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Jet Propulsion Laboratory
California Institute of Technology

Thermal Stability Design, Analysis and Verification of a Starshade

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Agenda

- Starshade design overview
- Thermal analysis overview
- Distortion analysis
- Monte Carlo analysis
- Testing and verification

Starshade Design

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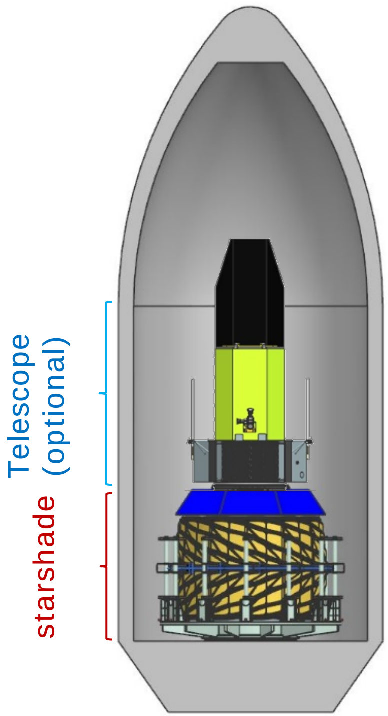
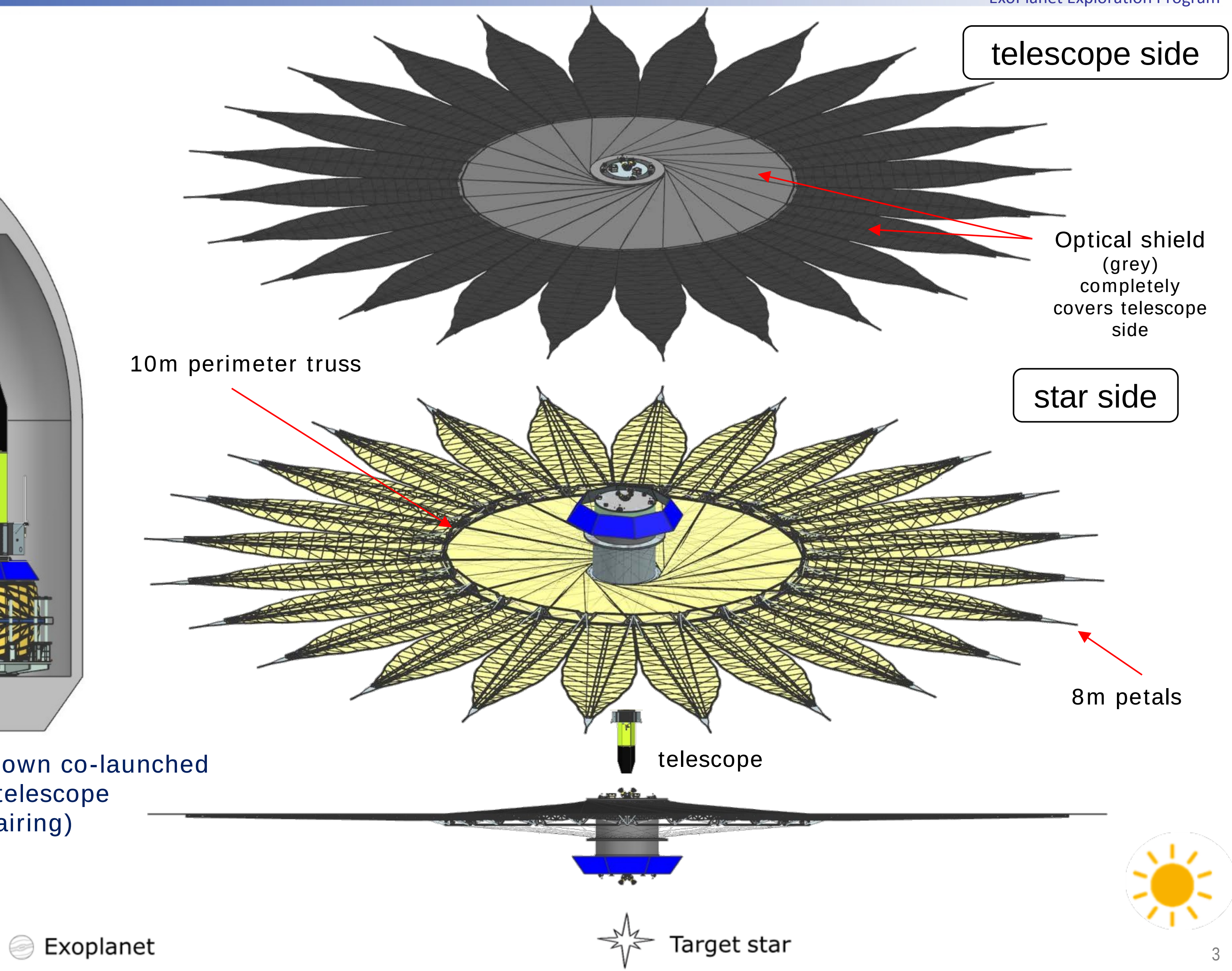
26m NI2 design with 8m petals for ExEp Architecture Trade Study

ExEP
ExoPlanet Exploration Program



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



Subsystem Definitions

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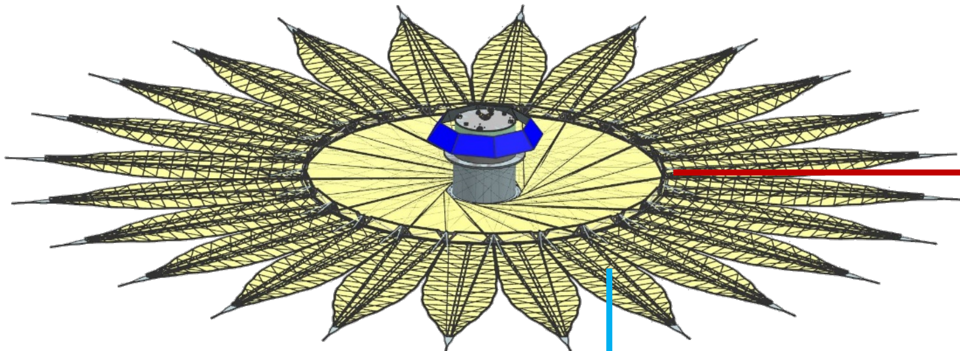
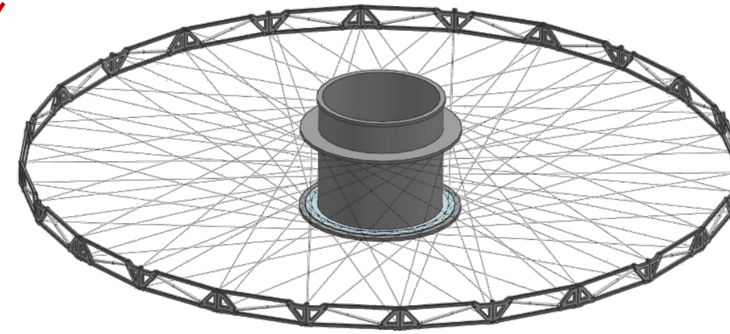
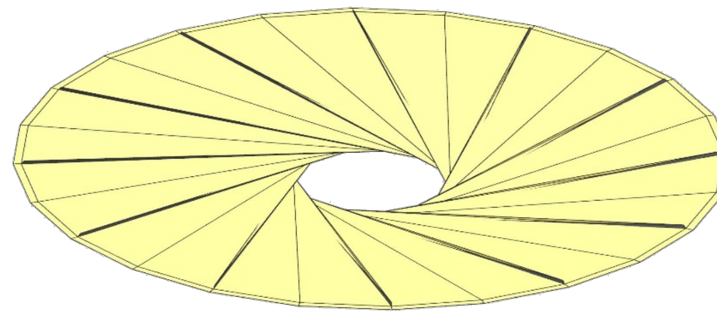


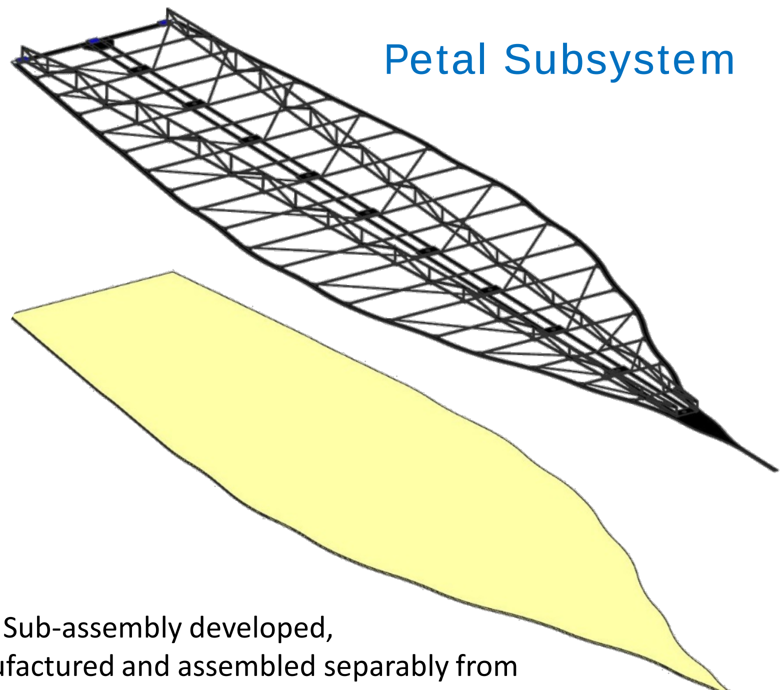


Truss + spokes + hub constitute separable structure w/defined interfaces to petal

