Starshade Mechanical to TRL-5
Starshade Mechanical Architecture & Technology Update
SPIE 2019
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Starshade S5 Baseline Design
26m NI2 design with 8m petals

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

Telescope (optional)

10m perimeter truss

Optical shield (grey) completely covers telescope side

Telescope side

star side

8m petals

telescope
HabEx 52m Starshade

16m long x 4m wide petals (qty 24)

20m dia. Inner disk w/ solar array

S5 26m Starshade (to scale)

HabEx 52m starshade in F9 fairing
*Not to scale for visualization purposes
26m Stowed Analysis Summary
• Meets all stiffness and strength requirements including placement of telescope co-launched on top of starshade

Deployed Analysis Summary
• S5: 1st mode > 1 Hz, 1st, in-plane = 17.3 Hz
• HabEx: 0.8 Hz
• Structure stable (truss buckling or loss of tensions, accelerations/thermal)
Subsystem Definitions

**Inner Disk Subsystem**

Petal Launch Restraint & Unfurl Subsystem (PLUS)

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

Petal developed, manufactured & assembled separate from inner disk, with defined interfaces at its base

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

Petal developed, manufactured & assembled separate from inner disk, with defined interfaces at its base
# Mechanical Subset of KPP’s & Error Budget

<table>
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<tr>
<th>Technology Gaps</th>
<th>KPP #</th>
<th>KPP Specifications</th>
<th>KPP Threshold Values</th>
<th>KPP Goals</th>
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</thead>
<tbody>
<tr>
<td>Petal Shape</td>
<td>5</td>
<td>Verify <strong>pre-launch accuracy</strong> (manufacture, AI&amp;T, storage)</td>
<td>≤ ± 70 µm</td>
<td>1 x 10⁻¹¹</td>
</tr>
<tr>
<td>Petal Position</td>
<td>7</td>
<td>Verify <strong>pre-launch accuracy</strong> (manufacture, AI&amp;T, storage)</td>
<td>≤ ± 300 µm</td>
<td>1 x 10⁻¹²</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Verify on-orbit <strong>thermal stability</strong></td>
<td>≤ ± 200 µm</td>
<td>5 x 10⁻¹³</td>
</tr>
</tbody>
</table>

*KPP #6 & 8 represented the largest unverified mechanical shape error contributor to contrast in the error budget prior to S5 project*

**Mechanical Shape Error**

2.1 x 10⁻¹¹

### Technology Gaps

- **KPP 5**: Pre-launch (Mfr., AI&T & storage) ≤ ± 70 µm 1 x 10⁻¹¹
  - 41% ≤ ± 50 µm
  - 25% ≤ ± 40 µm
  - ≤ ± 40 µm TDEM-09 measurements

- **KPP 6**: On-orbit thermal stability ≤ ± 80 µm 0.8 x 10⁻¹¹
  - 100% ≤ ± 40 µm
  - 100% ≤ ± 20 µm Unvalidated models

- **KPP 7**: Pre-launch (Mfr., AI&T & storage) ≤ ± 300 µm 0.1 x 10⁻¹¹
  - 41% ≤ ± 212 µm
  - 25% ≤ ± 100 µm
  - 100% ≤ ± 50 µm Unvalidated models

- **KPP 8**: On-orbit thermal stability ≤ ± 200 µm 0.1 x 10⁻¹¹
  - 100% ≤ ± 100 µm
  - 100% ≤ ± 50 µm Unvalidated models

### Threshold Values

- **Margin**
  - **KPP 6**: ≤ ± 40 µm
  - **KPP 7**: ≤ ± 20 µm Unvalidated models

- **KPP Goals**
  - **KPP 6**: ≤ ± 40 µm
  - **KPP 7**: ≤ ± 20 µm Unvalidated models

- **Contingency or MUFs**
  - **KPP 6**: ≤ ± 40 µm
  - **KPP 7**: ≤ ± 20 µm Unvalidated models

