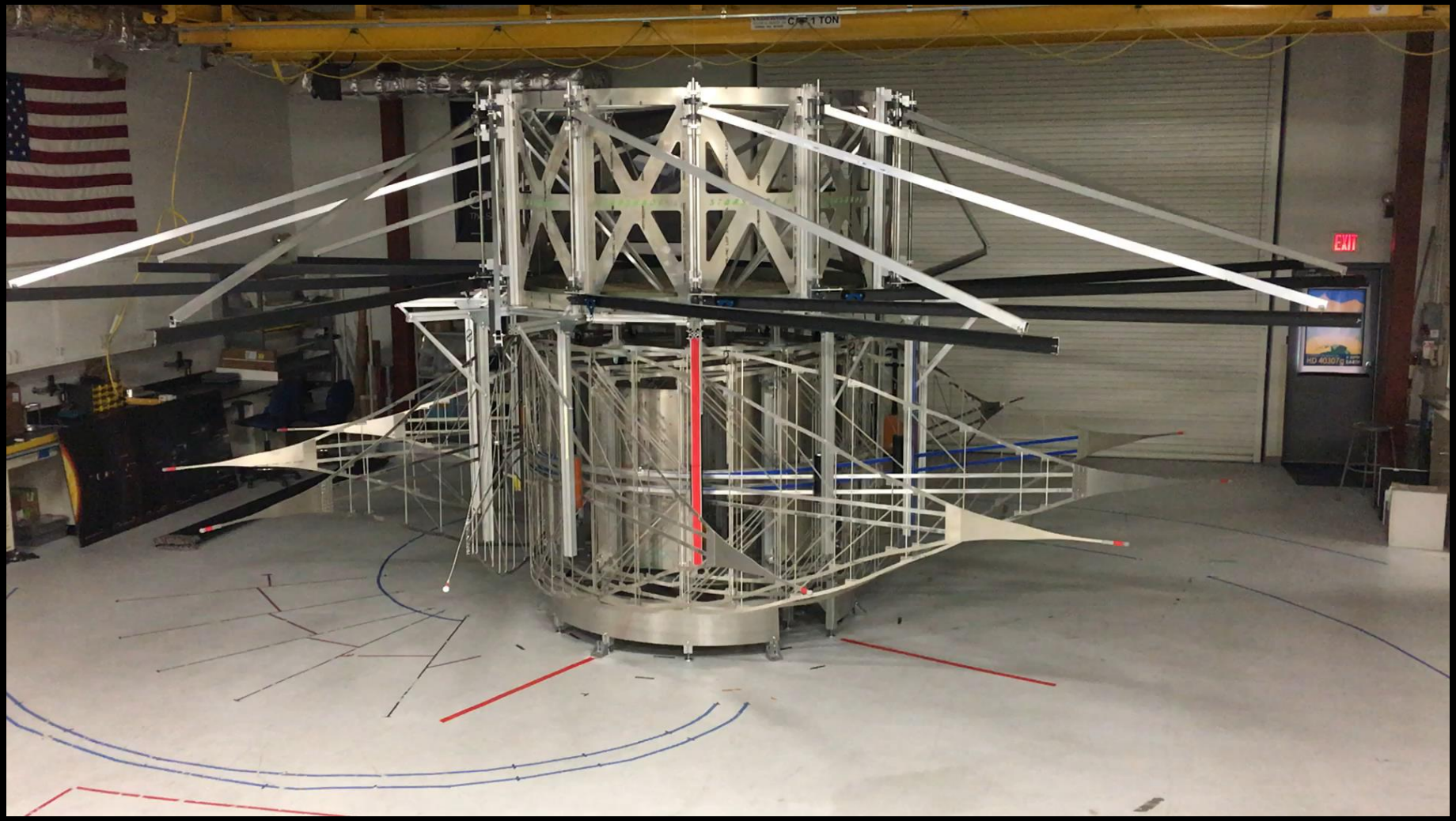
SBIR Award: Tendeg's Petal Launch Restraint and Unfurl System





