# Wrapped Petal Starshade Mechanical Architecture

## Summary Slides

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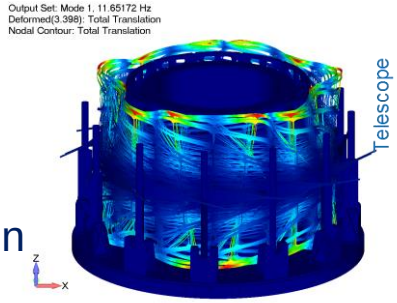
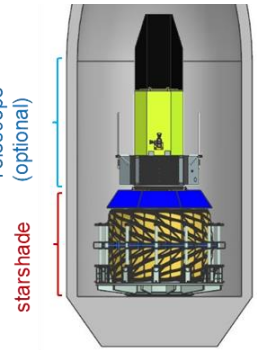
# Mechanical System Summary

## Stowed Analysis Summary

- 1st major lateral mass mode is at 51 Hz (Req't 10 Hz)
- 1st major axial mass mode is at 142 Hz (Req't 25 Hz)
- Strength margins of safety > 2.7
- Meets launch requirements for mission with telescope on top




Stowed config shown co-launched w/1.1m telescope (5m fairing)

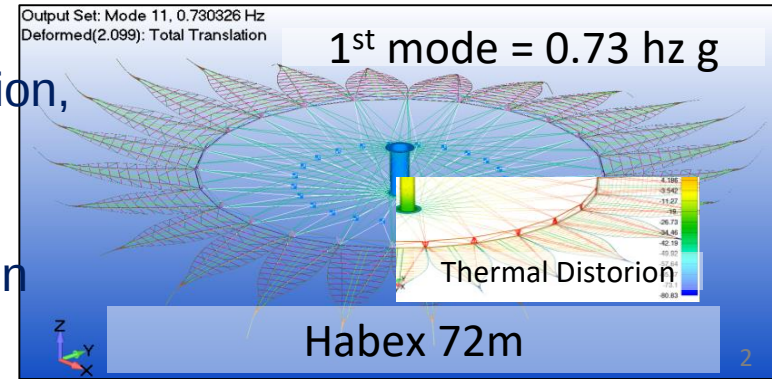
## Deployed Analysis Summary

- 1st mode is high at > 1 Hz, 1st in-plane at 17.3 Hz
- High margins
  - Structure Instability due to Spoke Pre-tension
  - Slacking spokes from retargeting thruster fire & thermal loads
- Contrast has low sensitivity to spoke preload or length variation & fault tolerant to missing (broken) spokes

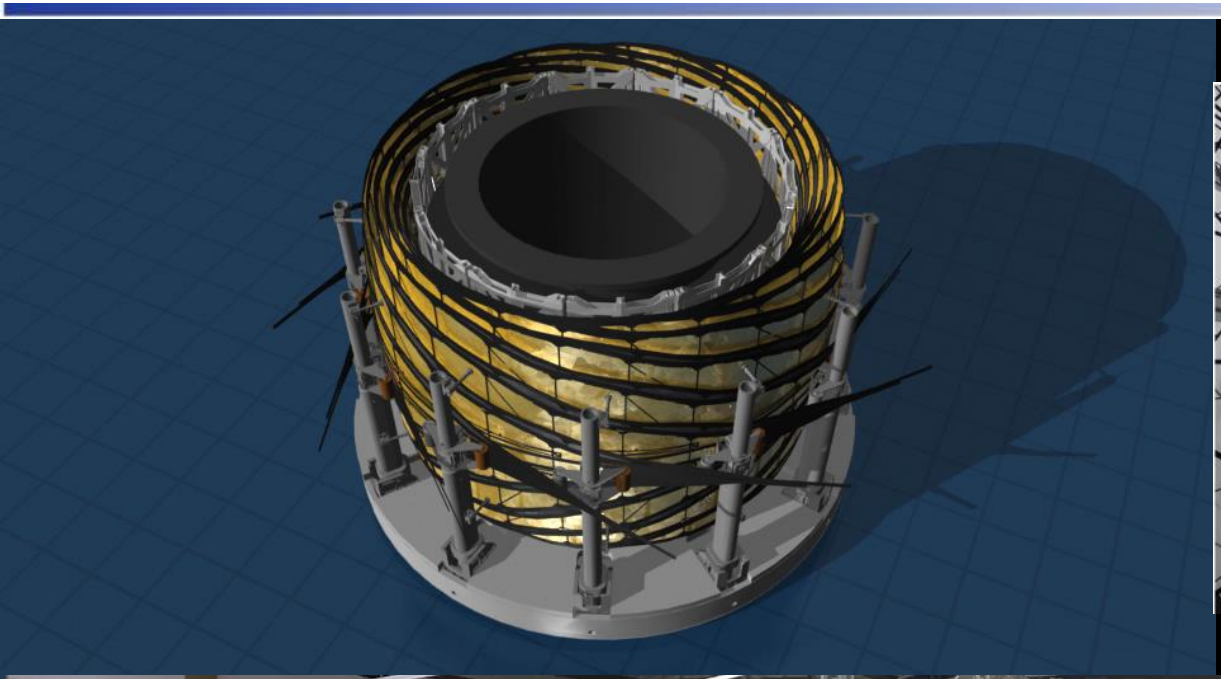
Demonstration of starshade development model

## Scalability

- Habex 72m Baseline Design scales in configuration, deployed structural analysis & thermal stability performance (STOP)
- Falcon 9 up to 92m & SLS 150m per configuration study



# PLUS Visualization & Hardware Deployment Overlay

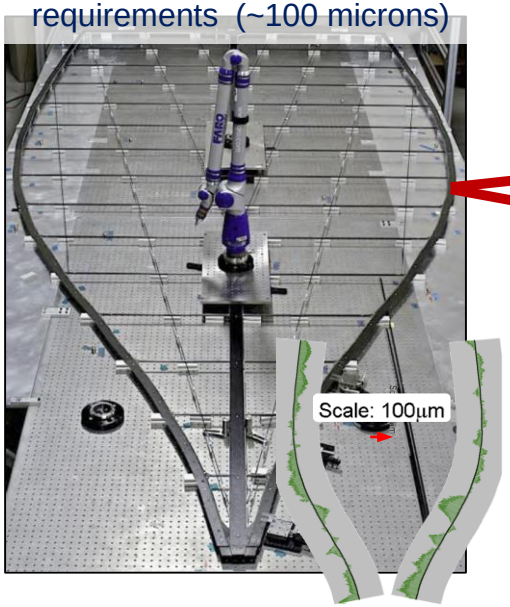


- PLUS testbed incipient deployments w/future upgrades to include medium fidelity launch restraints, rollers, and a pair of medium fidelity CFRP petals (simulators to serve as boundary conditions for pair of interest), more in TRL discussion

# Contrast At Max Expected Values

## *Total contrast well below shape error allocation of 3.36 x $10^{-11}$*

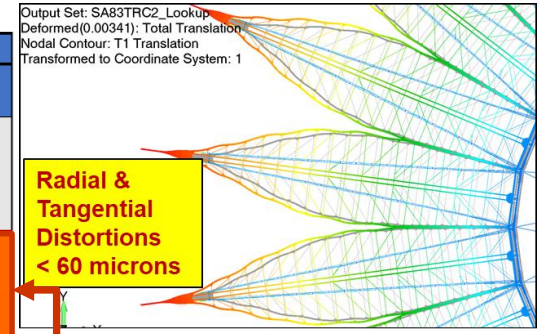
Petal manufactured shape meets flight requirements (~100 microns)



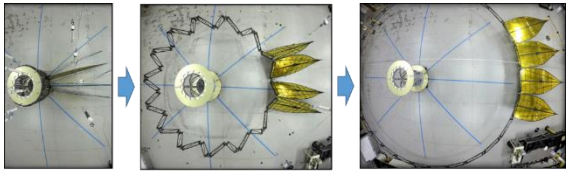

| Error Effect \ Error Source | | Ground: Manufacture | Ground: AI&T | Ground: Storage (creep) | Launch & Cruise: Launch | Launch & Cruise: Pre-deploy (creep) | Launch & Cruise: Deploy | On-Orbit: Materials (creep/moisture) | On-Orbit: Dynamics (thrusters) | On-Orbit: Thermal |
|---|---|---|---|---|---|---|---|---|---|---|
| In-Plane Starshade Shape | 1. Edge Segment Shape | 12 % | Carried under Petal Shape (Row 3) | | | | | | | |
| | 2. Edge Segment Position on Petal | | | | | | | | | |
| | 3. Petal Shape (incl. non-kinematic) | 5% | 3E-14 | 4E-16 | 9E-14 | 1E-14 | 2E-14 | 1E-13 | 5E-16 | 7 % |
| | 4. Petal Position on Disk | Carried under AI&T | 2 | 6E-14 | | | | | | |
| Out of Plane Starshade Shape | 5. Petal Shape | | | | 1E-14 | | | | | |
| | 6. Petal Position on Disk | | | | | | | | | |

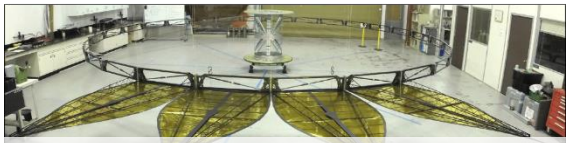
1.6% of Shape Error Allocation

% above is for total shape error allocation

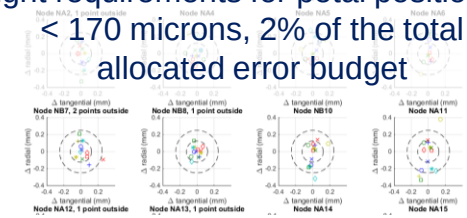


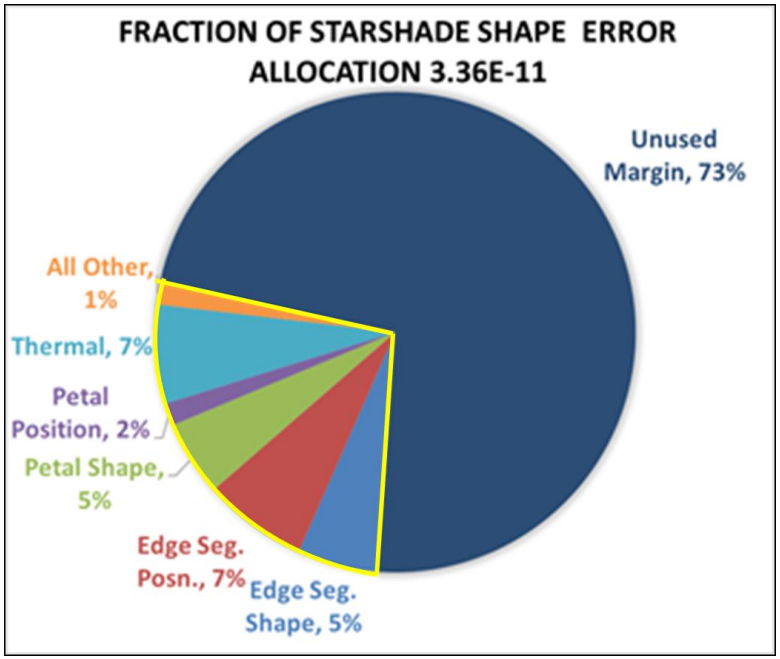

Thermal analysis at 2 design points (26m & 72m) shows thermal stability errors @ <7% of total error budget

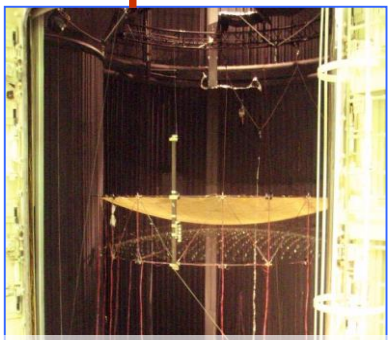




Perimeter truss has demonstrated flight requirements for petal position @ < 170 microns, 2% of the total allocated error budget





SMAP TRL6 TVAC Testing provides confidence in ability to achieve petal position on-orbit stability

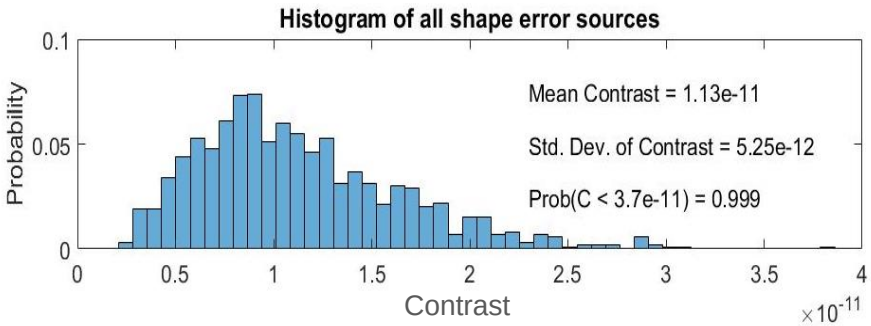
85 microns random = **4 x $10^{-13}$**

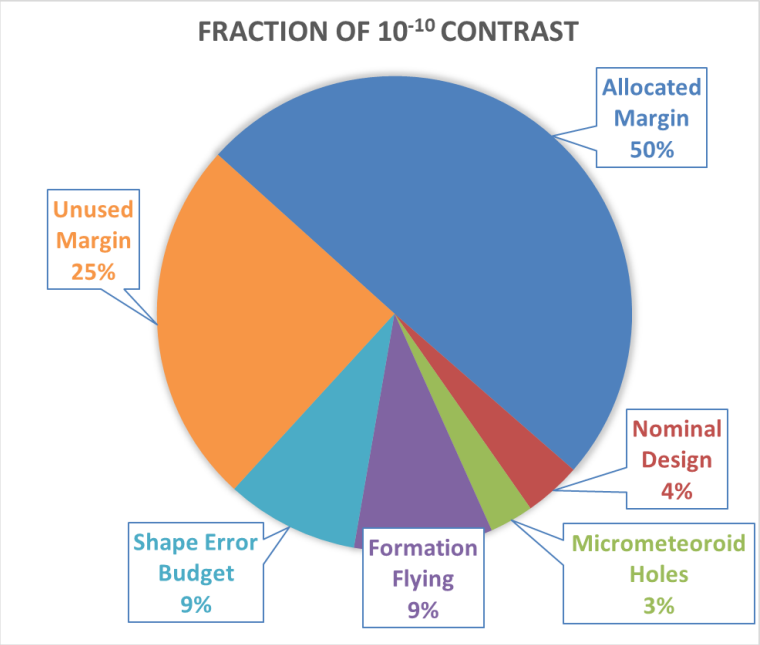
Model validation 7% typ

# Summary

## *Performance Goals met with Large Margin*

- ✓ **M-1: Meet on-orbit deployed shape stability and optical performance requirements**
  - ✓ W-1a: Credibly show at least 100% margin on driving Technical Performance Metrics (TPMs)
- ✓ **M-2: Deploy accurately and reliably to the desired shape**
  - ✓ W-2b: Credibly show at least 100% margin on derived deployment accuracy requirements
- All key errors modeled in detail.
- All CBEs look reasonable
  - Major sources of shape errors are edge segment positions and petal width and shape
- Stiff, stable truss accounts for just 6% of shape error budget, and just 1.5% of shape error allocation.
- Excellent thermal performance.
- Agreement between Top-Down Monte-Carlo and bottom-up Error Budget
- High probability of success At Max Expected Errors, with 100% contingency on all.