- **Nominal CBE Values**
  - **KPP 6**: Basis of estimate
  - **KPP 7**: TDEM-10 measurements

- **KPP Goals**
  - **KPP 6**: ≤ ± 40 µm
  - **KPP 7**: ≤ ± 20 µm Unvalidated models

- **Contingency or MUFs**
  - **KPP 6**: ≤ ± 40 µm
  - **KPP 7**: ≤ ± 20 µm Unvalidated models

- **Nominal CBE Values**
  - **KPP 6**: Basis of estimate
  - **KPP 7**: TDEM-10 measurements
Reference Mission:
26m starshade, 10m disc, 8m long x 2m max width petals (qty 24)

KPP Verification Activities Flow Chart

Petal Subsystem
- Medium fidelity w/ KPP relevant features
  - Article 1: 1.5m wide x 4m long

Inner Disk Truss Bay Assy
- Node
- Longeron
- ~1.3m long

Inner Disc Subsystem (IDS)
10m diameter

Optical Edge
- (Segment, ~1m long)

KPP Risk Reduction Activities
(critical environments for KPP's)
- Medium fidelity w/ KPP relevant features
- KPP Risk Reduction Activities
(critical environments for KPP's)

Remaining TRL-5 Activities
- Medium fidelity w/ all features
  - Article 2: 1.5m wide x 6m long

Decadal Input
- Medium fidelity w/ all features
- Medium fidelity w/ all features
  - Assembly level: Truss Bay @ full scale (~1.3m long)

Upgrade optical shield to medium fidelity also incl. petals
- Full Scale (10m dia)
Petal Activities Flow Chart w/ Activity Status

KPP Risk Reduction Activities (critical environments for KPP’s)

Remaining TRL-5 Activities

- Shape vs temp. test complete @ 5 micron accuracy, model validation on-going, preliminary results show large margin on requirement
- Shape post thermal cycle extremely stable (repeatable to a few microns)
- Deploy cycle (unfurl) & shape meas. upcoming

Petal Subsystem

Medium fidelity w/ KPP relevant features

Article 1: 1.5m wide x 4m long

Medium fidelity w/ all features

Article 2: 1.5m wide x 6m long

Petal in thermal chamber at Tendeg Facility in Louisville, Co.

NGAS-ATK & Southern Research provided optical measurement capability & data processing & Tendeg who was responsible for petal build & test campaign
Optical Edge Activities Flow Chart w/ Activity Status

- Pathfinder edges thru environments
- In-plane shape and scatter performance preserved & meet reqts
- Evan Hilgemann (edge lead engineer) has talk on this next

Optical Edge (Segment, ~1m long)

Edge Scatter
- Medium fidelity edge assembly
- Half length (0.5m)

Decadal Input

KPP Risk Reduction Activities
(critical environments for KPP’s)

Remaining TRL-5 Activities

Half length (0.5m) edge prototype
(top – telescope side, bottom – Star side)
Truss Bay Activities Flow Chart w/ Activity Status

Inner Disk Truss Bay Assy

KPP Risk Reduction Activities (critical environments for KPP’s)

Remaining TRL-5 Activities

Decadal Input

Medium fidelity w/ KPP relevant features

Component level: longeron & node assemblies (full scale)

Medium fidelity w/ all features

Assembly level: Truss Bay @ full scale (~1.3m long)

Longeron assemblies:
- Length vs temp. meets reqs (1 of 3 meas.)
- Post thermal cycle dimensional stability meets reqs (2 of 3 meas.)