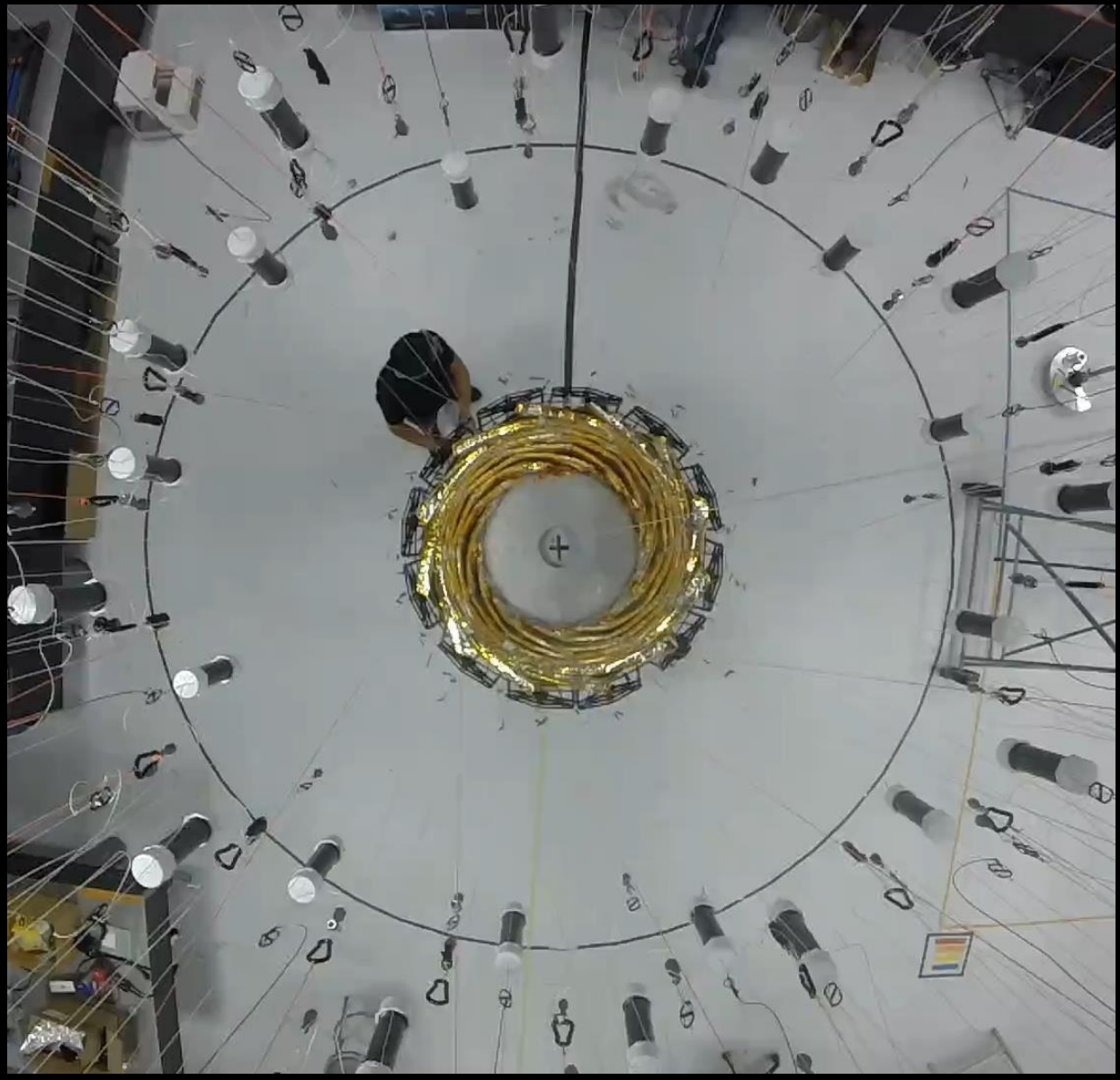
Petal Unfurler Testbed 2.0 Gravity Offloading

