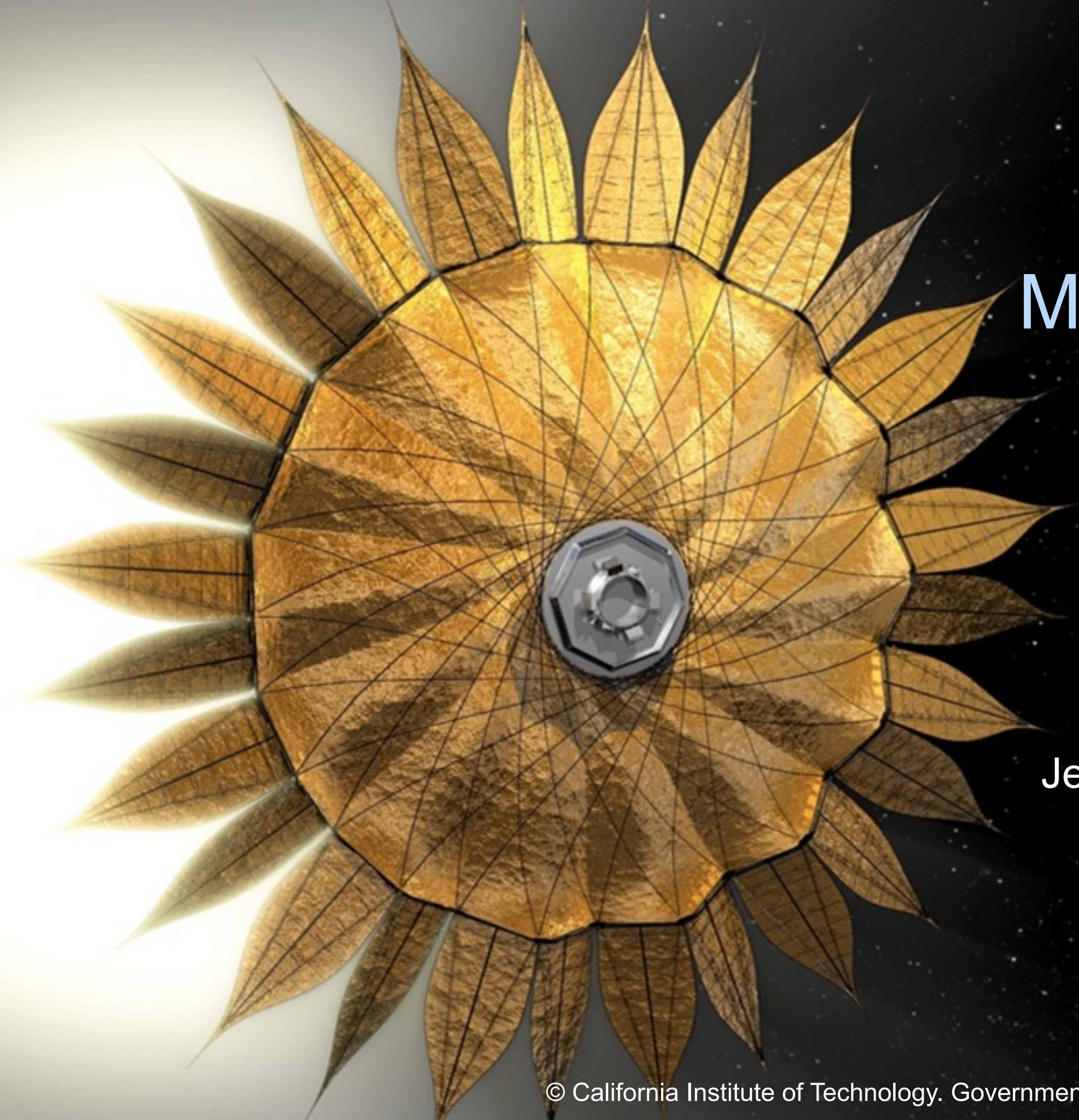


State of Starshade Technology: Mechanical Deployment & Stability

Manan Arya
Stanford University

Serena Ferraro
Jet Propulsion Laboratory, California Institute of Technology

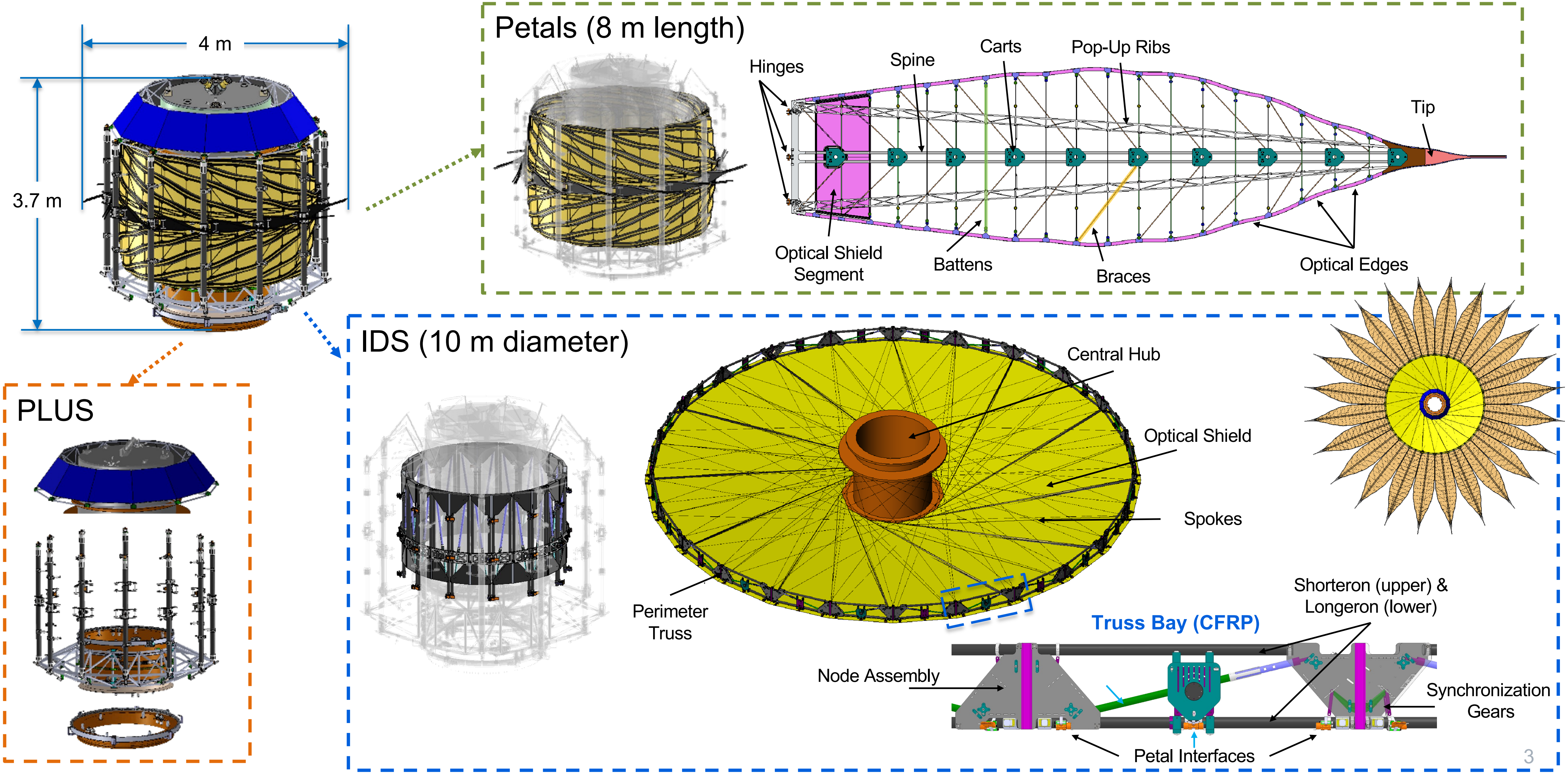
Starlight Suppression Workshop

August 9, 2023

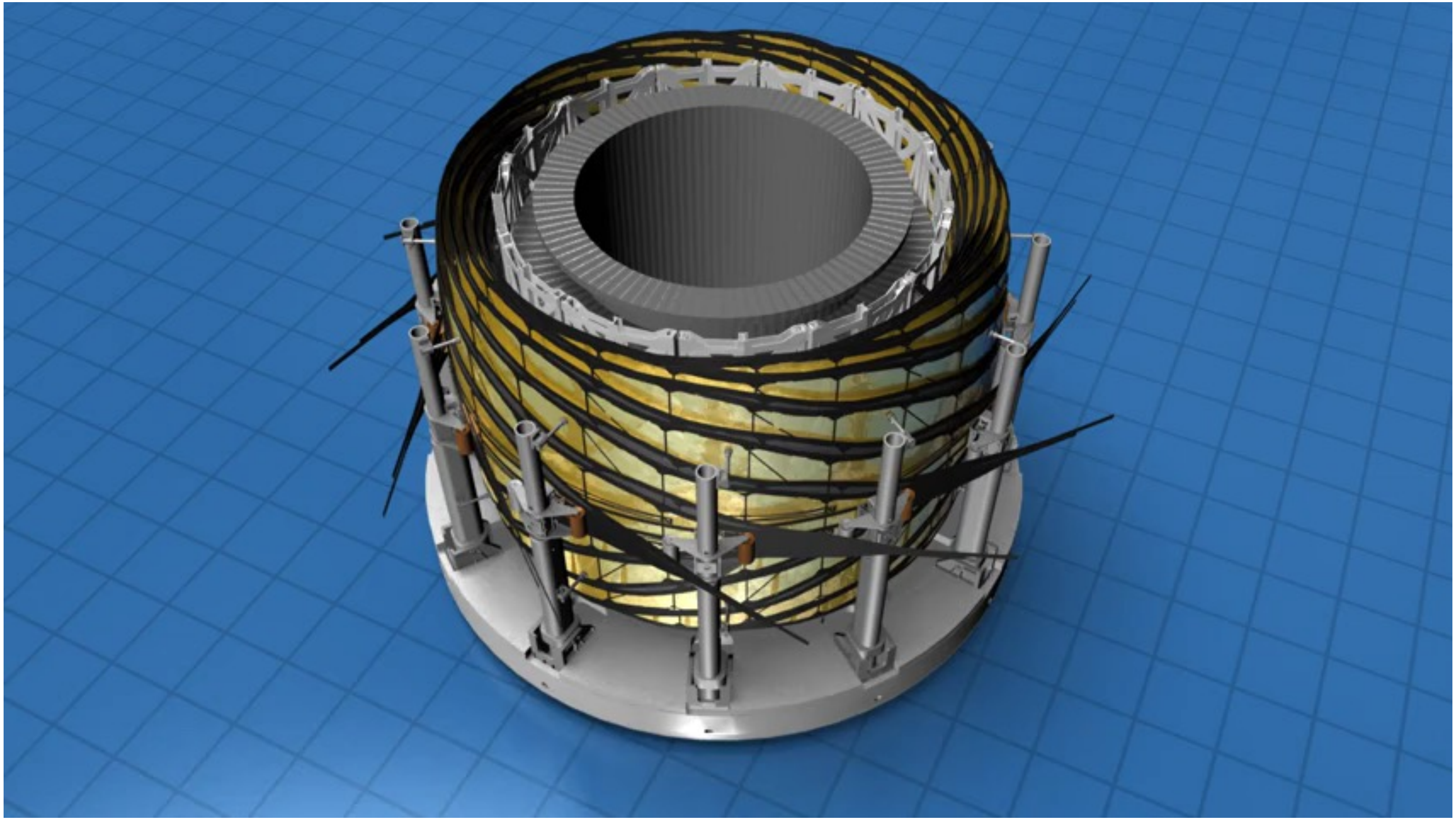
OUTLINE

1. Starshade Mechanical and Deployment Architecture
2. Mechanical Technology Development
3. Current Work
4. Future Steps

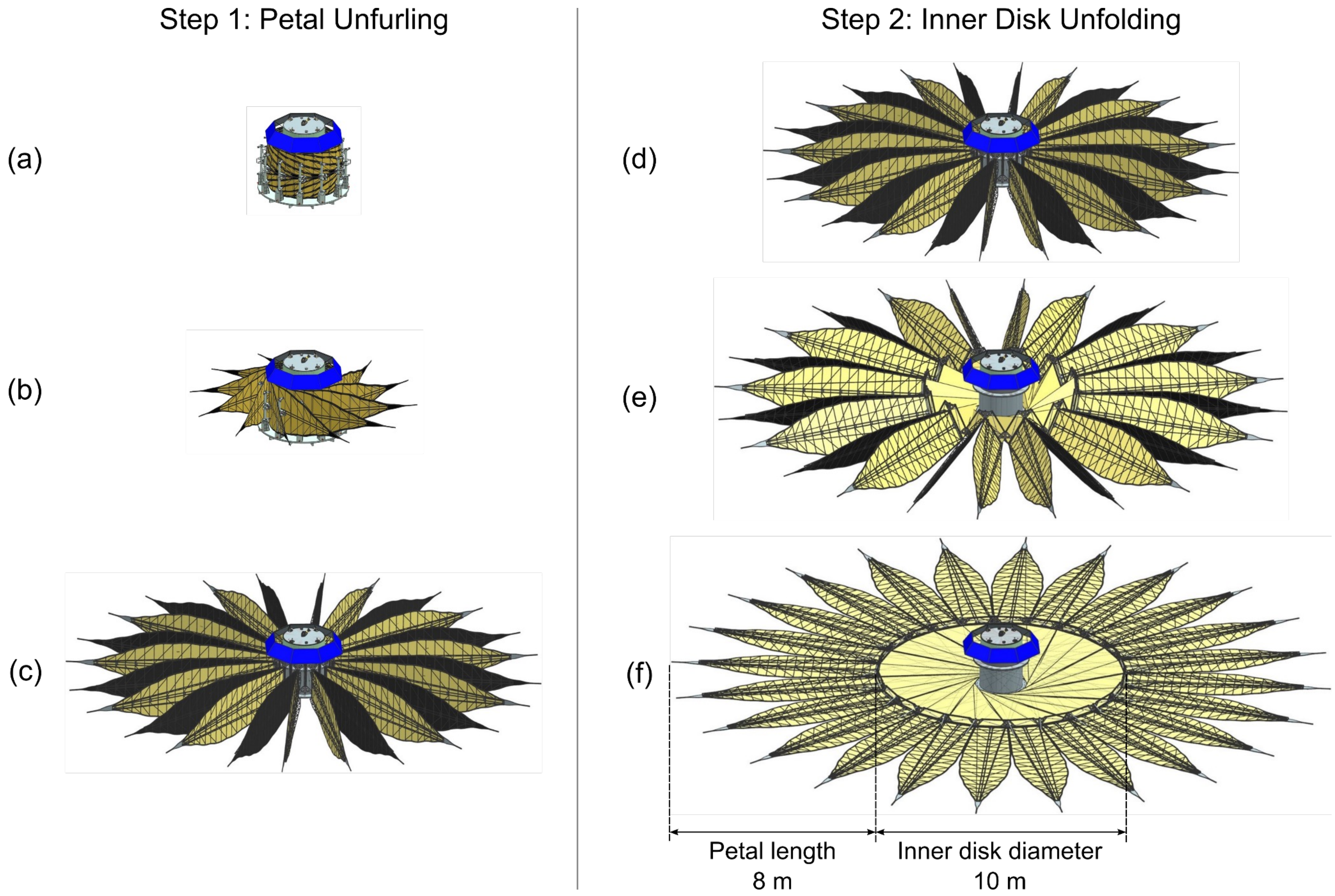
Starshade Mechanical Architecture



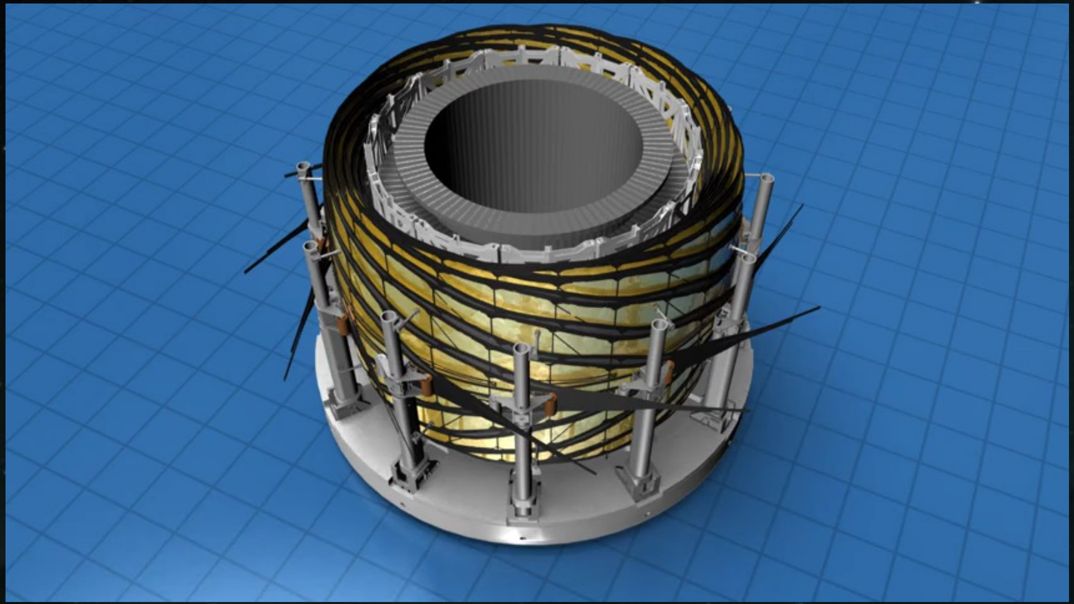
Starshade Deployment

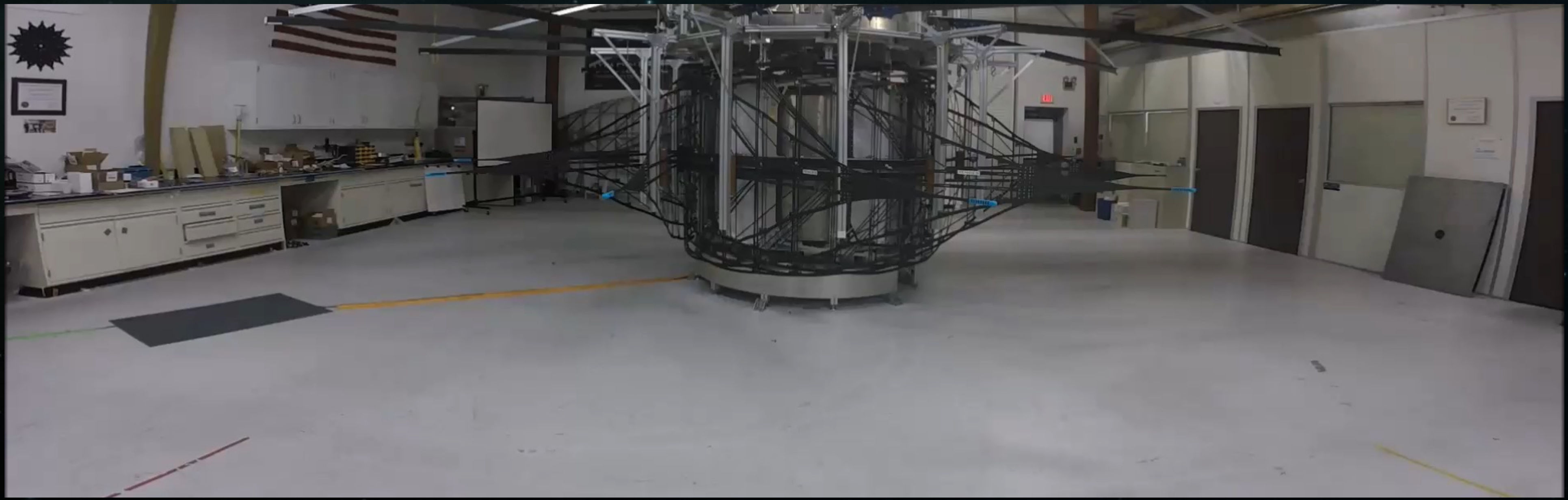


STARSHADE DEPLOYMENT

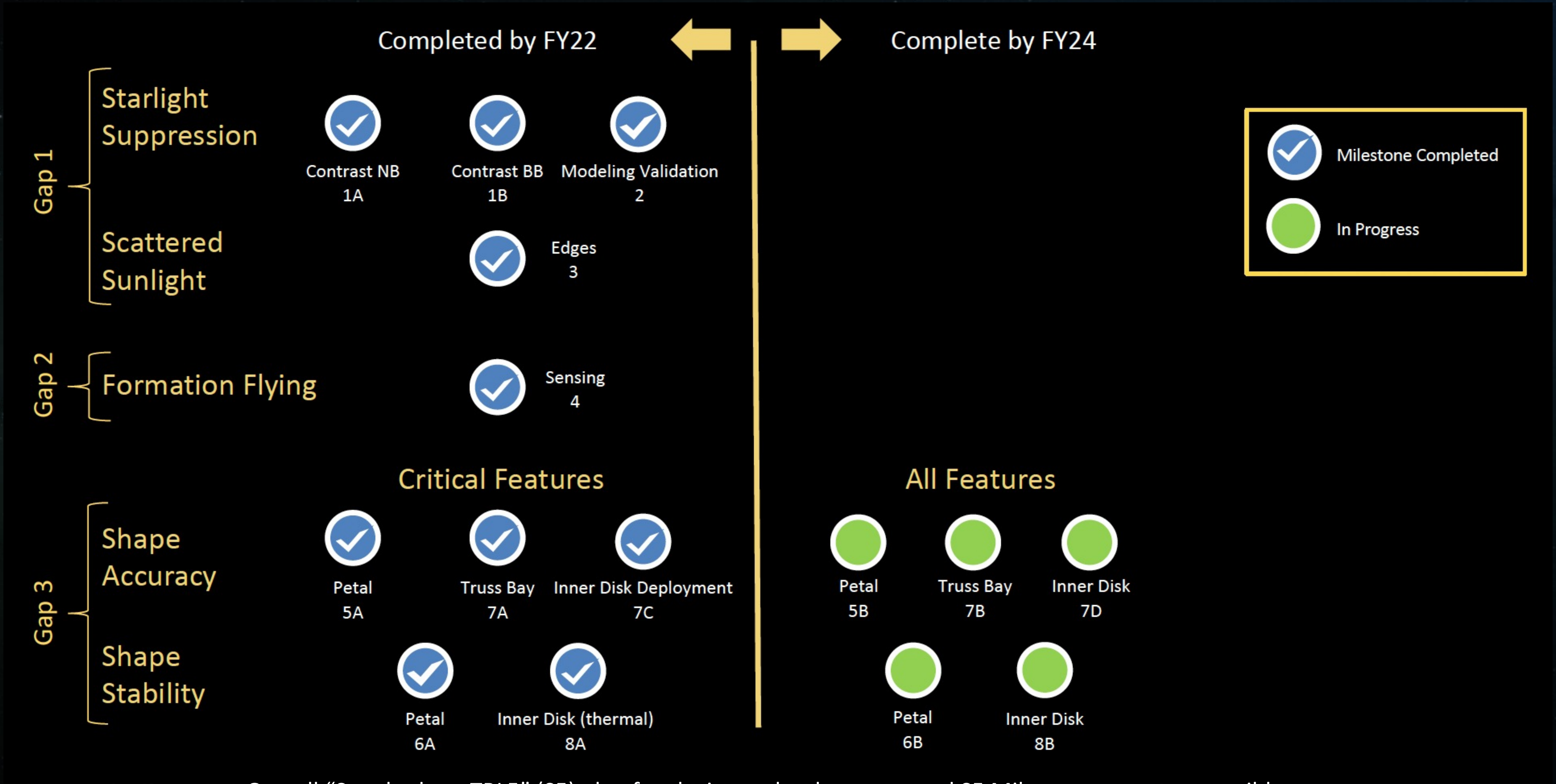


PETAL LAUNCH RESTRAINT & UNFURLING SUBSYSTEM (PLUS)





Path to TRL5: Closing Technology Gaps



Overall "Starshade to TRL5" (S5) plan for closing technology gaps and S5 Milestone reports accessible at https://exoplanets.nasa.gov/exep/technology/starshade/

STARSHADE MECHANICAL TRL5 MILESTONES

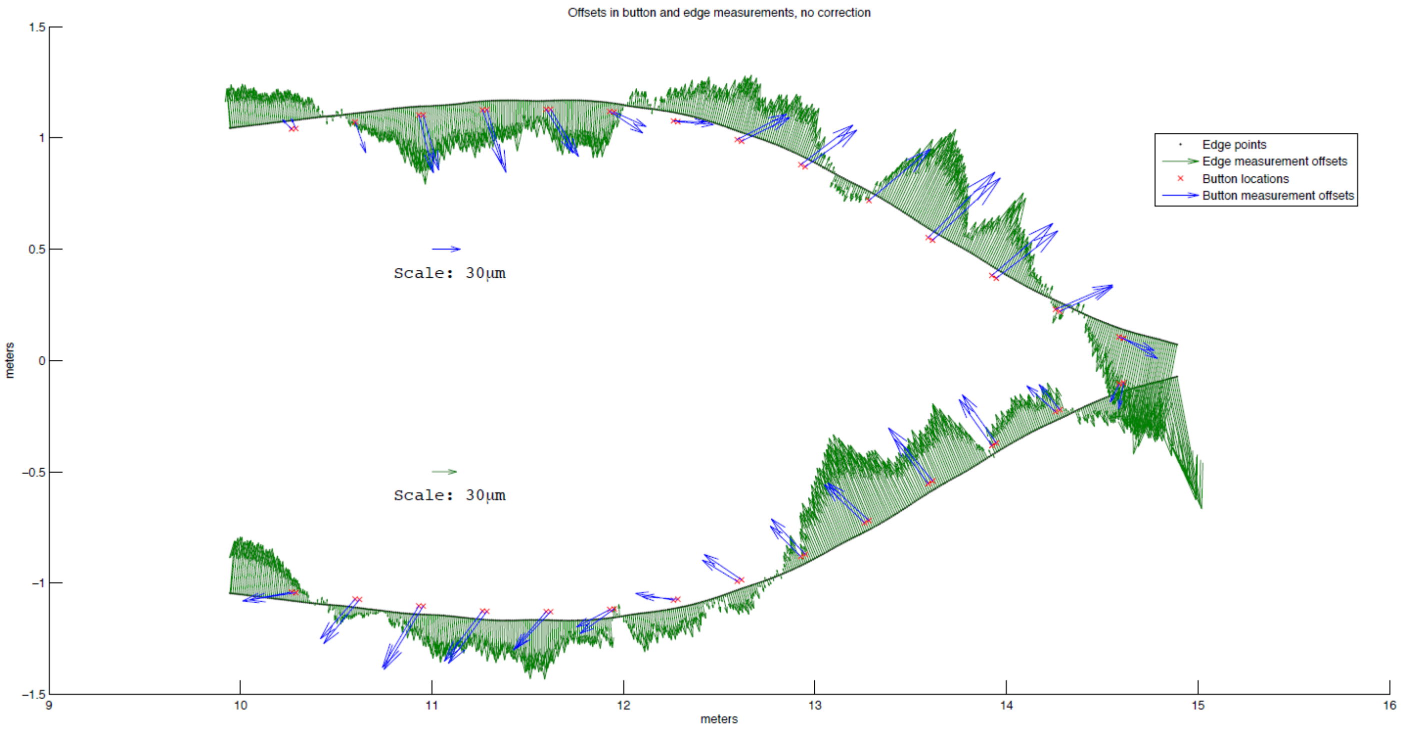
Key Performance Parameter (KPP)		"Critical features" milestones Completed by FY22		
KPP 5	Petal thermal-cycle stability & deployed shape accuracy	5A ✓	Petal test article with *shape-critical* features	
KPP 6	Petal thermoelastic shape stability	6A ✓		
KPP 7	Inner disk deployed shape accuracy	7C ✓	Inner disk test article	
	Inner disk thermal-cycle stability	7A ✓	Perimeter truss bay *components*	
KPP 8	Inner disk thermoelastic shape stability	8A ✓		

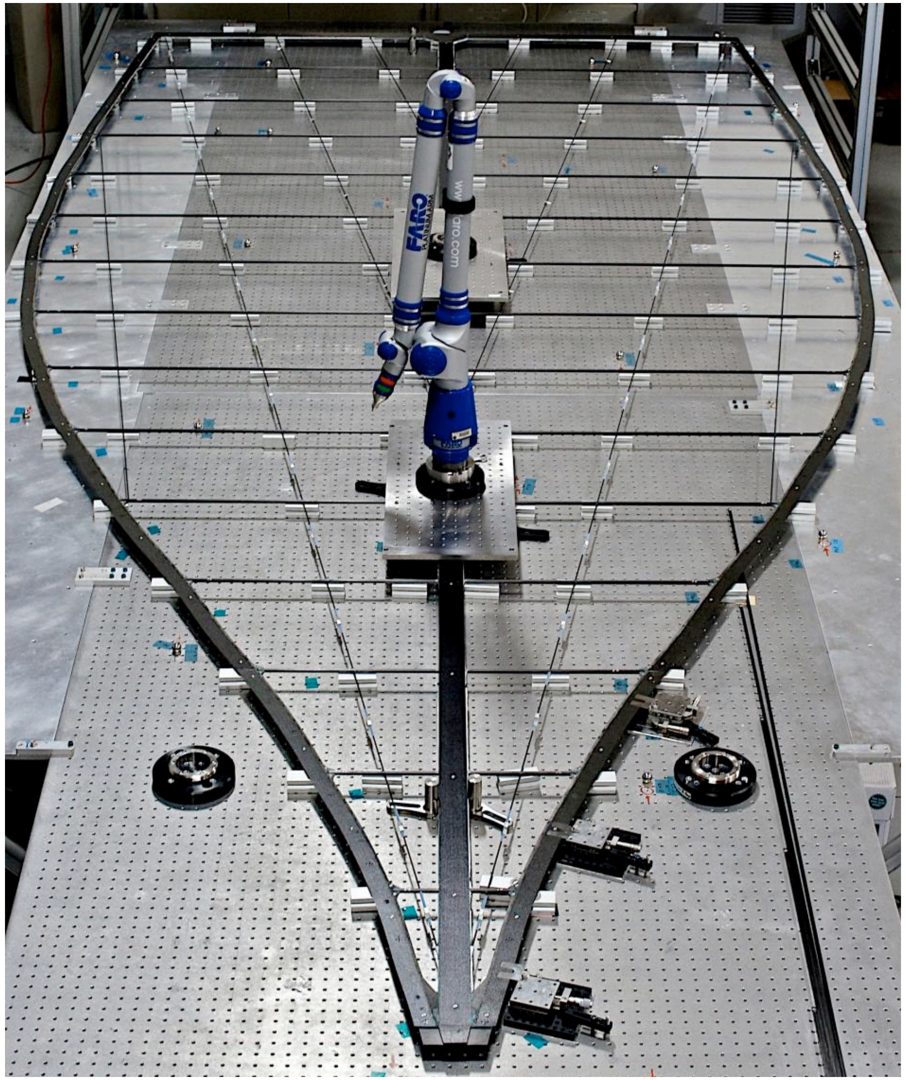
Starshade Mechanical TRL5 Milestones