Node Assembly:
- Testing and model validation in process
- Post thermal cycle dimensional stability meets reqs (2 of 3 meas.)
- Material data looks good

Nodeassy (left) & longeron assys (right) on Micro-Vu Measurement Machining at Tendeg Facility in Louisville, Co. Length vs temp measurement at NGAS-ATK in San Diego in IMF (interferometric measurement facility)
Inner Disk Activities Flow Chart w/ Activity Status

Decadal Input

KPP Risk Reduction Activities (critical environments for KPP’s)

Remaining TRL-5 Activities

Upgrade optical shield to medium fidelity also incl. petals

Full Scale (10m dia)

Inner Disc Subsystem (IDS)

Medium fidelity truss & spokes; optical shield w/ KPP relevant features

Full Scale (10m dia)

- Multiple successful deployments of 10m (full scale) Inner Disk Subsystem w/ truss, spokes and optical shield
- Deployment accuracy to date well within requirements (10x 10%, 3x 50%, 3x 80% and 1x full stow, more coming)
- Deployment FEA modeling efforts ongoing

Truss & shield at Tendeg Facility in Louisville, Co., measurements made with JPL Leica laser tracker
Inner Disk Deployment

Truss & shield deployment at Tendeg Facility in Louisville, Co.

Shield furling FEA developed by Roccor (Longmont, Co)
Petal Unfurl Subsystem Engineering Work

- PLUS testbed w/full set of petal has been deployed and characterized
- Future work to include test of 4x medium fidelity petals (CFRP) with upgraded interfaces and offloading to validate against deployment model
Backup Charts
TRL-5 Test Activities Flow Chart

**Risk Reduction Activities**
(TRL-4 + critical environments for KPP’s)

- **Article 1**: 1.5m wide x 4m long x 1.6cm thick
  - B.1 Measure, as reference, as-manufactured petal 2d edge profile, then verify petal shape after:
    - B.2 – deploy cycles,
    - B.3 - thermal cycles (deployed)
  - Validate analytical model of
    - B.4 – critical dimension vs. temperature
    - B.5 Petal shape response vs. I/F load

- **Article 2**: 1.5m wide x 6m long x 1.6cm thick
  - B.1 Verify petal 2d edge profile of Article 2 as-manufactured
  - Repeat tests B.2, B.3, B.4, B.5
  - B.7 Verify petal shape after storage (creep)

**Decadal Input**
(Mar ’20)

**Remaining TRL-5 Activities**

- **B.1 Verify** petal 2d edge profile of Article 2 as-manufactured
- **B.2, B.3, B.4, B.5**
- **B.7 Verify** petal shape after storage (creep)

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**Petal Subsystem**

- Mixed Scales
  - Note: full scale is 8m long, 2m wide, 1.6cm thick

- Optical Edge (Segment)
  - Half Scale (0.5m long)

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**Inner Disc Truss Bay Assy**

- Node
- Longeron
- Full-Scale: (1.3-m long)

**IDS structure @ med-fid, shield @ low-fid**

- C.2 Validate Disc analytical model via I/F load / petal position
- C.1 - Verify repeatable Disc deploy tolerances w/ TRL-4 Optical Shield installed

**Inner Disc Subsystem (IDS)**

- Full-Scale (10-m dia.)

**Deployment Control Subsystem (DCS)**

- Full-Scale (2.25-m stow dia.)

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**Sub-assembly level: longeron & node assemblies**

- A.3 - verify dim. @ sub-assy level after storage (creep)

- **C.3 - Verify repeatable disc deploy tolerances w/ TRL-5 Optical Shield installed** (after verifying shield opacity)

**Assembly level: Truss Bay**

- **Verify** Truss Bay critical dim.
  - A.6 – as-manufactured
  - A.7 - after thermal cycles (deployed)

- **Validate** Truss Bay model of critical dimension vs.:
  - A.8 – I/F Load
  - A.9 – temperature

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**IDS incl. shield @ med-fid**

- C.5 Validate disc model of deployment kinematics

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Reference Mission:
- 26m starshade, 10m disc, 8m long x 2m max width petals (qty 24)

*At relevant scale*
**Test Article 2 Description**

**Milestone 5B & 6B**

- **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 Assay’s are COTS MBF23 Ni/Fe alloy amorphous metal (MBF23) sandwiched with quasi-is 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)
**Petal Test Articles 1 & 2 Description**