SBIR Award: Roccor / Tendeg



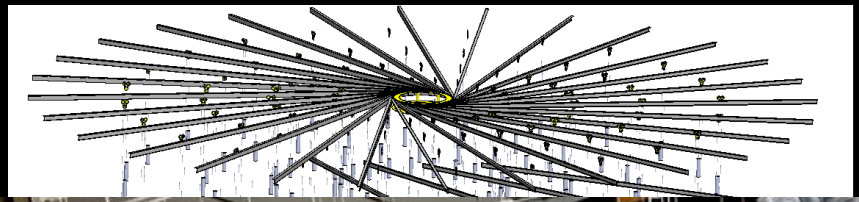
Optical Shield Deployment

5 m Prototype Demonstration



Optical Shield Testbed Gravity Offloading

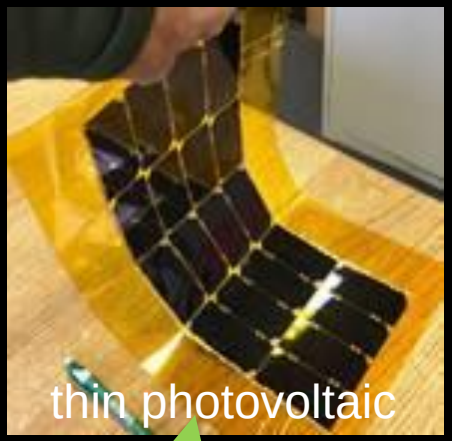
SBIR Award: Roccor / Tendeg



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

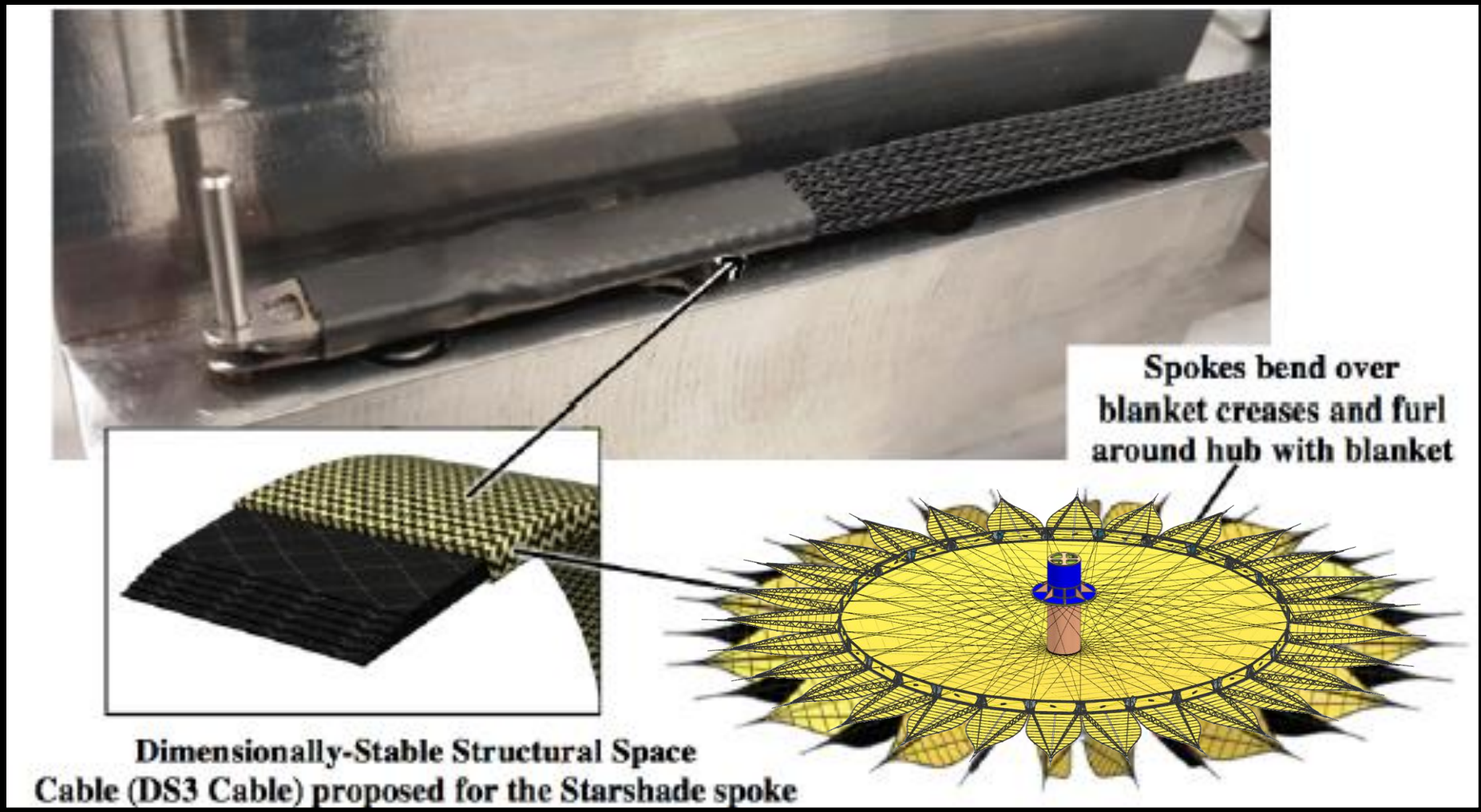
Optical Shield Solar Arrays

SBIR Award: Tendeg's Solar Array Integration



Inner Disk and Optical Shield Deployment

SBIR Award: Roccor's Dimensionally-Stable Structural Spoke



Deployment Accuracy and Shape Stability

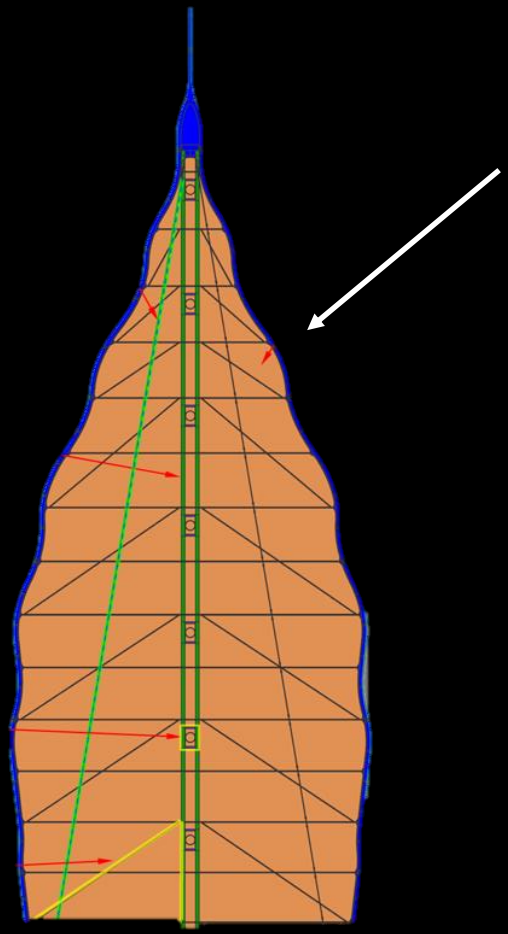
Petal Deployment Accuracy

Path to Close Gap:

- Complete Mechanical Deployment Architecture Trade Study by Q1 CY18
- Integrate an optical shield into the 10 m inner disk; deploy and demonstrate tolerances (using Roccor spokes)
- Optical shield material micrometeorite impact testing and model validation
- Deploy TRL 5 petal in unfurler testbed to demonstrate no contact (with simulation petals)
- Deploy at least ¼ of total TRL 5 petals at half/full scale

Optical Edge Development

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



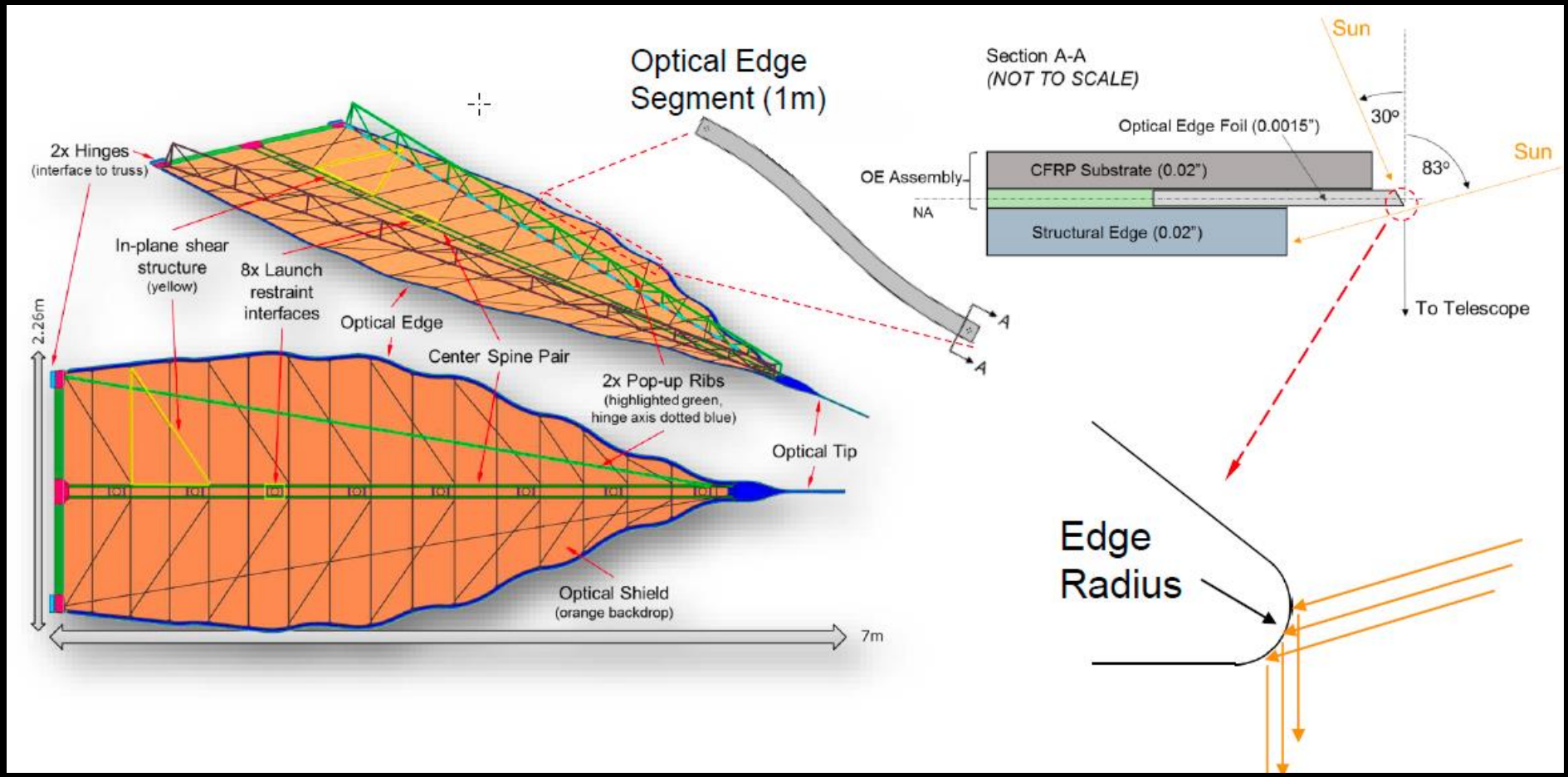
To avoid solar glare and scatter interference petal optical edges must be razor-sharp and exceedingly clean

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

Photonic Cleaning Technologies proposes to develop a novel pourable, peelable, low adhesion, residueless polymer coating that will clean and protect the starshade's amorphous metal edges from manufacture to launch.