Key Performance Parameter (KPP)		"Critical features" milestones Completed by FY22		"All features" milestones Complete by end of FY24	
KPP 5	Petal thermal-cycle stability & deployed shape accuracy	5A ✓	Petal test article with *shape-critical* features	5B	Petal section with *all* features
KPP 6	Petal thermoelastic shape stability	6A ✓		6B	High-fidelity petal numerical models
KPP 7	Inner disk deployed shape accuracy	7C ✓	Inner disk test article	7D	High-fidelity inner disk numerical models
	Inner disk thermal-cycle stability	7A ✓	Perimeter truss bay *components*	7B	Perimeter truss bay *assembly*
KPP 8	Inner disk thermoelastic shape stability	8A ✓		8B	

PETAL SHAPE ACCURACY

- In 2010, built a 5 m-long petal section
- “Optical edges” were 1 m-long composite segments
- Measured manufactured in-plane shape accuracy ±100 μm
  - Consistent with 3e-11 contrast degradation
  - Reminder: edge shape errors lead to contrast degradation





N. J. Kasdin et al, "Advancing technology for starlight suppression via an external occulter," Proc. SPIE 8151, 2011
N. J. Kasdin et al., "Technology demonstration of starshade manufacturing for NASA's Exoplanet mission program," Proc. SPIE 8442, 2012

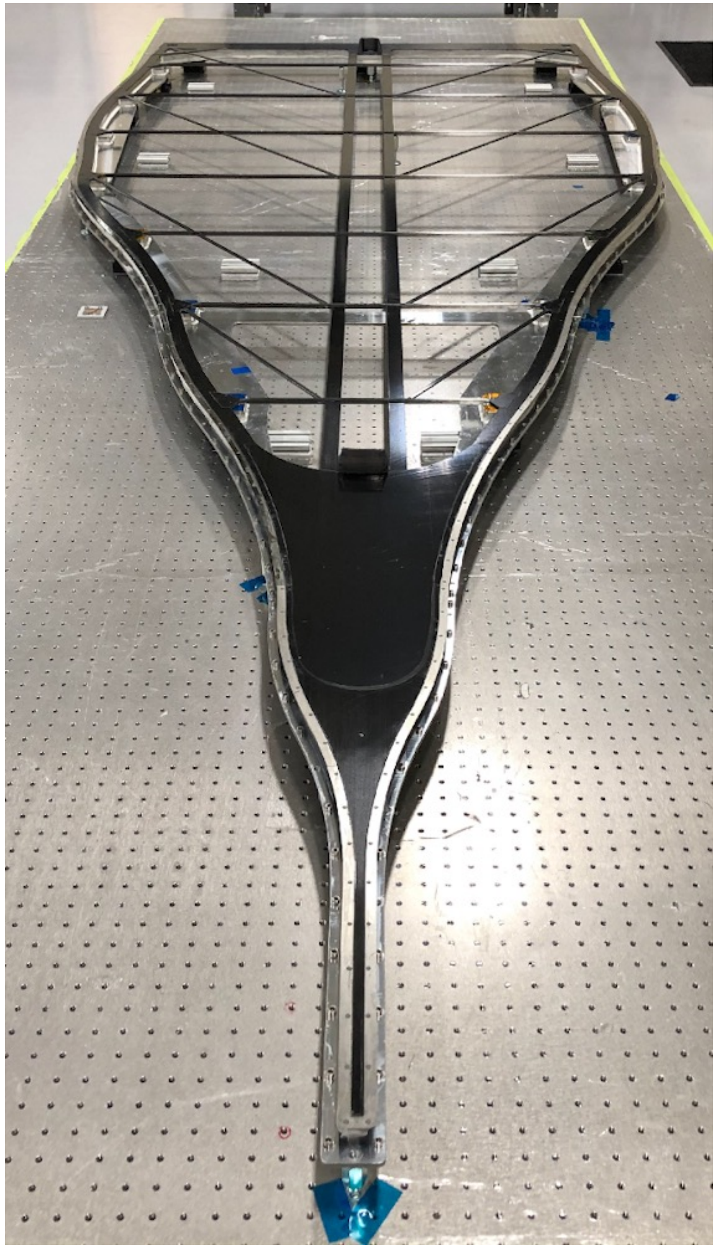
Petal Shape Stability

- In 2019, built higher-fidelity petal test article for S5 milestones
  - ¾-scale width, ½-scale length relative to Starshade Rendezvous Mission (SRM) concept

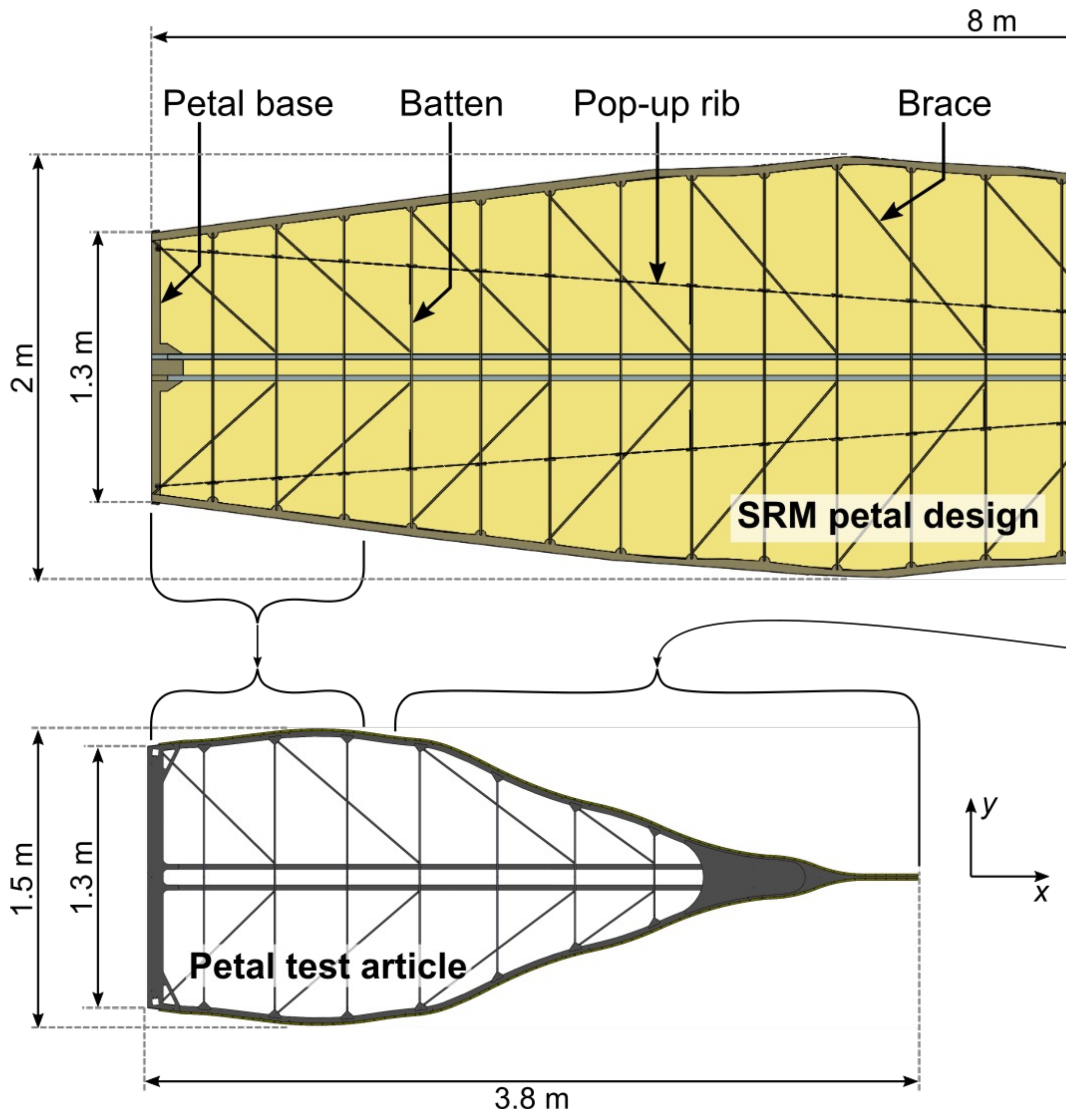
- Demonstrated:
  - Shape stability under deployment, thermal cycling
  - Thermoelastic shape stability