**Article 1 key purpose**: validate petal model and performance for structure response to temperature (key & driving petal components present)

**Article 2 key purpose**: demonstrate remaining environments with all components present

<table>
<thead>
<tr>
<th>Components</th>
<th>Article 1 Milestones 5A &amp; 6A</th>
<th>Article 2 Milestones 5B &amp; 6B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale:</td>
<td>Full: 2m wide 8m long 1.6cm thick</td>
<td>1.5m wide 6m long 1.6cm thick</td>
</tr>
<tr>
<td>Optical Edge</td>
<td>correct materials &amp; construction, not sharp or shape accurate</td>
<td>Relevant Components Present for Test</td>
</tr>
<tr>
<td>Tip Segment</td>
<td>medium fidelity</td>
<td>Relevant Components Present for Test</td>
</tr>
<tr>
<td>Structural Edge</td>
<td>not present</td>
<td>Medium Fidelity</td>
</tr>
<tr>
<td>Battens</td>
<td>I/F only</td>
<td></td>
</tr>
<tr>
<td>Braces</td>
<td>not present</td>
<td></td>
</tr>
<tr>
<td>Pop-up Ribs</td>
<td>not present</td>
<td></td>
</tr>
<tr>
<td>Petal-truss hinges</td>
<td>I/F only</td>
<td></td>
</tr>
<tr>
<td>Launch Restraint I/F (carts)</td>
<td>not present</td>
<td></td>
</tr>
<tr>
<td>Batten snubbers</td>
<td>form/fit only (for deployment demo function only)</td>
<td></td>
</tr>
<tr>
<td>Petal Shield</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tests</th>
<th>Article 1</th>
<th>Article 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verify shape Accuracy</td>
<td>NO (shape measured as reference only)</td>
<td>Structure + Edge</td>
</tr>
<tr>
<td>deploy cycles</td>
<td>YES</td>
<td>Structure + Edge</td>
</tr>
<tr>
<td>thermal cycles (deployed)</td>
<td>YES</td>
<td>Structure + Edge</td>
</tr>
<tr>
<td>critical dimension vs temperature (Validate Thermal Deformation Model)</td>
<td>YES</td>
<td>Structure + Edge</td>
</tr>
<tr>
<td>petal shape response vs I/F load (Validate Structural Model)</td>
<td>YES</td>
<td>Structure + Edge + base hinges + Truss Strut</td>
</tr>
<tr>
<td>long term storage (creep)</td>
<td>NO N/A</td>
<td>Structure + Edge + base hinges</td>
</tr>
</tbody>
</table>

**Petal Subsystem**

- Petal Assemblies (Inner and Outer)
- Optical Edge Segment (Substrata + Foil)
- Structural Edge
- Battens
- Braces
- Tip Segment
- Pop-up Ribs
- Petal-Truss Hinges
- Launch Restraint I/F (carts)
- Batten Snubbers
- Truss Strut

**Medium Fidelity**

- Petal Strut 2x (pink)
- Battens (Ex. In blue)
- Brace (diagonal) (Ex. In purple)
- Launch Restraint Interfaces
- Center spines (silver) (2x)
- Pop-Up-Rib (green) (PUR) (2x)
- Optical Edge (left & right)
- Optical Shield (yellow)

**Tests**

- Verify shape Accuracy
- deploy cycles
- critical dimension vs temperature (Validate Thermal Deformation Model)
- petal shape response vs I/F load (Validate Structural Model)
- long term storage (creep)

**Scale**

- Full:
  - 2m wide
  - 8m long
  - 1.6cm thick

**Components**

- Optical Edge Tip Segment Structural Edge Battens Braces Pop-up Ribs Petal-truss hinges Launch Restraint I/F (carts) Batten snubbers truss strut Petal Shield

**Tests**

- Verify shape Accuracy (NO)
- deploy cycles
- critical dimension vs temperature (Validate Thermal Deformation Model)
- petal shape response vs I/F load (Validate Structural Model)
- long term storage (creep)