Petal Fabrication

SBIR Award: Tendeg's Petal Optical Edge Integration



Optical Edge Development (Petals)

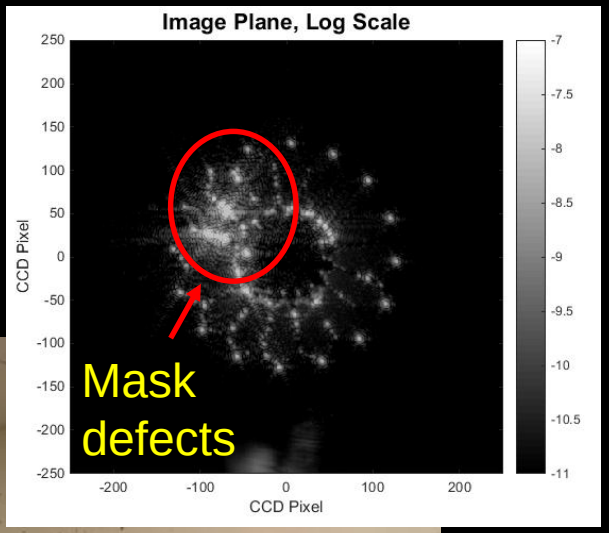
Starlight Suppression

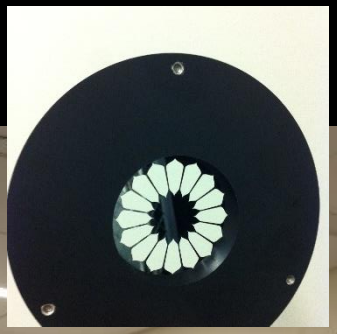
Plan to Close Gap:

- Currently trading optical edge materials, manufacturing techniques, and coatings to compare solar scatter and diffraction results
- Plan to develop sub-scale proof of concept edge prototype that meets in plane profile and solar scatter performance by December 2017
- Integrate optical edge onto flight-like petal
  - Bonding material
  - Edge protection and handling
  - Edge-to-edge segment interface and joining
  - Fabricating larger segments, getting to flight size
  - Environmental test of flight-like segments, including mounting

Optical Performance

Starshade Testbed at Princeton University





Jeremy Kasdin and Anthony Harness
Princeton University

Summary

- Starshade technology is progressing in all three technology gaps
- Mechanical architecture trade study will establish a baseline design and permit final development and approval of a complete TRL 5 technology development plan in the summer of 2018
- Starshade's future is pending Decadal Survey recommendations and NASA decision to maintain accommodation on WFIRST

Jet Propulsion Laboratory
California Institute of Technology

Additional Slides

Current Starshade Activities

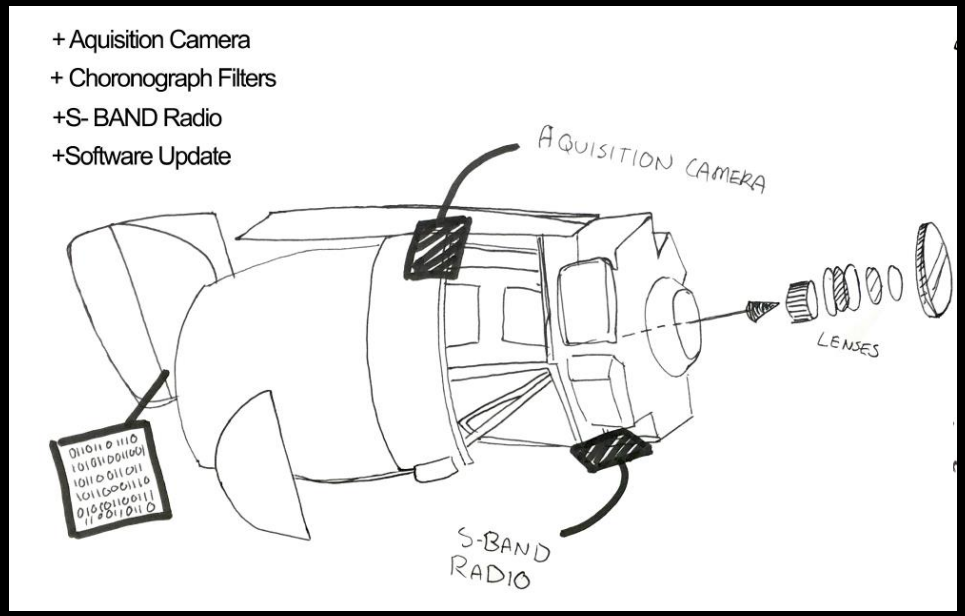
All since 2016!