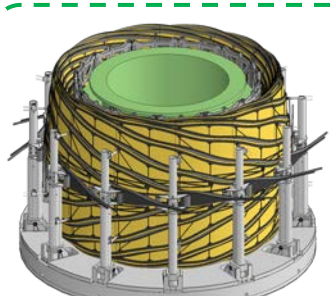


Inner Disk Subsystem

Petal Subsystem



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



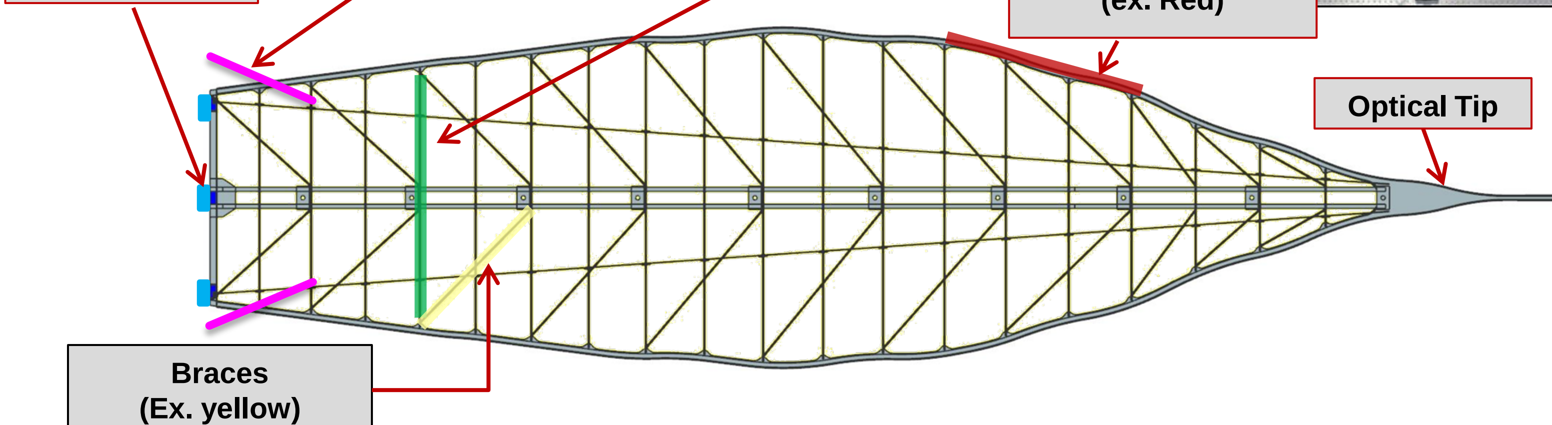
Petal Launch Restraint & Unfurl Subsystem (PLUS)

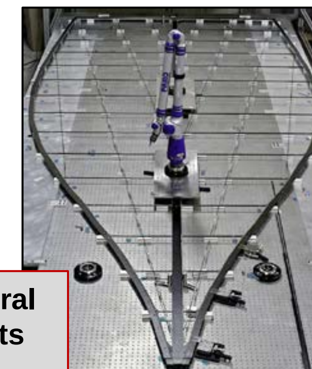
PLUS controls petal deployment & defines petal L/R interfaces (jettisoned after launch)

Petal Shape Critical Components

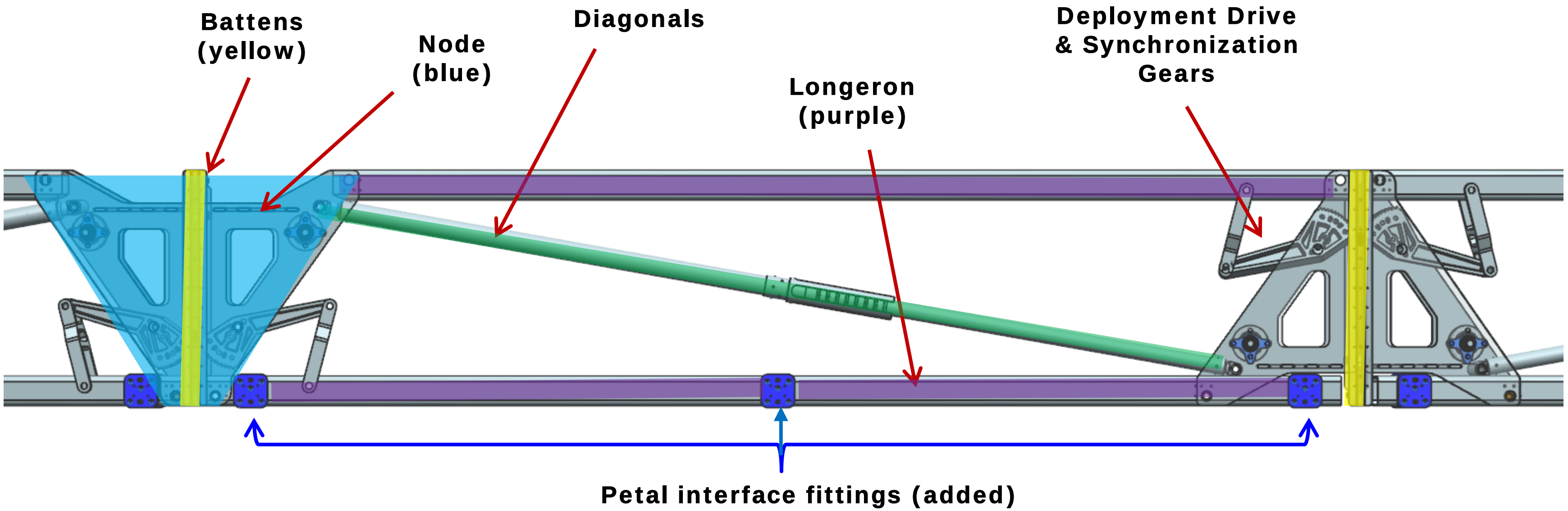
- Petal designed specifically to address in-plane shape stability
  - Battens maintain petal width (COTS & precise)
  - Edges are width-wise thin and “go where battens tell it to”
  - Braces (diagonals) provide in-plane shear stiffness to maintain shape
- Petal hinges maintain petal position relative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

Shape critical members





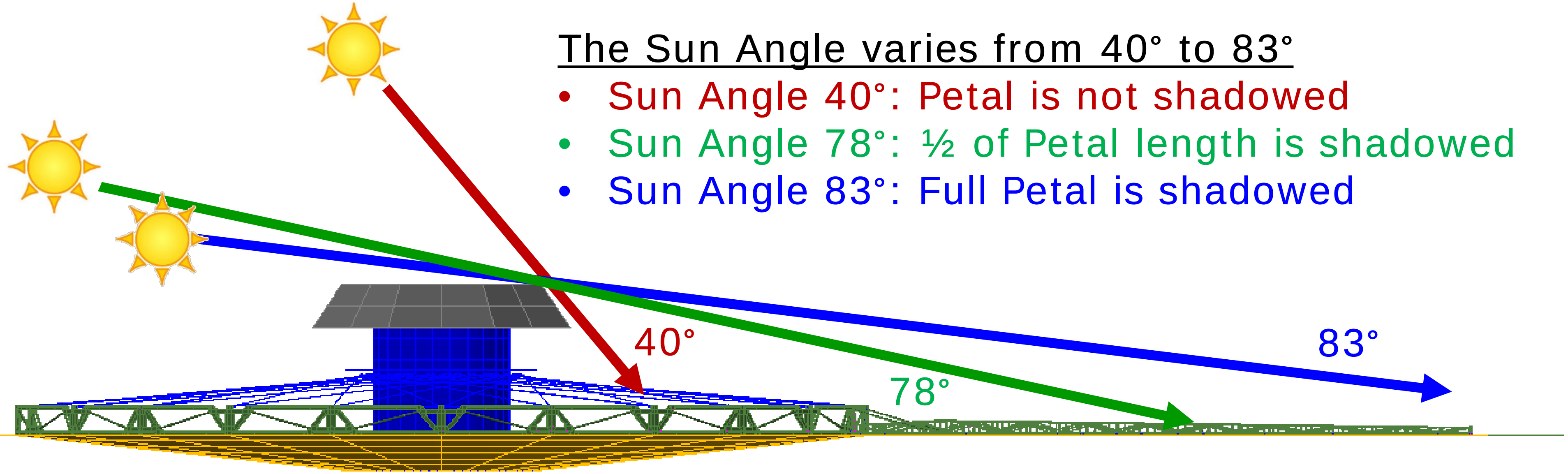
Inner Disk Design Basis
(Perimeter Truss)



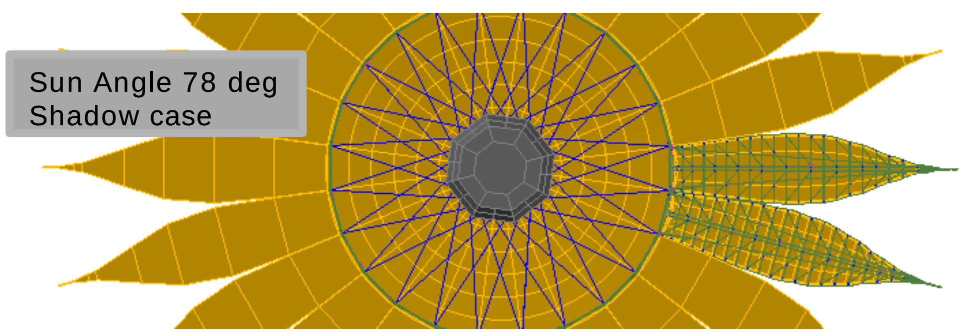
Sun Angles and Shadowing by Hub

<u>The Sun Angle varies from 40° to 83°</u>

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

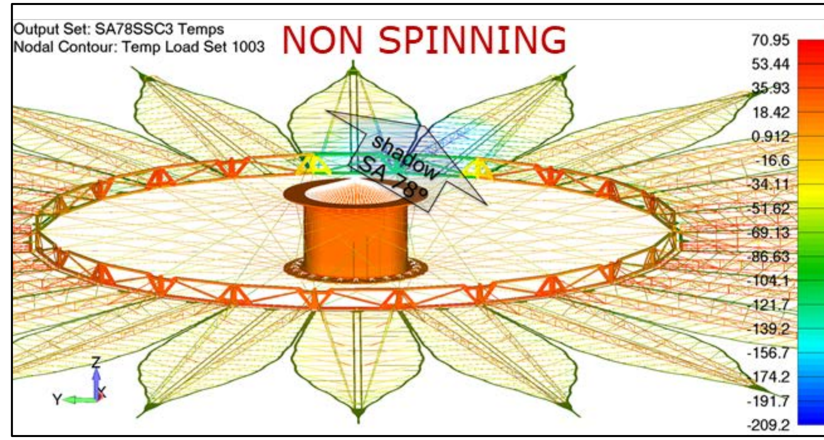


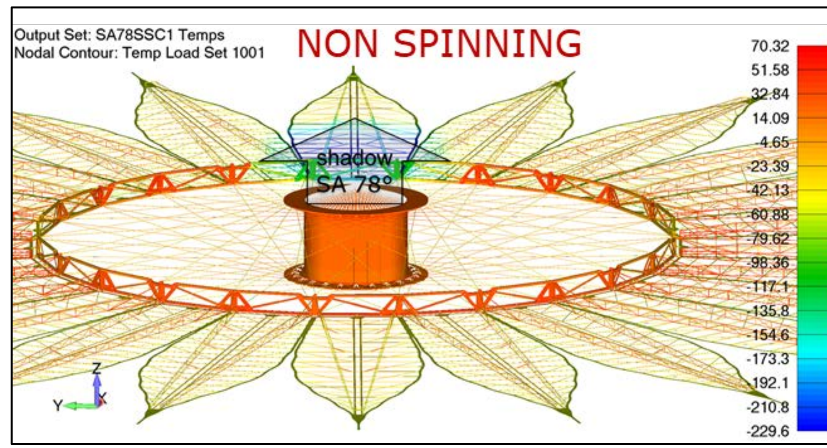
*** Slow rotation run every 3.75°. @1/3 RPM this is every 1.875 seconds, 96 positions. Temperatures available at each of the 96 locations.