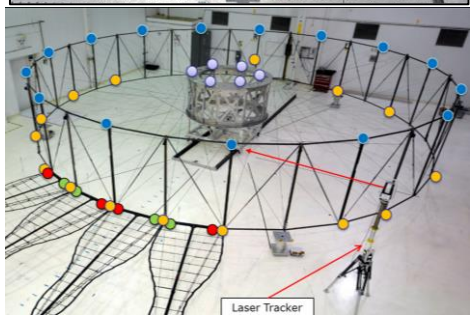


# Path to WFIRST Rendezvous

***Completed demonstrations of manufacturing & deployment tolerances***

TDEM-09: Petal Manufacture




TDEM-10: Disk Deploy

**2013** — Structure Sub-assy's at TRL-4

***Verify critical assy perf. in lab environment***
- *optical edges*
- *disk optical shield*
- *disk spokes*

*And characterize materials:*
- *petal battens*
- *disk longerons*
- *disk spokes*

On-going Efforts

**May 1 2019** — All Sub-assy's at TRL-4

***Verify critical Subsystem perf. in relevant environments:***
- *-½ scale Petal*
- *-Full-scale Truss Bay*
- *-Full-scale Inner Disk*
- *-Full scale PLUS*

Future Efforts

**Oct. 1 2019** — All Subsystems at TRL-5

***Partial System testing & TRL-6 pathfinder***

*Also demonstrates Habex readiness to Decadal Survey*

***Verify Full System perf. in relevant environments***

**Oct. 2023** — Starshade System at TRL-6

***Qualify Design w/ Proto-flight System*** *(flight unit)*

**Oct. 2026** — Starshade System at TRL-8

***System I&T***

**Oct. 2027** — Starshade is Launch Ready

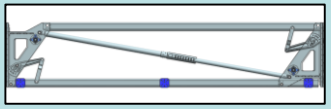
***All dates satisfy trade study criteria with large margins:***

***M3: TRL-4 by May 2019 (req'd is Nov. 2019)***
***M4: TRL-5 by Oct. 2019 (req'd is Oct. 2021)***
***M5: TRL-6 by Oct. 2023 (req'd is Jan. 2026)***
***M5: Launch Readiness by Oct. 2027 (req'd is Sept. 2028)***

# TRL-5 Test Activities NEW Plan w/addl. prototypes PRE-Decadal

**Decadal input (Nov. 19)**

**Full-Scale (1.3-m long)**



**Unit A**

**Unit B**

**Inner Disk Truss Bay (P5-1)**

*Verify Truss Longeron & Node components length:*
***- as-manufactured***
*- after **thermal cycles***

***Validate** Truss Longeron & Node component model of:*
***length vs. I/F Load***
***length vs. temp***

**Unit A**

*Verify Truss Bay length*
***as manufactured***
***Test 5-1***

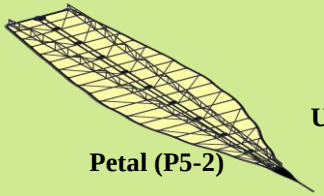
***Validate** Truss Bay model of **length vs. temp.***
***Test 5-2***

**Unit B**

*Verify Truss Bay shape:*
***- as-manufactured***
*- after **thermal cycles***
*-after **storage with creep***
***Tests 5-1, 5-5, 5-6***

***Validate** Truss Bay model of **length vs. I/F Load***
***Test 5-3***

**Full width (~1.6m), thickness (1.6cm), foreshortened length (4m)**



**Unit 1**

**Unit 2**

**Petal (P5-2)**

*Meas. Petal shape:*
***as-manufactured***
*Verify Petal shape:*
*after **deploy cycles,***
*after **thermal cycles***
***Tests 5-1, 5-4, 5-5***

***Validate** Petal model of shape vs. I/F load*
*Test 5-7*

***Validate** Petal model of **shape vs. temp.***
***Test 5-8***

*Cont. design of edge, shield & DCS I/F's*

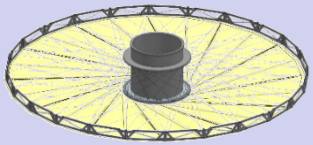
*Final Petal Design*

*Verify petal shape as-manufactured*
*Test 5-1*

*Verify petal shape after **deploy cycles***
***Test 5-4***

*Validate Petal model of shape vs. I/F load*
*Test 5-7*

**Full-Scale (10-m dia.)**



**Inner Disk (P5-3)**

*Verify repeatable Disk*
***deploy tolerances***
***w/ POC Optical Shield***
*(after verifying opacity)*
***Test 5-9***

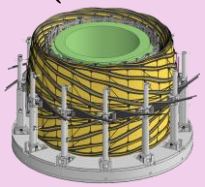
*Verify OS opacity at truss-bay & petal I/F's*
***Test 5-12***

***Validate** Disk model of shape vs. spoke load*
*Test 5-11*

*Verify repeatable Disk*
***deploy tolerances w/***
***TRL-5 Optical Shield***
*(after verifying opacity)*
***Test 5-9***

***Validate** Disk model of **deployment kinematics***
***Test 5-10***

**Full-Scale (2.2-m inner dia.)**



**Deploy. Control System (P5-4)**

*Verify DCS unfurls with no edge contact*

***Test 5-13***

***Validate** DCS model of **deployment kinematics***

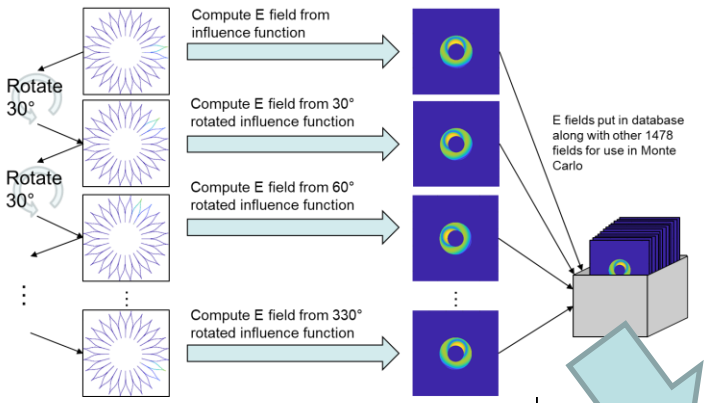
***Test 5-14***

*Additional PLUS sub-assy test verification work (TBD):*
*e.g. vibe, cold test,*

*TBD work as needed: Early environmental tests of critical sub-assys if needed to define sub-system*

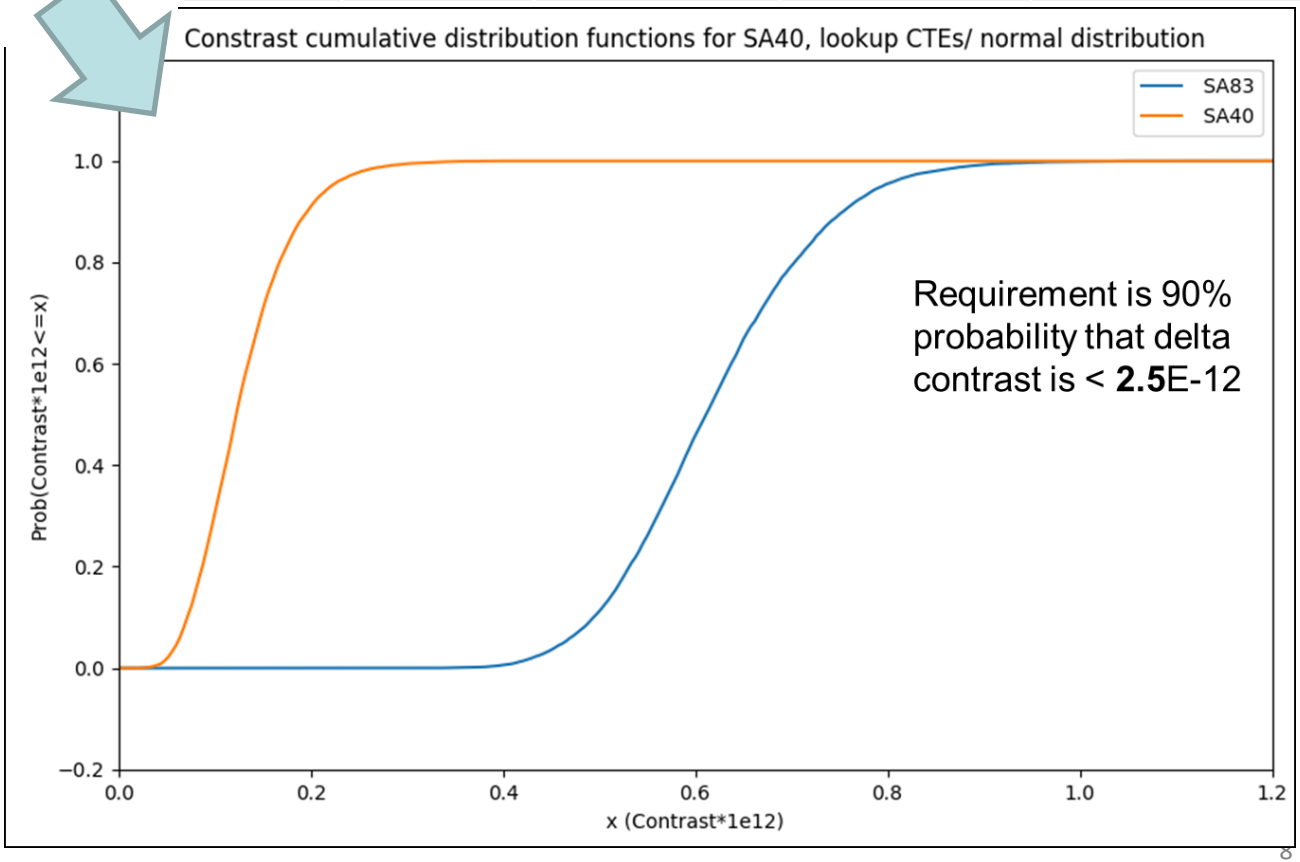
**Critical test for this test article**

# Monte Carlo of Contrast Response to CTE Variation with Temperature Mapping




## Monte-Carlo Analysis Results:

| Sun Angle | Samples | Prob contrast <=2.5e-12) | Mean contrast*1e 12 | 90th percentile *1e12 |
|---|---|---|---|---|
| 83° | 10000 | 100% | 0.619 | 0.754 |
| 40° | 10000 | 100% | 0.130 | 0.196 |




## STOP Analysis Results:

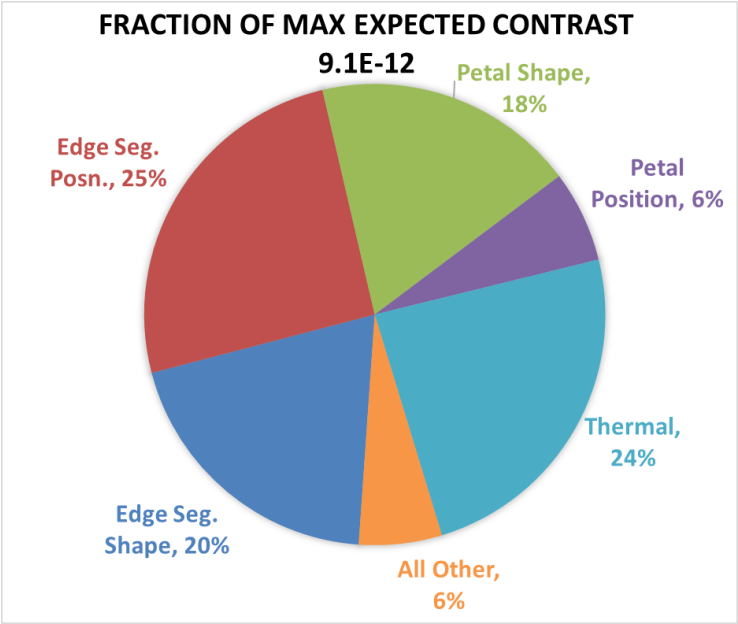
| Sun Angle | Contrast*1e12 |
|---|---|
| 83° | 0.588 |
| 40° | 0.025 |

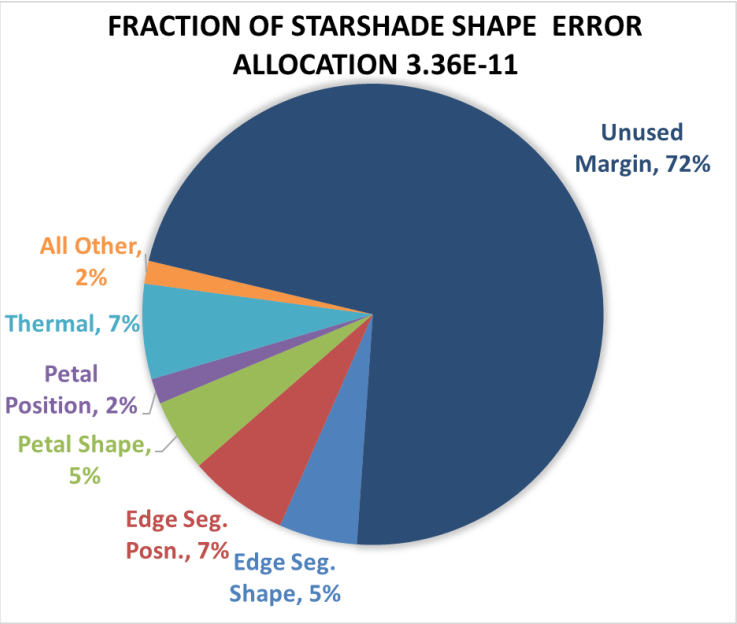
# Contrast At Max Expected Values

## *Total contrast well below shape error allocation of 3.36 x $10^{-11}$*

| Error Effect \ Error Source | | Ground | | | Launch & Cruise | | | On-Orbit | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Manufacture | AI&T | Storage (creep) | Launch | Pre-deploy (creep) | Deploy | Materials (creep/moisture) | Dynamics (thrusters) | Thermal |
| In-Plane Starshade Shape | 1. Edge Segment Shape | 1.8E-12 / 5% | Carried under Petal Shape (Row 3) | | | | | | | |
| | 2. Edge Segment Position on Petal | 2.4E-12 / 7% | | | | | | | | |
| | 3. Petal Shape (incl. non-kinematic I/F) | 1.7E-12 / 5% | 3E-14 | 4E-16 | 9E-14 | 1E-14 | 2E-14 | 1E-13 | 5E-16 | 2.2E-12 / 7% |
| | 4. Petal Position on Disk | Carried under AI&T | 5.1e-13 / 2% | 6E-14 | | | | | | |
| Out of Plane Starshade Shape | 5. Petal Shape | 1.6% of Shape Error Allocation | | | | | | | | |
| | 6. Petal Position on Disk | 1E-14 | | | | | | | | |

% above is for total shape error allocation



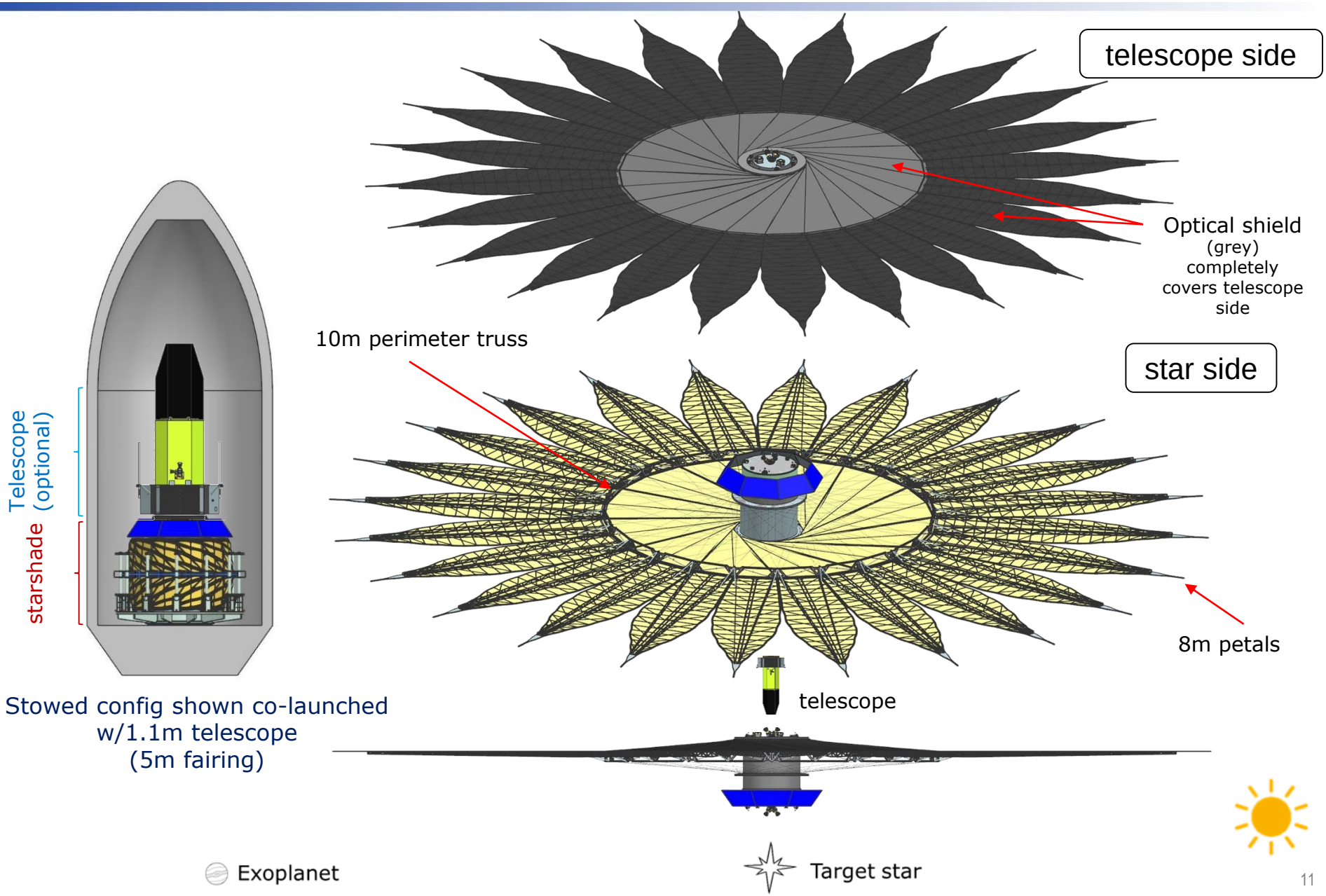



# Performance Estimates

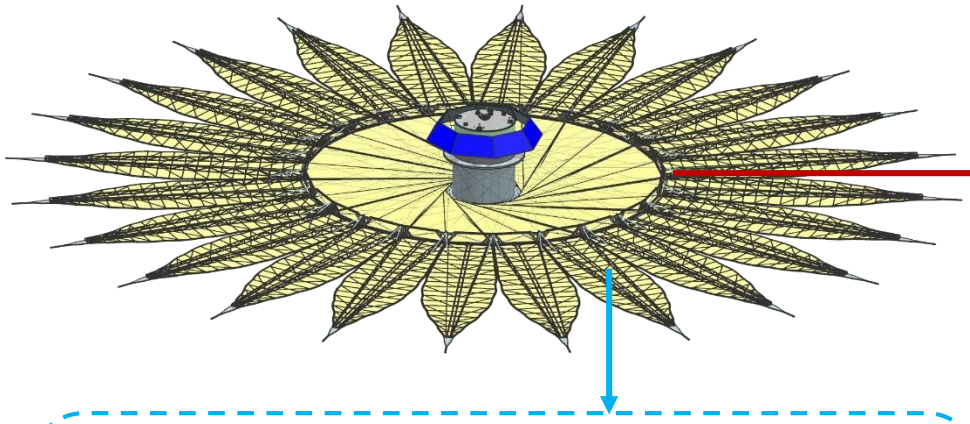
- **The bottom-up error budget demonstrates large margin, beyond the unallocated 100%**
  - **Currently assumes all error terms are treated as independent and uncorrelated**
- **A top-down Monte Carlo simulation demonstrates 100% margin with > 99% confidence for the max expected errors (with maturity based contingencies/MUFs)**
  - **Accounts for terms that combine in a optically coherent fashion and error source correlations**