1. Starshade Technology Project (TRL 5)
   - Conducting mechanical architecture trade between folded and wrapped petal designs with Northrop Grumman and JPL teams
   - Preparing technology development plan for remaining work to reach TRL, which will be reviewed by NASA Astrophysics Division (APD) for approval
2. Decadal Survey mission concept (HabEx)
3. Decadal Survey probe study (WFIRST Rendezvous)
4. WFIRST Accommodation Study (with coronagraph)
5. In-space assembly study (100 m-class starshades)
6. Lots of new starshade SBIRs in all phases

Starshade Accommodation on WFIRST (Feb 2017)

Possibility of imaging an exo-Earth in the next decade

- SMD and APD continue to ask WFIRST Project to study starshade accommodation and its impact on the spacecraft and coronagraph
  - Descope options are available before and after the Project SRR
  - Possibility to demonstrate starshade technology in space (along with coronagraph technology) and observe habitability of near-by exoplanets
  - Final decision whether to fly a starshade mission awaits 2020 Decadal Survey recommendations



Optical Performance

Starlight Suppression

Need:

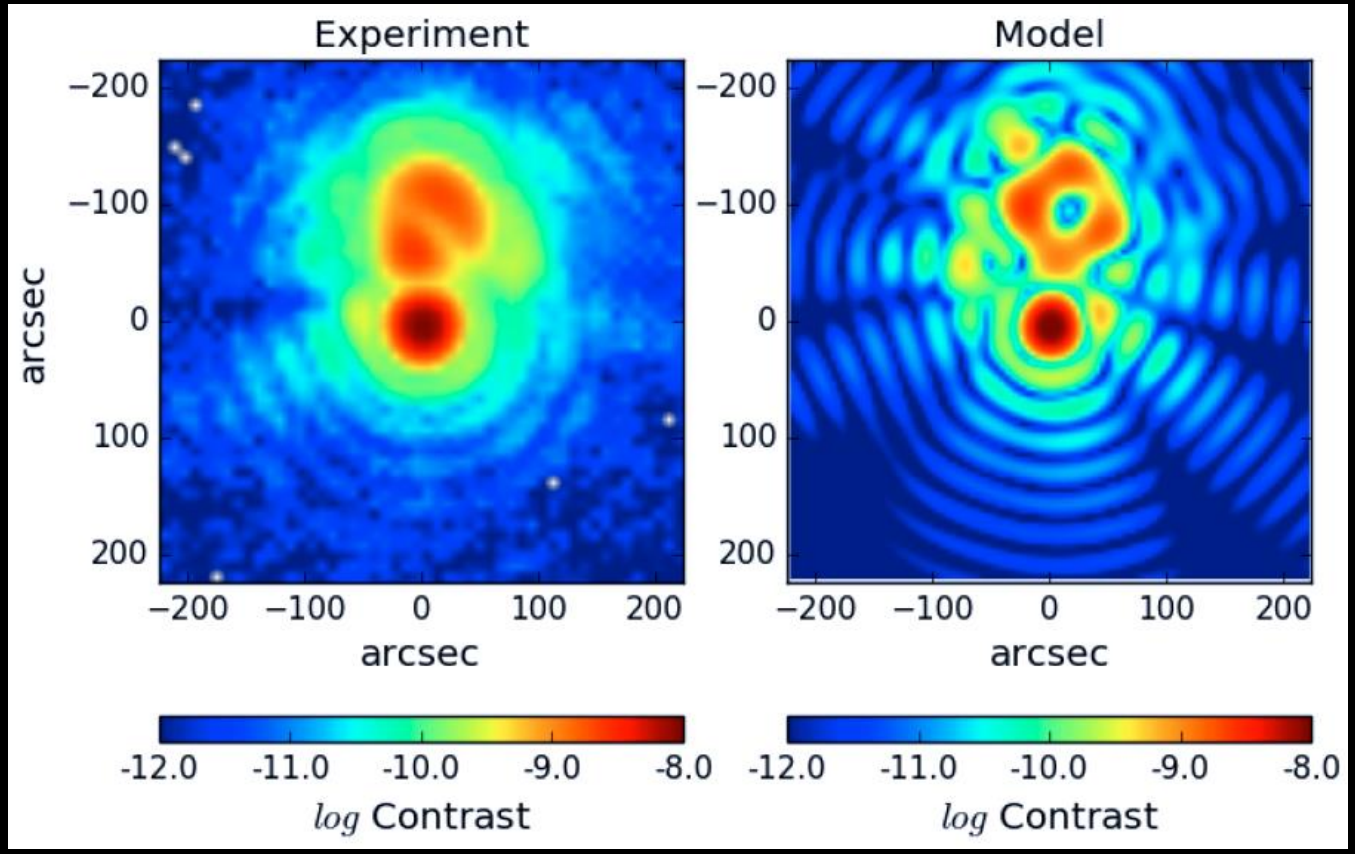
- Validate optical performance models through demonstrations achieving starlight suppression ≤ 10^{-9} in scaled flight-like geometry (flight-like Fresnel number) across a broadband optical bandpass
- Demonstrate that the validated models are traceable to ≤ 10^{-9} suppression system performance in space

Current Capabilities:

- Flight sub-scaled demonstration being conducted on the Princeton Optical Testbed have achieved 3×10^{-8} suppression.
- Models and testbed results are converging

Optical Performance

Testbed Data – Modeling Converging (Princeton Testbed)



Harness et al SPIE 2016

Optical Performance

Starlight Suppression (S-2)

Plan to Close Gap:

- Continually improving models for higher fidelity simulation (e.g. out of plane defects, in-air ground test modeling and validation) and error budget validation

- Plan to measure ultimate contrast with well fabricated starshade mask in Princeton testbed by December 2017

- Areas for future focus to reach TRL 5:
  - Optical performance model and error budget validation
  - Ground-based tests with intentionally defective starshades
  - Potential follow-on demonstrations (Workshop on October 10-11):
    - Additional wavelengths in Princeton Testbed
    - Larger scale testbed demonstration (XRCF, Hyperloop)
    - Additional in-air / starlight suppression demonstration for TRL 6

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Optical Edge Development (Petals)

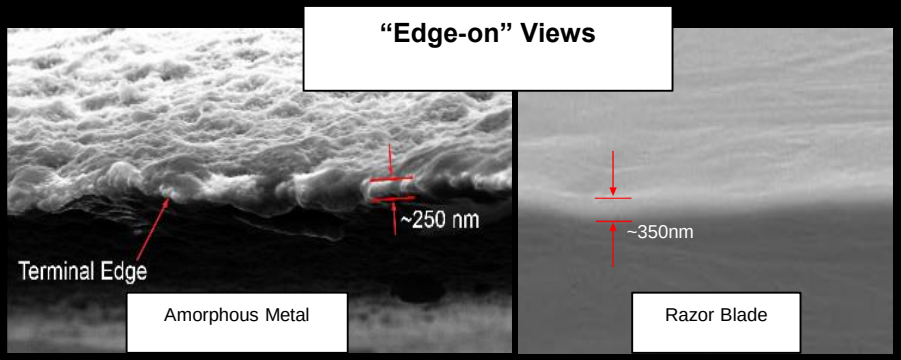
Scattered Sunlight Suppresion

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)