- Materials, components, joint geometry representative of SRM design
  - Amorphous metal foil optical edges
  - Carbon-fiber-reinforced polymer (CFRP) for structure
    - M55J/cyanate ester laminates
    - Pultruded unidirectional CF/epoxy rods
  - Engineering epoxy (EA9394) used to bond components together

- Omitted features that are not critical to preserving the width profile of the petal
  - Out-of-plane ribs
  - Opacity blanket
  - Launch restraint interfaces

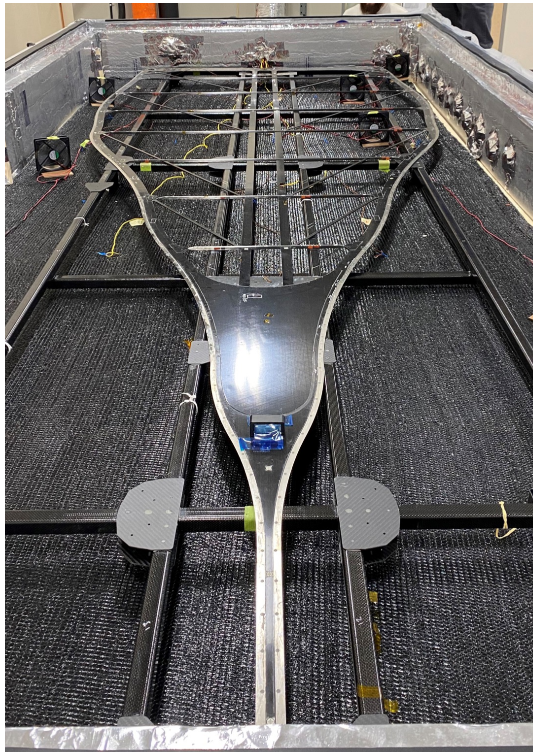


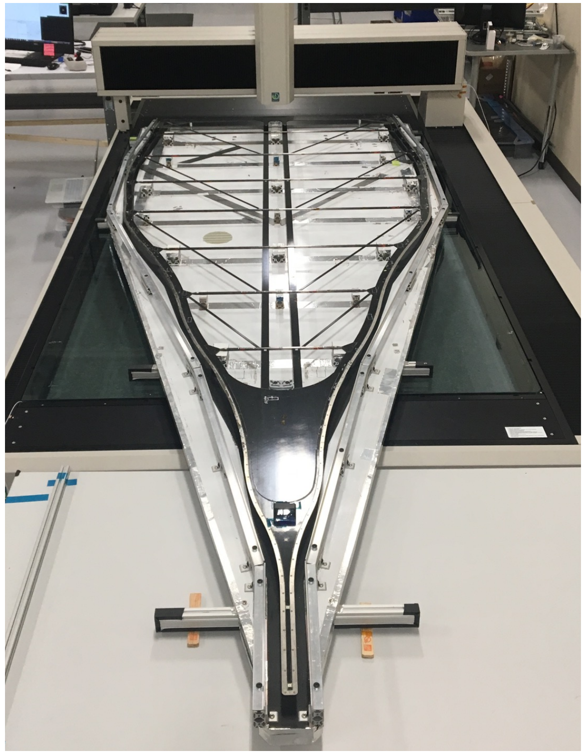
PETAL SHAPE STABILITY



PETAL SHAPE STABILITY

- Subjected petal test article to 50 thermal cycles (± 50°C)
- Subjected petal test article to 5 furl-and-deploy cycles (simulating wrapping around 2.3 m-diameter)
- Measured petal shape after thermal cycles, furl cycles, compare to reference shape to calculate width change
  - MicroVu measurement machine (microscope on a *x-y* translation stage) used for petal shape measurement

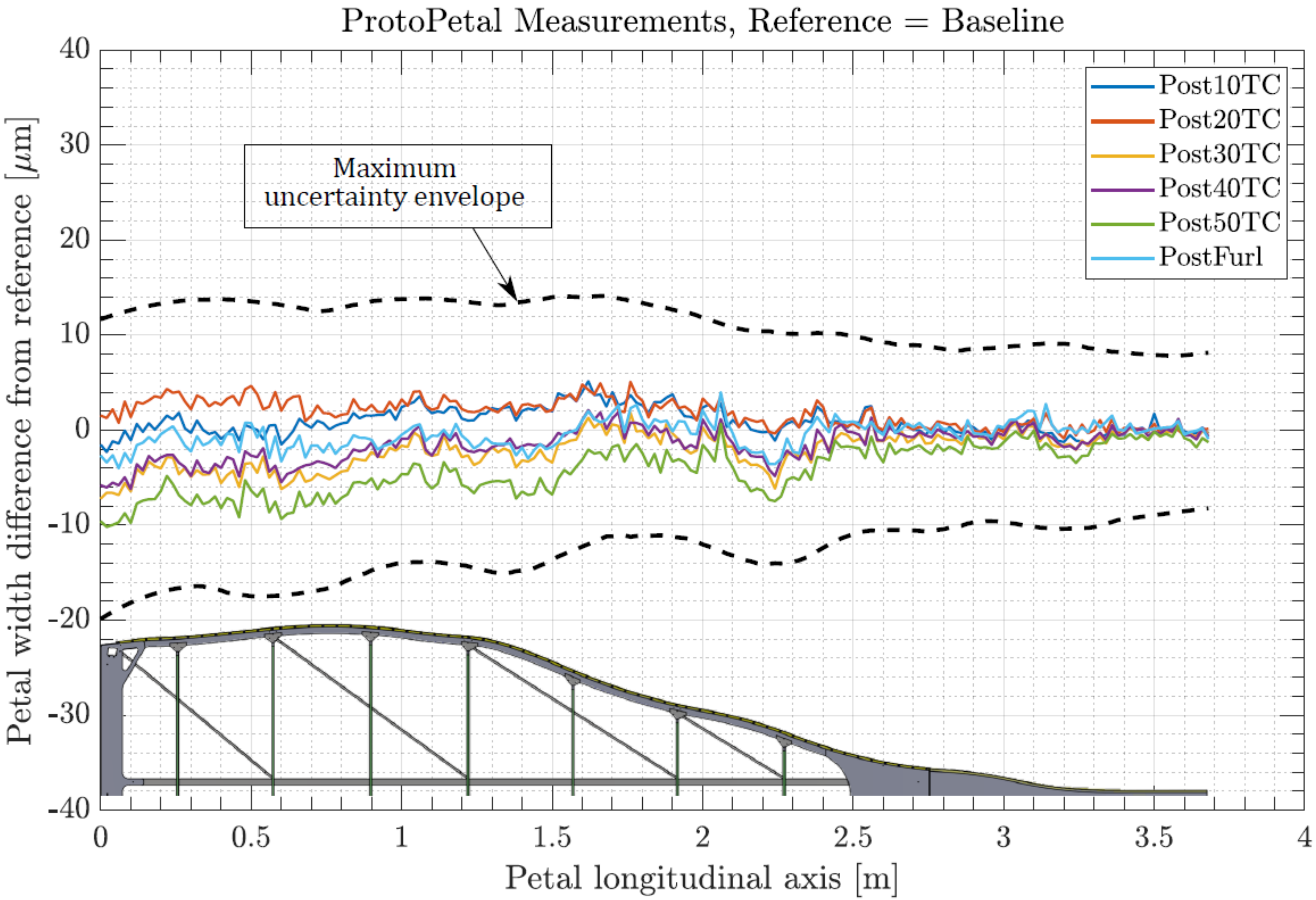




M Arya et al., Demonstration of deployment repeatability of key subsystems of a furled starshade architecture, *JATIS*, vol 7, no 2, pp 021202, 2021

Petal Shape Stability

- Measured width changes were within allocations, with margin



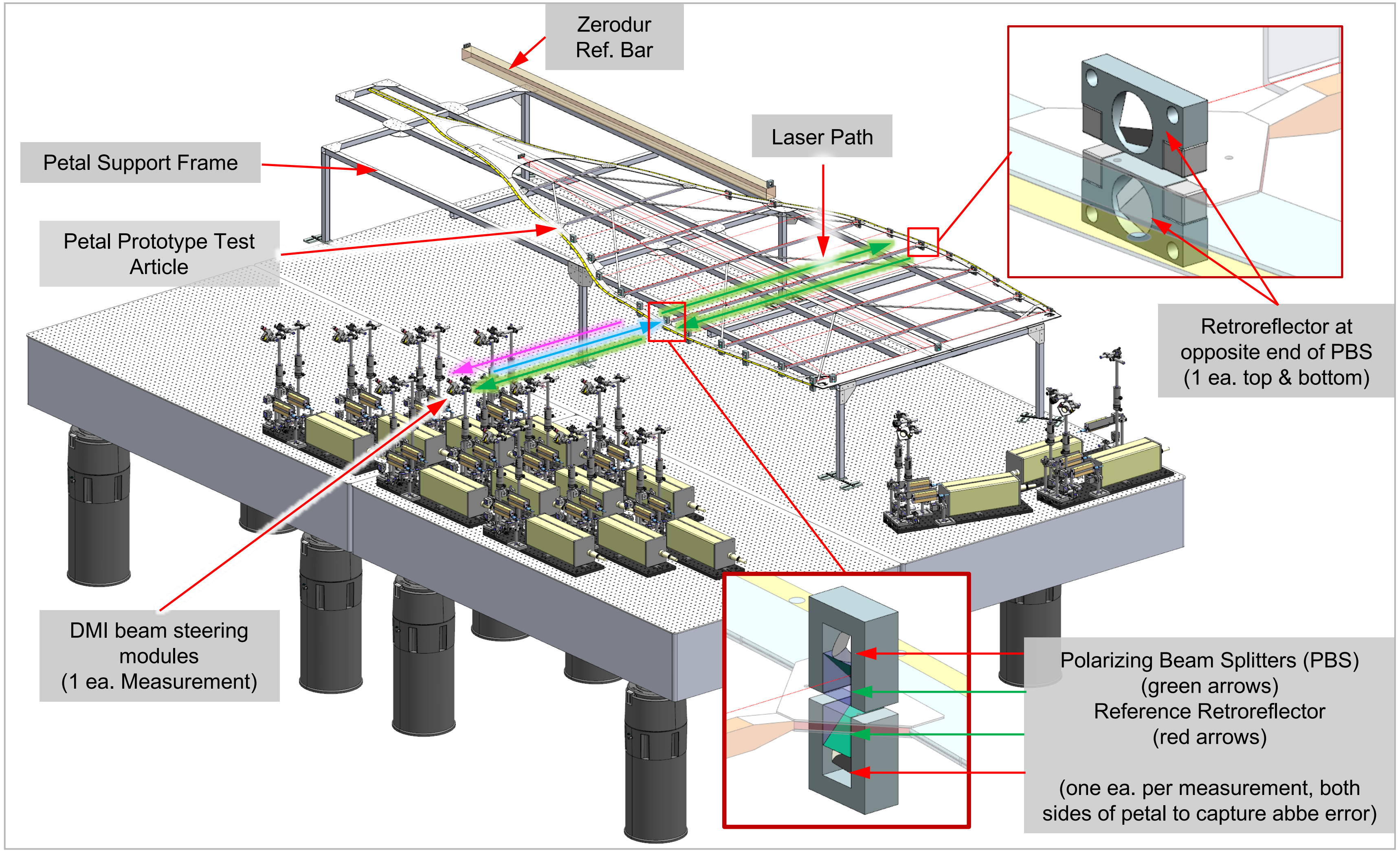
Petal Thermoelastic Shape Stability

Approach:

- Validate petal thermoelastic deformation finite element model (FEMAP/Nastran) using experiments on the petal test article
- Use validated model to predict in-space deformations due to expected in-space thermal loads

Subjected petal test article to thermal soaks, measured change in critical dimensions using laser interferometry

Developed finite element model that matched measured dimensional changes to within measurement uncertainty



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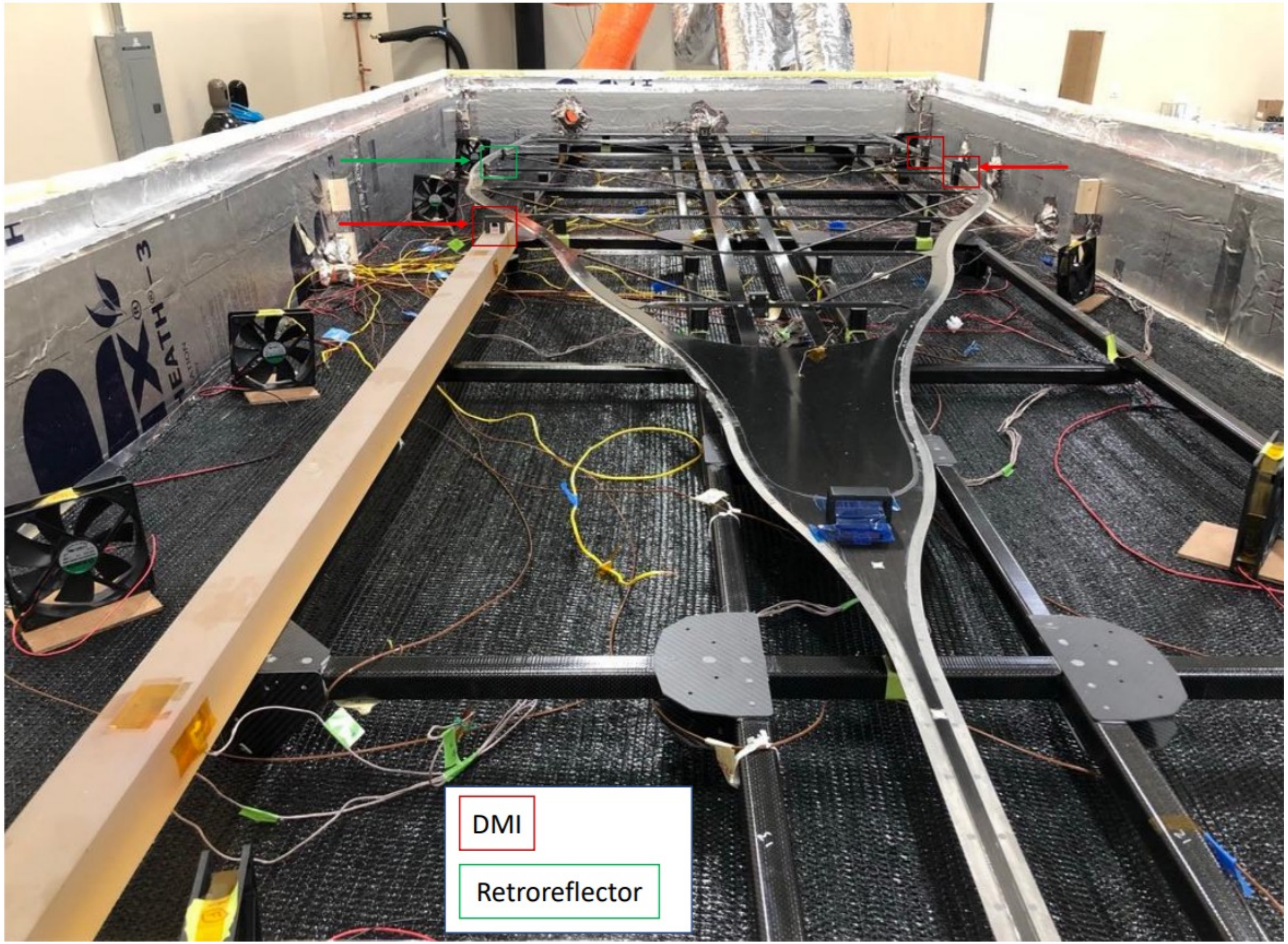
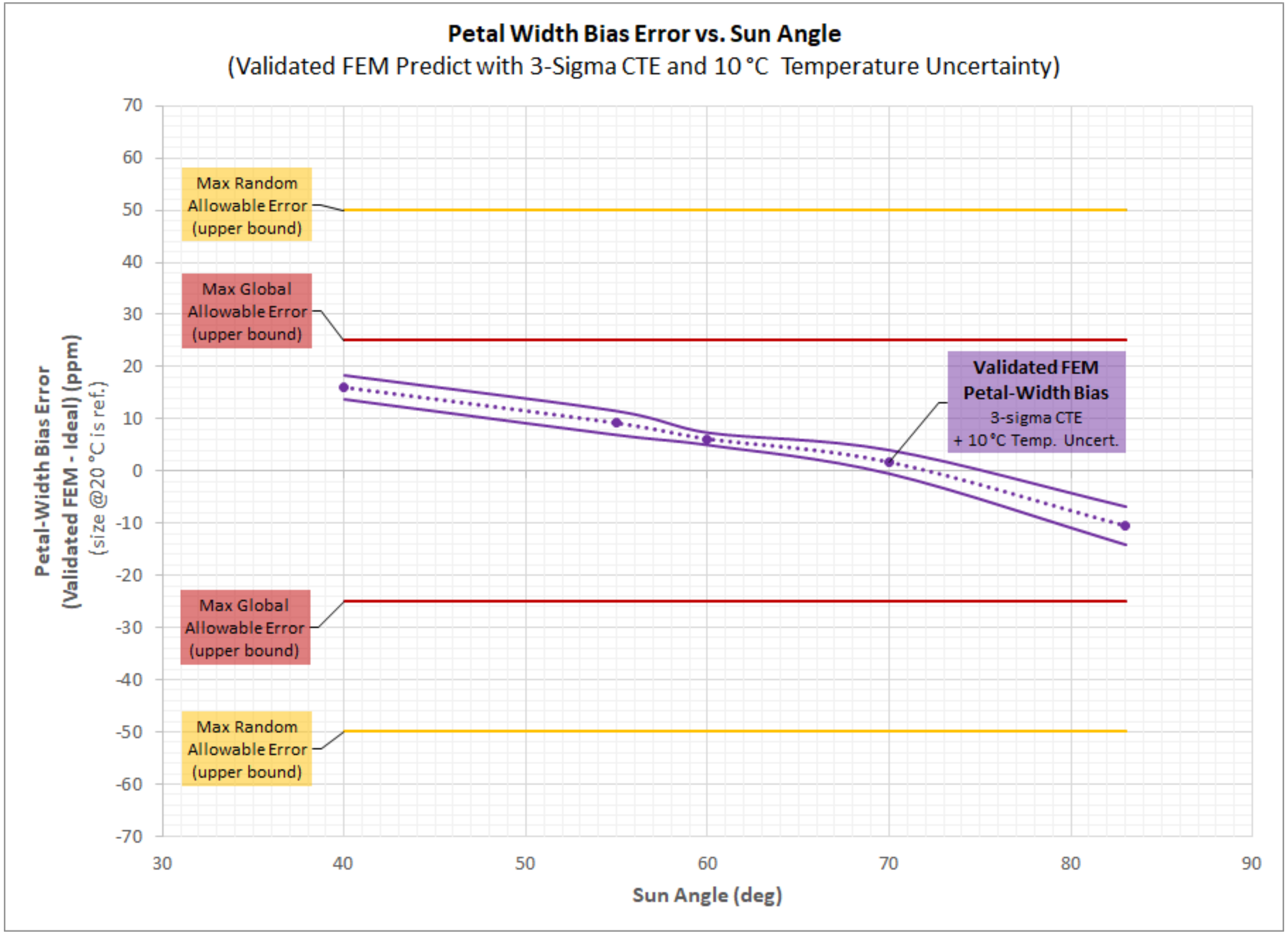