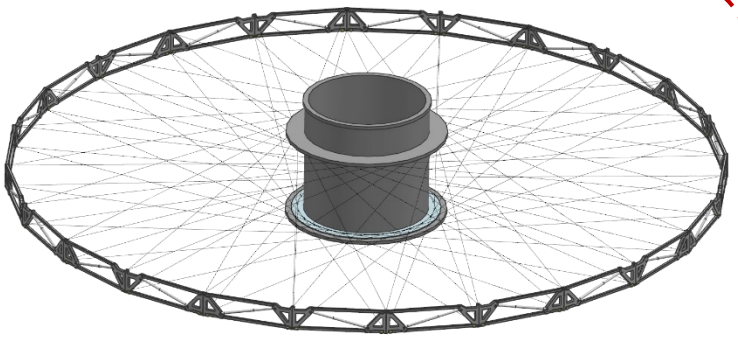
# Starshade Wrapped Design

## 26m NI2 design with 8m petals for ExEp Architecture Trade Study

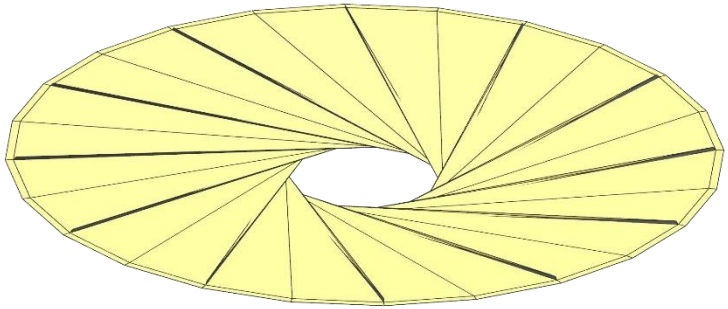


# Subsystem Definitions



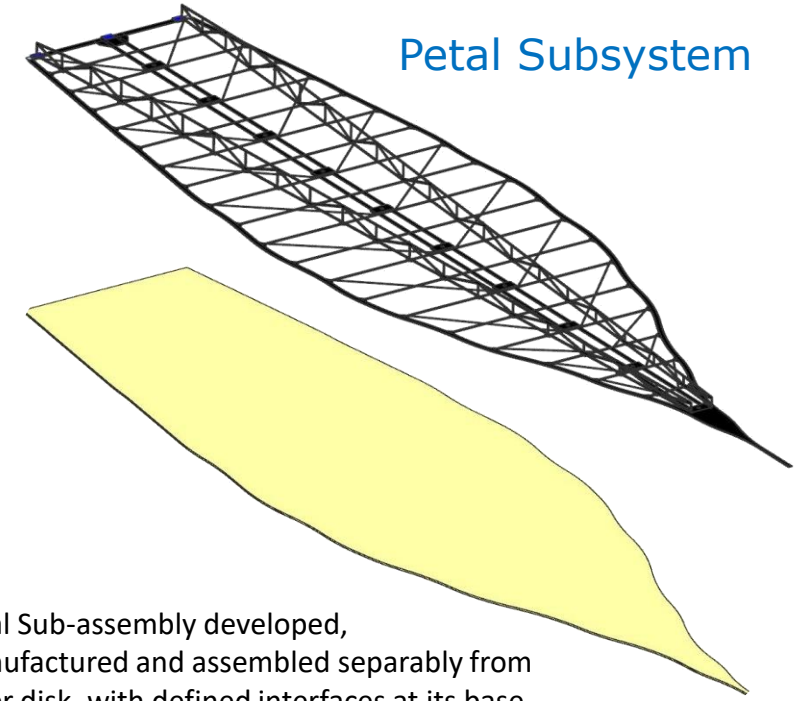


Truss + spokes + hub constitute separable structure w/defined interfaces to petal

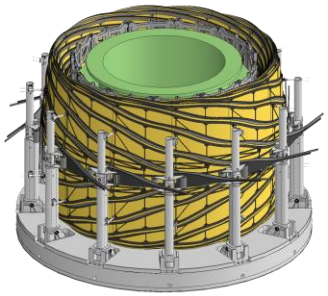


Inner Disk Subsystem

Petal Subsystem



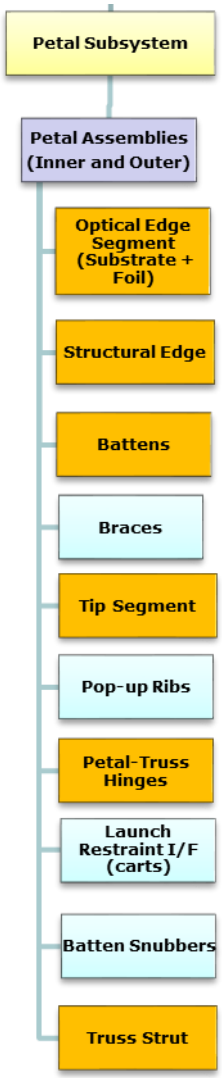
Petal Sub-assembly developed, manufactured and assembled separably from inner disk, with defined interfaces at its base



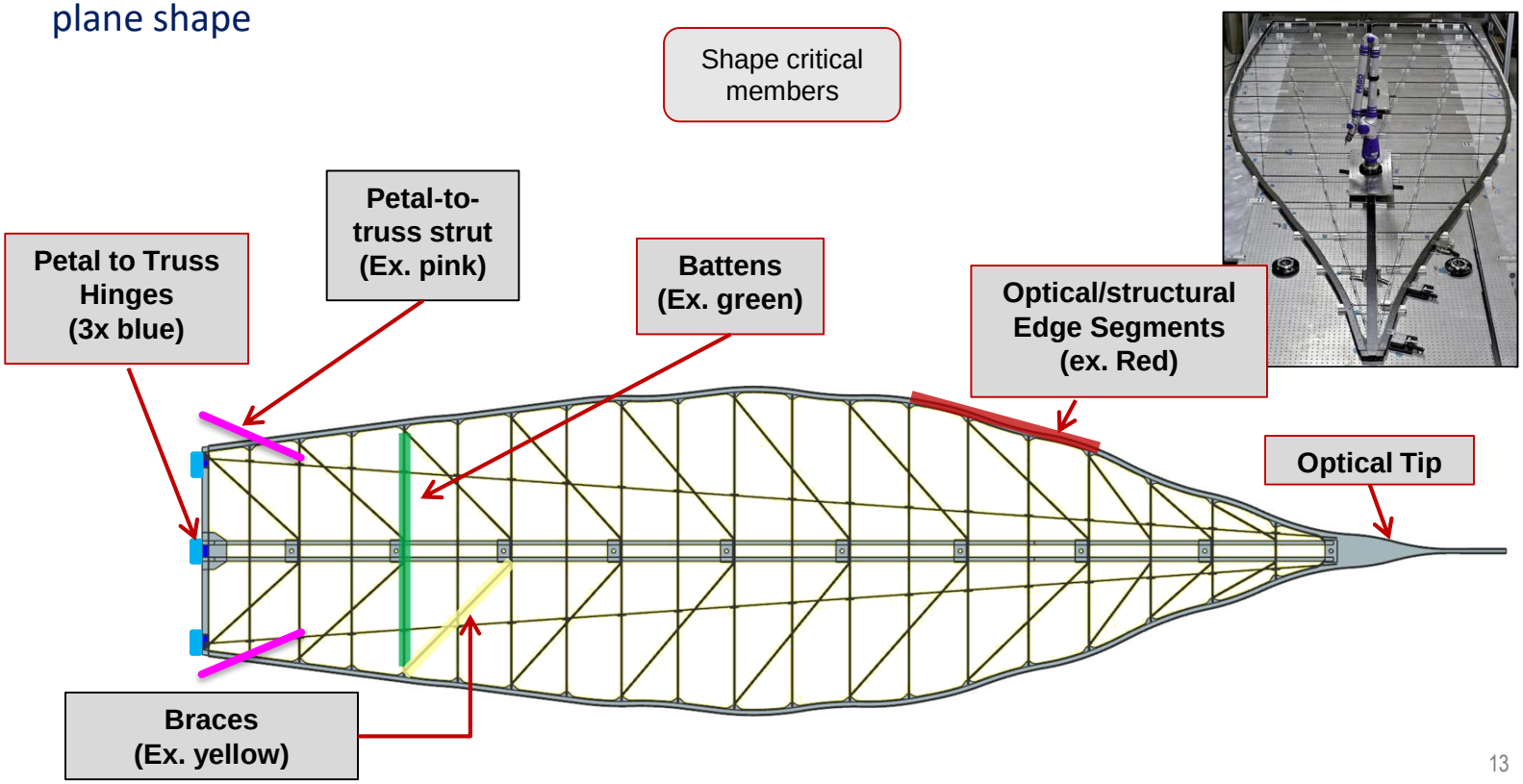
Petal Launch Restraint & Unfurl Subsystem (PLUS)

PLUS controls petal deployment & defines petal L/R interfaces (jettisoned after launch)

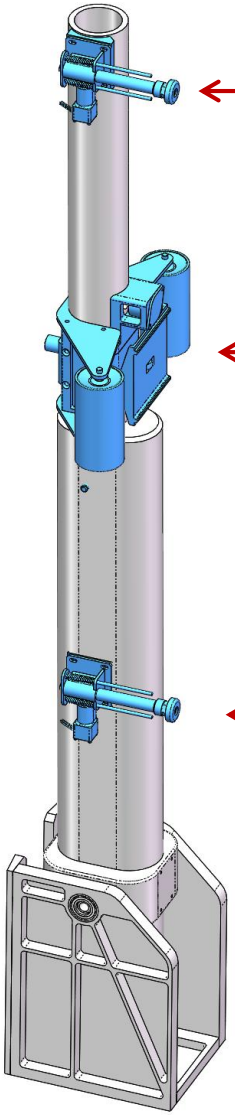
# Petal Shape Critical Components




- Petal designed specifically to address in-plane shape stability
  - Battens maintain petal width (COTS & precise)
  - Edges are width-wise-thin and "go where battens tell it to"
  - Braces (diagonals) provide in-plane shear stiffness to maintain shape
- Petal hinges maintain petal position relative to truss (w/std avail. precision)
- Petal-to-truss struts provide out-of-plane support & must minimally influence in-plane shape



# Roller Arm Assembly in Launch Restraint Config



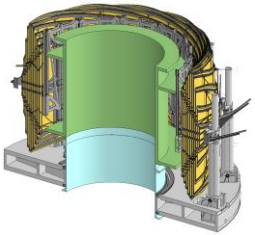
Upper Batten Snubbers
(Shown engaged)

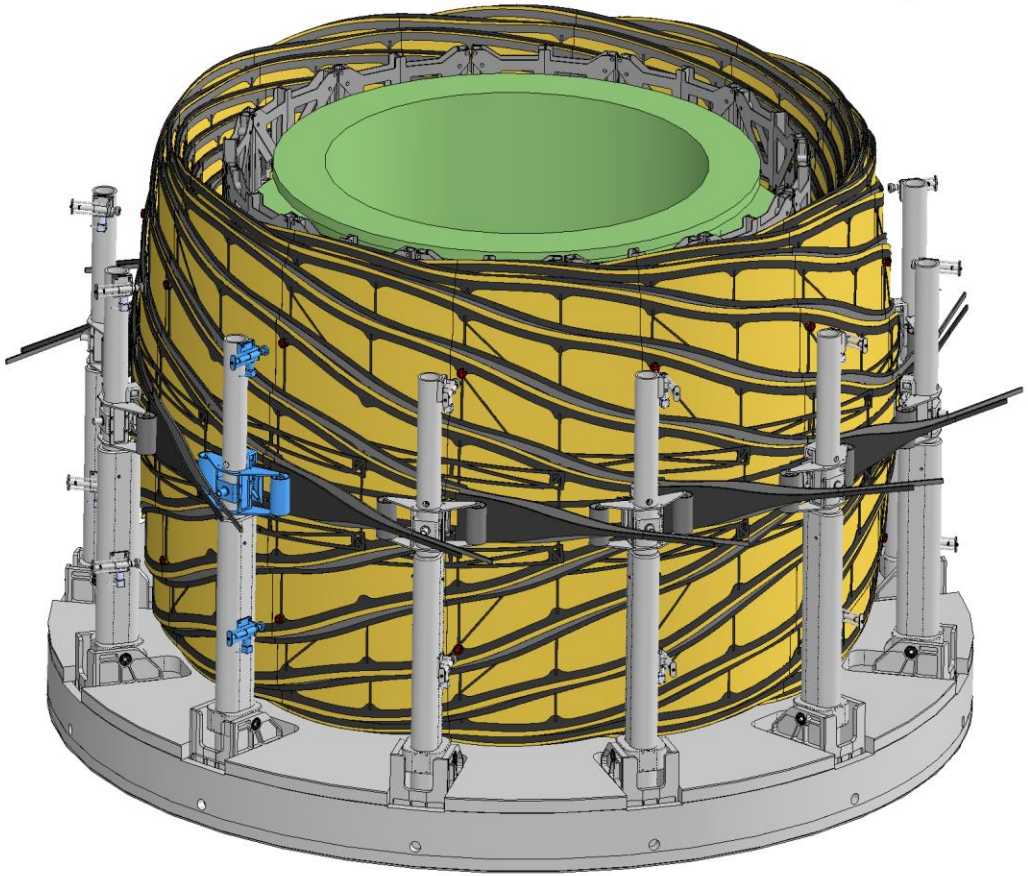
Launch Restraint Cart Preload Assy
(Shown engaged)

Lower Batten Snubbers
(Shown engaged)

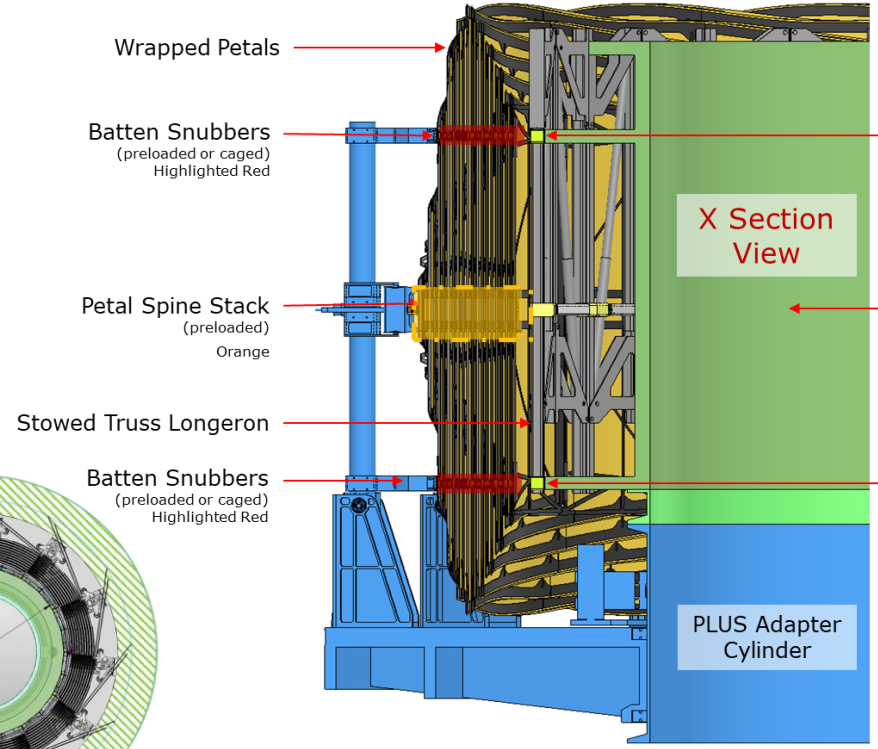
Trunnion
(attaches to carousel plate)

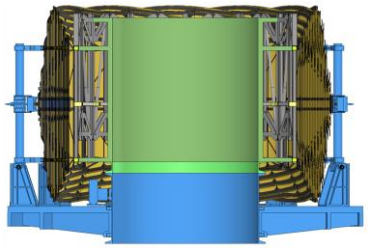
*Arm in Launch Configuration





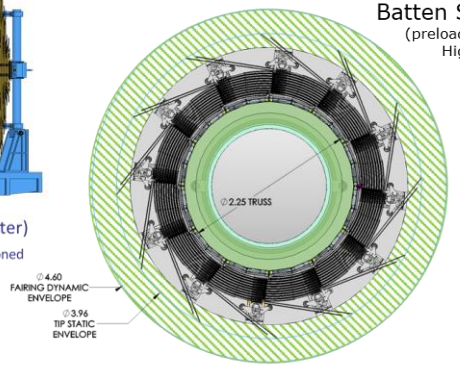
# Cross Section View

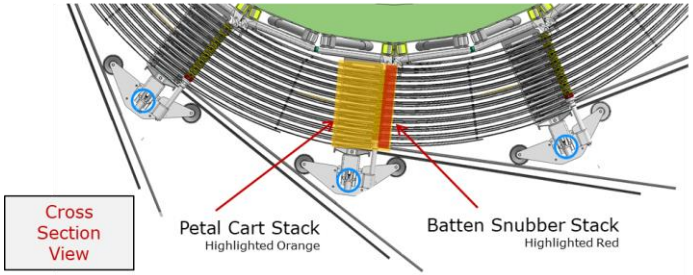


PLUS (Roller Arms, Carousel, PLUS Adapter)