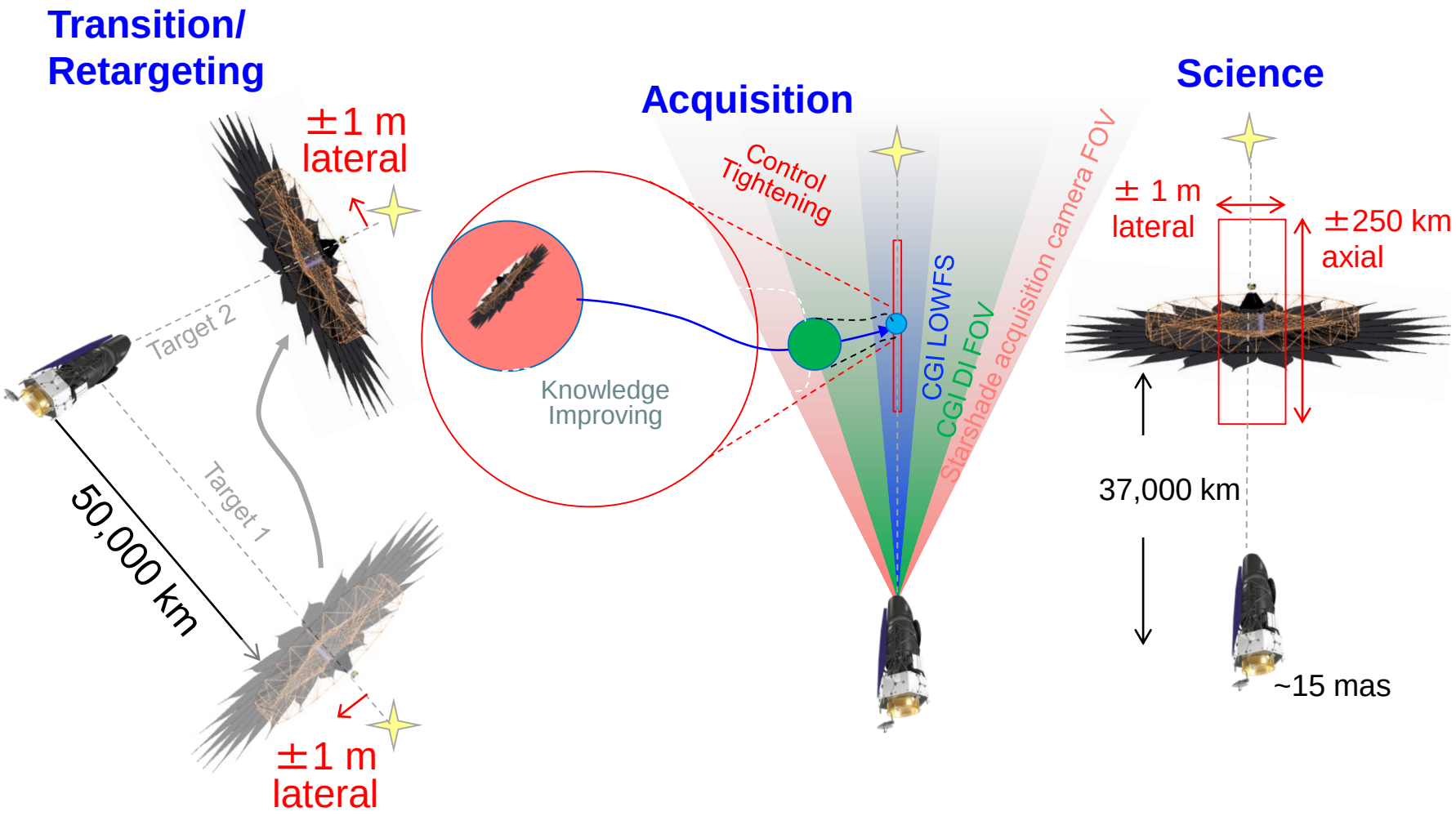


Comparable edge sharpness achieved between etched amorphous metal edges and Gem razor blades

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

Formation Flying

High Level Operations Concept

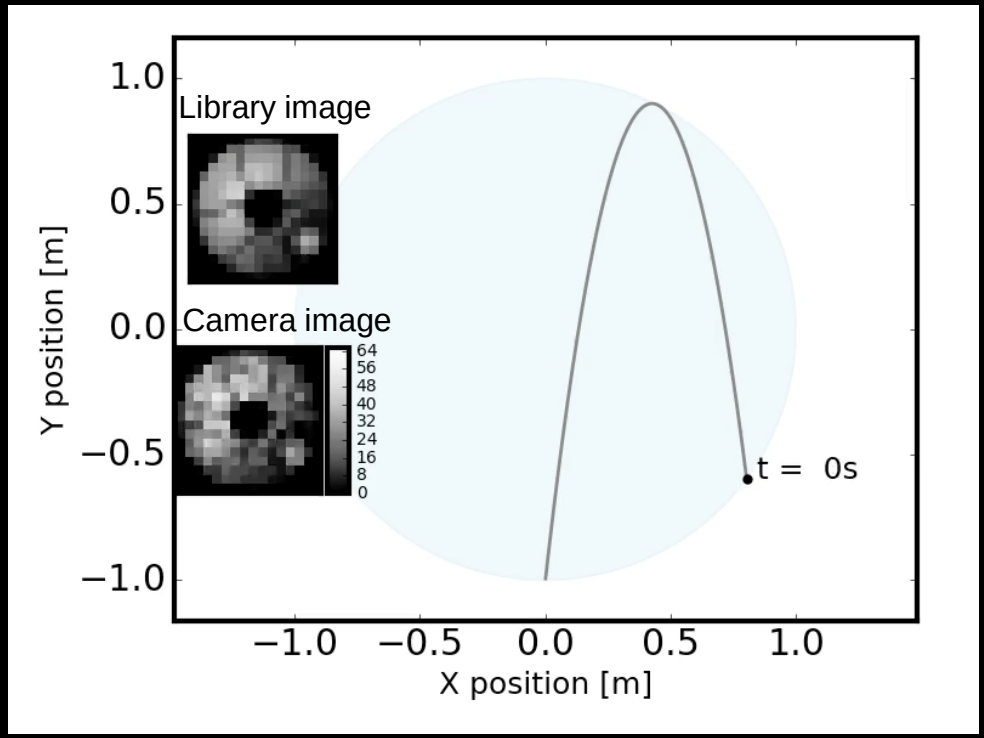


Formation Flying
Lateral Offset Sensing

Current Capabilities:

Pattern recognition approach developed while working WFIRST option

- Using pupil plane wavefront sensor and out-of-band stellar diffraction allows for accurate sensing at the ~cm level around all target stars
- Approach is being tested in the lab and the measurements compared with a model.



Guiding on an 8th magnitude, solar-type star. Trajectory fire occurs at 0s. Pupil plane camera exposure time is 1 second. Precision is 2 cm.

POC: Michael Bottom (JPL)

Formation Flying
Lateral Offset Sensing

Path to Close Gap

- Upgrade Formation Flying Testbed with lower diffraction optics
- Create library of simulated detector images of starshade's laser beacon offset to the leaked starlight pattern.
- Computer match testbed image to a library of images to identify real off-set
- Develop control algorithm to work with testbed sensing data

Petal Deployment Accuracy

Deployment Accuracy and Shape Stability (S-5)

Need:

- Deployment tolerances demonstrated to ≤ 1 mm (in-plane position) with flight-like, minimum half-scale structure, simulated petals, opaque structure, and interfaces to launch restraint after exposure to relevant environments
- Deploy petals with no edge damage

Current Capabilties:

- Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12 m prototype and no optical shield; no environmental testing
- Optical shield prototypes fabricated and demonstrated
- Unfurling testbed constructed