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

26m N12 design with 8m petals for ExEp Architecture Trade Study

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

Telescope side

Optical shield (grey) completely covers telescope side

star side

10m perimeter truss

8m petals

Telescope (optional)
Subsystem Definitions

Petal Subsystem

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

Inner Disk Subsystem

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

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
Inner Disk Design Basis
(Perimeter Truss)

- Battens (yellow)
- Node (blue)
- Diagonals
- Longeron (purple)
- Deployment Drive & Synchronization Gears
- Petal interface fittings (added)
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

<table>
<thead>
<tr>
<th>Comment</th>
<th>Gradient</th>
<th>Max/Min Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>NON-Spinning</td>
<td>300 C</td>
<td>70 C / -230 C</td>
</tr>
<tr>
<td>Spinning</td>
<td>90 C</td>
<td>65 C / -95 C</td>
</tr>
</tbody>
</table>

- **NON-Spinning**: Shadow clocking orientation has little effect on max/min temps, only moves cold portion of starshade.
- **Spinning**: Averages temperatures symmetrically around spin axis. Transient has negligible effect on contrast.
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
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”)

### Temperature Plot
- **20 C**
- **-96 C**

### Radial Translation
- 20 C: 0.0022”
- -96 C: 0.0019”

### Tangential Translation
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”)

![Temperature Plot](image)

- **Radial Translation**
- **Tangential Translation**
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 each other
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)

1. **Thermal Analysis**
2. **FEM w/ CTE Lookup Tables at a nominal CTE**
3. **Displacement from FEM**
4. **Create E field from FEM distortions**
5. **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

- Rotate influence function displacement by 30° (x12 rotations)
- Create E field from influence function/rotated influence function
- 126 influence functions
- 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

<table>
<thead>
<tr>
<th>Component Group</th>
<th>Components Per Petal</th>
<th>Total Influence Functions per Petal Pair</th>
<th>Resulting E Fields (post rotations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battens</td>
<td>19</td>
<td>38</td>
<td>456</td>
</tr>
<tr>
<td>Braces</td>
<td>22</td>
<td>44</td>
<td>528</td>
</tr>
<tr>
<td>PUR</td>
<td>2</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>Spines</td>
<td>2</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>OE, OE TIP</td>
<td>3</td>
<td>6</td>
<td>72</td>
</tr>
<tr>
<td>Roots</td>
<td>1</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Longerons</td>
<td>1</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Shorterons</td>
<td>1</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Diagonal</td>
<td>1</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Nodes</td>
<td>2</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>Hinges</td>
<td>3</td>
<td>6</td>
<td>72</td>
</tr>
<tr>
<td>Struts</td>
<td>2</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>PUR Struts</td>
<td>2</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>Tip Structures</td>
<td>1</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Spokes</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hub</td>
<td>N/A</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

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)
Sample Case: Batten 1 on Petal 1, SA83

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

  - Rotate 30°
  - Compute E field from influence function
  - Rotate 30°
  - Compute E field from 30° rotated influence function
  - Compute E field from 60° rotated influence function
  - Compute E field from 330° rotated influence function

E fields put in database along with other 1478 fields for use in Monte Carlo
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.)
• **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

Average temperature - 3 std. dev. = -86.0 °C
Average temperature + 3 std. dev. = -60.8 °C
CTE std. dev. = 0.025 ppm/C
CTE probability distributions
Creating CTE Distributions w/ Lookup Tables: Example

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
• 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. $\text{CDF}(x) = \text{Prob}(\text{contrast} \leq x)$)
  – Other statistical information, such as percentiles and correlations (which give information about which variables affect the contrast the most)
Cumulative Distribution Function Example

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

CDF(x) = 0.4568
CDFs for all CTE Distributions and Sun Angles, Spinning

Requirement is 90% probability that delta contrast is < 2.5E-12
## Results Summary - Spinning

### Monte-Carlo Analysis Results:

<table>
<thead>
<tr>
<th>Sun Angle</th>
<th>Samples</th>
<th>Prob(contrast (\leq 2.5\times10^{-12}))</th>
<th>Mean contrast*(1\times10^{12})</th>
<th>90th percentile*(1\times10^{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>83°</td>
<td>10000</td>
<td>100%</td>
<td>0.619</td>
<td>0.754</td>
</tr>
<tr>
<td>40°</td>
<td>10000</td>
<td>100%</td>
<td>0.130</td>
<td>0.196</td>
</tr>
</tbody>
</table>

### STOP Analysis Results:

<table>
<thead>
<tr>
<th>Sun Angle</th>
<th>Contrast*(1\times10^{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>83°</td>
<td>0.588</td>
</tr>
<tr>
<td>40°</td>
<td>0.025</td>
</tr>
</tbody>
</table>
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