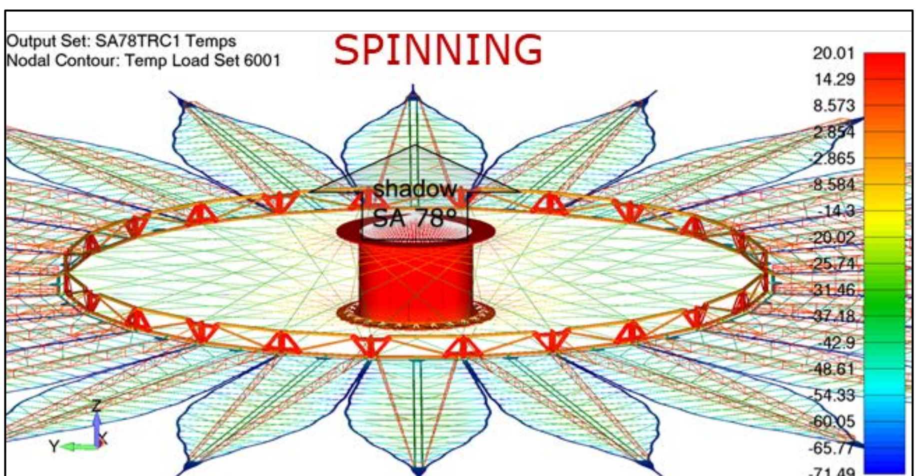


Non-spinning Shadow Orientation Conclusions

	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 Transient has negligible effect on contrast	90 C	65 C / -95 C







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Sun Angle 78

Comparison of Spinning to Non-Spinning

ExEP

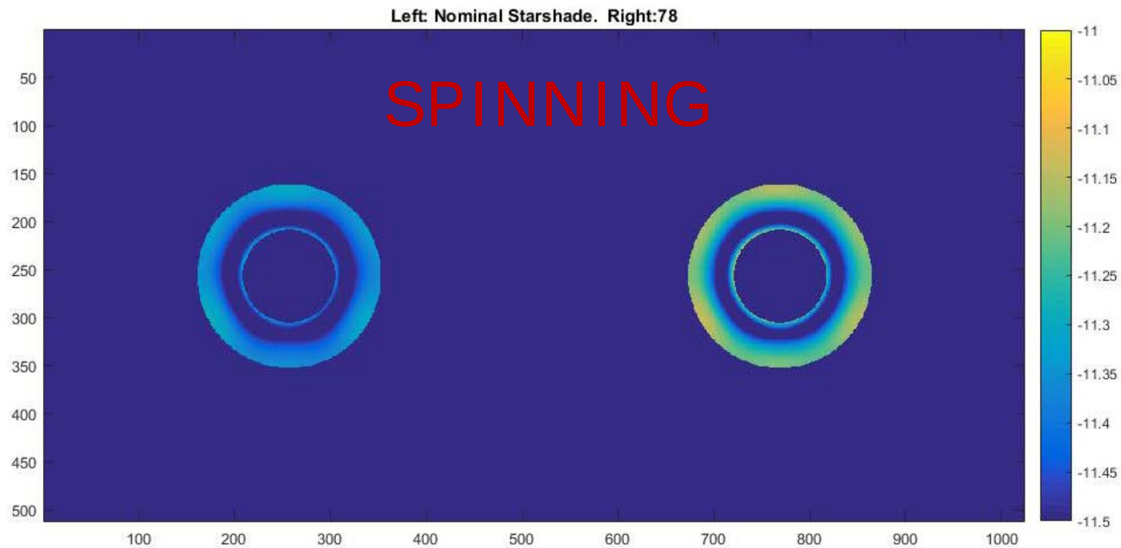
ExoPlanet Exploration Program

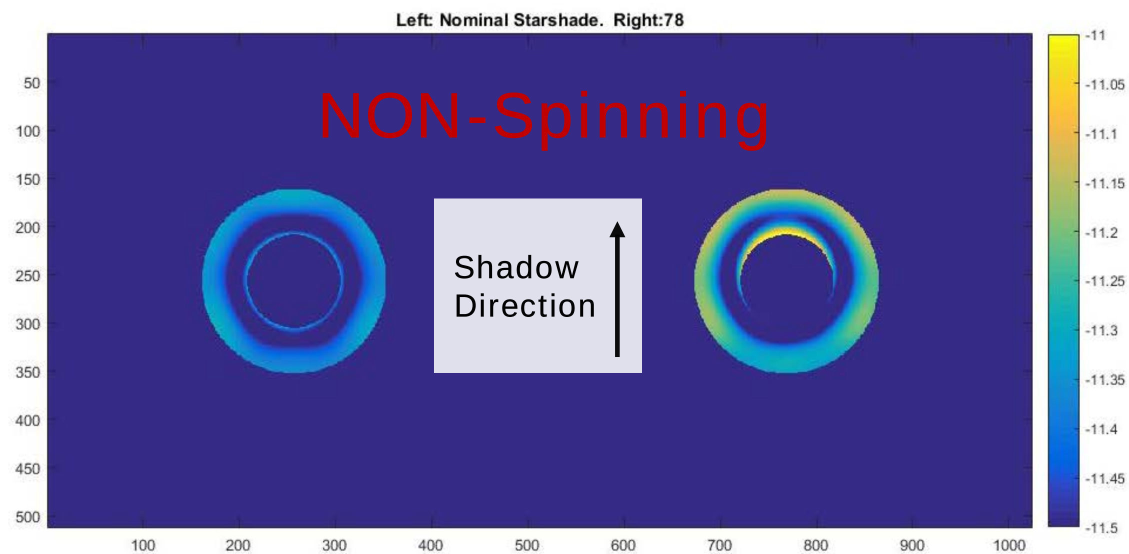
Spinning

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

NON-Spinning

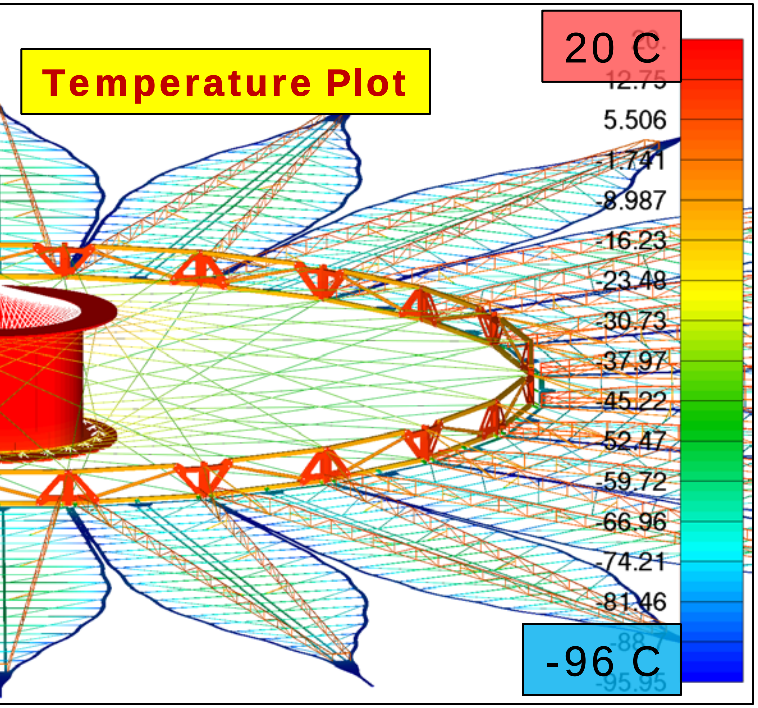
- Largely distorted shadowed petals :
  - Shift high contrast annulus toward shadow
  - Reduce contrast in petal distorted zone