**Medium Fidelity**

- Structure + Edge
- Structure + Edge + Shield
- Structure + Edge + base hinges + Truss Strut
- Structure + Edge + base hinges

**Petal Subsystem**

- Petal Assemblies (Inner and Outer)
- Optical Edge Segment (Substrata + Foil)
- Structural Edge
- Battens
- Braces
- Tip Segment
- Pop-up Ribs
- Petal-Truss Hinges
- Launch Restraint I/F (carts)
- Batten Snubbers
- Truss Strut

**Medium Fidelity**

- Petal Strut 2x (pink)
- Battens (Ex. In blue)
- Brace (diagonal) (Ex. In purple)
- Launch Restraint Interfaces
- Center spines (silver) (2x)
- Pop-Up-Rib (green) (PUR) (2x)
- Optical Edge (left & right)
- Optical Shield (yellow)

**Tests**

- Verify shape Accuracy (NO)
- deploy cycles
- critical dimension vs temperature (Validate Thermal Deformation Model)
- petal shape response vs I/F load (Validate Structural Model)
- long term storage (creep)

**Medium Fidelity**

- Structure + Edge
- Structure + Edge + Shield
- Structure + Edge + base hinges + Truss Strut
- Structure + Edge + base hinges
**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 disc 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)
### Milestone 7A Hardware Key Purpose

Validate performance for critical dimension vs temperature at the **sub-assembly** level, longeron & node assemblies (key & driving components present)

### Milestone 7B Hardware Key Purpose

Validate performance for critical dimension vs temperature at the **assembly** level, longeron & node assemblies (key & driving components present)

<table>
<thead>
<tr>
<th>Components</th>
<th>IDS for Milestone 7A</th>
<th>IDS Milestone 7B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of Assembly</td>
<td>Sub-assembly Level</td>
<td>Assembly Level</td>
</tr>
<tr>
<td>Lorgeon Assembly</td>
<td>medium fidelity</td>
<td>Medium Fidelity</td>
</tr>
<tr>
<td>Node Assembly</td>
<td>medium fidelity</td>
<td></td>
</tr>
<tr>
<td>Diagona Assembly</td>
<td>not present</td>
<td></td>
</tr>
<tr>
<td>thermal cycles (deployed)</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>critical dimension vs temperature (Validate Thermal Deformation Model)</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>long term storage (creep)</td>
<td>NO</td>
<td></td>
</tr>
</tbody>
</table>

**Scale:** Full: ~1.3m long

1/2 length or greater

Relevant Components Present for Test

Full

Relevant Components Present for Test

Full

Relevant Components Present for Test

Full
Inner Disk Test Articles for Milestone 7D Description

- **Tests:** Verify repeatable truss deployment tolerances with OS installed, Validate disc model of deployment kinematics, Validate disc 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 (Existing prototype to be upgraded)
**Inner Disk Test Articles for Milestones 7C & 7D Description**

**Milestone 7C hardware key purpose:** Verify deployment performance of inner disk (perimeter truss) in the presence of an optical shield with deployment relevant features (key & driving petal components present)

**Milestone 7D hardware key purpose:** Verify deployment performance of inner disk (perimeter truss) with optical shield and petals with all relevant features

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**Scale:**
- 10m diameter
- 10m dia

**Relevant Components Present for Test**
- 10m dia

**Perimeter Truss**
- Medium Fidelity

**Spokes**
- form, fit & function sufficient

**Hub**
- Low Fidelity, deployment critical features present

**Optical Shield**
- Medium Fidelity (hub = form/fit/function)

**4x full petal + petal stubs**
- not present

**Inner disk shield to petal shield interface**
- not present

**Inner disk shield to hub interface**
- not present

**Tests**
- Verify shape Accuracy (deploy cycles)
- YES
- Perimeter truss, spokes, hub
- YES
- Perimeter truss, spokes, hub