PETAL THERMOELASTIC SHAPE STABILITY

Predicted in-space thermoelastic petal shape change is within allocation, with margin

As predicted by experiment-validated model of thermoelastic distortion

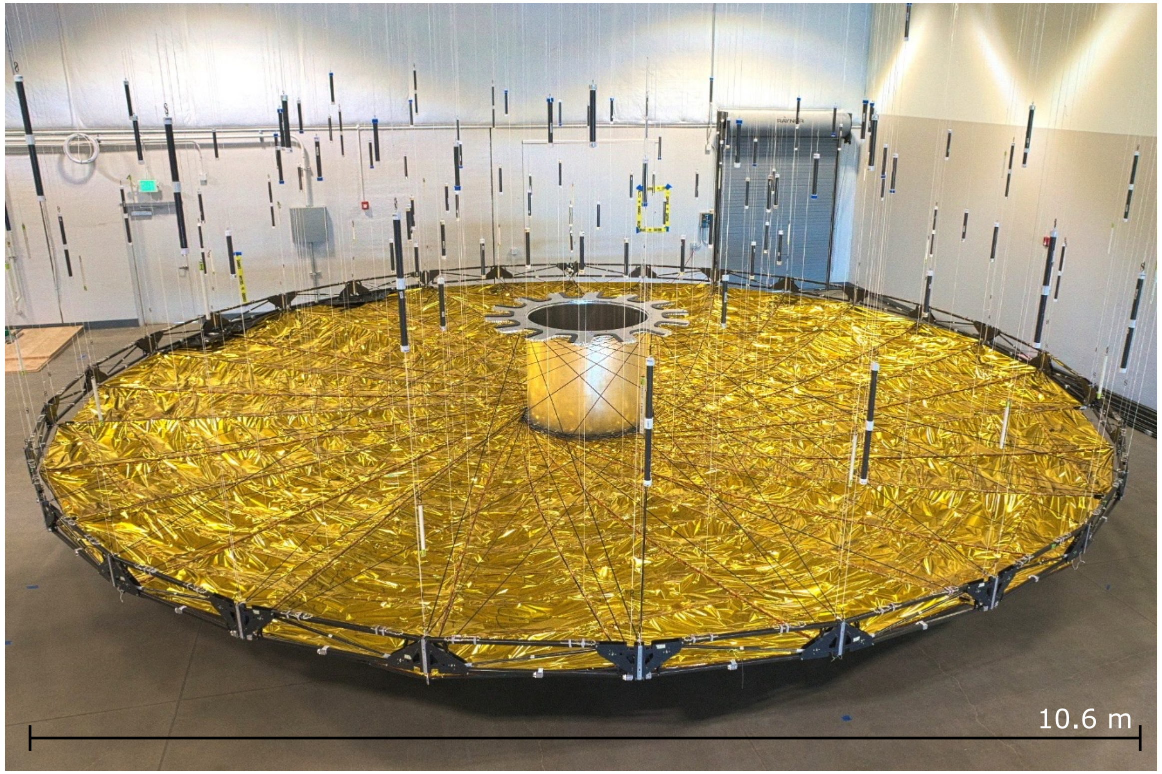


Inner Disk Deployment Accuracy

Built full-scale (10 m diameter) inner disk test article

- Perimeter truss, spokes are medium-fidelity (flight-like materials, geometry)
- Optical shield is low-fidelity

Deployed 22 times, measured deployed shape each time to quantify deployment accuracy

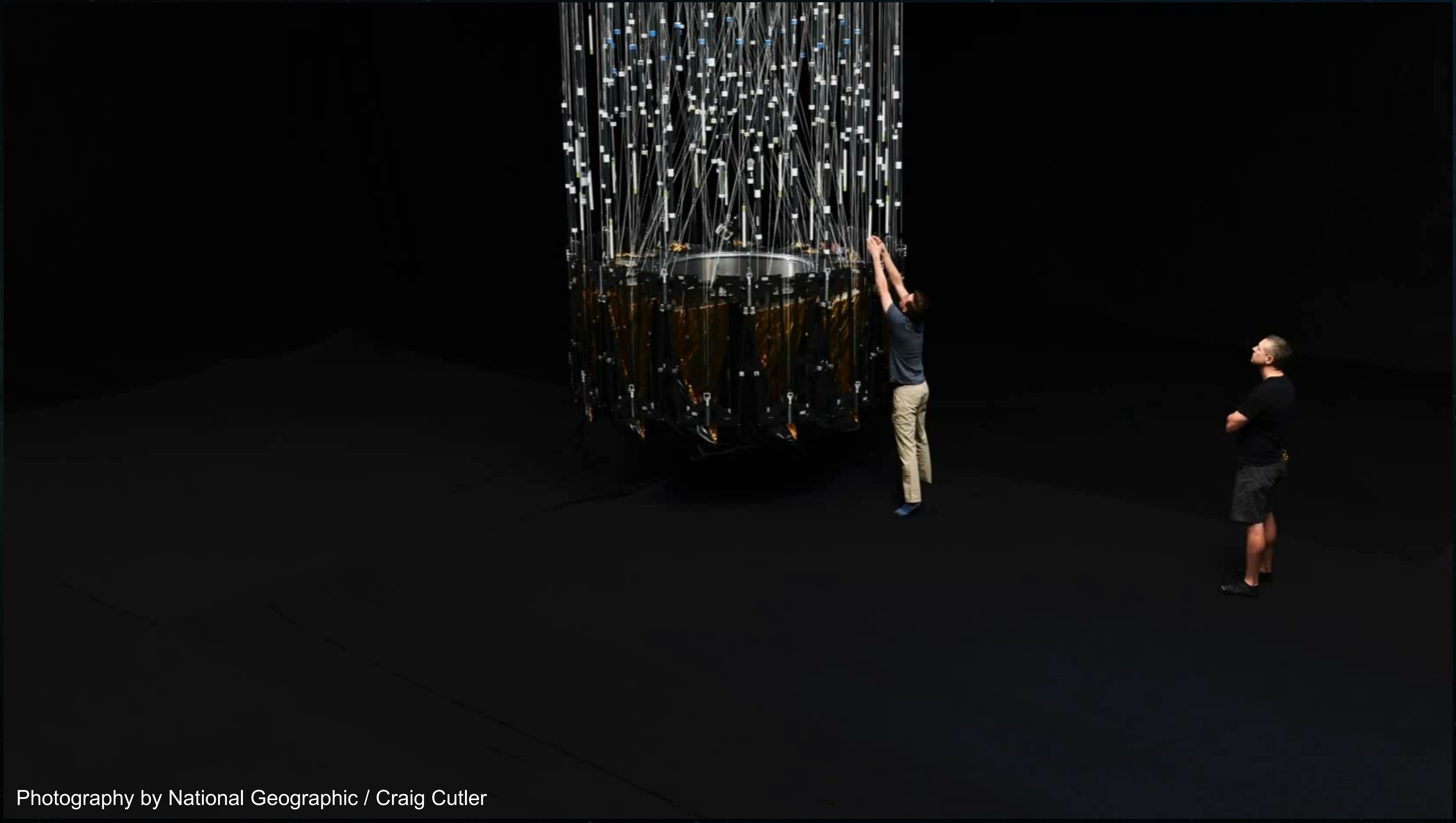


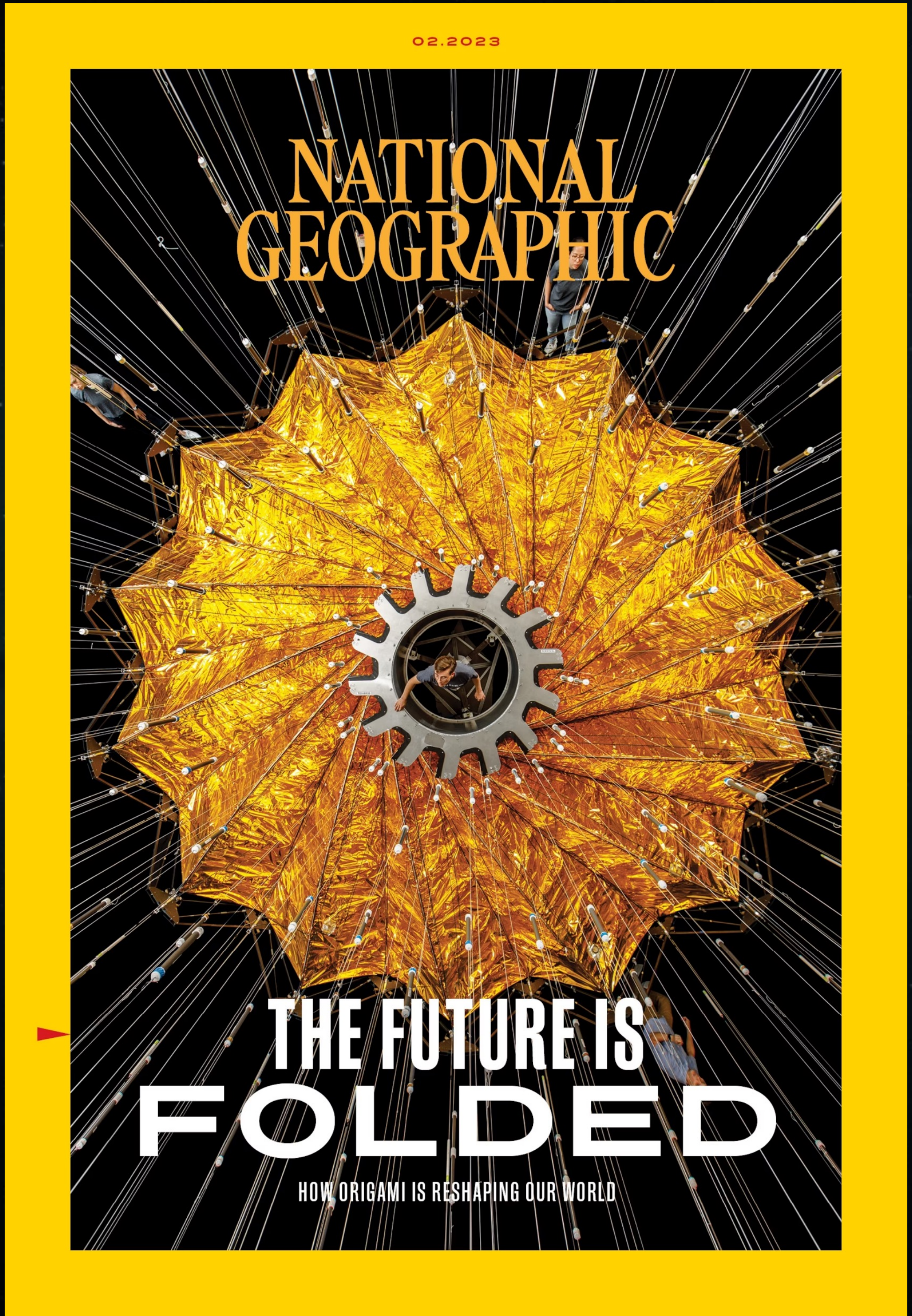
Deployed

Stowed

M Arya et al., Demonstration of deployment repeatability of key subsystems of a furled starshade architecture, *JATIS*, vol 7, no 2, pp 021202, 2021

Inner Disk Deployment


Photography by National Geographic / Craig Cutler


02.2023
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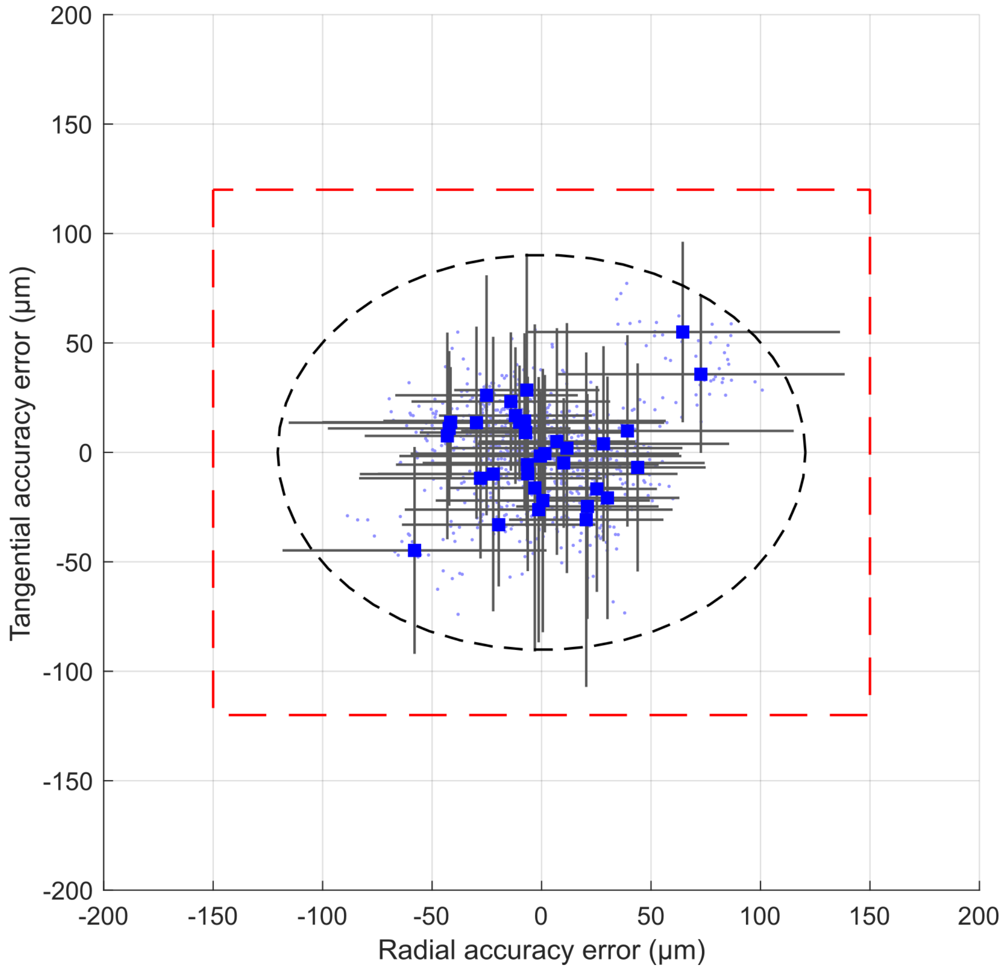
THE FUTURE IS
FOLDED
HOW ORIGAMI IS RESHAPING OUR WORLD

Inner Disk Deployment Accuracy



150 μm radial random allocation, 3σ
120 μm tangential random allocation, 3σ

Accuracy errors of 34 petal interfaces over 22 deployments

Mean accuracy errors of 34 petal interfaces

Conservative 3σ bounds on spread of the 34 petal interfaces over the 22 deployments

3σ bounds on deployment accuracy calculated using Monte Carlo analysis: 121 μm radial, 91 μm tangential

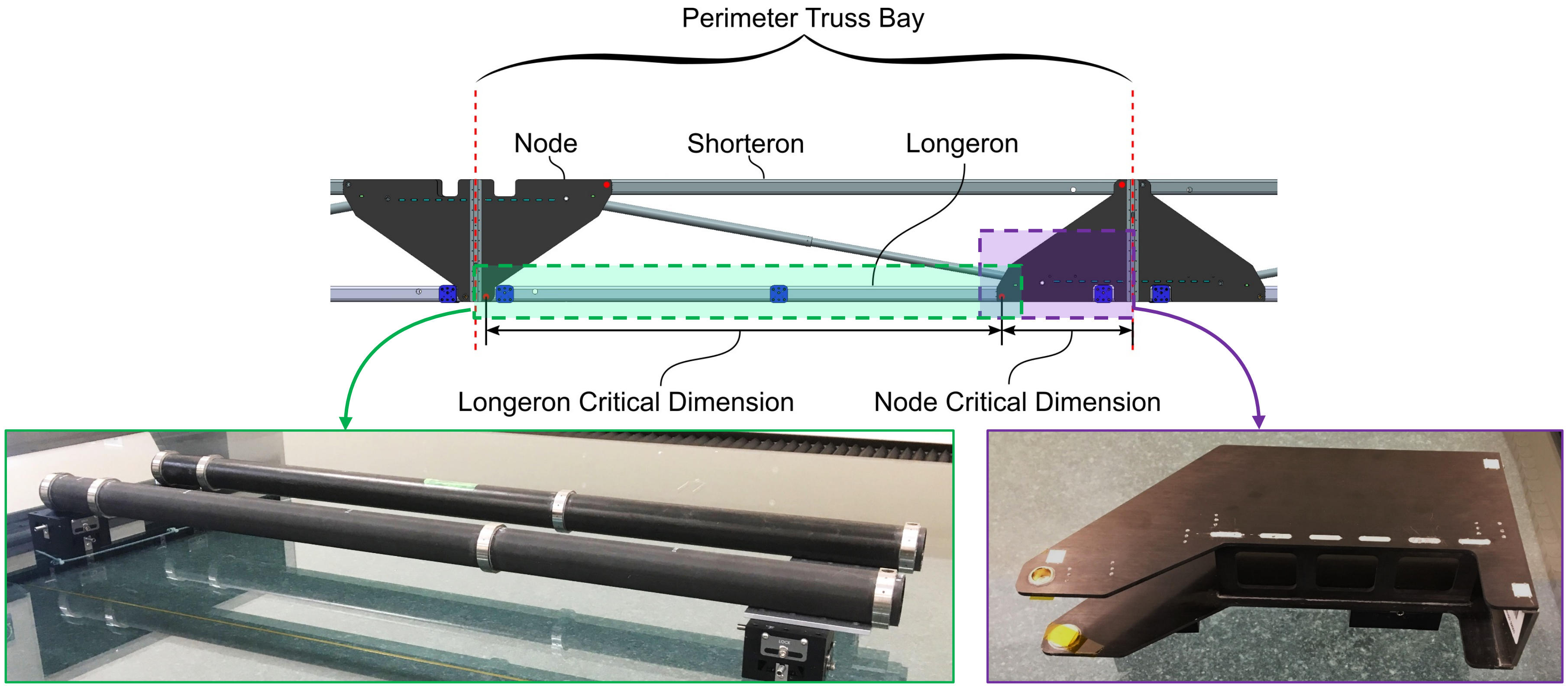
Measured accuracy errors are within allocations, with margin

M Arya et al., Demonstration of deployment repeatability of key subsystems of a furled starshade architecture, *JATIS*, vol 7, no 2, pp 021202, 2021

Inner Disk Thermal-Cycle Stability

Approach: subject key components of the inner disk perimeter truss to thermal cycles, & verify dimensional stability

Inner disk deployed stability is set almost entirely by the perimeter truss, which has repeating units called “bays”