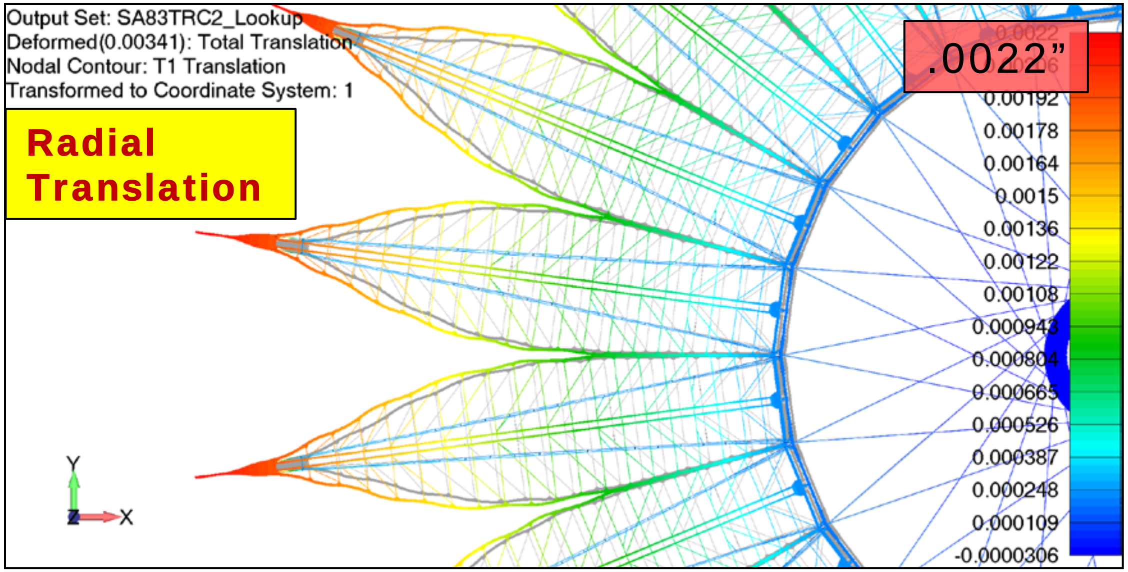


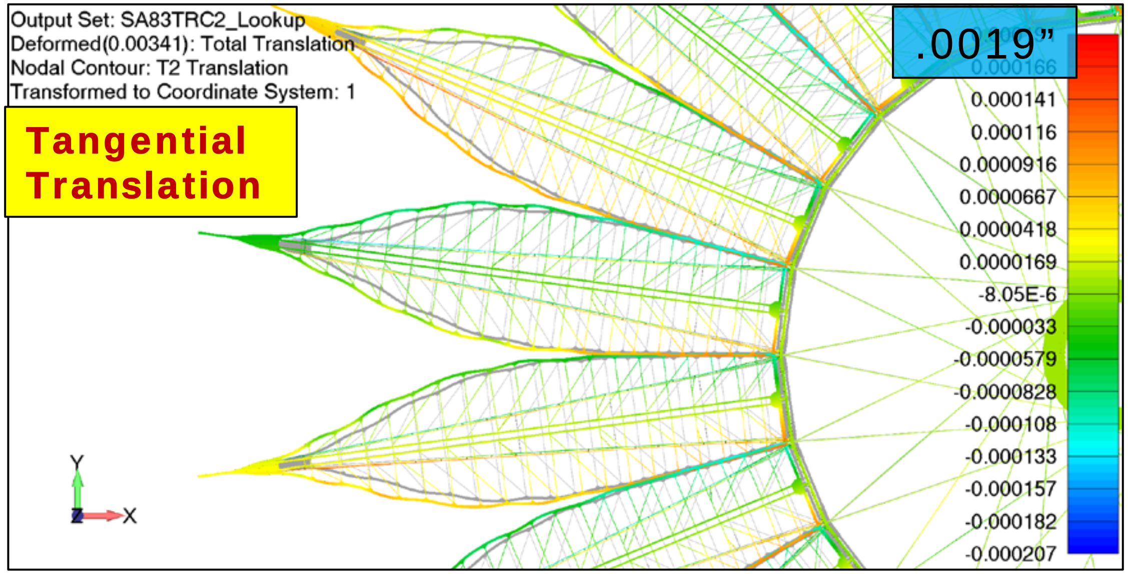


SA83 SPINNING Distortions

- **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")

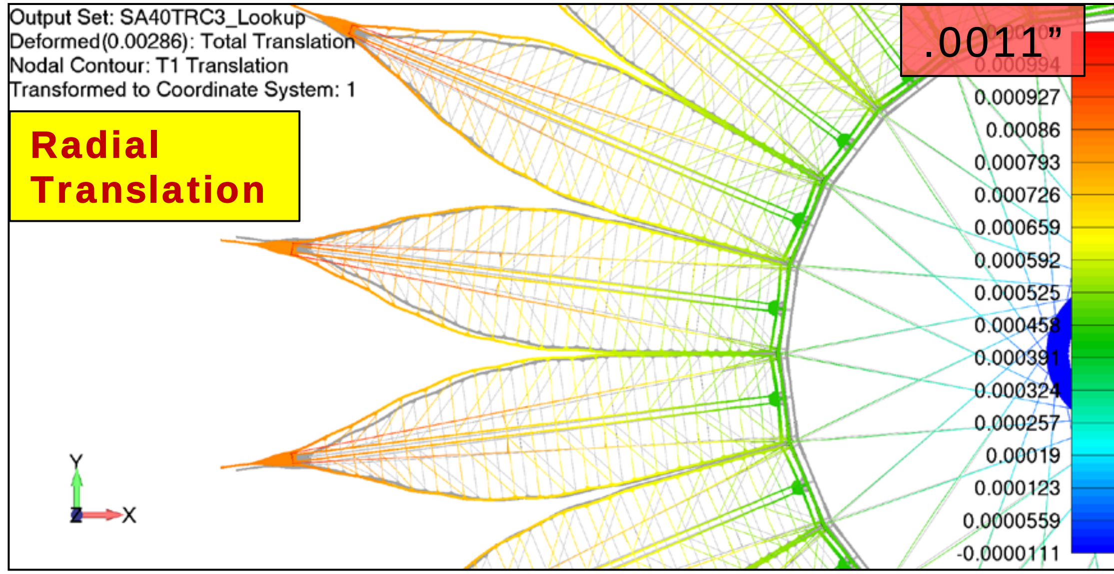


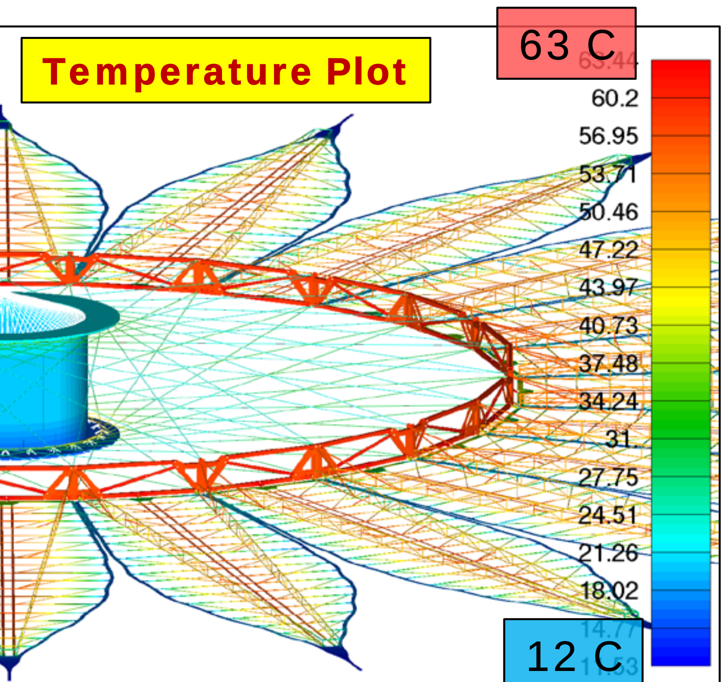


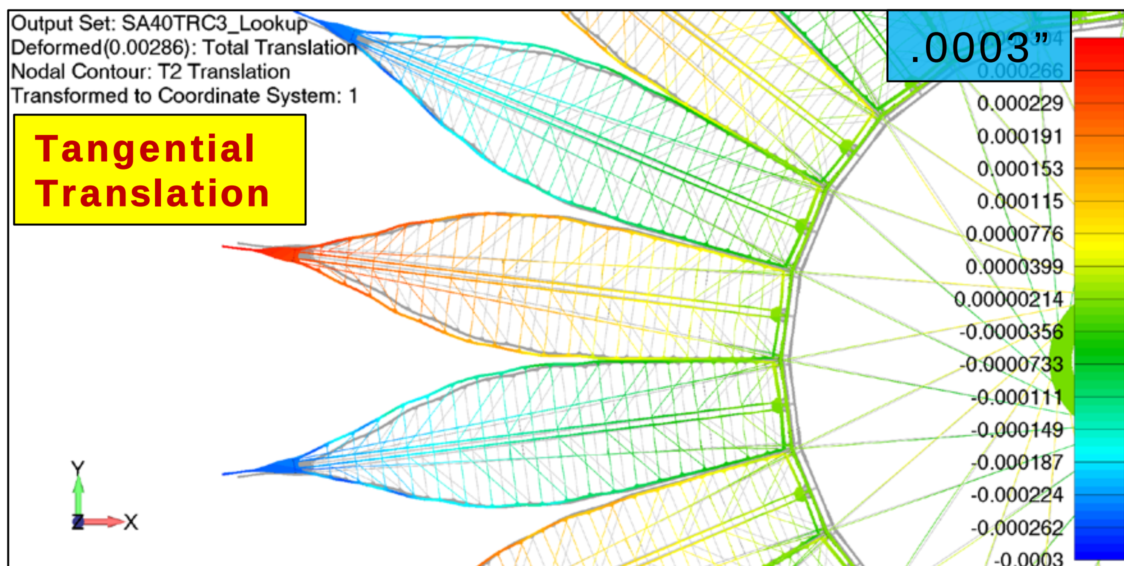


SA40 SPINNING Distortions

- **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")