*** Roller-arm/carousel/plus adaptor assy jettisoned after launch (total mass = 608 kg)



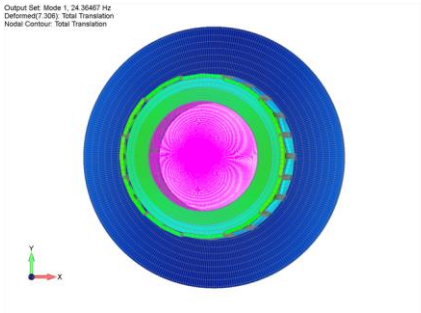



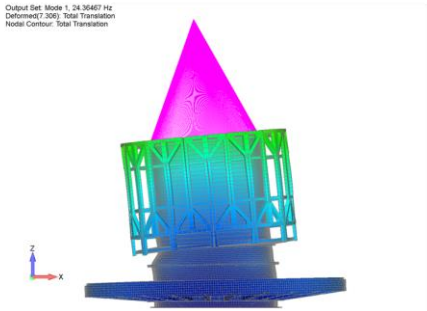
# Stowed Configuration Modal Analysis

## Dedicated Mission

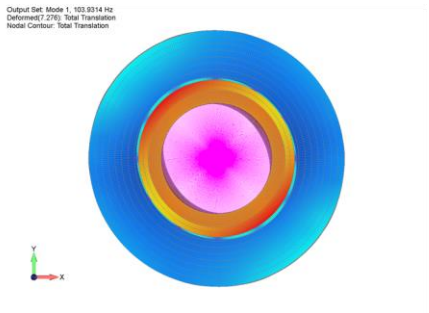
- The primary modes were also checked assuming the dedicated mission configuration
  - Telescope mass was taken from *"Exo-S STDT Final Report," Table 7.2-1*
  - Mass = 1,644 kg, Axial CG = 1.7 meters
    - Per Table 7.2-1, the propellant required for Starshade would decrease from 2000 kg to approximately 49 kg
    - Propellant mass in the FEM was conservatively left at 2000 kg
  - Impacts to the Petal tip, structural edge, and roller arm modes due to the additional telescope mass were negligible
- Critical frequencies and mass participation fractions
  - First primary lateral mode = 24.50 Hz (Mass participation = 1,770 kg)
  - First primary axial mode = 104.24 Hz (Mass participation = 2,842 kg)

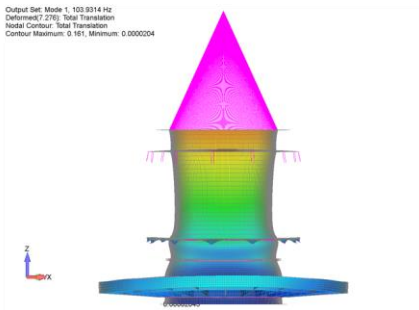
- Requirement: First primary lateral mode greater than 10 Hz
- First primary lateral mode
  - Frequency = 24.36 Hz
    - Mass participation = 619 kg (1,366 lb)
      - Mass participation fraction = 0.11
    - Additional lateral modes occur in this frequency range
  - Petals and roller arms are hidden for clarity





- Requirement: First primary axial mode greater than 25 Hz
- First fundamental axial mode
  - Frequency = 103.93 Hz
    - Mass participation = 1,709 kg (3,767 lb)
      - Mass participation fraction = 0.30
  - Petals and roller arms are hidden for clarity

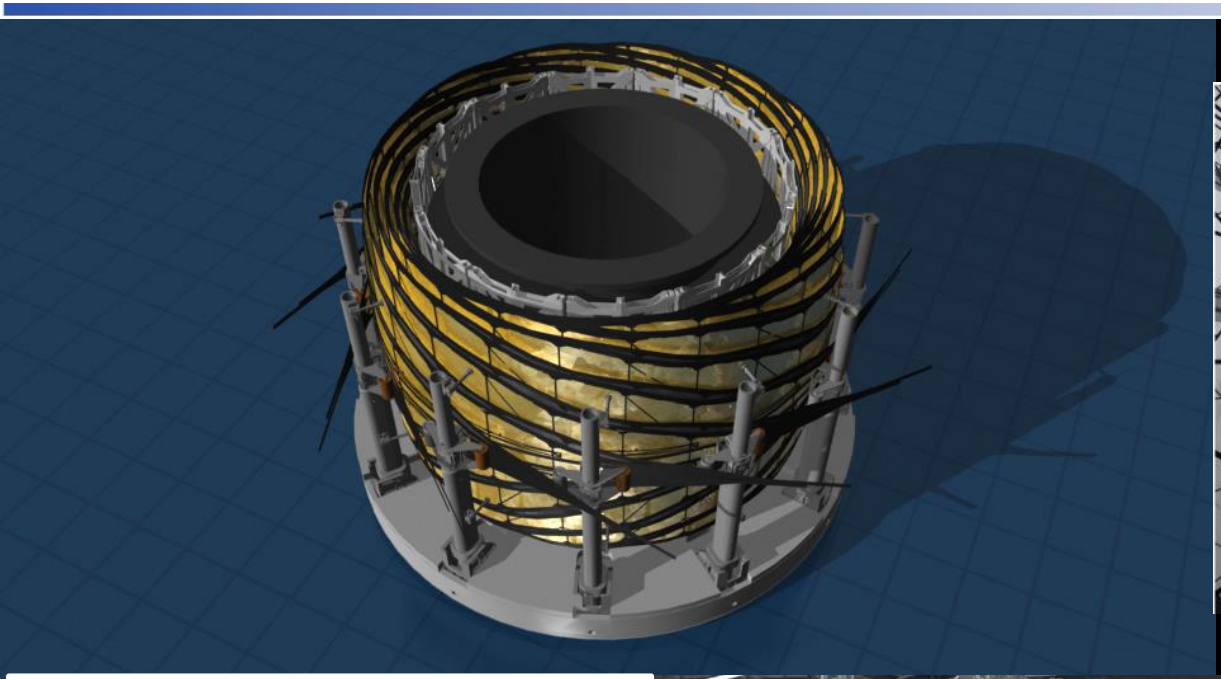




# Stowed Analysis Summary

- Rendezvous Mission
  - 1st major mass lateral mode is at 51 Hz (Req't 10 Hz)
  - 1st major mass axial mode is at 142 Hz (Req't 25 Hz)
  - Strength margins of safety > 2.7 against falcon 9 user's guide
  - Peak displacements within dynamic fairing envelope
  - Petal edge and tip relative displacements show large margin on petal to petal interaction
- Dedicated Mission (with telescope)
  - 1st major mass lateral mode is at 25 Hz (Req't 10 Hz)
  - 1st major mass axial mode is at 104 Hz (Req't 25 Hz)

# Visualization & Hardware Overlay



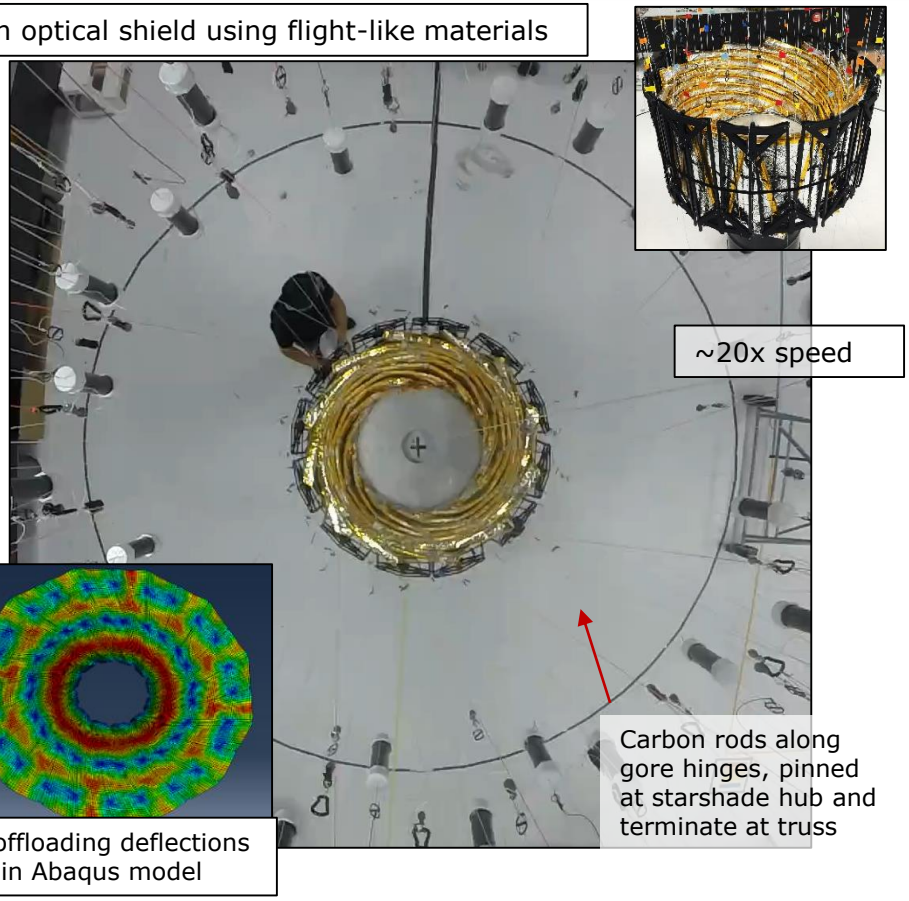
- Full scale motorized prototype (2.25m diameter stow), petal simulators have same furling stiffness and design as flight design
- Defines petal interfaces needed for TRL-5
- Deployment is **quasi-static** (~30-60min deployment) (video below is ~20x for ~20 min deployment)
- Requires only 1 motor for deployment (flight unit will have 2 for redundancy)
- Future upgrades to include medium fidelity launch restraints, rollers, and a pair of medium fidelity CFRP petals (simulators to serve as boundary conditions for pair of interest), more in TRL discussion
- ADAMS modeling effort to commence June 2018

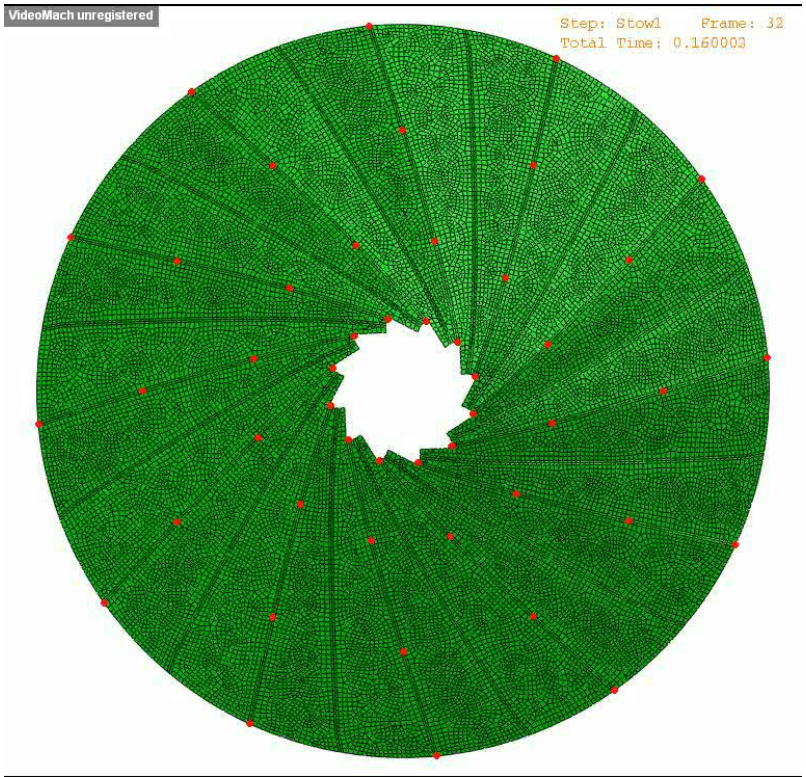
# Inner Disk Optical Shield Deployment & Simulations

5m prototype (1/2 flight scale):

- flight-like materials, learn about required features to enable flight design (e.g. gravity offloading & test)
- Understand shield, spacecraft, truss, & petal relative deployment and required features (e.g. carbon rods for hub/starshade structural connection, analysis pending)

5m optical shield using flight-like materials



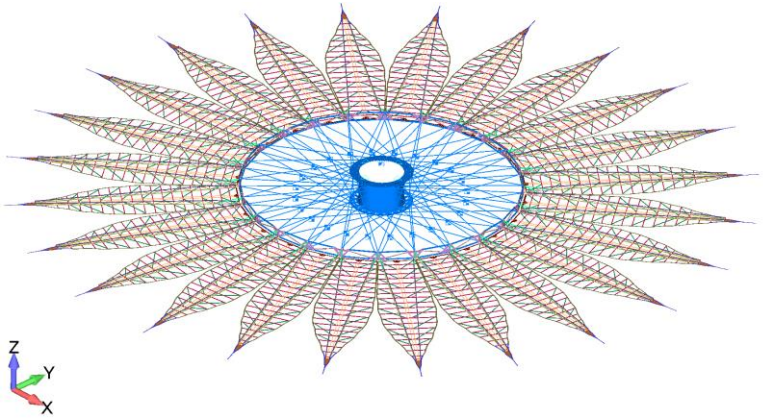




Deployment Simulation Model in Abaqus:

- Preliminary Abaqus deployment simulation model developed (T. Murphey) & utilized to understand 1g offloading
- Capability exists to combine a future, more developed model with the perimeter truss ADAMS model

# Modes & Structure Margin

- Wrapped Starshade is ~600kg,
  - 20% of BOL system mass, 50% of EOL system mass
- Modes of interest
  - 1st system mode 1.06Hz
  - First significant truss and petal in-plane mode at F656 = 17.3 Hz (width preserving)

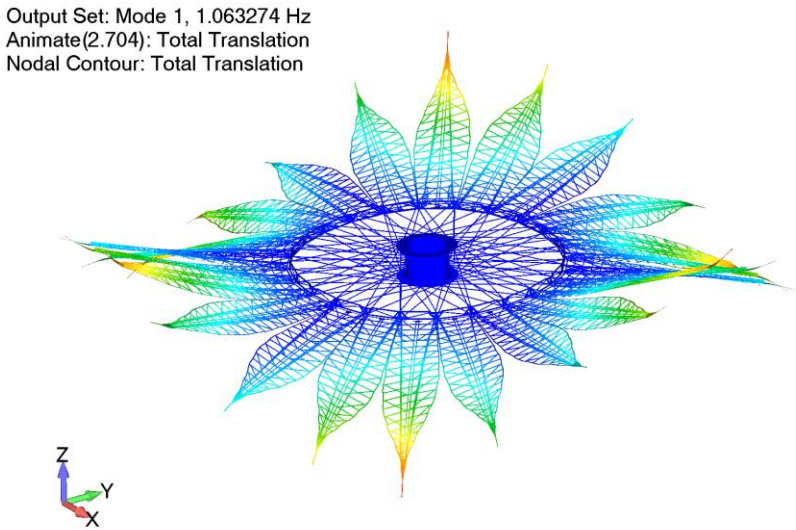



## Margin on Structure Instability due to Spoke Pre-tension

Why analyze elastic instability?