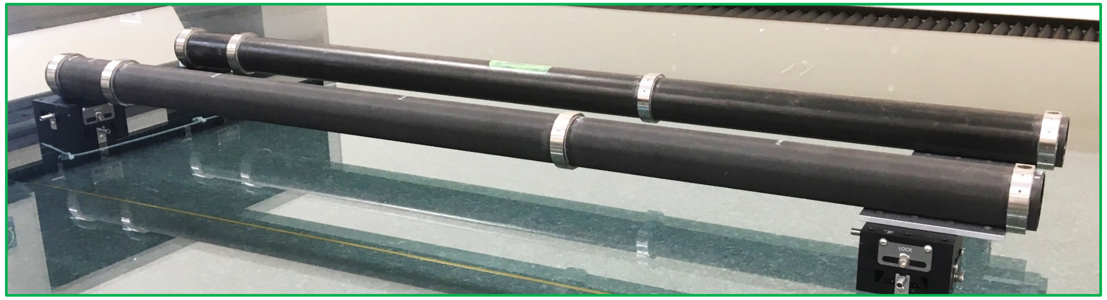
Inner Disk Thermal-Cycle Stability

Longeron and node components are flight-like in terms of materials, constructions, and dimensions

- CFRP (M55J/cyanate ester)
- Invar fittings
- Engineering epoxy (EA9394) for bonded joints

Subjected to 50 thermal cycles each (70°C to –25°C)

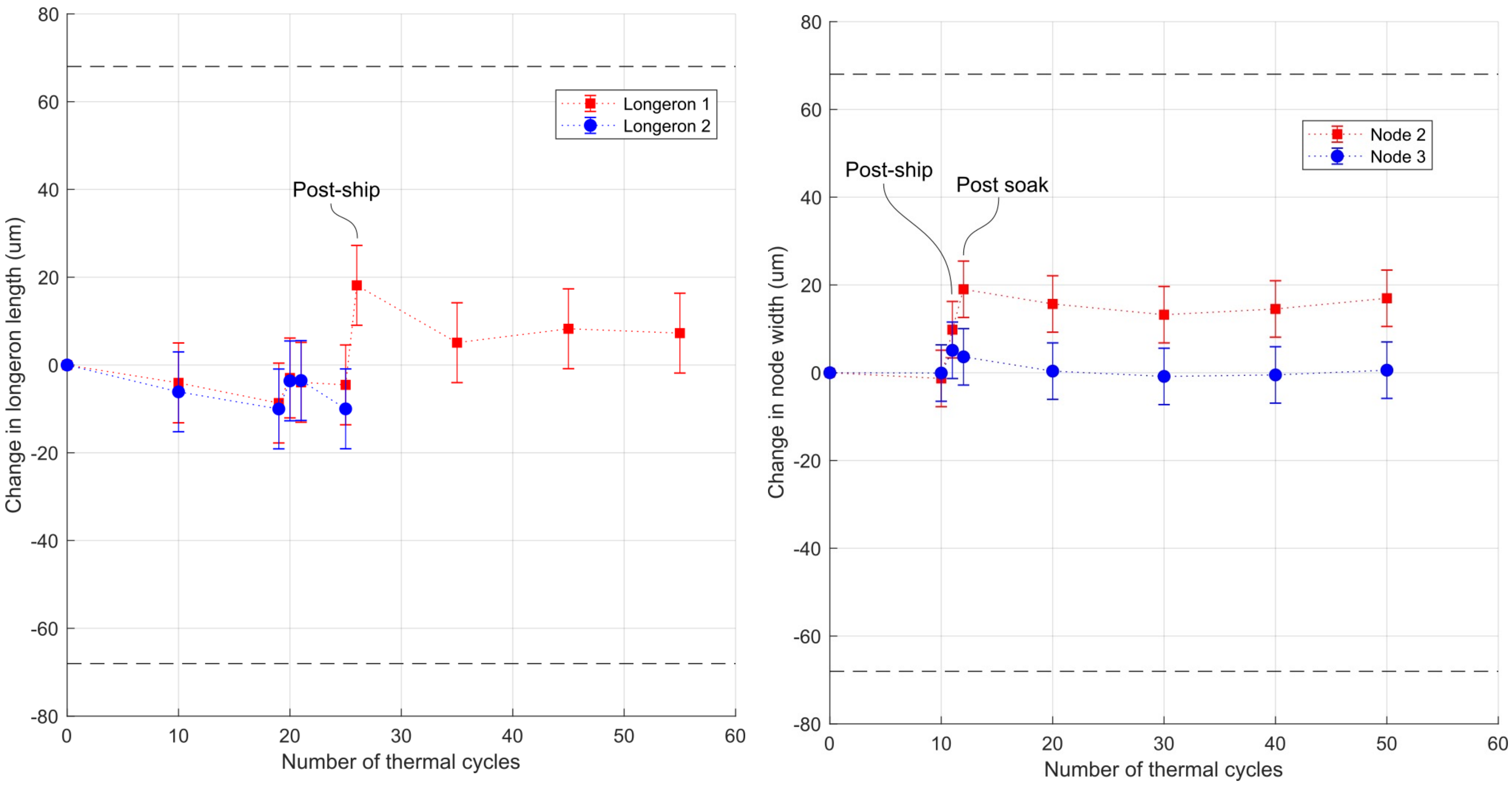
Critical dimensions measured before and after thermal cycles using MicroVu measurement machine



Longerons

Node

Inner Disk Thermal-Cycle Stability



Change in dimensions within allocations, with large margin

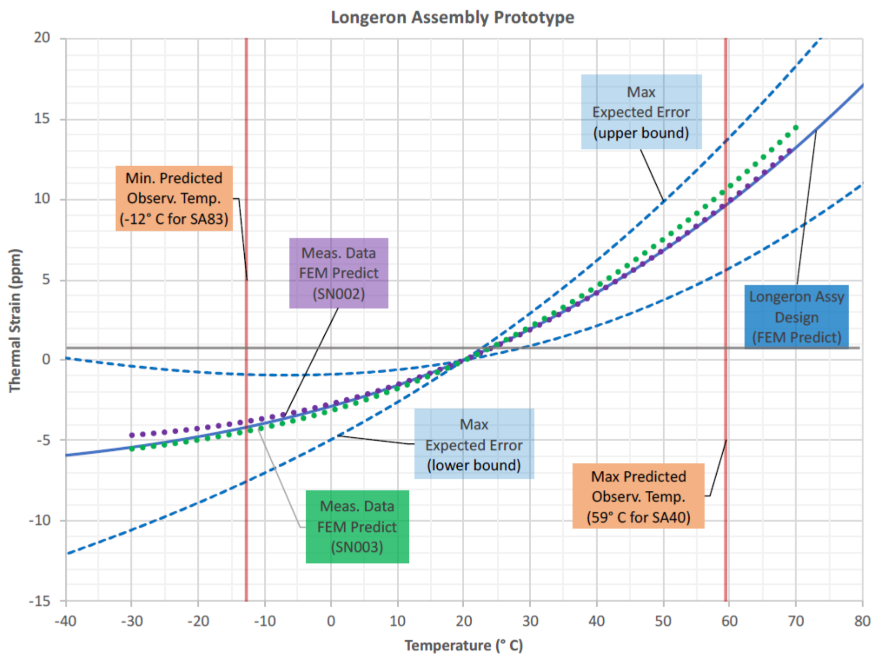
Inner Disk Thermoelastic Shape Stability

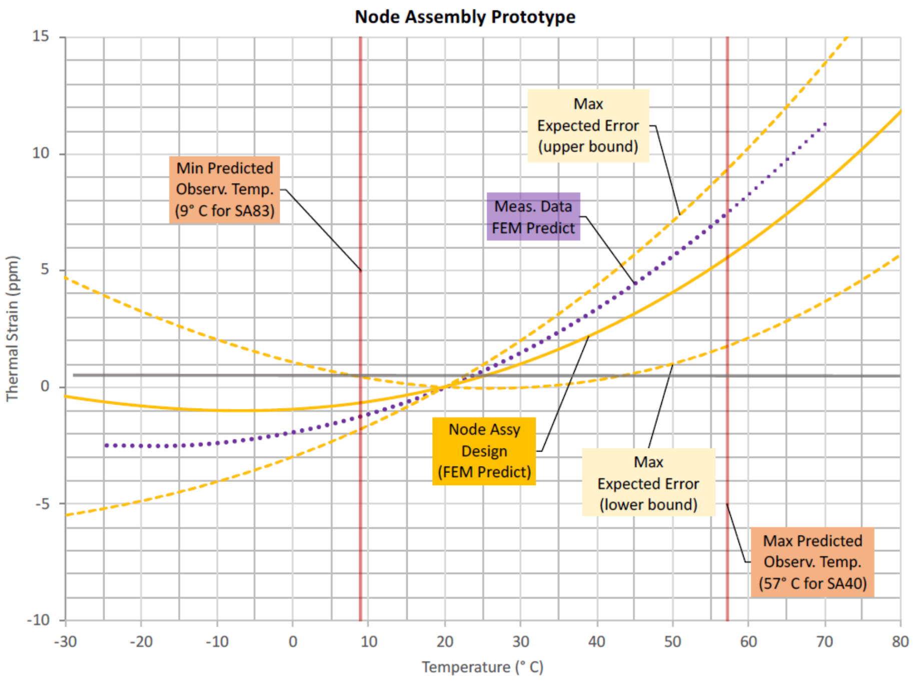
Approach:

- Validate thermo-elastic deformation finite element model using experiments on longeron, node test articles
- Use validated model to predict in-space thermal deformations of the inner disk

Used NG's Interferometric Metrology Facility (IMF) to measure critical dimensions of the longeron, node test articles over 70°C to -30°C temperature range

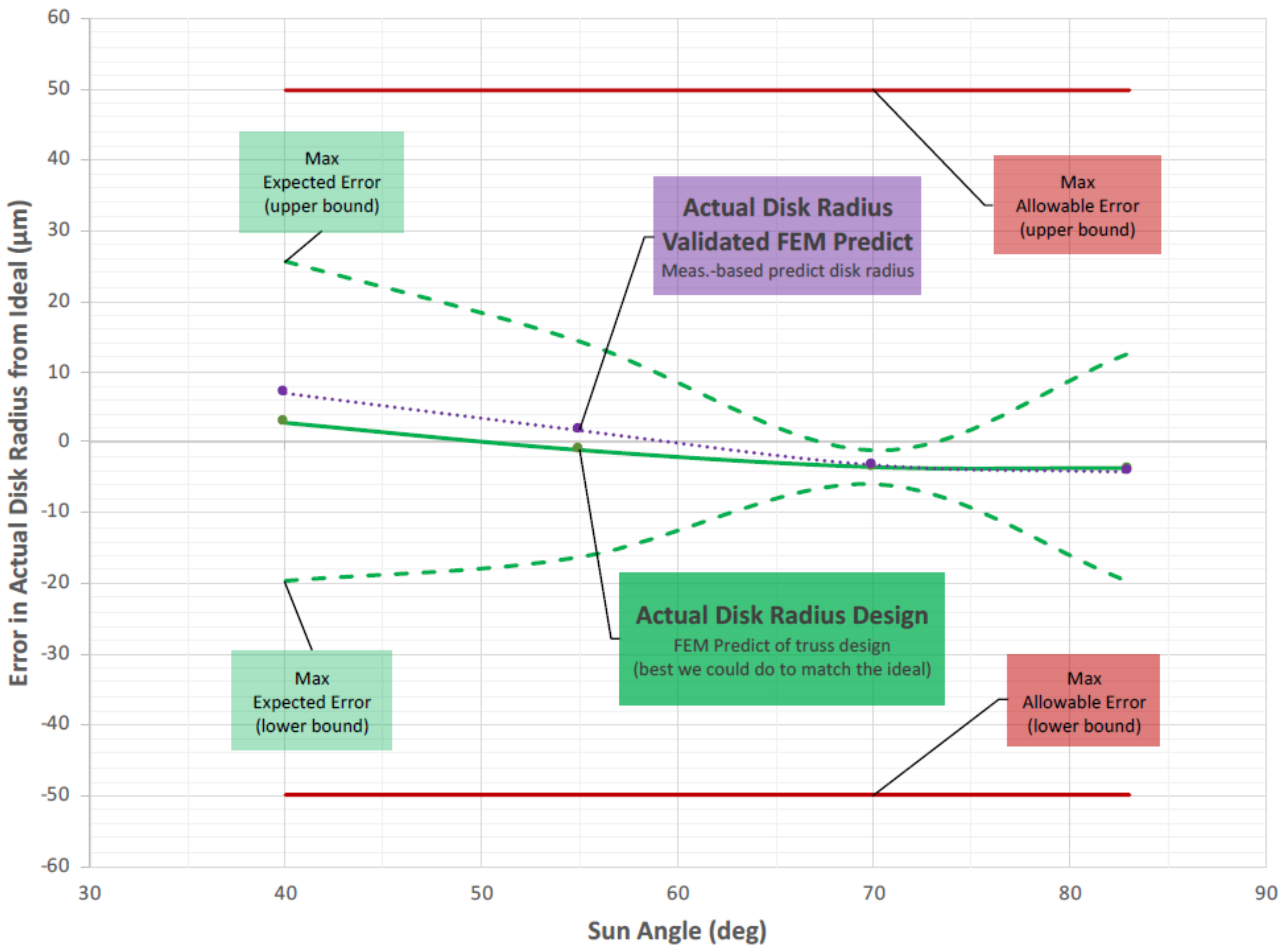
Validated model predicts change in dimensions well:





Inner Disk Thermoelastic Shape Stability

Validated model predicts in-space inner disk deformation well within allocations



OUTLINE

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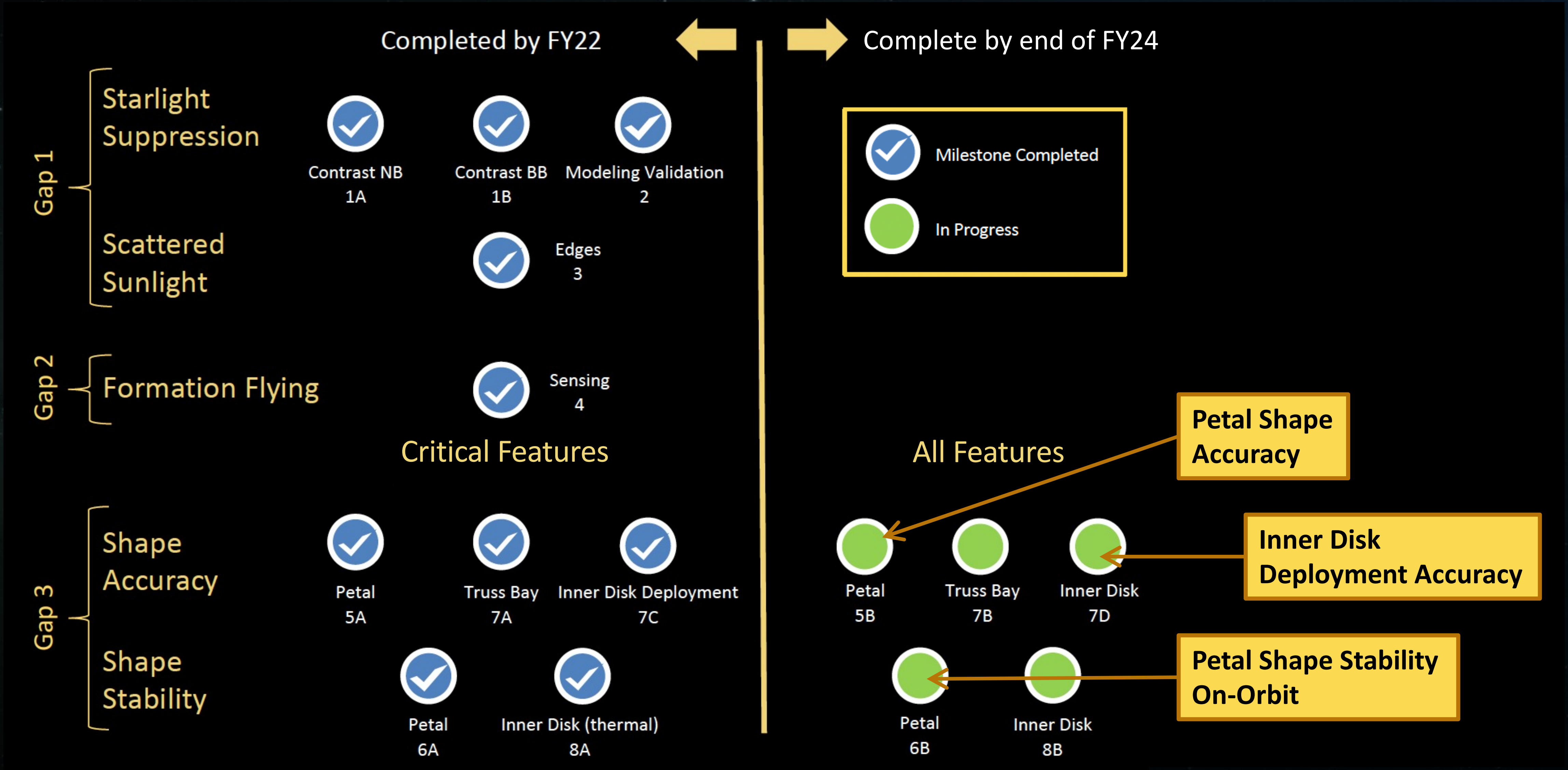
Path to TRL5: Closing Technology Gaps



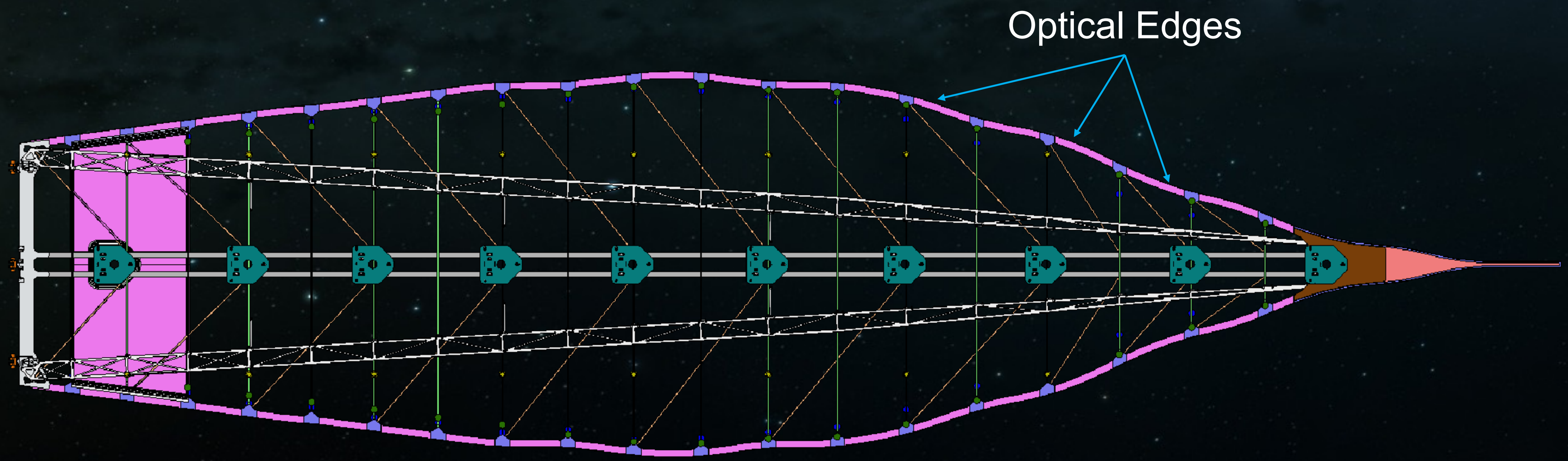
Overall "Starshade to TRL5" (S5) plan for closing technology gaps and S5 Milestone reports accessible at https://exoplanets.nasa.gov/exep/technology/starshade/