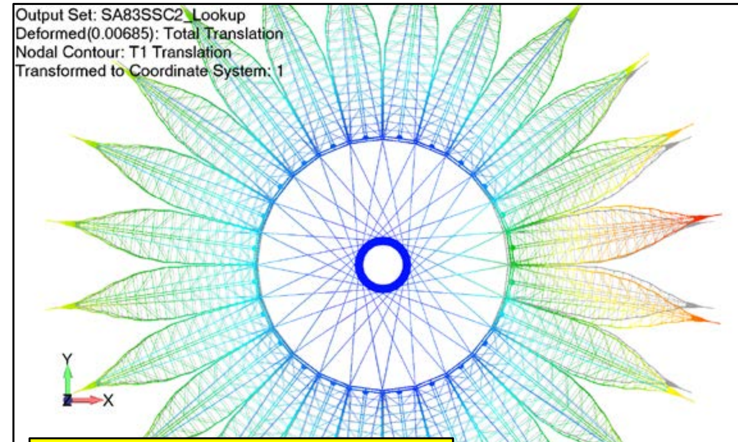


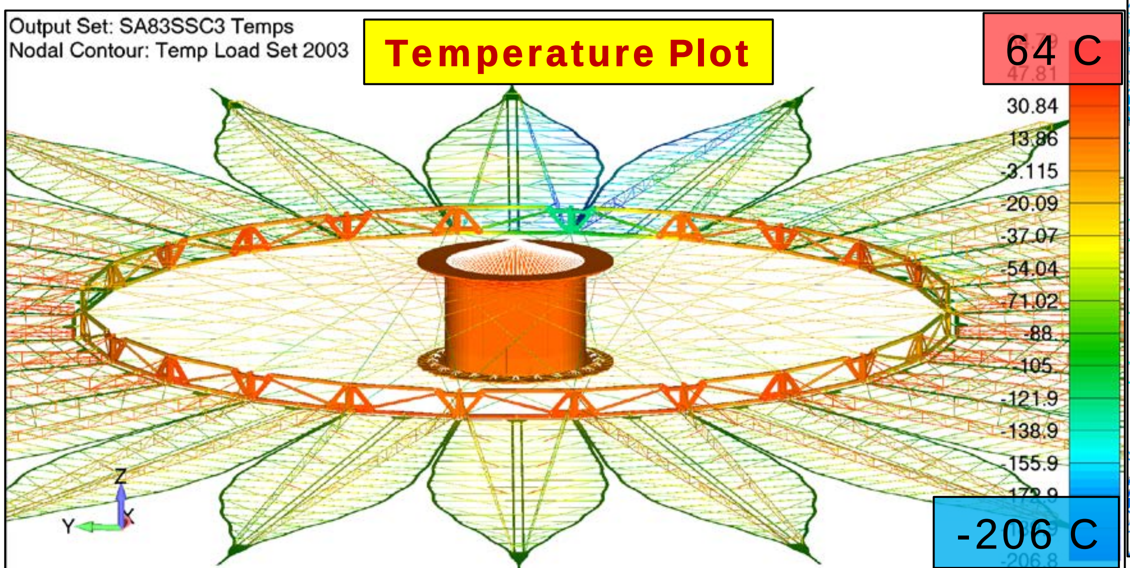


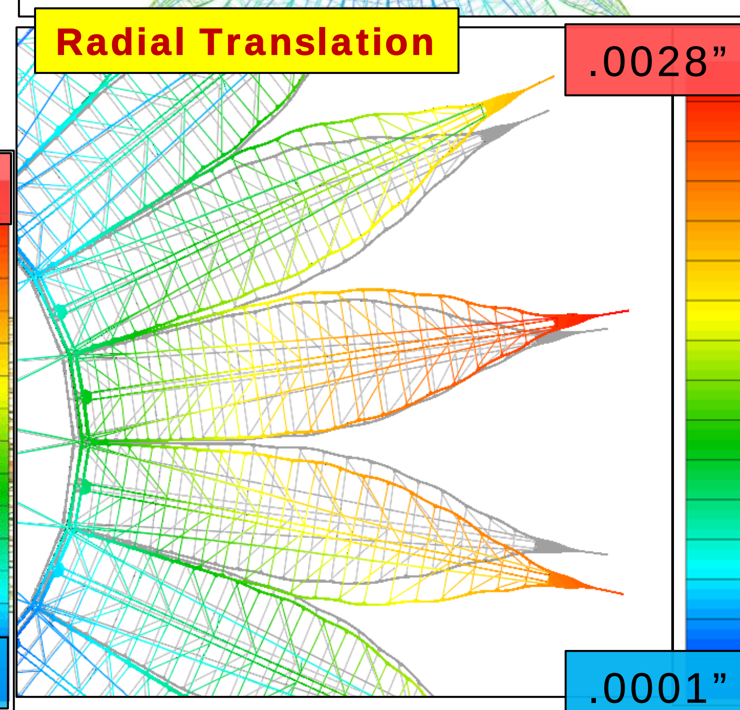


Sun Angle 83, NON-spinning, Distortions

- 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

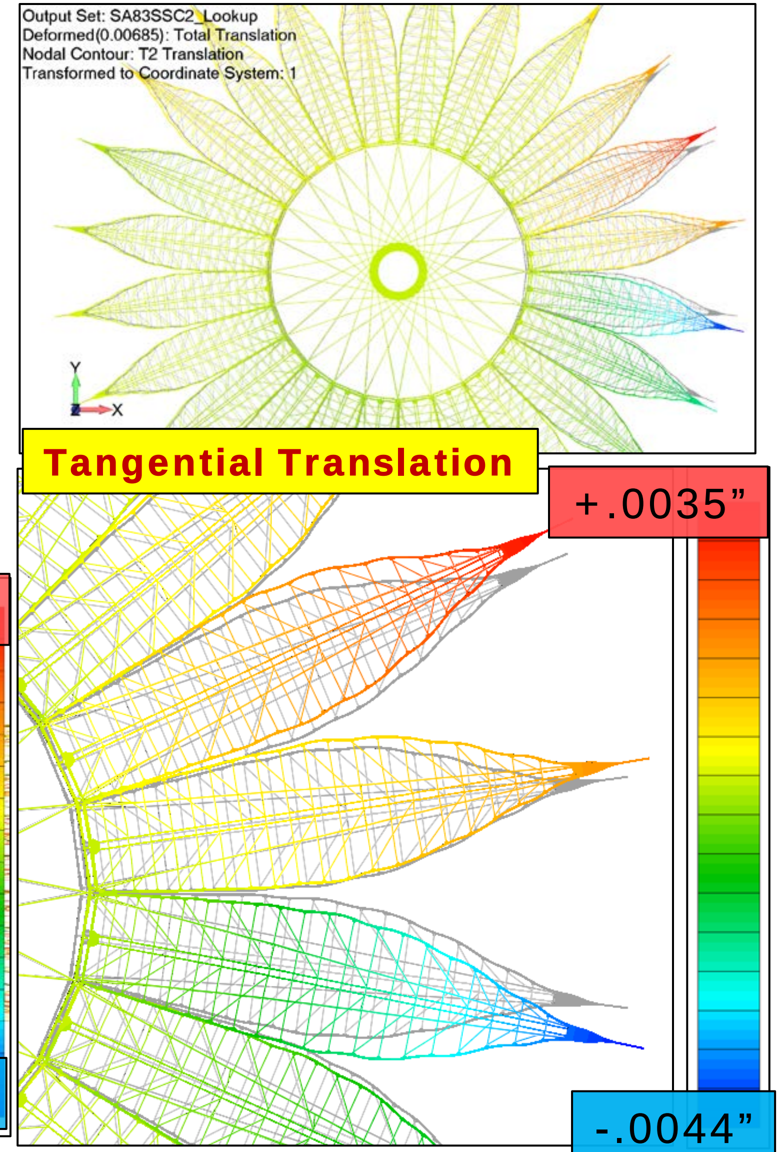


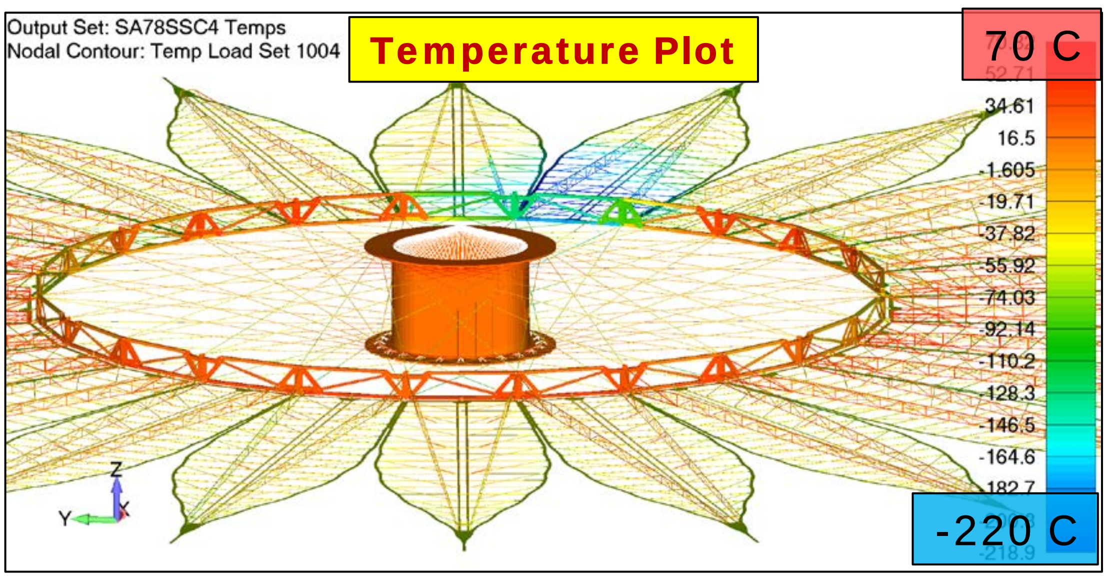




Sun Angle 83, NON-spinning, Distortions

- 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
- <u>**Raw**</u> distortions on order of 100 microns (0.004”)
  - Truss bays in shadow are cold, and grow (neg CTE), and splay petals apart from eachother





Thermal Distortion Analysis

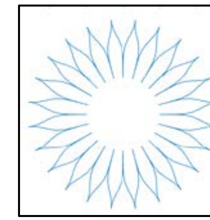
- Two analyses for the impact of thermal distortion on contrast:
  - STOP Analysis: uses thermal mapping and nominal CTE values (temperature dependent) to compute contrast for each sun angle
  - Monte-Carlo Analysis: uses random distributions on CTEs to determine statistical distribution on contrast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

STOP Analysis (for each sun angle)

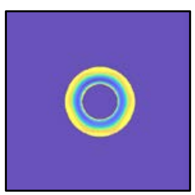
Thermal Analysis

FEM w/ CTE Lookup Tables at a nominal CTE

Displacement from FEM



Create E field from FEM distortions



Compute contrast from E field

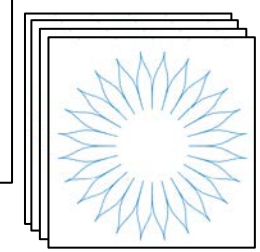
Monte Carlo Analysis (for each sun angle)