- As a pre-tensioned structure, we want to verify the tension in the spokes is not close to buckling the compression portion of the structure (perimeter truss)

| Deisgn Spoke Load | Spoke load to buckle perimeter truss | Margin |
|---|---|---|
| 16 lbs | 1536 | HIGH |



# Deployed Analysis Summary

- 1st mode is high at > 1 Hz
- 1st in-plane mode is at 17.3 Hz & is petal width preserving
- High margin on Structure Instability due to Spoke Pre-tension
- High margin on slacking spokes from retargeting thruster fire
- High margin on bounding case thermal loads slacking spokes
- Contrast is <u>insensitive</u> to spoke preload or length variation
- Fault tolerant to missing (broken) spokes (negligible impact)

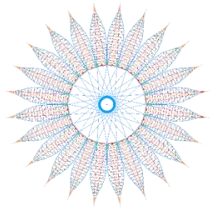
# Agenda

STOP analysis refresher of results for representative cases* :

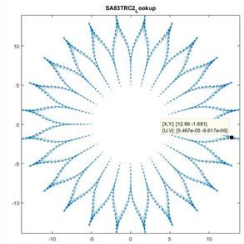
- Thermal analysis (temperature) results
- Thermal distortion results
- Resulting contrast due to nominal thermal distortion & comparison to the error budget

• CTE variability monte-carlo study results

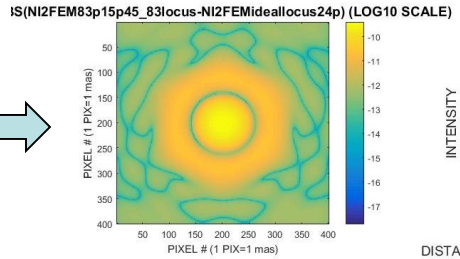
* Subset of sun angle cases showing representative temperatures & distortions/results, full set in backup

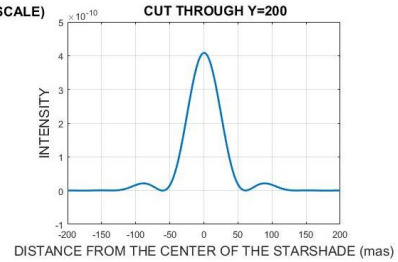


Thermal analysis temperature results mapped to structural FEM

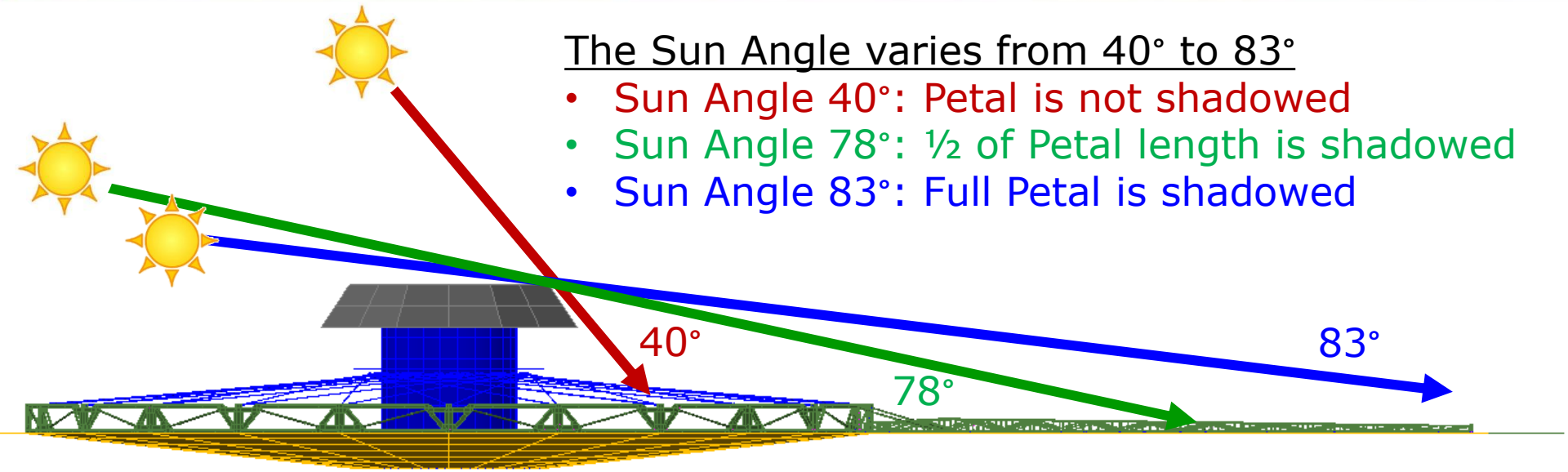


Quiver plot of resultant thermally induced shape distortion



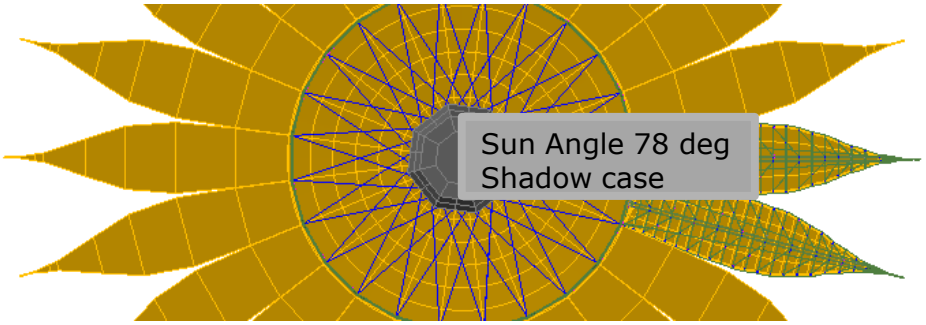
# Sun Angles and Shadowing by Hub




The Sun Angle varies from 40° to 83°

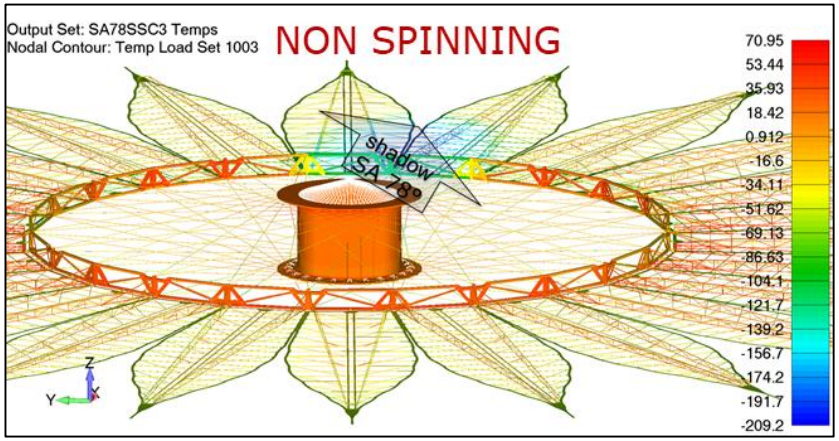
- Sun Angle 40°: Petal is not shadowed
- Sun Angle 78°: ½ of Petal length is shadowed
- Sun Angle 83°: Full Petal is shadowed

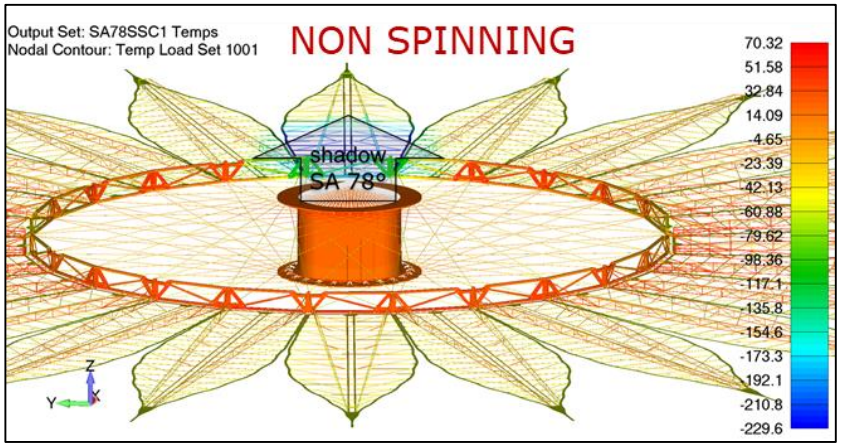
*** Slow rotation run every 3.75°. @1/3 RPM this is every 1.875 seconds, 96 positions. Temperatures available at each of the 96 locations.

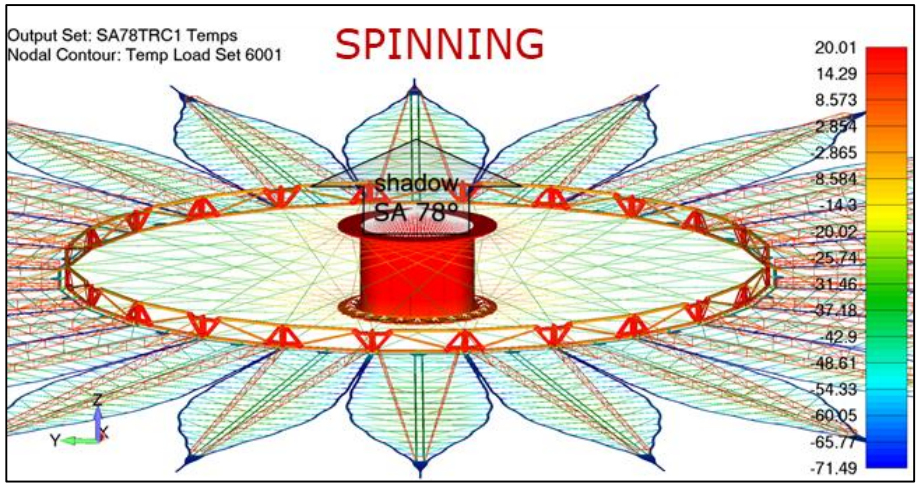


# Non-spinning Shadow Orientation Conclusions

| | Comment | Gradient | Max/Min Temp |
|---|---|---|---|
| **NON-Spinning** | Shadow clocking orientation has little effect on max/min temps, only moves cold portion of starshade | 300 C | 70 C / -230 C |
| **Spinning** | Averages temperatures symetrically aound spin axis<br>Transient has negligible effect on contrast | 90 C | 65 C / -95 C |



# Sun Angle 78

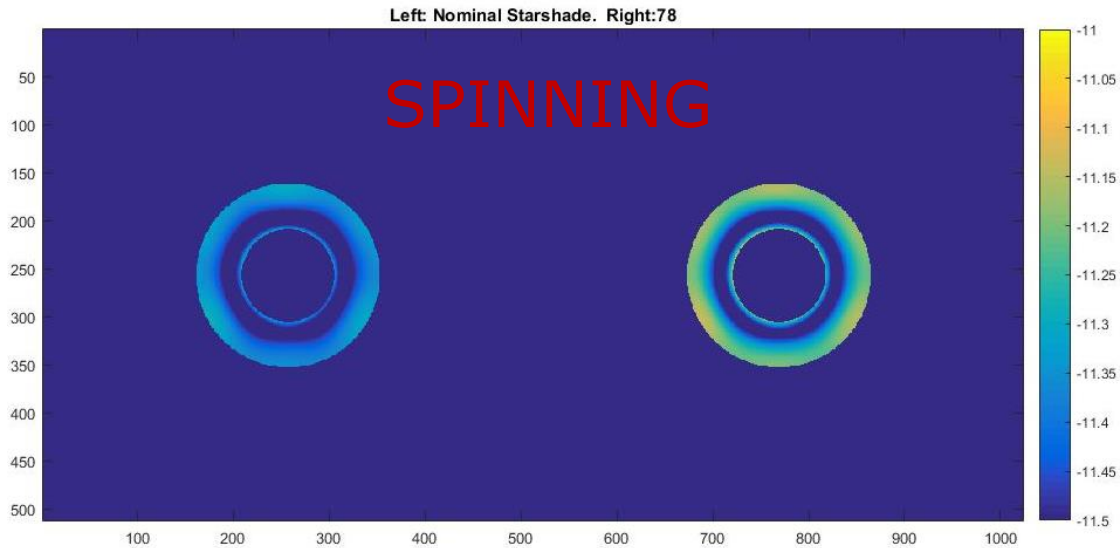
## Comparison of Spinning to Non-Spinning

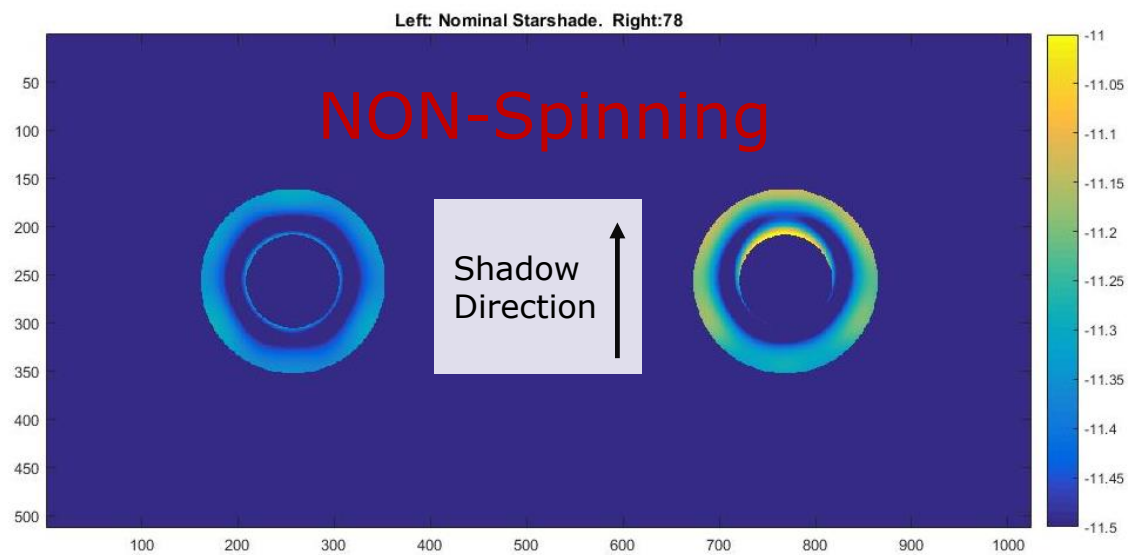
### Spinning

- Spinning has a telescope axis-symmetric contrast
- Contrast varies radially

### NON-Spinning

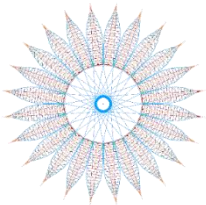
- Largely distorted shadowed petals :
  - Shift high contrast annulus toward shadow
  - Reduce contrast in petal distorted zone



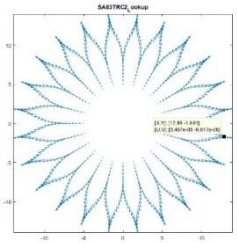



# What did we do?

- Thermal elastic distortions are caused by the combination of temperature and CTE
- Thermal analysis results (temperatures) were mapped to the structural model
- CTE material cards were populated with CTE lookup tables, CTE vs temp
  - CFRP ply data test data characterization produces “nominal” CTE curves
  - Ply CTE data combines with layup to produce nominal layup CTE curve based CFRP layup design
  - Wrapped design utilizes 2 different layups
    - Structural Members (most) - Quasi-iso layup from NGAS
    - Optical Edge - Quasi-iso layup with the addition of the amorphous metal foil and 5 mil epoxy each side
    - Truss longerons - Quasi-iso layup with the addition three invar fittings that attach petal hinges
    - Uni-directional pultruded members utilized for JPL’s SWOT program
  - What about variation in CTE? Sensitivity to variation in mean CTE by layup type, and variation in CTE from component to component (for a given layup design) will be varied in a wide enough range to capture bounding variations and to check sensitivity to these bounds.



Thermal analysis temperature results mapped to structural FEM



Quiver plot of resultant thermally induced shape distortion

# Thermal Distortion Contrast Results

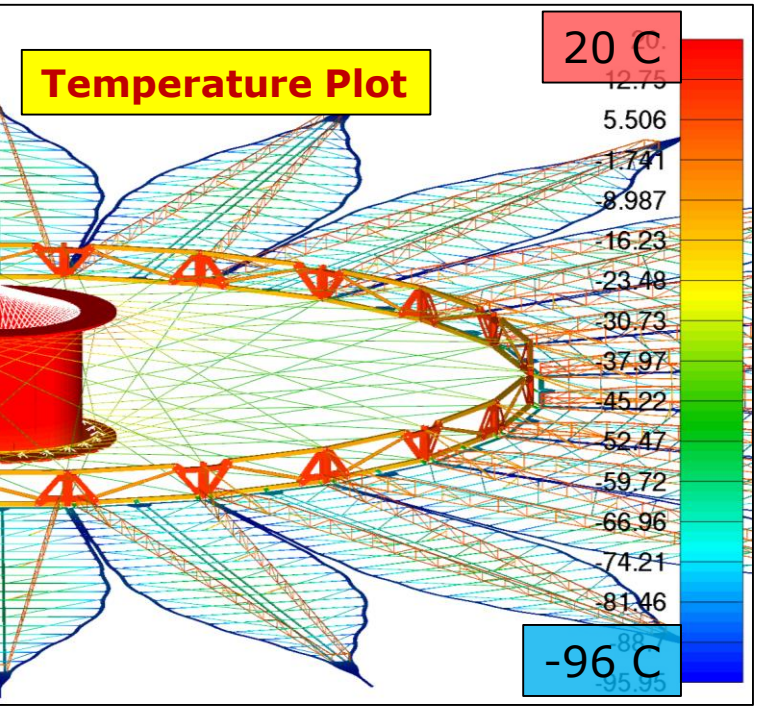
| Case | ***CBE*** *Delta Contrast x 1e-12* | ***Max Expected*** *Delta Contrast w/ 100% contingency x 1e-12* | ***Max Expected*** *% of Starshade Allocated Shape Error (3.4 e-11)*** |
|---|---|---|---|
| ***Spinning*** | | | |
| 40 deg* | *0.002* | *0.01* | *>1%* |
| 78 deg | *0.398* | *1.592* | *4.6%* |
| 83 deg* | *0.655* | *2.62* | *7.7%* |
| ***Non-Spinning*** | | | |
| 40 deg | *0.06* | *0.24* | *>1%* |
| 78 deg | *0.45* | *1.81* | *5.3%* |
| 83 deg | *0.56* | *2.24* | *6.5%*** |