PETAL SHAPE ACCURACY

Milestone 5: Petal thermal-cycle stability & deployed accuracy (manufacturing, AI&T, storage, deployment)

MANUFACTURING

Milestone 5B: manufacturing accuracy goal for 8 m-long petal is <= 23 μm RMS

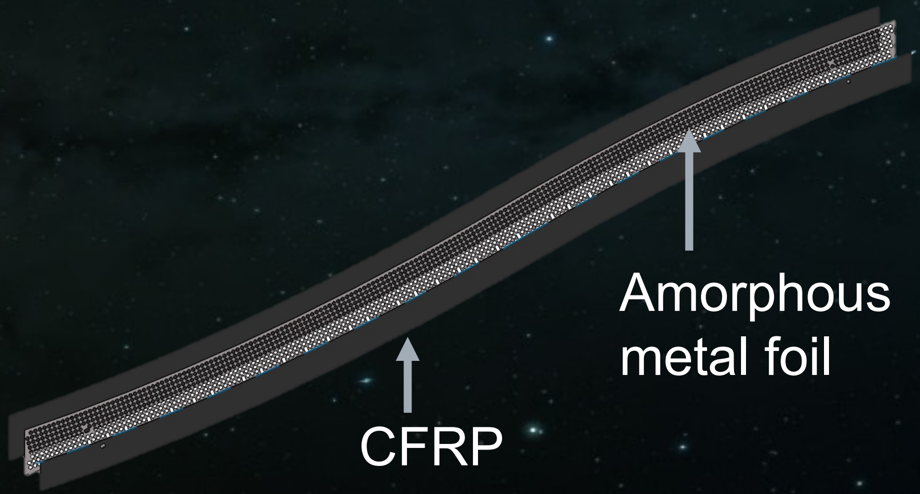


Petal Shape Accuracy

Milestone 5: Petal thermal-cycle stability & deployed accuracy (manufacturing, AI&T, storage, deployment)

MANUFACTURING

Milestone 5B: manufacturing accuracy goal for 8 m-long petal is <= 23 µm RMS



0.75m edge segment assembly

PETAL SHAPE ACCURACY

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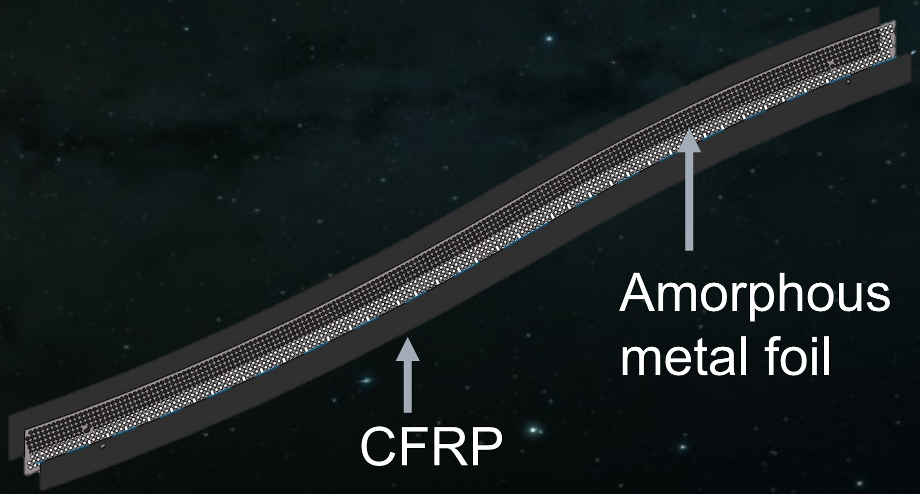

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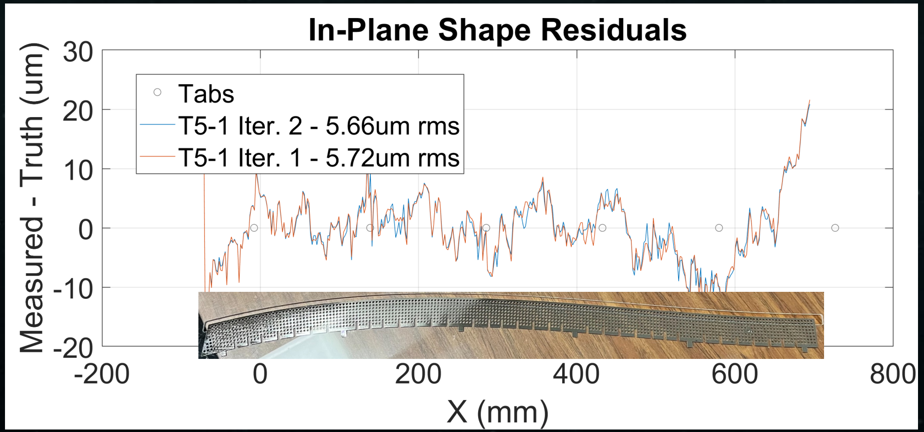

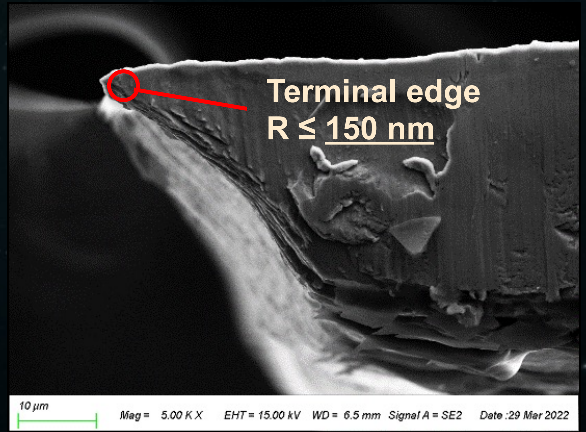

Etched amorphous metal foil with in-plane error of 6 µm RMS and terminal edge radius of 150 nm

Petal Shape Accuracy

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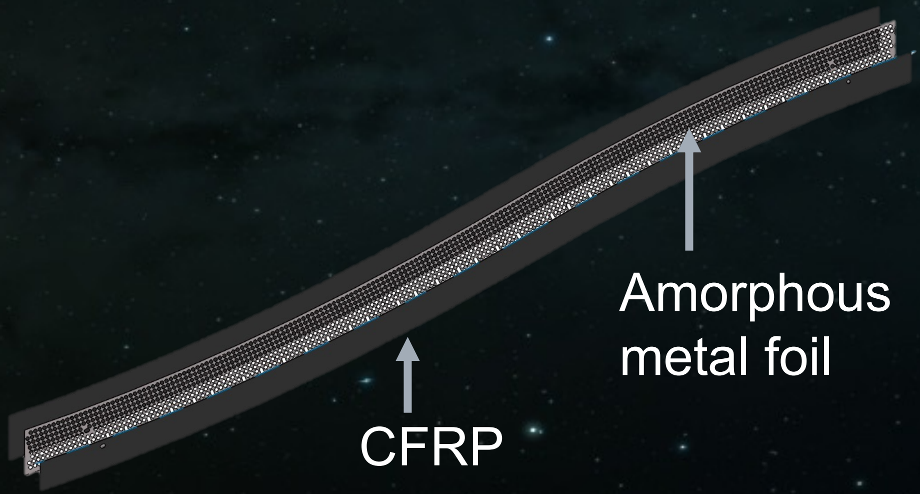
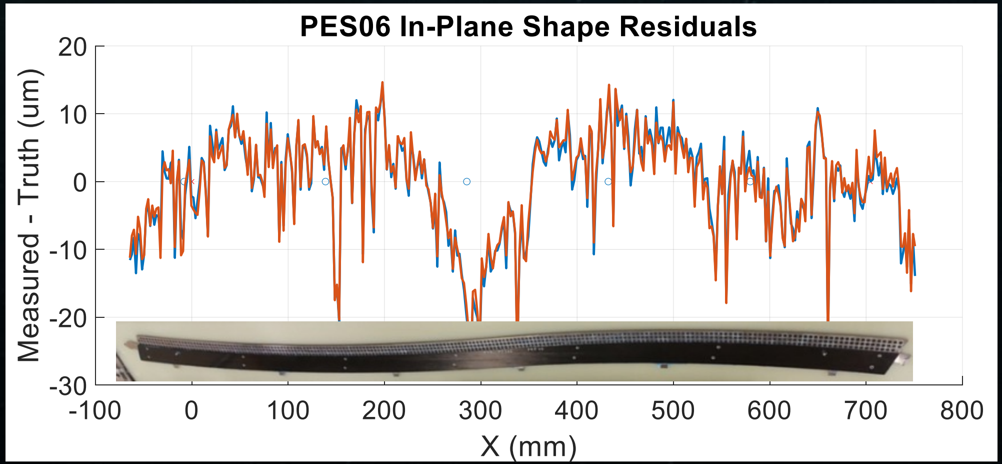


0.75m edge segment assembly

Built flight-like optical edges with 7 μm RMS accuracy and 1 μm RMS residual shape error after environmental testing



PETAL SHAPE ACCURACY

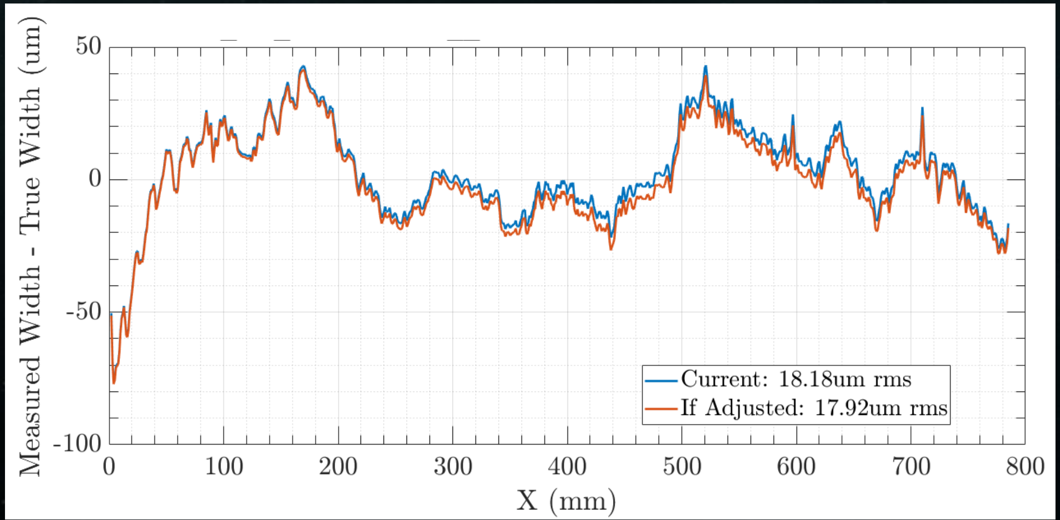
Milestone 5: Petal thermal-cycle stability & deployed accuracy (manufacturing, AI&T, storage, deployment)

MANUFACTURING

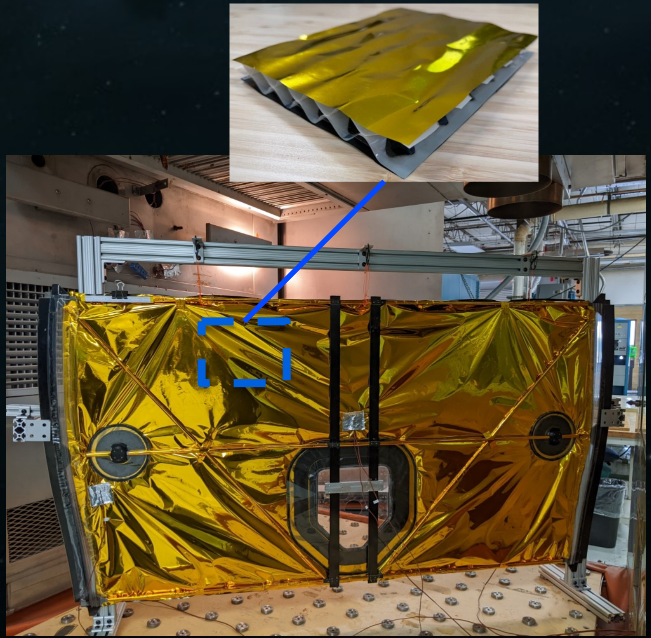
Milestone 5B: manufacturing accuracy goal for 8 m-long petal is <= 23 μm RMS

Built section of 6 m-long petal structure with 18 μm RMS accuracy and tested interfaces of petal frame to optical shield

6 m-long petal section being assembled



Measurement of petal width error after assembly



Petal frame to optical shield interfaces tested at -120ºC

Petal Shape Accuracy

Milestone 5: Petal thermal-cycle stability & deployed accuracy (manufacturing, AI&T, storage, deployment)

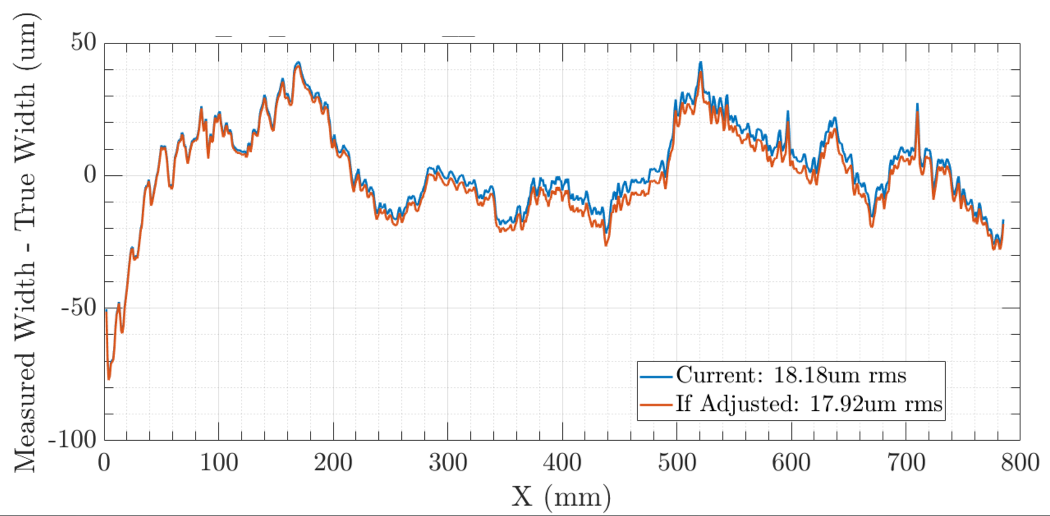
MANUFACTURING

Milestone 5B: manufacturing accuracy goal for 8 m-long petal is <= 23 µm RMS

Applicable to modular assembly concept of HWO 16 m-long petal

Built section of 6 m-long petal structure with 18 µm RMS accuracy and tested interfaces of petal frame to optical shield

6 m-long petal section being assembled



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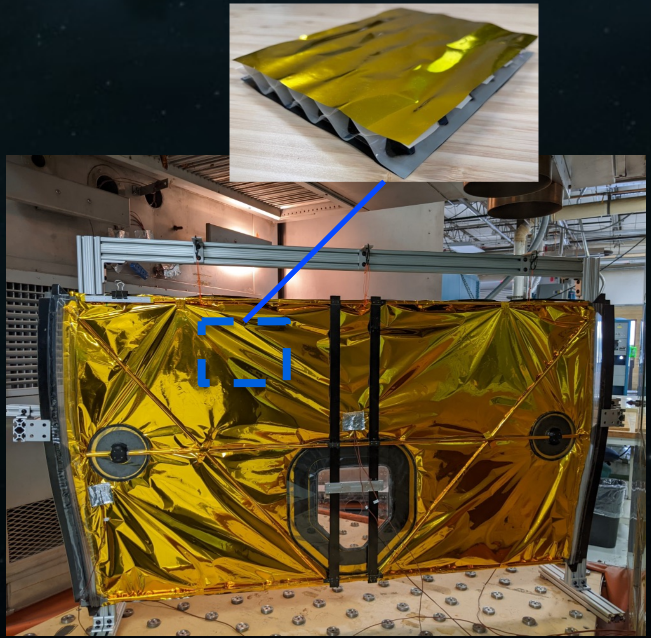
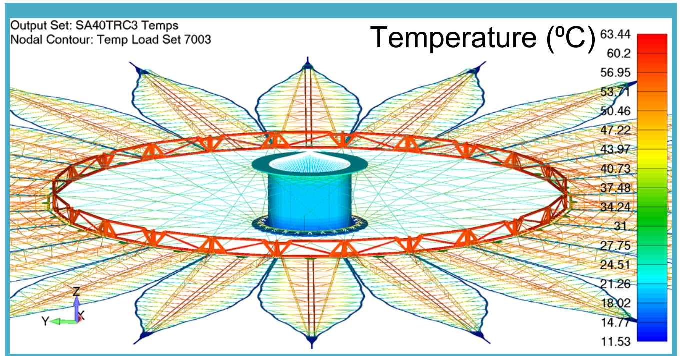


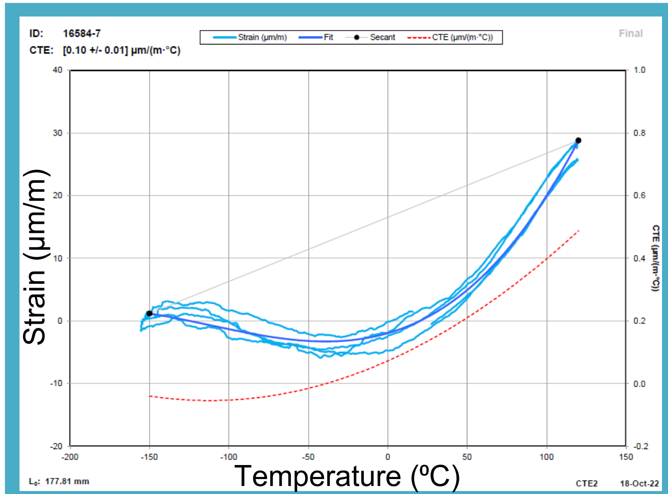
Petal frame to optical shield interfaces tested at -120ºC

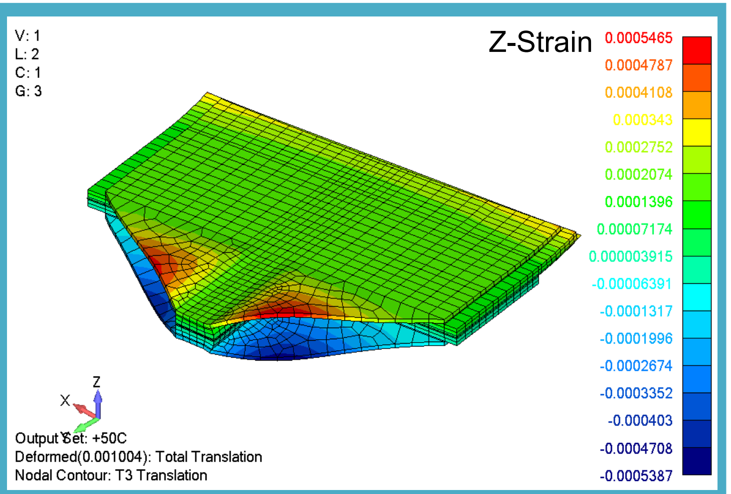
Petal Shape Stability On-Orbit

Milestone 6B: Petal subsystem with *all features* demonstrates on-orbit thermal stability