Thermal Analysis

FEM w/ a bulk CTE per structural component

Displacements for each CTE group with sun angle temps

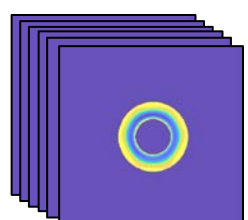
126 influence functions



Create E field from influence function/rotated influence function

Rotate influence function displacement by 30° (x12 rotations)

1490 E fields



Monte Carlo (Dakota) w/ Normal distributions on CTEs w/ lookup tables (fields combined by superposition)

Statistics on distribution of contrast function giving probability of being below given contrast values

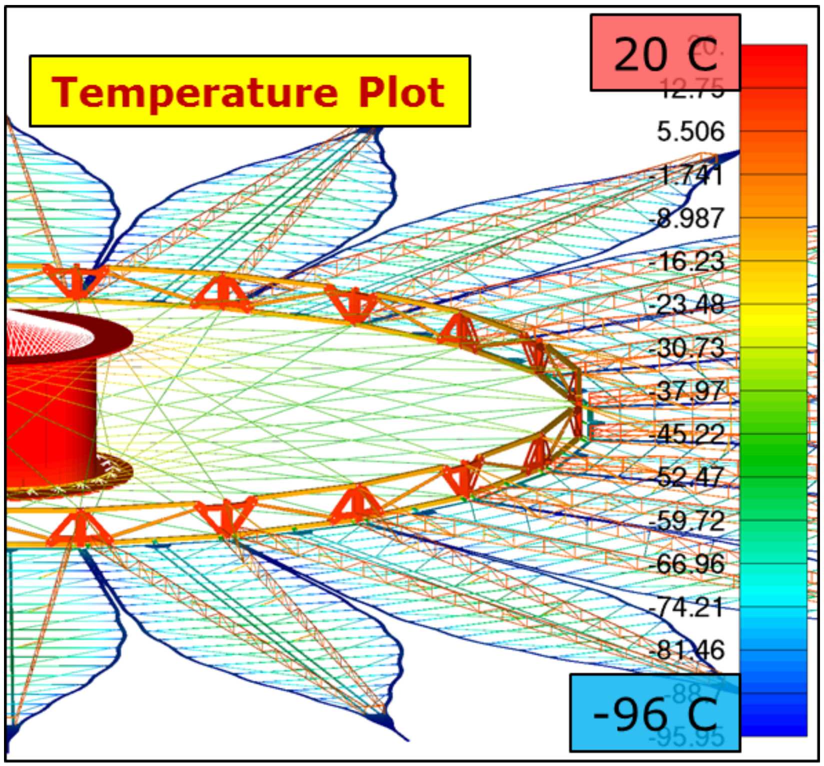
Monte Carlo CTE Influence Functions

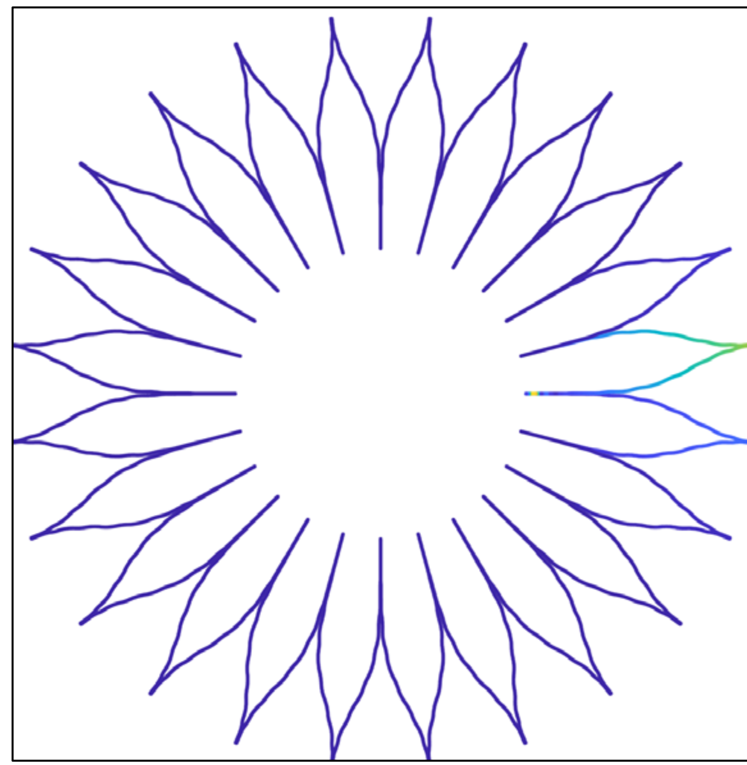
- Influence functions were created by setting a specified component at –1ppm/C CTE and all other components at 0 CTE with a given sun angle temperature mapping
- Assumed spinning Starshade

Component Group	Components Per Petal	Total Influence Functions per Petal Pair	Resulting E Fields (post rotations)
Battens	19	38	456
Braces	22	44	528
PUR	2	4	48
Spines	2	4	48
OE, OE TIP	3	6	72
Roots	1	2	24
Longerons	1	2	24
Shorterons	1	2	24
Diagonal	1	2	24
Nodes	2	4	48
Hinges	3	6	72
Struts	2	4	48
PUR Struts	2	4	48
Tip Structures	1	2	24
Spokes	N/A	1	1
Hub	N/A	1	1
		Total Number of Influence Functions = 126	Total Number of Computed E fields = 1490

Sample Case: Batten 1 on Petal 1, SA83

- FEM was run at SA83 with batten 1 on petal 1 at -1ppm/C CTE, everything else at 0 → influence function (thermal distortion of perimeter)





Influence Function for batten 1 on petal 1, SA83

Sample Case: Batten 1 on Petal 1, SA83

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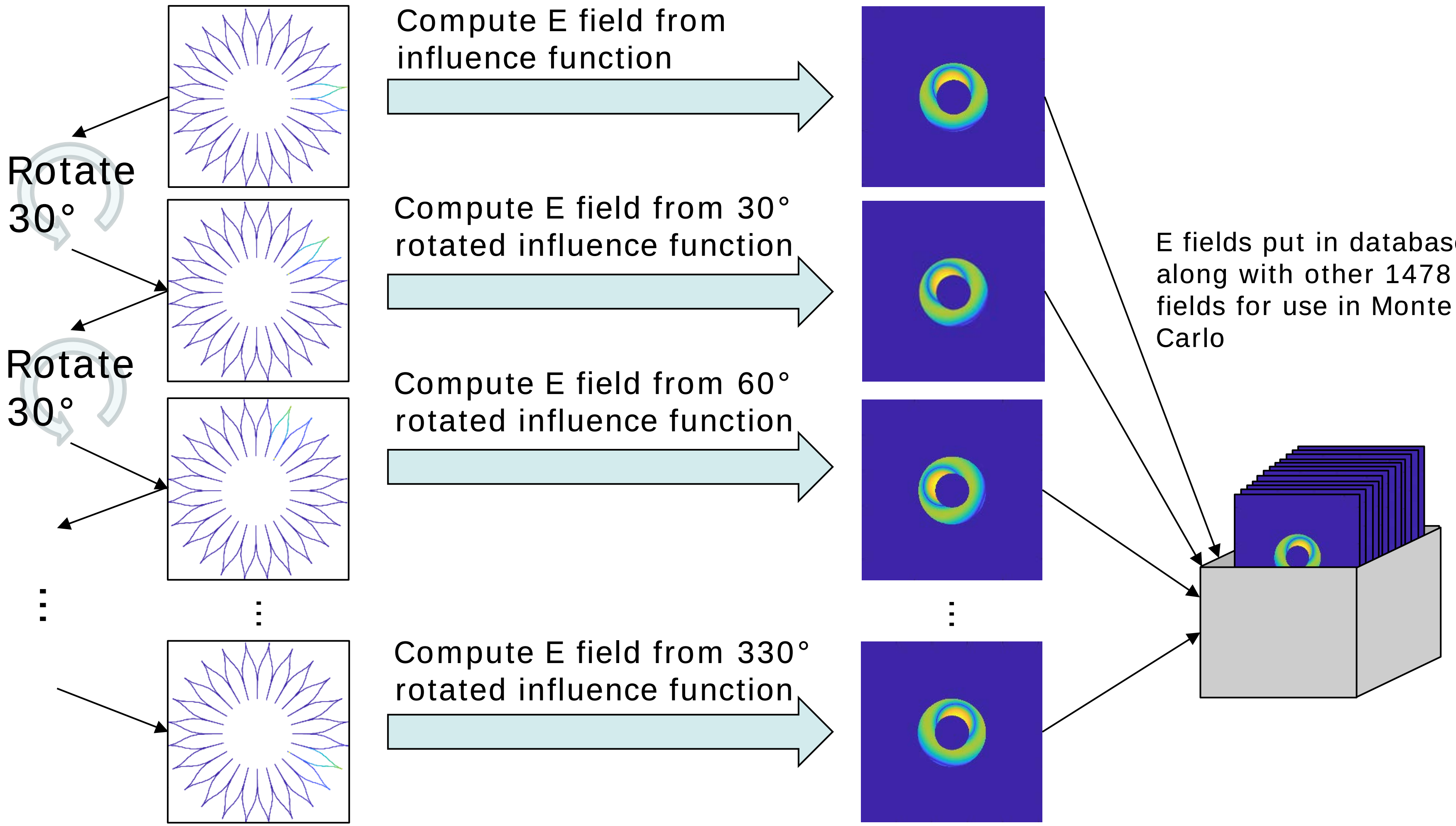
- Compute the E field from the influence function, rotate 11 times and compute each E field:



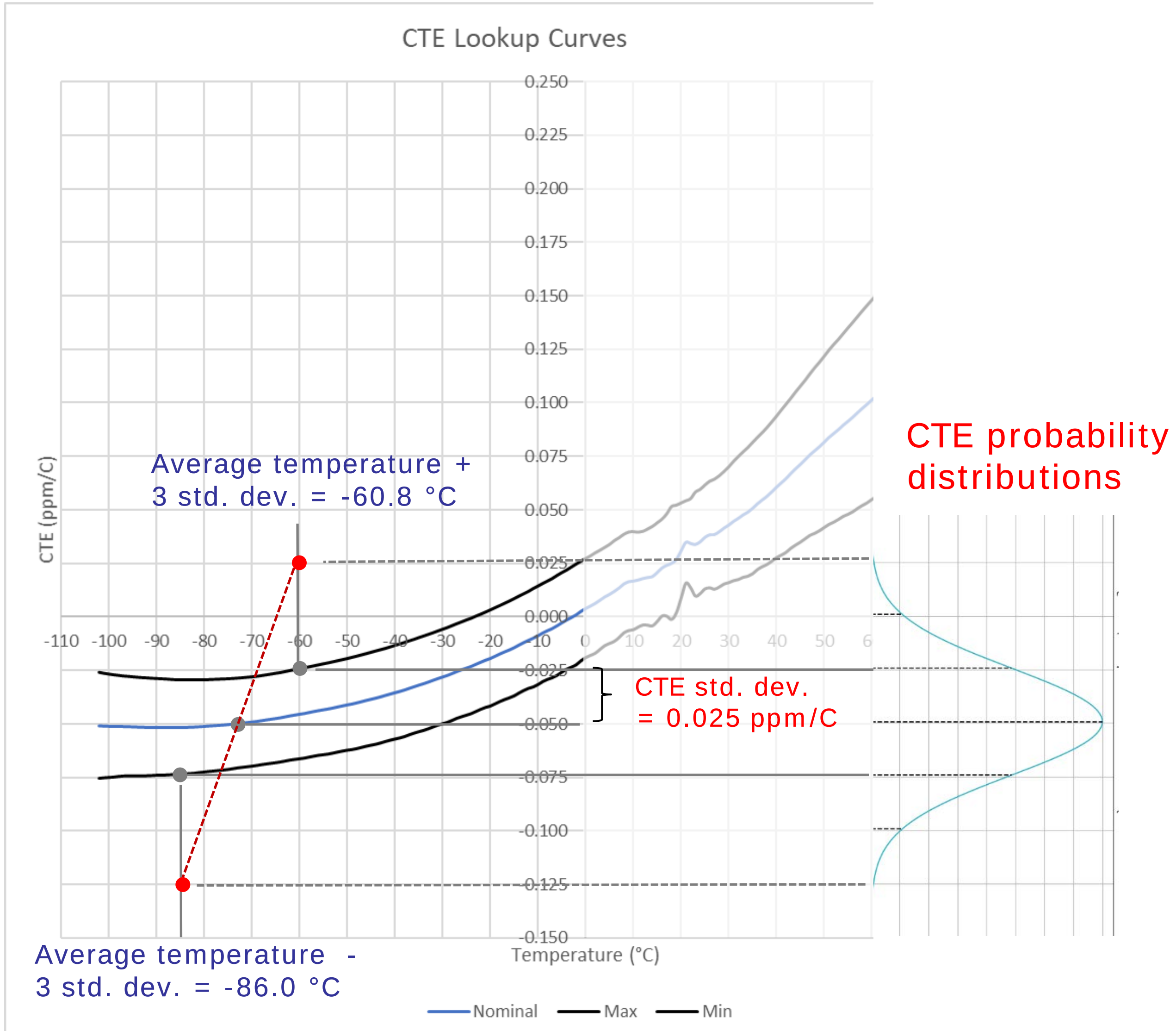
Creating CTE Distributions w/ Lookup Tables

- 4 material lookup curves vs. temperature:
  - Intermediate modulus CFRP (petal battens and braces, spokes)
  - High Modulus CFRP (petal spine and root, truss longerons and nodes)
  - HM CFRP + AM foil (optical edge and tip)
  - Invar (petal hinges)
- Each lookup curve includes a nominal CTE with minimum and maximum error bands based on measured data
- Temperature statistics on each component group for a given spinning sun angle case:
  - Average temperature
  - Standard deviation
- Create CTE distributions assuming temperature is distributed between average temperature ± 3 std. dev.:
  - Average CTE = Nominal CTE @ average temperature
  - Average CTE + 1 std. dev. = Maximum CTE @ (average temp. + 3 std. dev.)
  - Average CTE - 1 std. dev. = Minimum CTE @ (average temp. - 3 std. dev.)

Creating CTE Distributions w/ Lookup Tables: Example

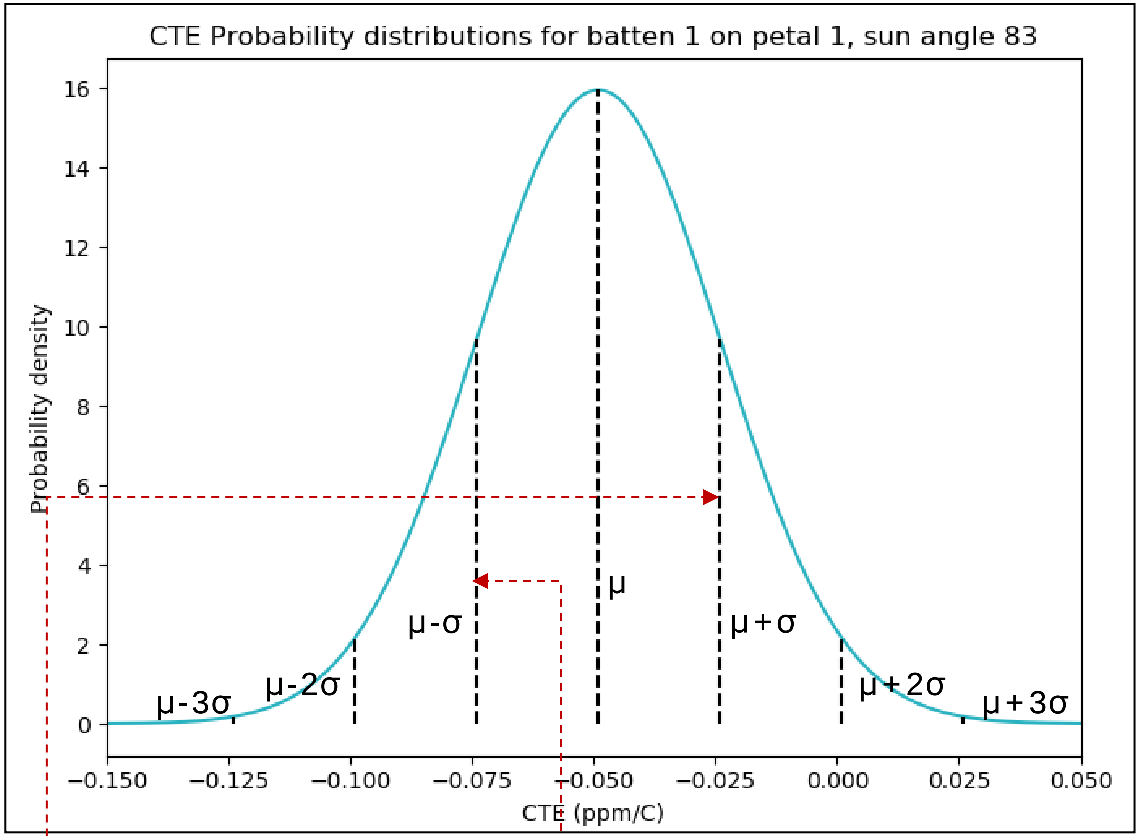
- **Sample case: SA83 batten 1 on petal 1**
  - Material: IM CFRP
  - Average temperature: -73.4°C
  - Standard deviation: 4.2 °C

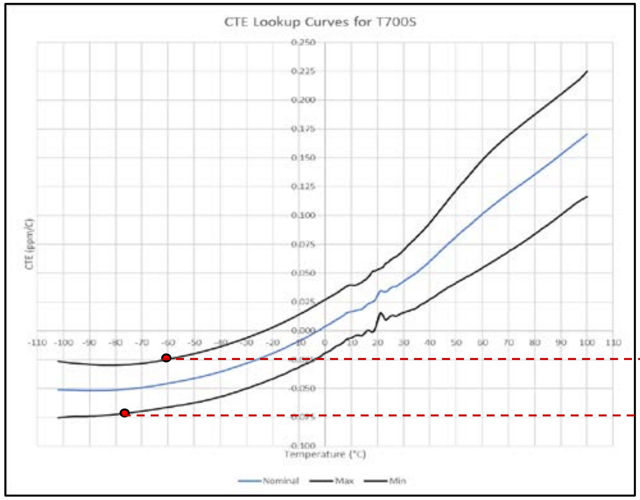
Normal Distribution Parameters:
Mean = -0.049 ppm/C
Std. Deviation = upper bound – mean = 0.025 ppm/C
CTE 3σ range: -.125 to +.025 ppm/C



CTE Distributions used in Monte Carlo analysis
Sample case: SA83 batten 1 on petal 1

Normal Distribution Parameters:
Mean = -0.049 ppm/C
Std. Deviation = 0.025 ppm/C





Statistical Results

- From Monte-Carlo get:
  - Mean CTE and standard deviation w/ confidence intervals
  - Cumulative distribution function (CDF) for the contrast, which gives the probability that the contrast is below a given value (i.e. CDF(x) = Prob(contrast <= x))
  - Other statistical information, such as percentiles and correlations (which give information about which variables affect the contrast the most)