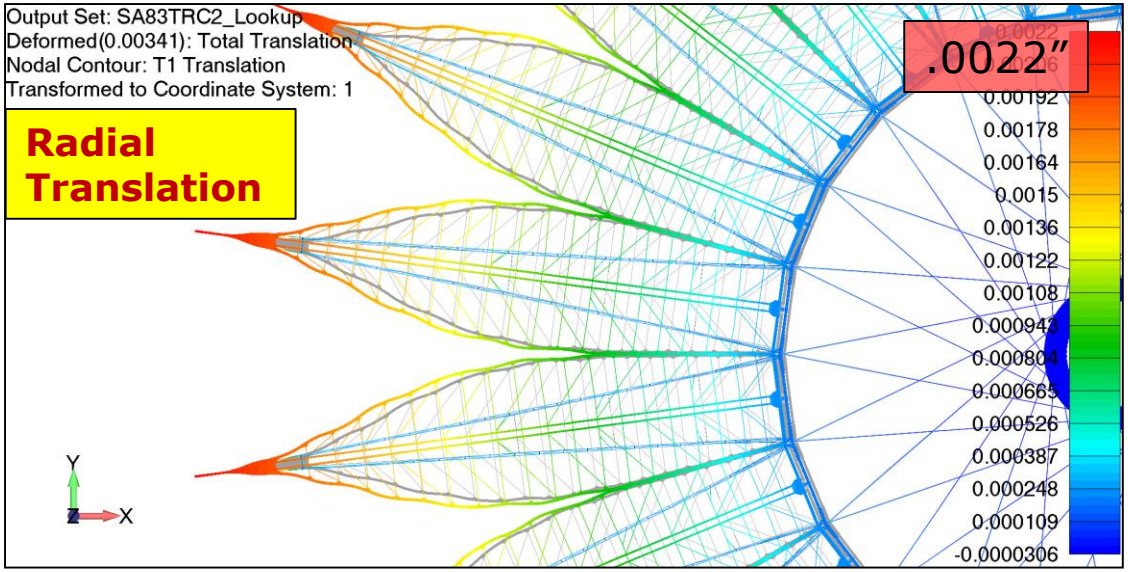
* Utilizes CTE for truss longeron w/ petal interface fittings affecting longeron CTE (w/no CTE design compensation)

** Error budget carries CBE contrast from spinning results, non-spinning shown for reference only

# SA83 SPINNING Distortions

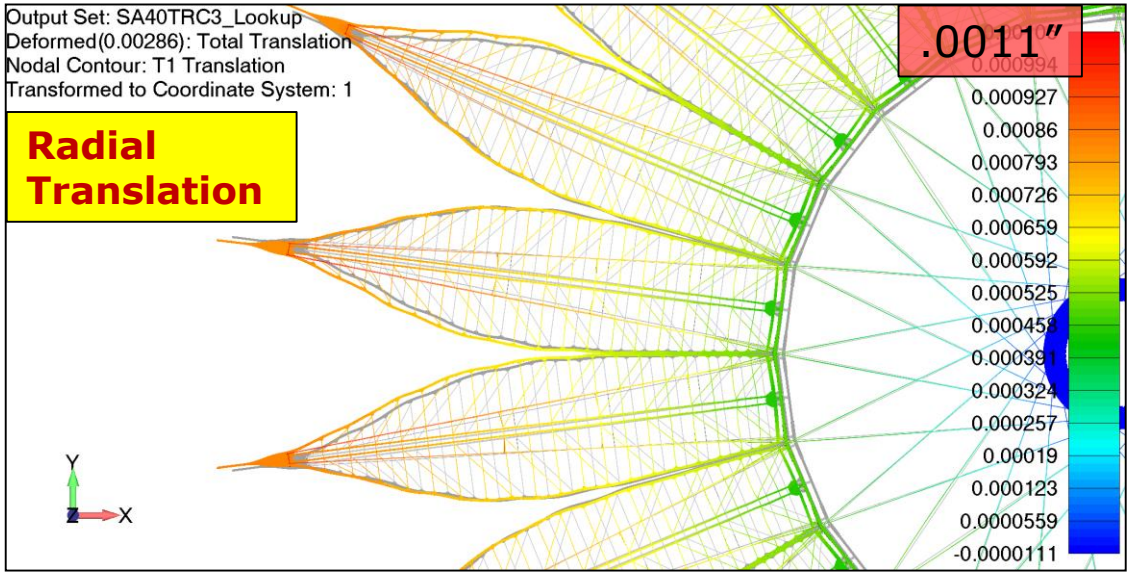
- **Raw** distortions on order of 50 microns (0.002”)
- Distortions correspond to temperature results (thermal analysis), e.g.
  - Truss @ 20 C (room temp) = almost no shape change
  - Petal dT = -65 C, 50 microns (0.002”)

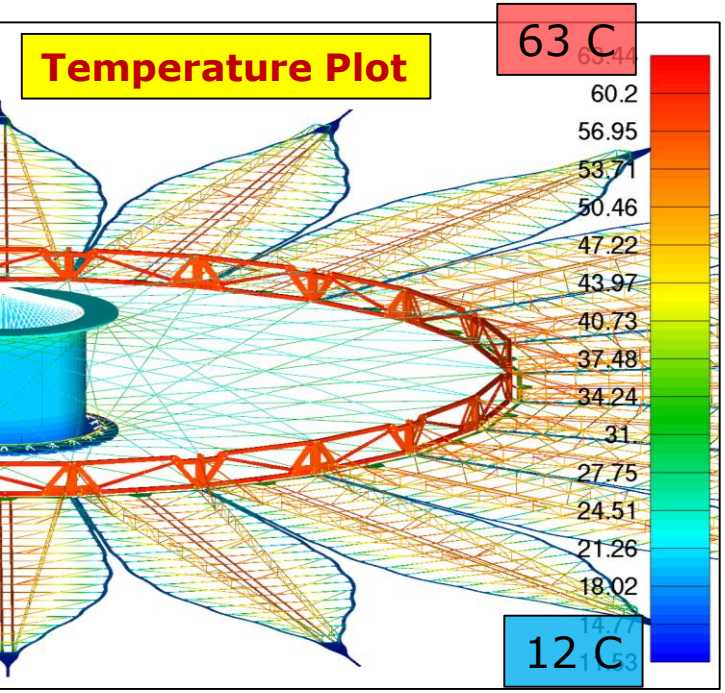


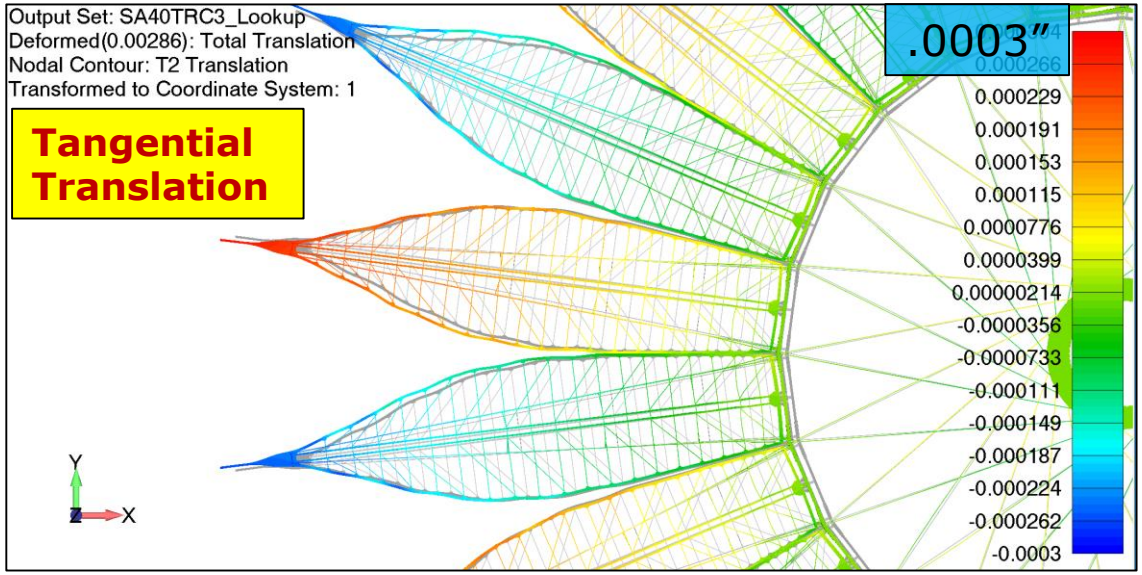



# SA40 SPINNING Distortions

- **Raw** distortions on order of 50 microns (0.001”)
- Distortions correspond to temperature results (thermal analysis), e.g.
  - Truss @ 60 C (dT = 40C), ~25 micron radial expansion
  - Petal dT = ~+40 C, 30 microns (0.002”)

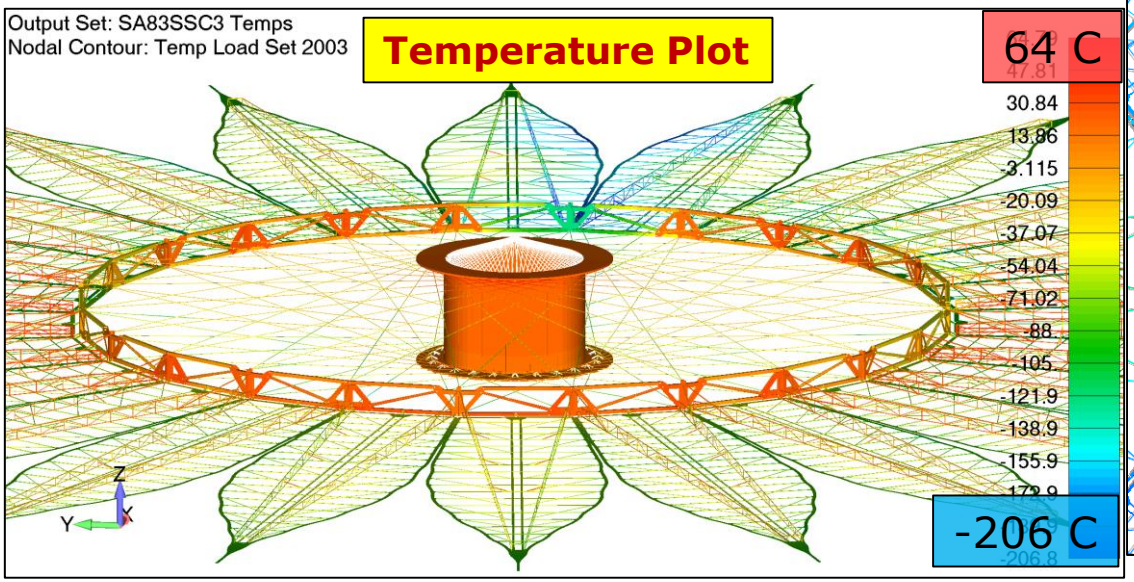


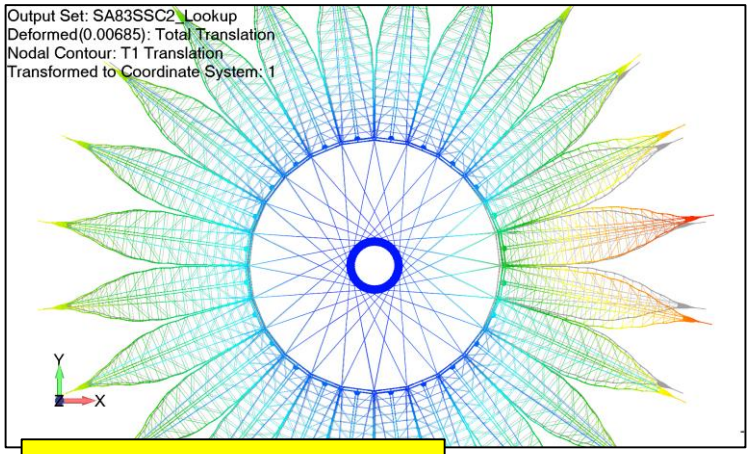



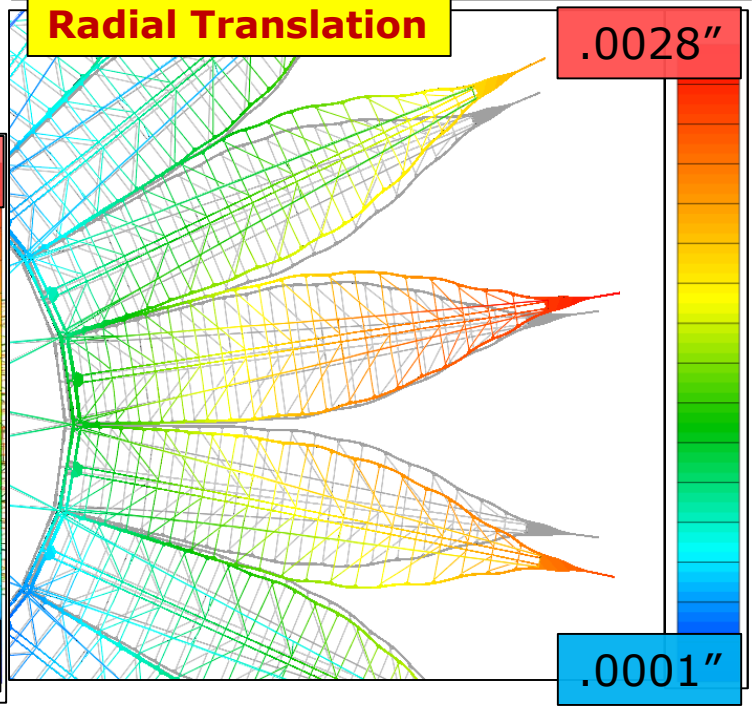



# Sun Angle 83, NON-spinning, Distortions

- Sun Angle 83 degrees produces representative distortions and worst case contrast, shown as example of NON-spinning results
- **Raw** distortions on order of 75 microns (0.003”)
- Distortions correspond to temperature results (thermal analysis), e.g.
  - Truss HOT @ 70 C (dT = 50C), ~25 micron radial expansion
- Cold Petals are longer, disrupts apodization function

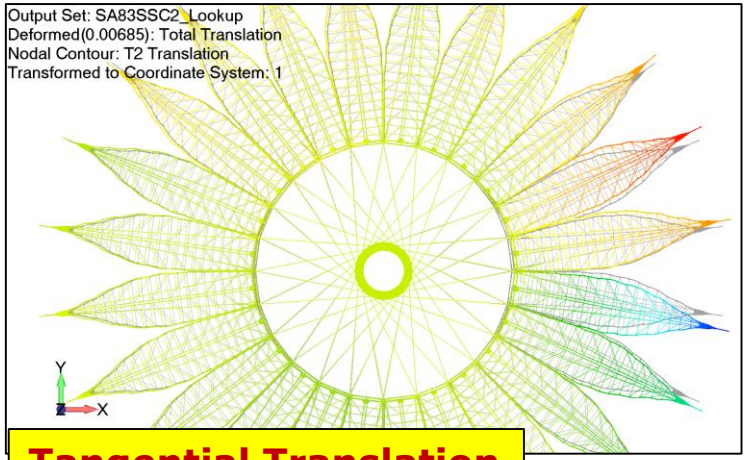


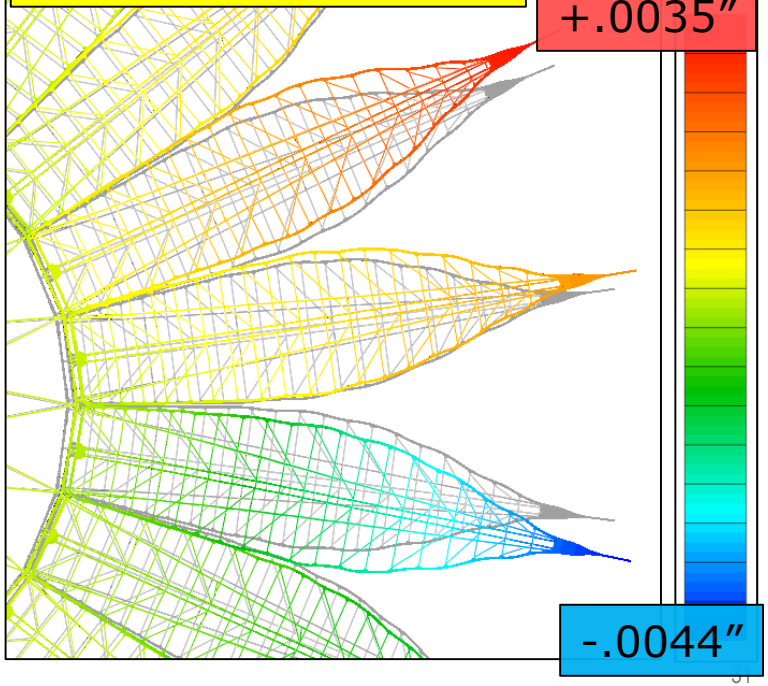



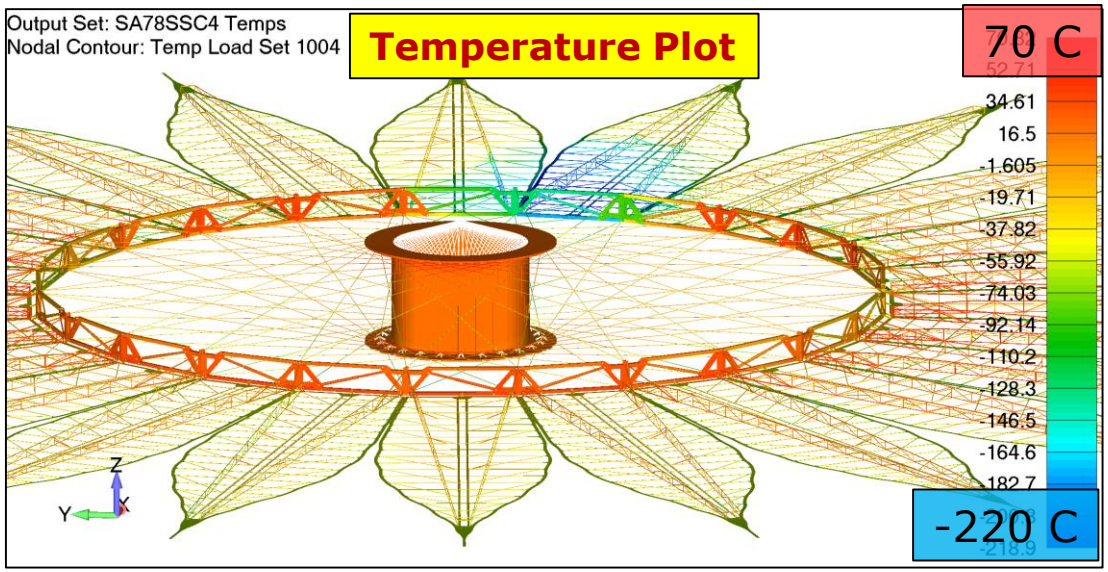
# Sun Angle 83, NON-spinning, Distortions