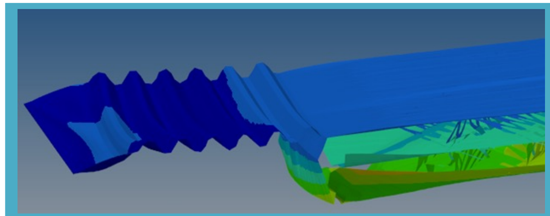


Updated thermal model of spinning starshade at several sun angles

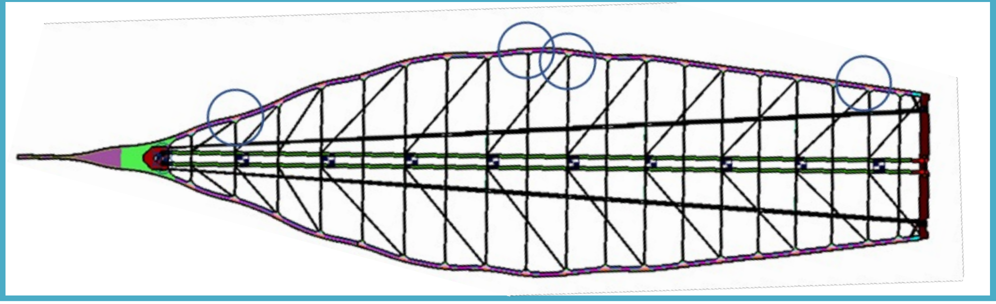




Built 3D petal joint model with new material properties from updated test data



Built petal structural model with all features: hinges, pop-up ribs, optical shield for on-orbit thermal stability predictions

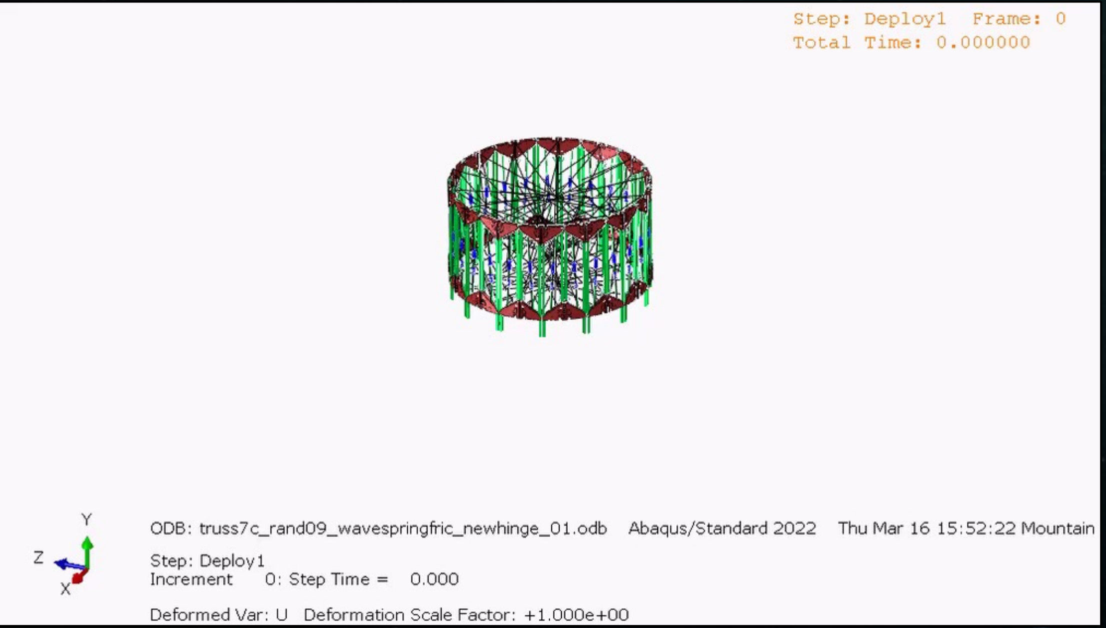


Petal structural model will be used to predict the elastic deformation of deployed petals due to thermal effects during science observations

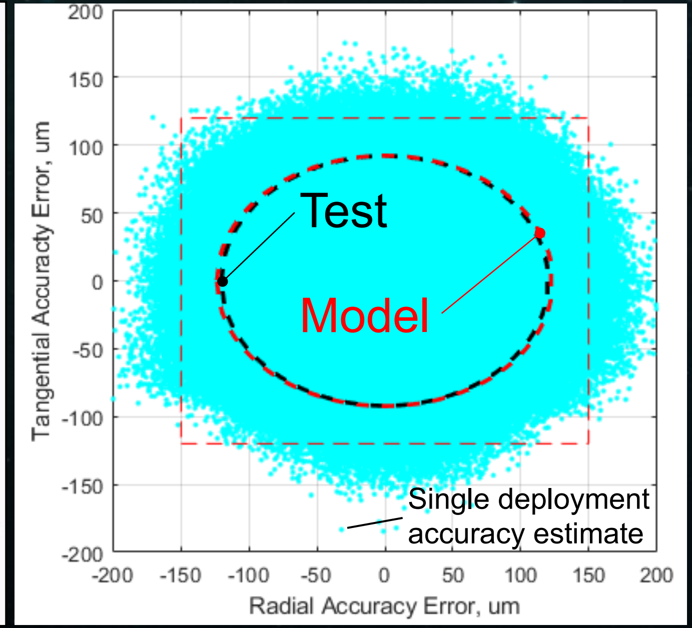
INNER DISK DEPLOYMENT ACCURACY

Milestone 7D: Inner disk subsystem with *all features* demonstrates deployment accuracy

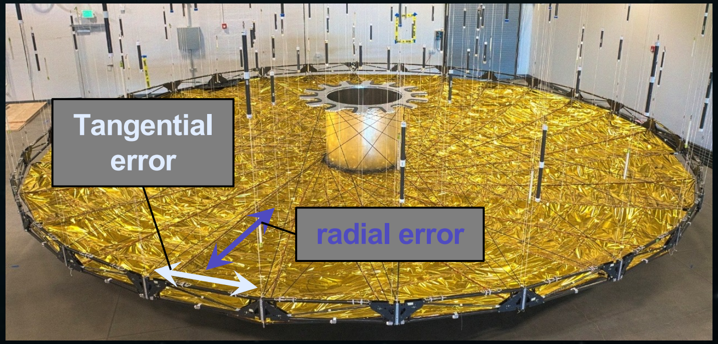
Developed inner disk deployment model that precisely replicates testbed results demonstrated by previous milestone (inner disk with critical features deployment accuracy), for model validation



Deployment model of inner disk testbed built for previous milestone



Accuracy Error 3σ, um			
	Test	**FEM**	**% Diff**
Radial	120.9	123.5	2.1%
Tangential	92.5	92.4	-0.1%

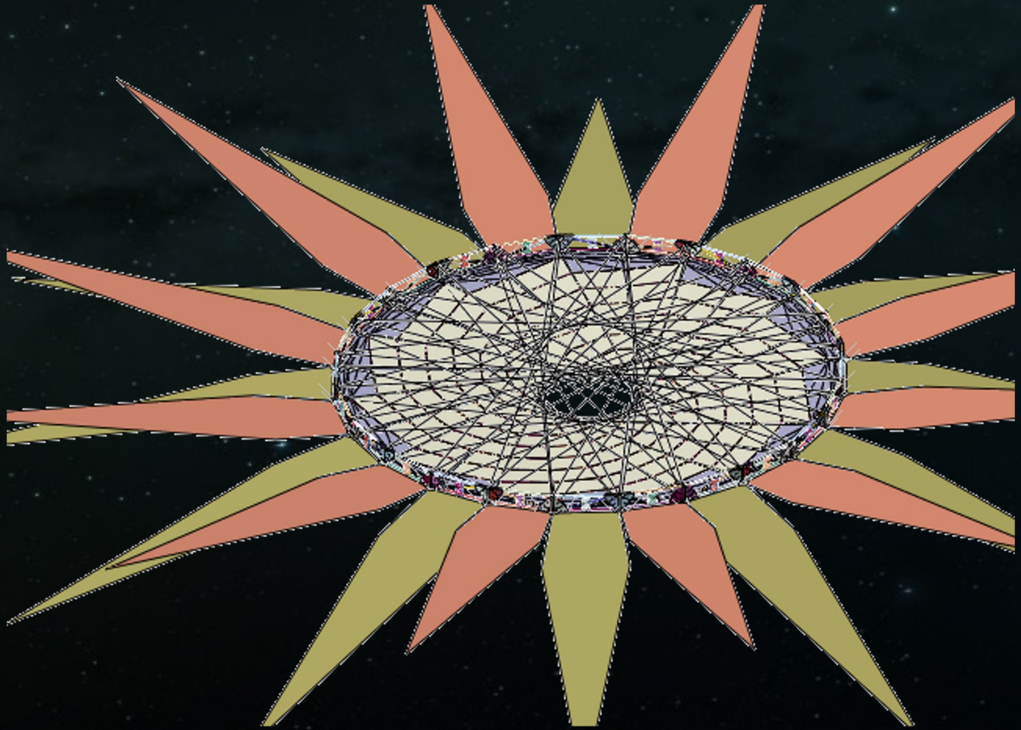


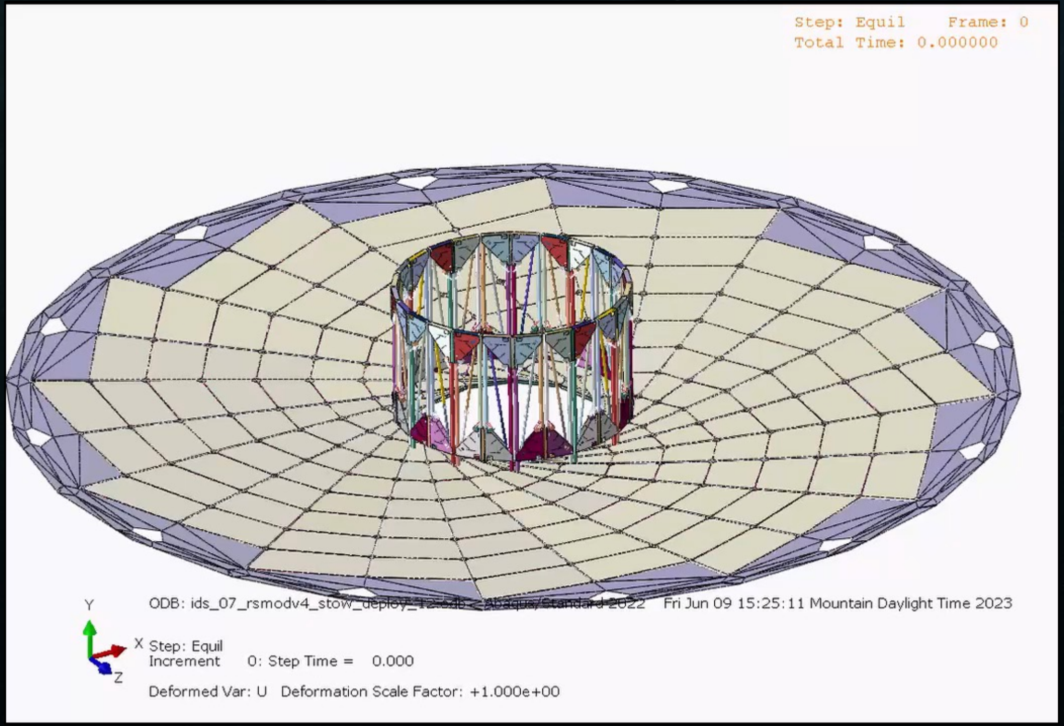
Model-test correlation results expressed in in radial and tangential accuracy errors

Inner Disk Deployment Accuracy

Milestone 7D: Inner disk subsystem with *all features* demonstrates deployment accuracy

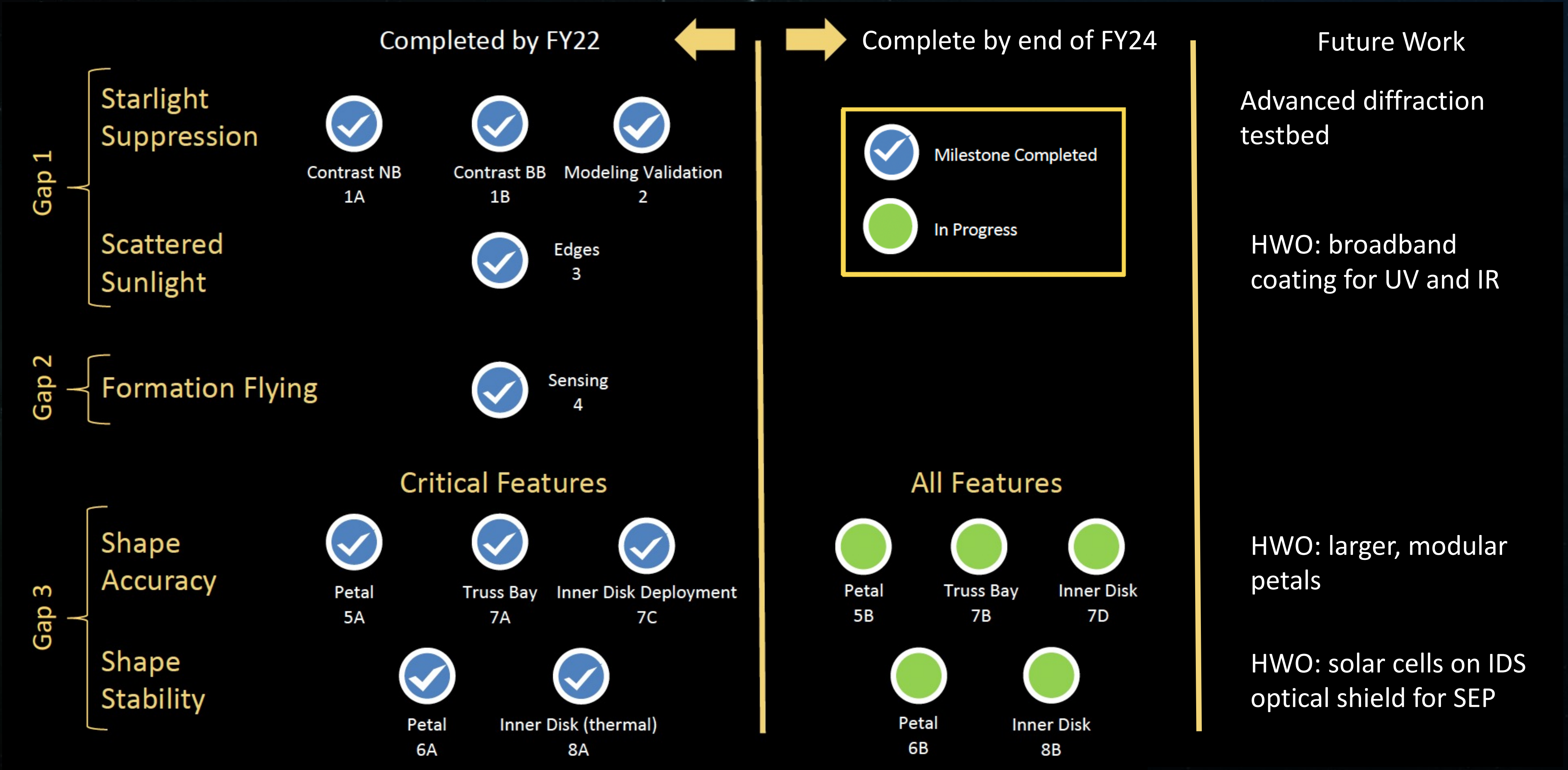
- Developed inner disk deployment model including all features (petals, updated optical shield design, optical shield to perimeter truss interfaces, updated perimeter truss geometry, etc.)
- Model will be used for sensitivity studies (cable friction, preload, hinge gaps, etc.) and on-orbit deployment predictions





Deployment model of new inner disk (petals hidden in deployment video)

Path to TRL5: Closing Technology Gaps



Overall "Starshade to TRL5" (S5) plan for closing technology gaps and S5 Milestone reports accessible at https://exoplanets.nasa.gov/exep/technology/starshade/

OUTLINE

1. Starshade Mechanical and Deployment Architecture
2. Mechanical Technology Development
3. Current Work
4. Future Steps

Mechanical Steps Towards 60 meter Starshades

Reference concepts for S5 effort:

- Starshade Rendezvous Mission (SRM), 26 meter starshade
- HabEx, 52 meter starsahde

What is needed to demonstrate mechanical technology readiness for a starshade suited for HWO?

60 meter dia. (16 m-long petals, 28 m-dia. disk)

1. Petal manufacturing shape accuracy at relevant scales
   - Have demonstrated this at ~1.6 m petal width, but HWO starshade designs have 4.4 m petal width; will need new approach to build larger petals
   - Novel petal construction methods will require investigations into:
2. Petal thermoelastic shape stability
3. Petal deployment, thermal-cycle, and storage shape stability

4. Inner disk deployment accuracy
   - Demonstrate with integrated solar array
5. Inner disk thermoelastic shape stability
6. Inner disk thermal-cycle and storage shape stability

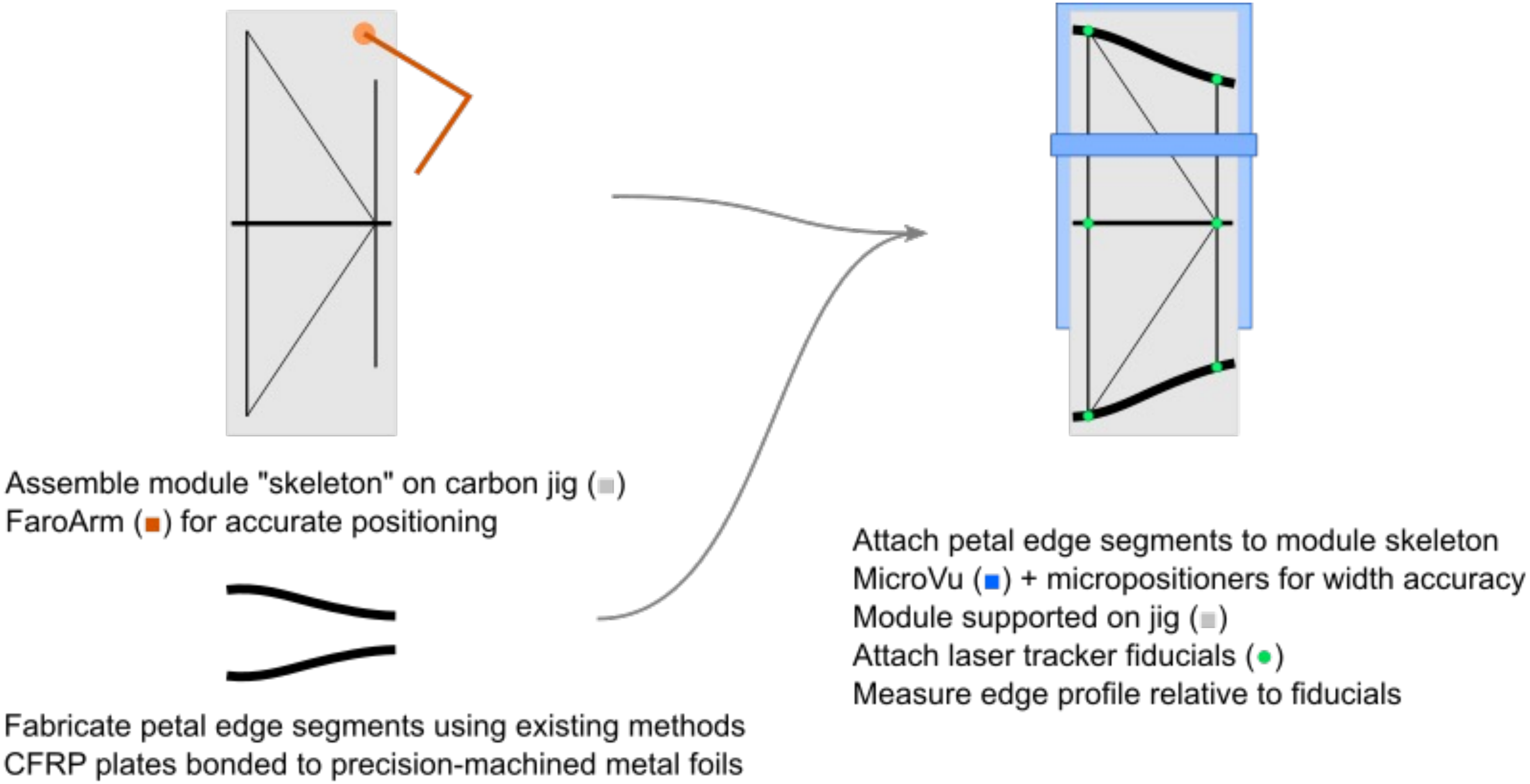
BACKUP

STEPS TOWARDS ~60-METER-CLASS STARSHADES

Building large ~17 m-long modular petals

Exploit and combine proven approaches:

- Build accurate petal “modules”
- Module size comparable to current petal test articles
- Stitch modules together to make larger petal



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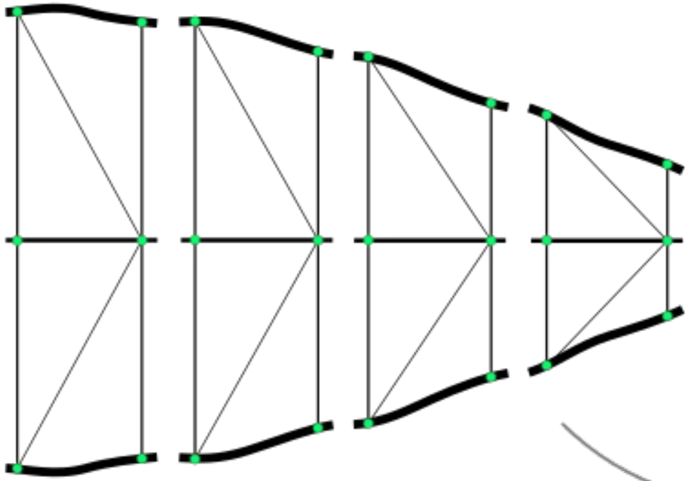
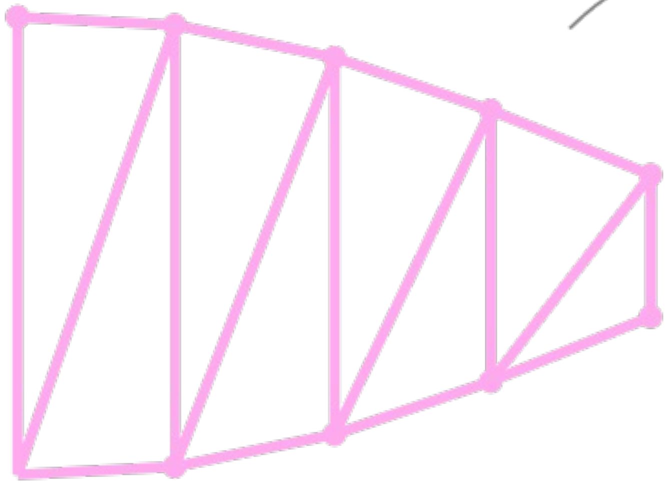
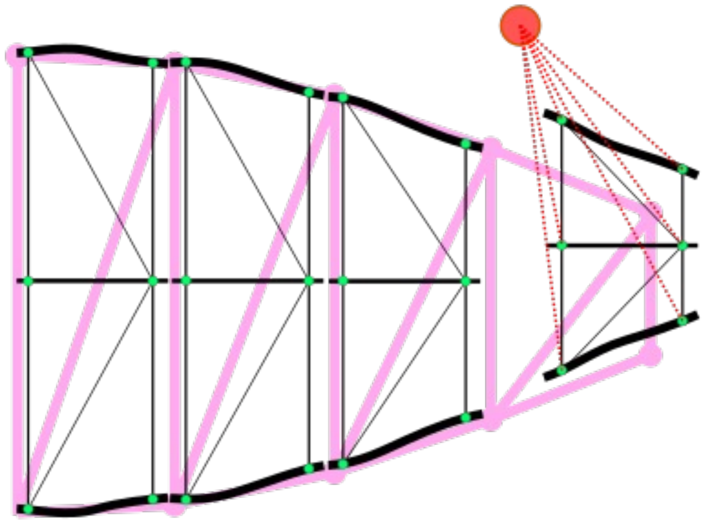


Fabricate 4x modules



Assemble partial petal "strongback" (■)
Stiff, stable, 3D truss structure
Off-the-shelf CFRP tubes, metallic nodes



Stitch 4x modules together on partial strongback
Laser Tracker (●) metrology of module fiducials (●)
Micropositioners to adjust module rigid-body positions
Flexures support modules without in-plane deformation

STEPS TOWARDS ~60-METER-CLASS STARSHADES

Initial estimates of tolerances and associated contrast degradation at the inner working angle fall within error budget allocations for large starshades

Error Source	Tolerance (±μm)	IWA Contrast
Edge segment bonding	16	0.8e-13
Module fabrication metrology	43	9.7e-13
Module-to-Module assembly	60	0.9e-13
Thermal strain during assembly	20	0.4e-13
Miscellaneous (see text)	43	0.7e-13
Petal assembly shape tolerance	**100**	**1.25e-12**
Petal width bias (furling, storage, hygroscopic)	180	2.5e-13
TOTAL (all pre-launch errors)	204	1.5e-12

Table 2: Max-expected petal shape manufactured error. Tolerances are combined in quadrature while contrast is a simple summation.

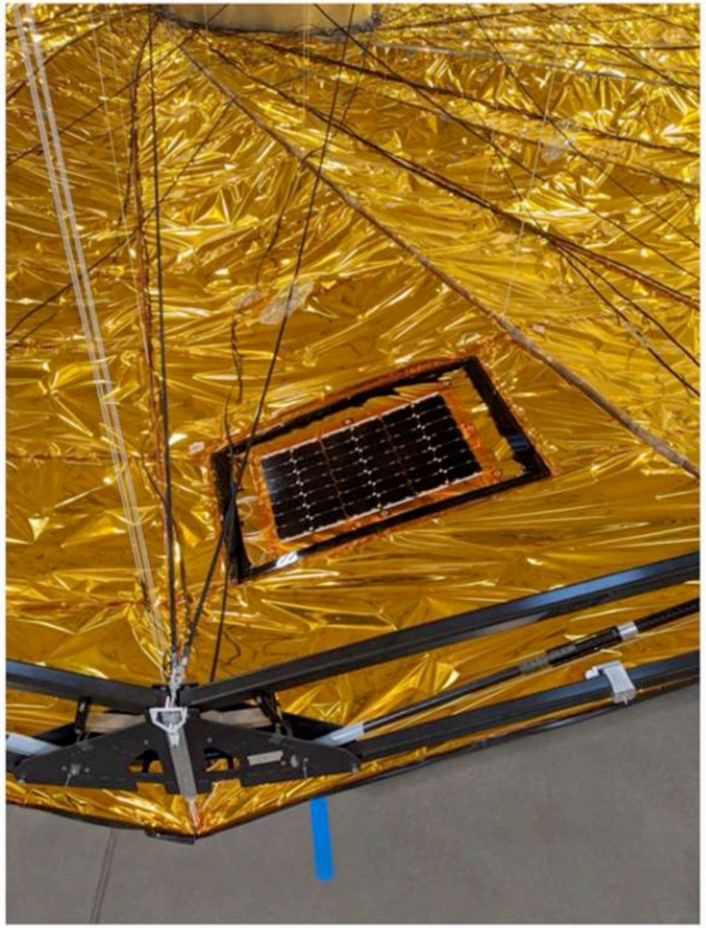
STEPS TOWARDS ~60-METER-CLASS STARSHADES

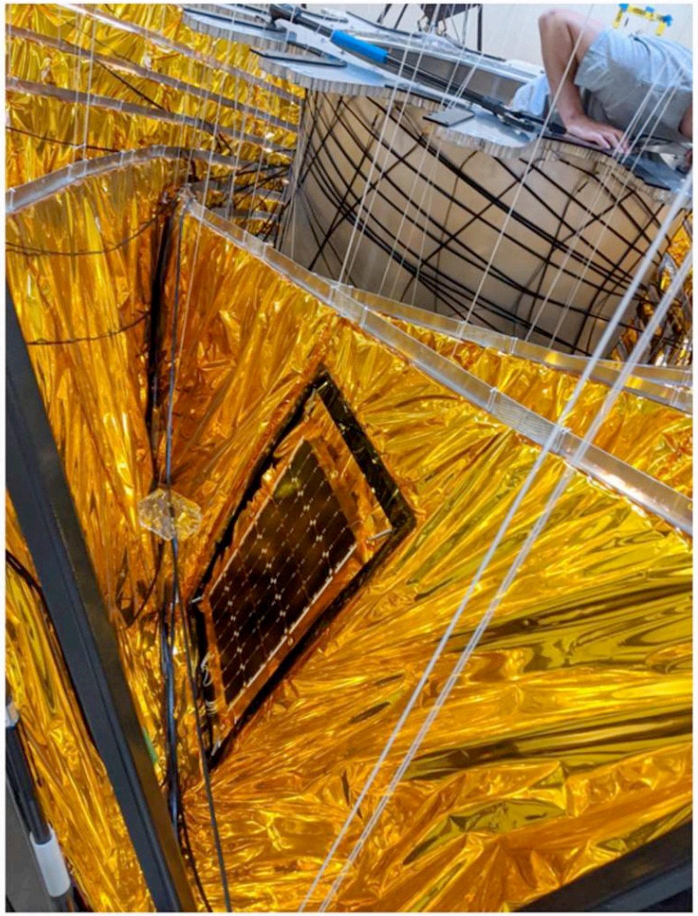
Large starshades will need to be propelled by solar-electric propulsion

Put PV cells on IDS OS

Preliminary studies have already demonstrated that the current inner disk optical shield design can host PV cells (stow-deploy testing showed no degradation)

Further design and testing is needed, especially with regards to power harnessing for DC power delivery from OS to hub





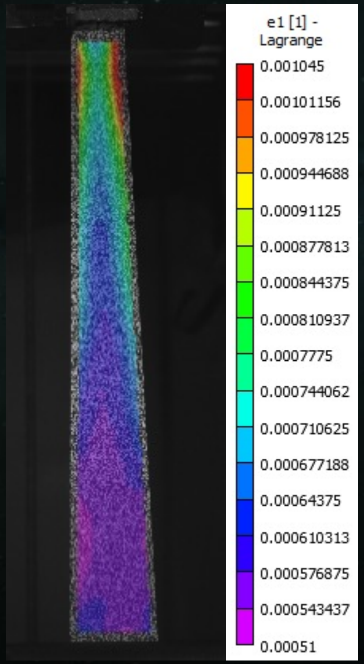
Summary of S5 Mechanical Milestones

- Optical Edges: sharpness, coating
- Petals: 4 m with environmental test, precision shape, 5 m precision shape
- Inner Disk: 10 m with origami shield, precision deployment

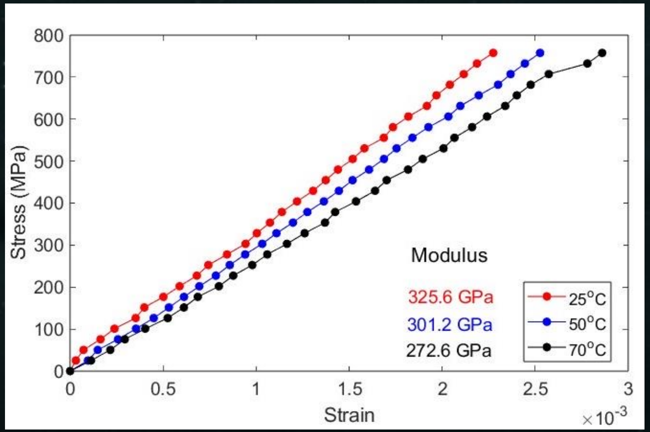
Ongoing Numerical Studies for Viscoplasticity

Objective is to predict viscoplastic behavior of starshade petal and IDS to estimate residual deformation after **storage**

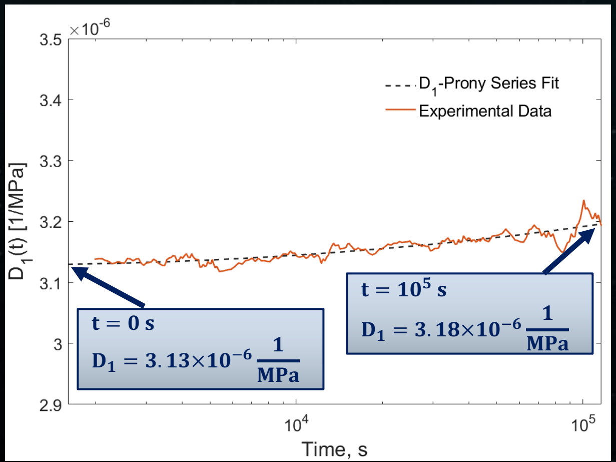
- Completed time-dependent material model based on tests conducted on samples of M55J/PMT-F6
- Material model will be used in FE analysis to predict the viscoplastic deformation of furled petals and stowed truss bay due to creep effects



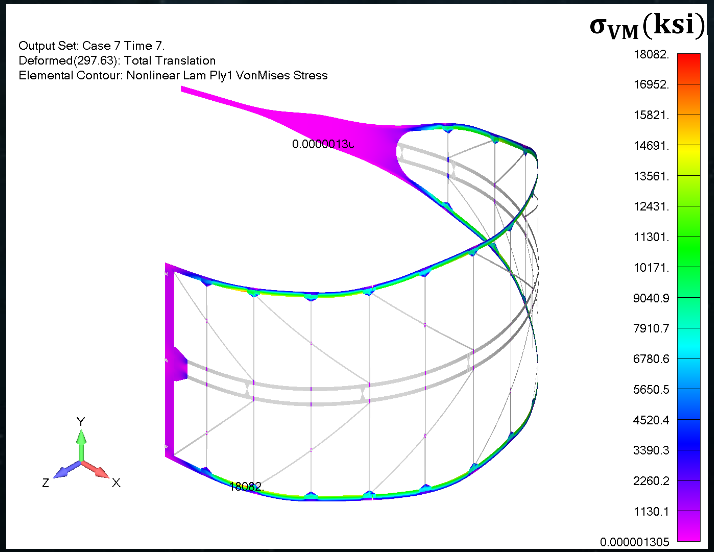
Material tests of unidirectional, trapezoidal samples under axial load and room temperature



Stress/strain curves at temperature



Time-temperature superposition principle: creep compliance modulus



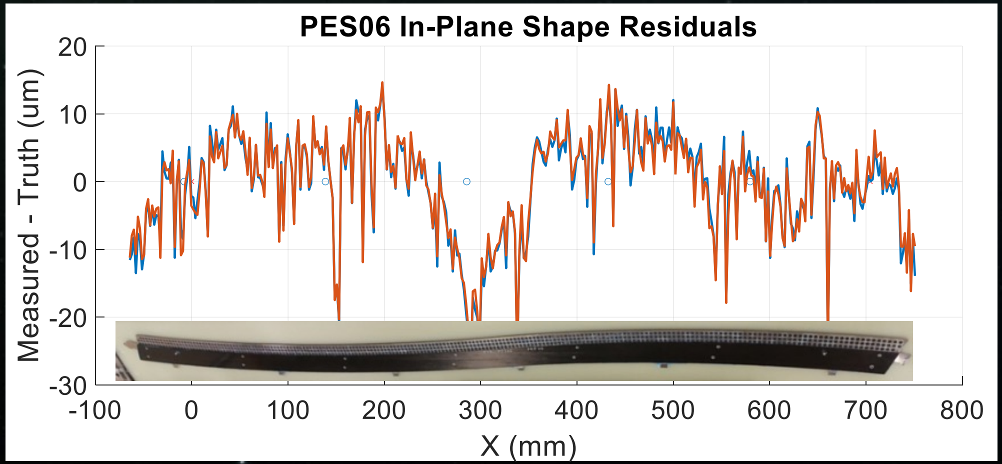
Elastic FE model. Viscoplastic model of furled petal will be implemented

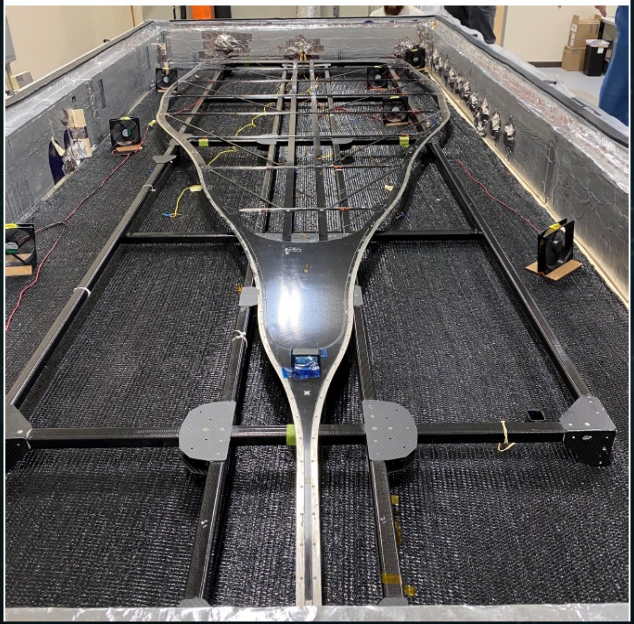
Petal Shape Accuracy and Stability (Gap 3)

Key performance parameters for 8 m-long petal

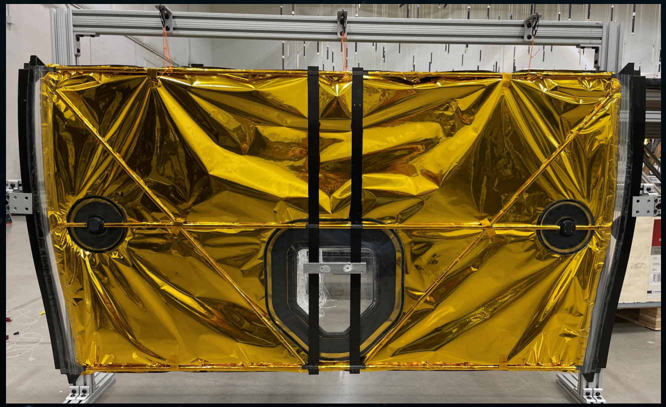
- Pre-Launch Shape Accuracy <= 70 μm
- On Orbit Thermal Stability <= 24 ppm

Built flight-like optical edges with ~7 μm rms accuracy and ~2 μm rms residual shape error after environmental testing





Built and tested 4 m-long prototype. Test-validated finite element model predicts on-orbit thermal stability within allocation



Built section of 6 m-long prototype to test interfaces (e.g. petal frame to optical shield)

Inner Disk Deployment Accuracy (Gap 3)

Inner disk deploys by winding a cable that runs through the perimeter truss