Cumulative Distribution Function Example

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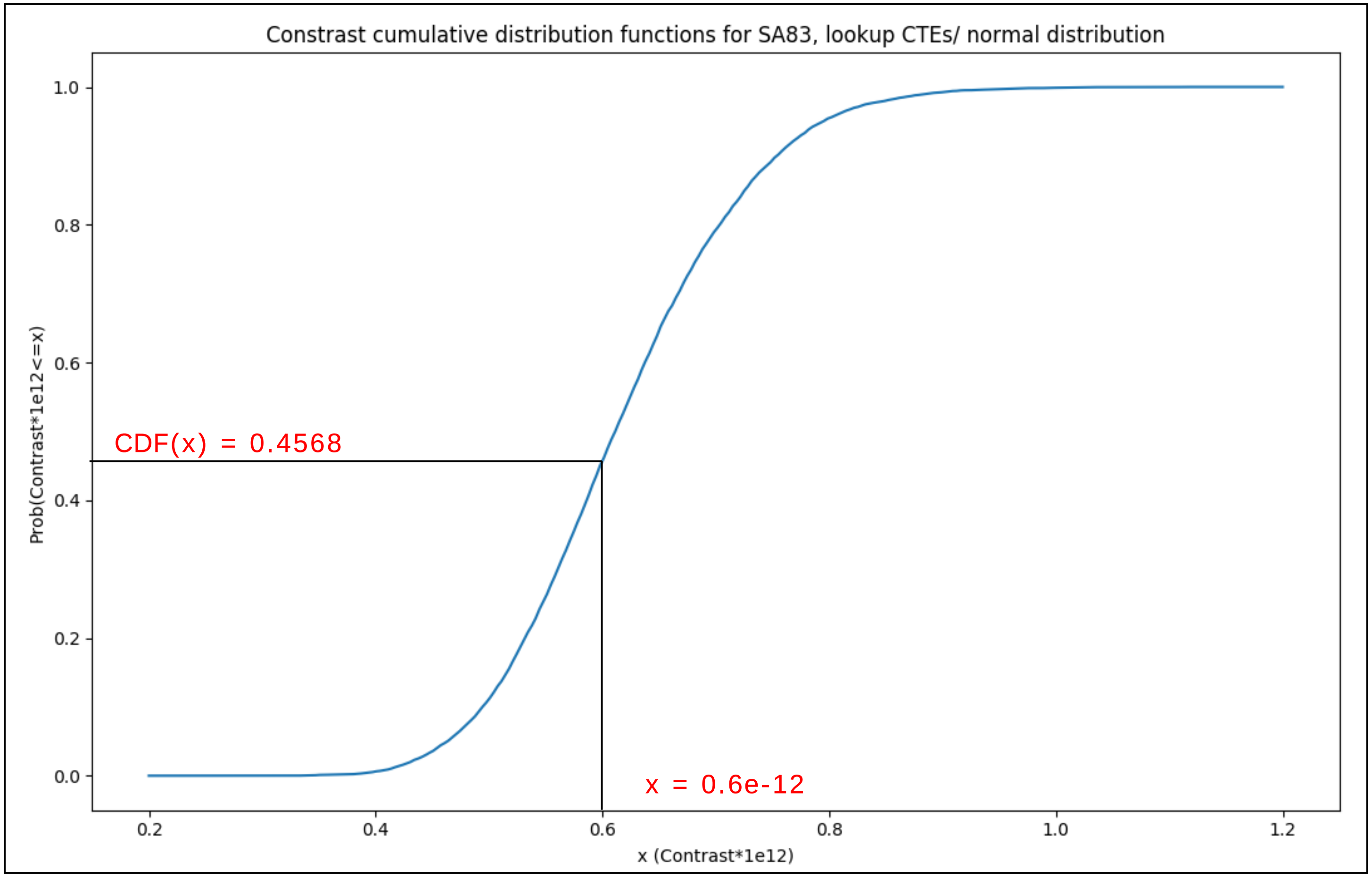
- Sun angle 83°, spinning
- Normal distribution on CTEs
- Probability that the contrast is below **0.6e-12** is 0.457



CDFs for all CTE Distributions and Sun Angles, Spinning

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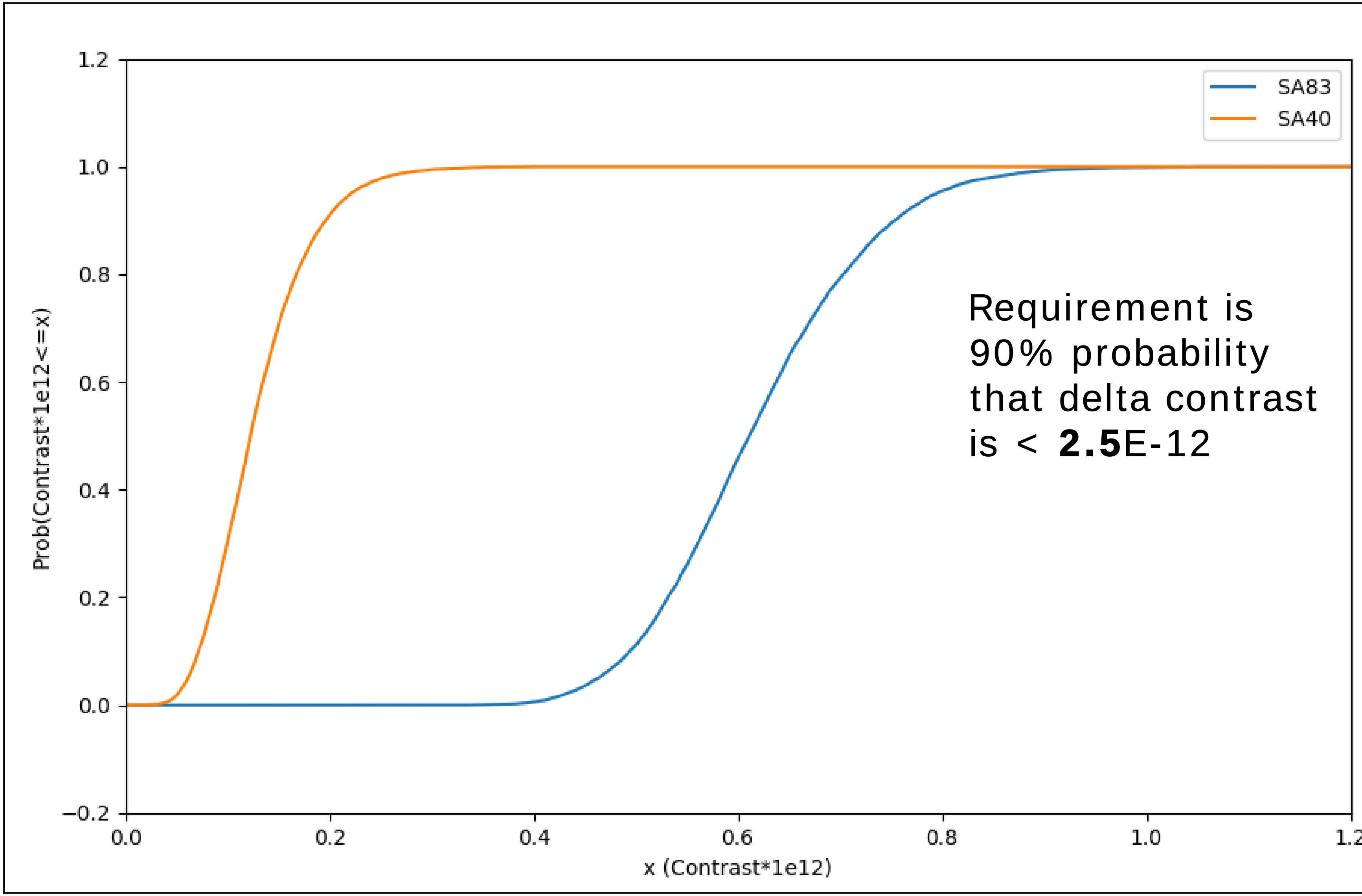


Results Summary - Spinning

Monte-Carlo Analysis Results:

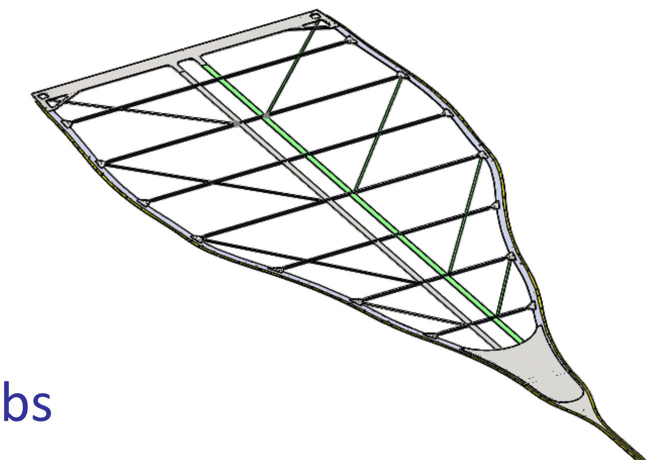
Sun Angle	Samples	Prob(contrast <=2.5e-12)	Mean contrast*1e12	90^{th} percentile*1e12
83°	10000	100%	0.619	0.754
40°	10000	100%	0.130	0.196

STOP Analysis Results:

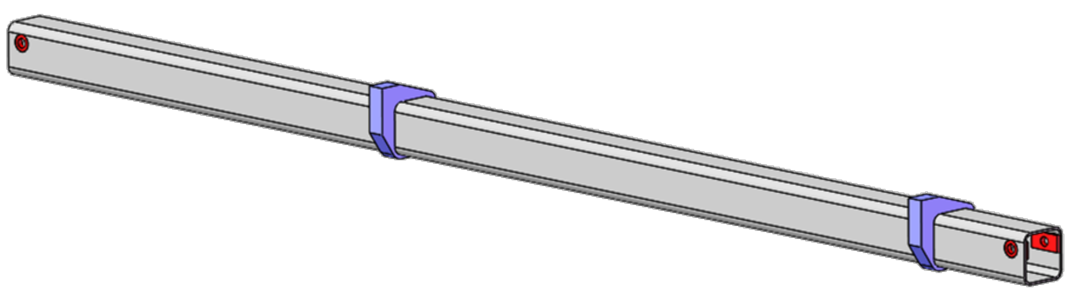
Sun Angle	Contrast*1e12
83°	0.588
40°	0.025

Verification and Testing

- Fabricating a flight-like petal
  - High modulus CFRP QI layup for edge, root, spine and tip
  - Pultruded intermediate modulus carbon fiber/epoxy for battens and braces
  - Applying flight like bonding practices, fixturing and curing



- Fabricating a CTE truss bay
  - Longeron with bonded fittings
  - Node assembly with fittings and shear webs



Verification and Testing

- Testing
  - Components' shape will be tested before and after thermal cycling
  - Bonded assemblies will be shape tested before and after thermal cycling

  - Raw components CTE tested (battens, braces, HM CFRP QI and Uni)
  - Petal assemblies will be CTE tested (batten assembly)
  - Petal will be tested in TVAC chamber with laser interferometry
  - Truss longerons and nodes will be CTE tested
- Analysis Correlation
  - Petal, longeron and node assemblies' finite element models will be checked against CTE results