- Sun Angle 83 degrees produces representative distortions for the steady state sun angle cases and is the worst case contrast for steady state, shown as example of NON-spinning results
- **Raw** distortions on order of 100 microns (0.004”)
  - Truss bays in shadow are cold, and grow (neg CTE), and splay petals apart from eachother




**Tangential Translation**



# Summary

* Preliminary analysis shows max expected thermally deformed starshade meets requirements for both spinning and non-spinning configurations over working sun angles

| Case | CBE Delta Contrast x 1e-12 | Max Expected Delta Contrast w/ 100% contingency x 1e-12 | Max Expected % of Starshade Allocated Shape Error (3.4 e-11)** |
|---|---|---|---|
| ***Spinning*** | | | |
| 40 deg* | *0.002* | *0.01* | *>1%* |
| 78 deg | *0.398* | *1.592* | *4.6%* |
| 83 deg* | *0.655* | *2.62* | *7.7%* |
| ***Non-Spinning*** | | | |
| 40 deg | *0.06* | *0.24* | *>1%* |
| 78 deg | *0.45* | *1.81* | *5.3%* |
| 83 deg | *0.56* | *2.24* | *6.5%** * |

* Utilizes CTE for truss longeron w/ petal interface fittings affecting longeron CTE (w/no CTE design compensation)

** Error budget carries CBE contrast from spinning results, non-spinning shown for reference only

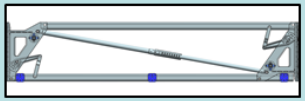
# Thermal Distortion Analysis

- Two analyses for the impact of thermal distortion on contrast:
  - STOP Analysis: uses thermal mapping and nominal CTE values (temperature dependent) to compute contrast for each sun angle
  - Monte-Carlo Analysis: uses random distributions on CTEs to determine statistical distribution on contrast for each sun angle

# RFA #5: Test Article Descriptions
# Prototype Test Plan

## *** 1-page summaries of each TRL-5 test article on subsequent slide ***

**Full-Scale (1.3-m long)**



**Inner Disk Truss Bay (P5-1)**

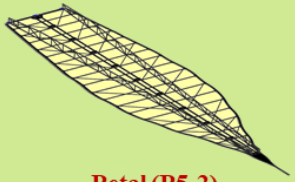
**Unit A**

- *Verify Truss Bay length* ***as manufactured*** — *Test 5-1*
- *Validate Truss Bay model of* ***length vs. temp.*** — *Test 5-2*

**Unit B**

- *Verify Truss Bay shape* ***as manufactured*** — *Test 5-1*
- *Validate Truss Bay model of* ***length vs. I/F Load*** — *Test 5-3*
- *Verify Petal shape & Truss-Bay length after* ***thermal cycles*** — *Petal & Truss-Bay are tested at same time, in same chamber, but they are not connected.* — *Test 5-5*
- *Verify Petal shape & Truss-Bay length after* ***storage with creep*** — *Petal & Truss-Bay are tested at same time, in same chamber, but they are not connected.* — *Test 5-6*

**1/2-Scale (4-m long)**



**Petal (P5-2)**

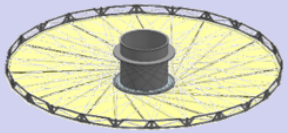
**Unit A**

- *Verify Petal shape as* ***manufactured*** — *Test 5-1*
- *Verify petal shape after* ***deploy cycles*** — *Test 5-4*

**Unit B**

- *Verify petal shape as* ***manufactured*** — *Test 5-1*
- *Verify petal shape after* ***deploy cycles*** — *Test 5-4*
- *Validate Petal model of* ***shape vs. I/F load*** — *Test 5-7*
- *Validate Petal model of* ***shape vs. temp.*** — *Test 5-8*

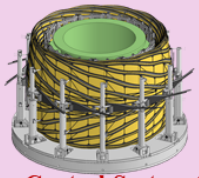
**Full-Scale (10-m dia.)**



**Inner Disk (P5-3)**

- *Verify repeatable Disk* ***deploy tolerances w/ OS*** *(after verifying opacity)* — *Test 5-9*
- *Validate Disk model of* ***deployment kinematics*** — *Test 5-10*
- *Validate Disk model of* ***shape vs. spoke load*** — *Test 5-11*
- *Verify OS opacity at truss-bay & petal I/F's* — *Test 5-12*

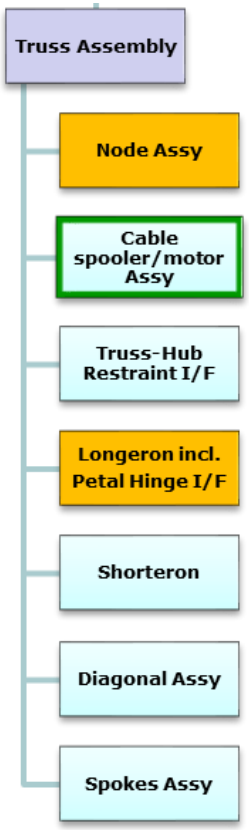
**Full-Scale (2.2-m inner dia.)**



**Deploy. Control System (P5-4)**

- *Verify DCS unfurls Petals with no edge contact* — *Test 5-13*
- *Validate DCS model of* ***deployment kinematics*** — *Test 5-14*

# RFA #5: Test Article Description
# Prototype 5-1: Disk Truss Bay

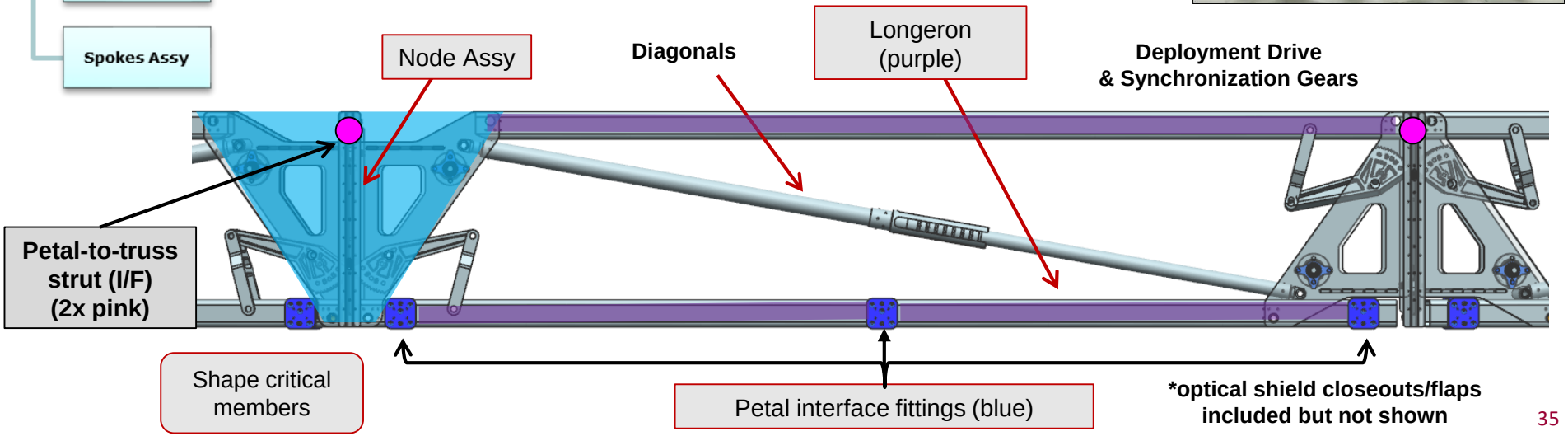



- **Tests**: Verify truss bay dimensions (manufacture), Validate Truss Bay model of length vs. temperature
- **Critical components for tests**: longeron & node
  - average longeron length + node width defines the disk radius (petal position)
- **Scale**: Full (1.3-m long) Truss Bay assembly of medium fidelity (or better)
- **Components**:
  - Longerons are quasi-iso CFRP* tubes with invar petal I/F fittings & I/F to gear assy's
  - Nodes are quasi-iso CFRP* plates with CFRP 'clips' (jointery) & I/F to gear assy's
  - Diagonals are quasi-iso CFRP* tubes with invar end fittings
  - Optical shield close-outs/flaps included (black kapton XC), (not shown in image)
  - Interfaces to Petal: Petal Strut & Petal interface fittings (invar)

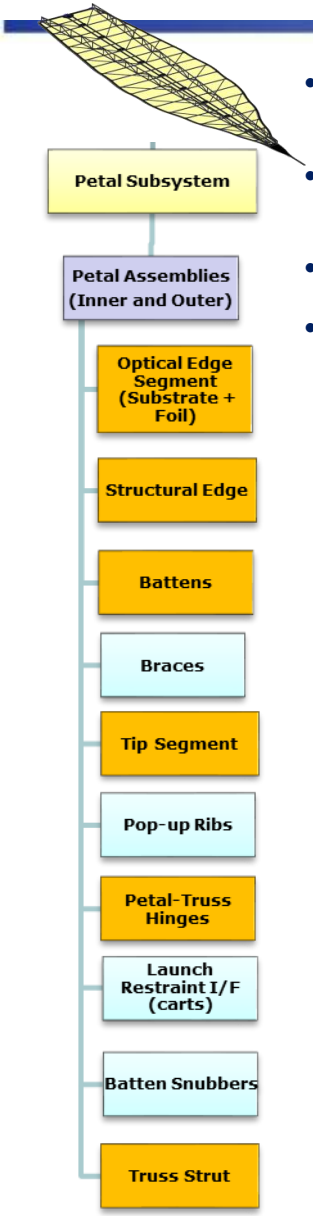
*(M55J with cyanate ester resin, per shared NG materials assumption)

** Critical components boxed in red below, orange on left

*** Materials are medium fidelity (space-flight compatible)



# RFA #5: Test Article Description
# Prototype 5-2: Petal



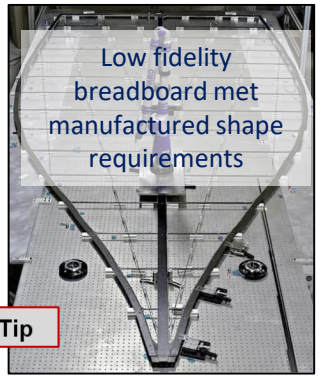

- **Tests**: Verify petal shape as manufactured, shape stability after deploy & thermal cycles & storage (creep), Validate petal model of shape vs. temperature
- **Critical components for tests**: battens*, optical edge, tip, interfaces to truss, & secondarily: braces, spines, interfaces to PLUS (batten length defines petal width*)
- **Scale**: Half (0.65m wide at base, 4m long), medium fidelity (or better)
- **Components**:
  - Materials are medium fidelity (space-flight compatible)
  - Battens are uniaxial pultruded CFRP** COTS material, incl. batten snubbers
  - Optical Edge & Tip Assy's are COTS MBF23 Ni/Fe alloy amorphous metal (MBF23) sandwiched with quasi-iso CFRP* plate, room temp epoxy (reviewed TRL-5 activity developing that product, not discussed in detail here)
  - Interfaces to truss: petal strut assy & petal to truss hinge assemblies (invar hinges)
  - Optical shield including close-outs
  - Spines including carts launch restraints, braces, rib assy

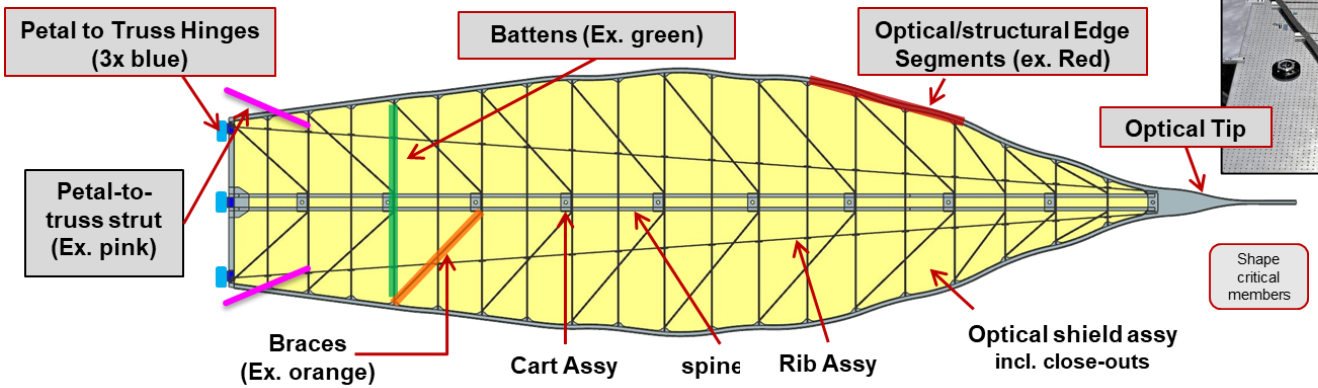
* M55J with cyanate ester resin, per shared NG materials assumption

** T700S data is measured data from JPL SWOT flight program

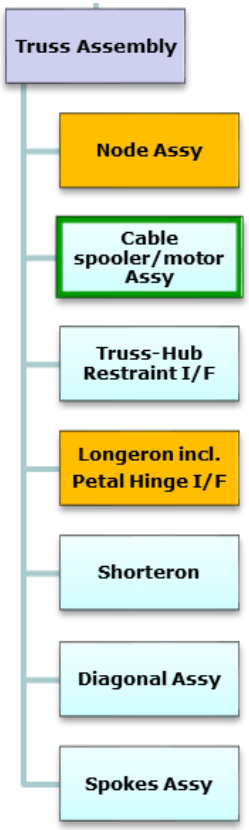
*** Critical components boxed in red below, orange on left

**** Materials are medium fidelity (space-flight compatible)



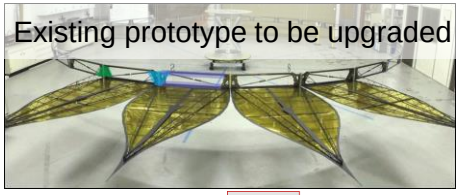
# RFA #5: Test Article Description
# Prototype P5-3: Inner Disk Subsystem

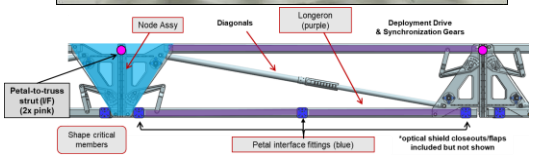


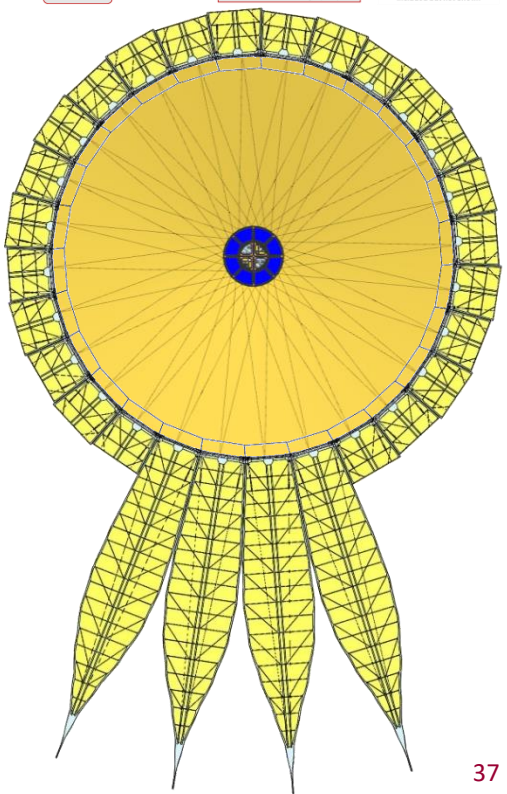

- **Tests**: Verify repeatable truss deployment tolerances with OS installed, Validate Disk model of deployment kinematics, Validate Disk model of shape vs. spoke load, Verify OS opacity at truss-bay & petal I/F's
- **Critical components for tests**: All truss components, spokes, optical shield, petals (bases + full simulators)
- **Scale**: Full (10m diameter) @ medium fidelity ***(upgrade of existing prototype)***
- **Components**:
  - Longerons/shorterons are quasi-iso CFRP* tubes with petal I/F fittings
  - Nodes are quasi-iso CFRP* plates w/ Al center beam
  - Diagonals are quasi-iso CFRP* tubes (Al end fittings)
  - CFRP spoke assemblies (metal fittings)
  - Central hub assy (Al)
  - Synchronization gear assemblies (Ultem)
  - Optical shield close-outs/flaps to petal simulators (black kapton XC)
  - Redundant drive spool/motor assemblies (Al/Steel)
  - Interfaces to Petal: Petal Strut & Petal interface fittings (Al)
    - Full petal simulations on 4 locations (all features, TBD matl.)
    - Petal bases suff. for petal-truss I/F on all bays (all features, TBD matl.)

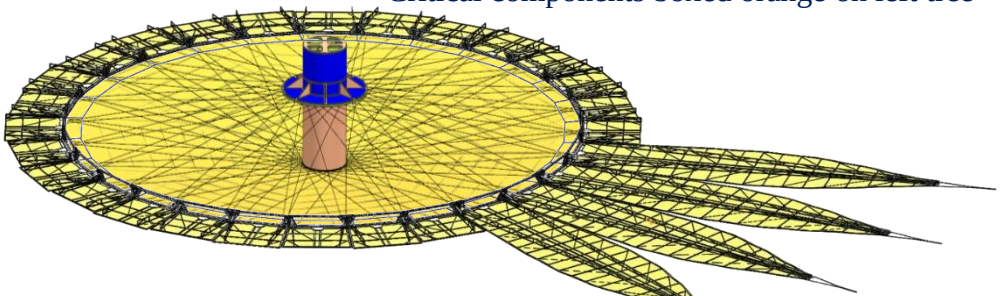
*(M55J with cyanate ester resin, per shared NG materials assumption)

** Critical components boxed orange on left tree

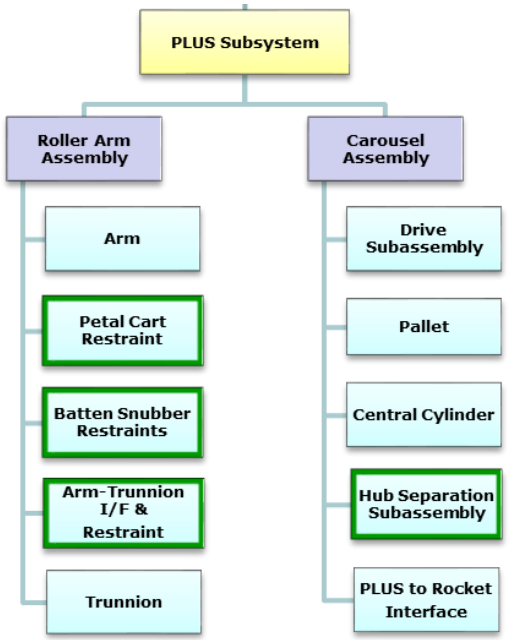


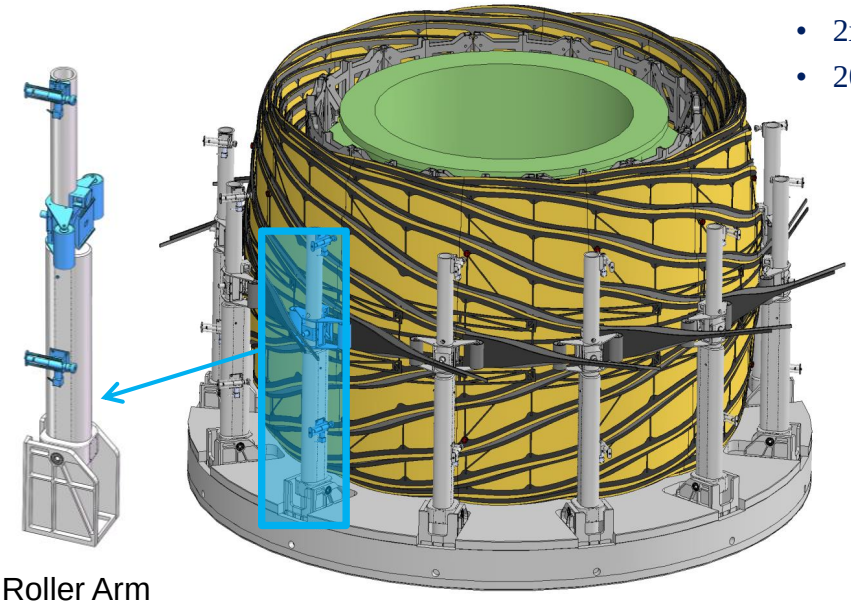





# RFA #5: Test Article Description
# Prototype P5-4: Deployment Control System




- **Tests**: verifying no edge contact during unfurl and validate the analytical model of deployment kinematics
- **Critical components for tests**: Rollers incl. tip management, 2x 6m composite petals, 2x I/F petals and remaining simulators
  - Key components to enable medium fidelity petal unfurling
- **Scale**: Full 2.25m core + 6m petals (shortened length, full width/thickness ***(significant upgrade/overhaul of existing prototype)***
- **Components**:
  - Roller arm assemblies (all new, medium fidelity): rollers and tip management, batten snubber and cart restraints
  - Carousel motorized drive system (existing)
  - Petals: all petals incl. all features, e.g. rib assy's & optical shields, snubbers, carts
    - 2x 6m composite petals (new)
    - 2x interface petals (boundary condition for CFRP petals) (new)
    - 20 simulator petals (flexural stiffness of petal, existing in starshade lab)



Roller Arm

Existing prototype to be upgraded

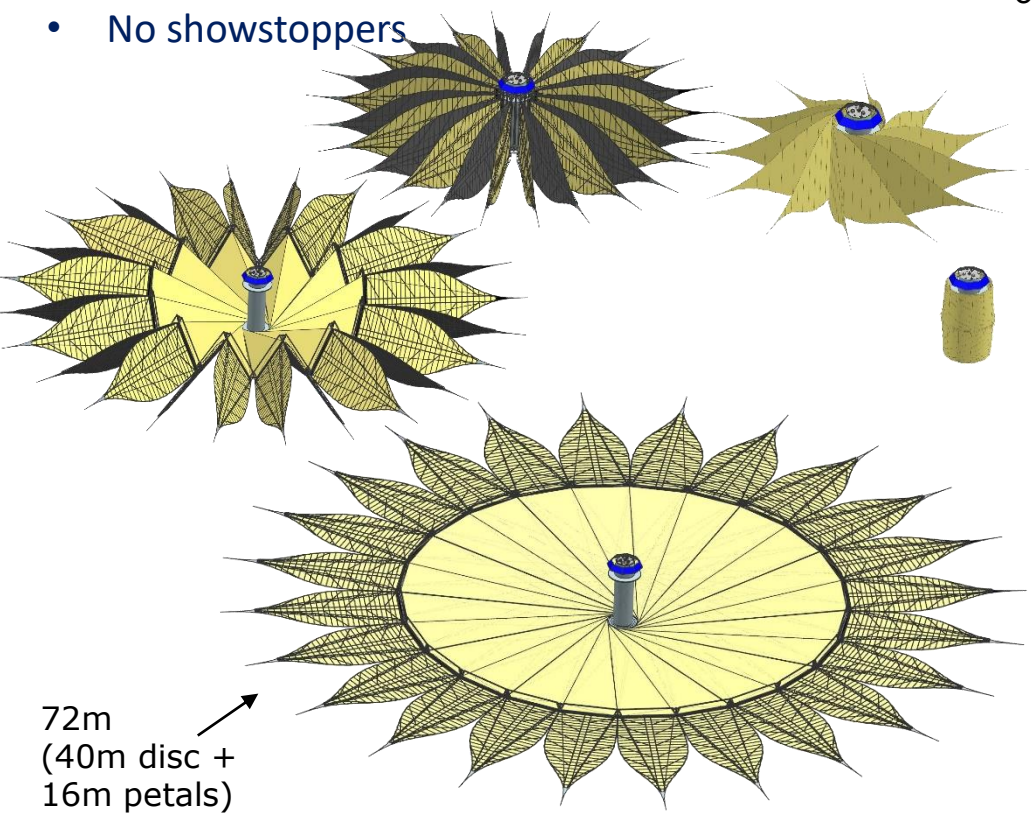
# Technology Summary

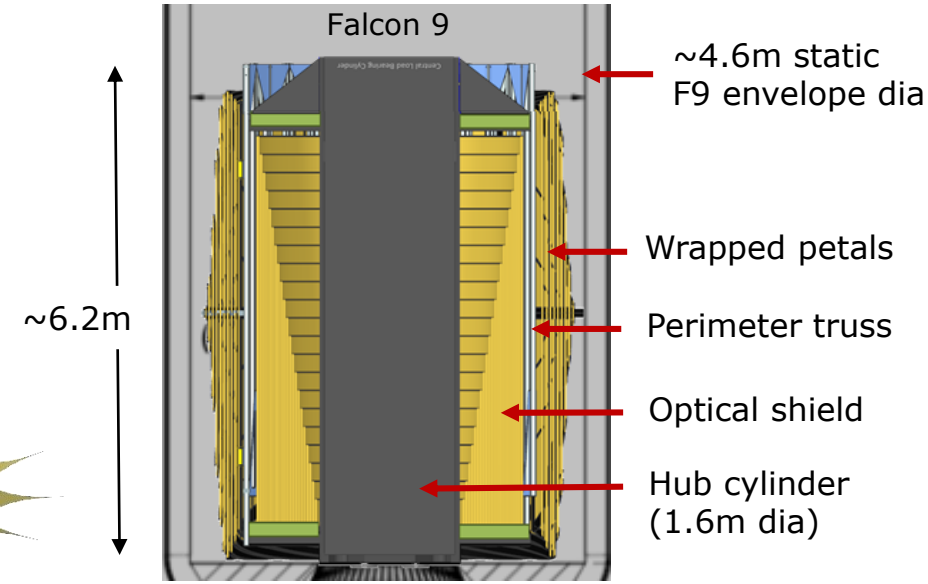
- **A detailed plan for TRL-4/5 is presented that focuses on validating the error budget**
- **Wrapping up the trade study now gives us just enough time to achieve a high level of technology readiness before the initial Decadal Survey input, scheduled for Nov. 2019**
- **An aggressive schedule achieves TRL-5 for all starshade subsystems prior to this date**
  - **We have reasonably high confidence to retire the major performance risk issues (petal shape and position)**

# Scalability to HabEx

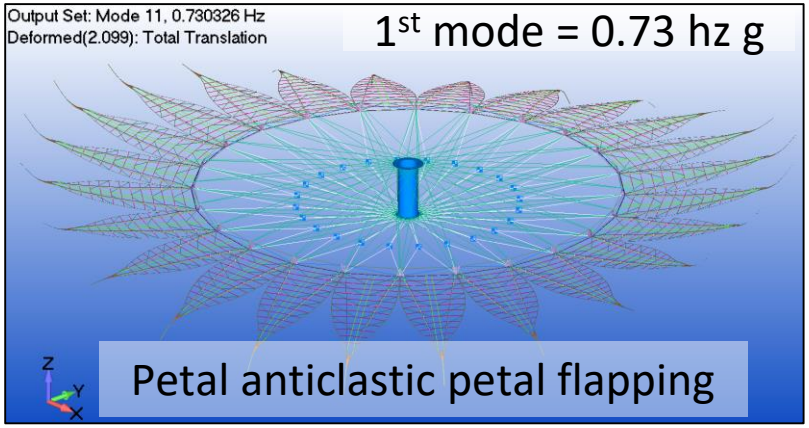
## Configuration & Deployed Analysis

- 72m point design per HabEx STDT study (40m disc, qty 24, 16m petals)
- Rendezvous launch in Falcon 9 (5m fairing)
- Baseline configuration scaled
- Modal analysis promising w/ 1st mode @ 0.72hz
- Error budget scales linearly with starshade size
- No showstoppers




Starshade mass (CBE)= ~2,350 kg
* Based on structural FEM model



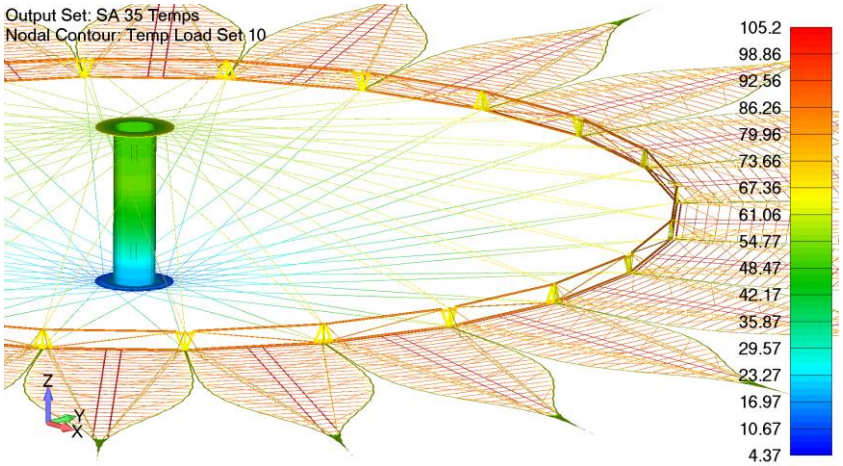
# Habex STOP Analysis

| Case | ***CBE*** *Delta Contrast x 1e-12* | ***Max Expected*** *Delta Contrast w/ 100% contingency x 1e-12* | ***Max Expected*** *% of Starshade Allocated Shape Error (3.4 e-11)*** |
|---|---|---|---|
| ***Spinning*** | | | |
| 35 deg | *0.446* | *1.784* | *5%* |
| 59 deg | *0.044* | *0.176* | *<1%* |
| 83 deg | *0.027* | *0.108* | *<1%* |

Notes:

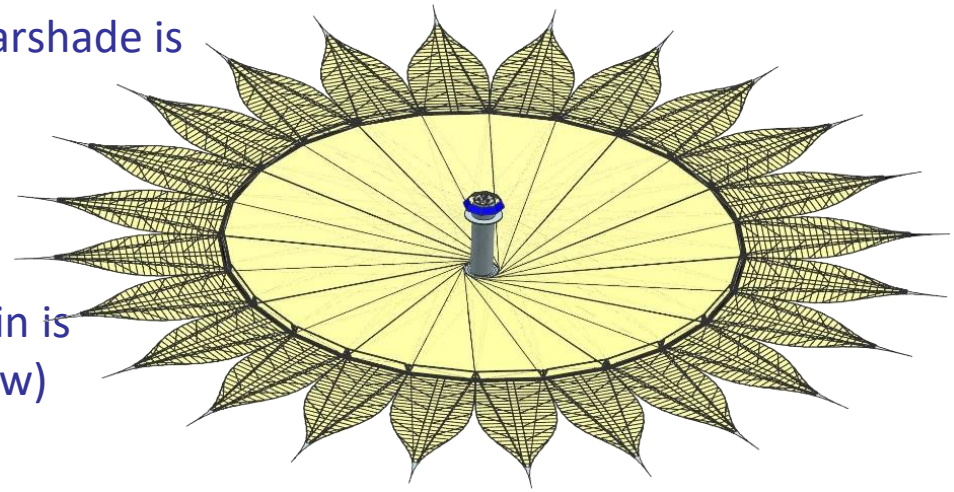
- Only ran spinning cases run for sun angles 35, 59 & 83
- CTE numbers by component from trade study applied to habex config (less longeron fittings, but incl. edge foil)
- Thermal config assumes raw CFRP & black kapton shield on sun side, no thermal optimization
  - Conservative because trade study has shown silicon kapton overlay reduces temperature extremes for structure and thus deformations

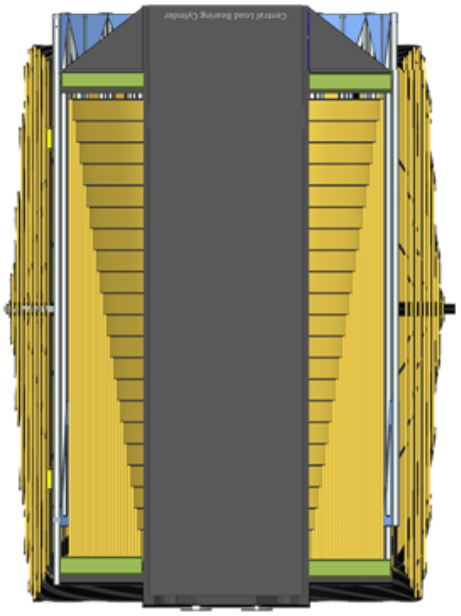
** HabEx shape error allocation is currently *similar* to the 26m design, comparison drawn for reference only



# Scalability Factors

- For a given fairing size, maximum size of starshade is limited by:
  - Diameter of the fairing
    - Sufficient volume for propulsion tanks
    - Sufficient volume for optical shield (min is assumes multiple layers lay flat for stow)
    - # of petals and wrap "pitch"
      - Min # of petals 16, fewer petals wrap thinner (but taller)
      - Min pitch = petal thickness (5/16" up to ½")
  - Height of fairing
    - Fewer petals = wider petals = taller stow height (& thus interplay with stow diameter)
    - Sufficient volume for propulsion tanks
      - Smaller hub cylinder requires taller cylinder for same vol. of tanks & S/C
- Many knobs to turn to tailor design to desired starshade size and meet fairing specs





# Summary

- Habex 72m Baseline Design
  - Wrapped design scales in both configuration and deployed stiffness to be credible for a HabEx 72m design
  - Preliminary STOP analysis shows wrapped 72m design meets thermal performance requirements
- Falcon 9 supports up to 92m per configuration study
- SLS block 1 8.4m dia fairing supports up to ~150m per configuration study (LUVOIR)
- Scalability Breaking Point
  - Design is versatile and parameters can easily be tailored to meet starshade overall size requirements, while still meeting deployed stiffness, with also meeting launch vehicle requirements