---

**Existing prototype to be upgraded**
Test Article Description
Deployment Control System (PLUS)

- **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)
Cross Section View

- Wrapped Petals
- Batten Snubbers (preloaded or caged) Highlighted Red
- Petal Spine Stack (preloaded) Orange
- Stowed Truss Longeron
- Batten Snubbers (preloaded or caged) Highlighted Red
- Truss to Flange Connection (Ball in groove, free to slide in the axial DOF)
- Central Cylinder
- Truss to Flange Connection (pinned)

PLUS (Roller Arms, Carousel, PLUS Adapter)

*** Roller-arm/carousel/plus adapter assy jettisoned after launch (total mass = 608 kg)
Optical Shield Solar Array SBIR
(Tendeg SBIR)

• Product Description:
  • SolAero is constructing a solar cell string of IMM cells to be assembled to the Tendeg starshade optical shield solar array for testing (an array is 4 strings combined in a frame structure that gets attached to an optical shield gore)
  • In one array, a single string will be electrically active for test verification. These cells will be IMM cells that are leftover and/or lower efficiency

• Risks
  • Matching the interaction of array and OS to create a simple, low risk stow and deploy
  • Individual cell breakage due some localized interference of adjacent OS, spoke, frame, cabling etc

• Testing:
  • Electrical continuity of IMM cell in stow/deploy from array to hub connector, frame to OS interface, cell mechanical survivability, CTE mismatch design, temperature limits
  • Testing to be performed on a standalone “quad-gore” (4x gores only), not in presence of the rest of the shield
  • Not tested – More than 4x string config in a frame, multiple string electrical routing, vibe

Regarding the solar cell IMM5J TRL:
• TRL7/8 in early 2019, and TRL9 expected by 2020
• SolAero: “...in preparation for full scale flight program using this IMM cell ... accompanied by a full S-111 qualification*....

*S-111 qualification is the gold standard which was established by the Air Force, SMC, and NASA, and qualifies a given cell technology to the full range of space applications...”
S5 Error Tree

WFIRST-Starshade Rendezvous at 1.52 λ/D IWA

Science investigations
- Study metallicity of Gas Giants
- Detect & Characterize Earth 2.0
- Study Circumstellar Disks

Photometric noise ≤ 20X planet, at IWA
Systematic noise calibrated to SNR of 10

Background
- Other stars (galactic and extra-galactic) V > 30
- Solar Zodi V > 29 per PSF at 760 nm
- Exo-Zodi V > 28 per PSF at 1.5X solar density
- Reflected bright bodies V > 30 ≤ 32 99% of time
- Solar Edge Scatter V > 25 mags in 2 lobes at IWA
- Instrument Contrast 1 x 10^-10
- Starshade Background Telescope Time Variant

KPP 1 Demo viable in lab at subscale (no hidden physics)
HabEx reserve at 1.36 λ/D IWA 0.4 x 10^-11
Flight dev. margin ≥100% margin 4 x 10^-11

Allocated Instrument Contrast 3.6 x 10^-11

Starlight thru micrometeoroid holes 0.1 x 10^-11
Nominal specified shape 0.4 x 10^-11
Mechanical Shape Error 2.1 x 10^-11
Lateral Formation Control ≤ ± 1 m 1 x 10^-11
Lateral Formation Sensing ≤ ± 30 cm

KPP 5 Petal Shape 1.8 x 10^-11
Other petal shape/position errors (Launch, cruise & non-thermal on-orbit stability) 0.1 x 10^-11

KPP 6 On-orbit thermal stability ≤ ± 80 μm 0.8 x 10^-11
KPP 7 Pre-launch (Mfr., AI&T & storage) ≤ ± 300 μm 0.1 x 10^-11
KPP 8 On-orbit thermal stability ≤ ± 200 μm 0.1 x 10^-11

KPP 3 Instrument Contrast 1 x 10^-10
Sunlight thru micrometeoroid holes V > 31 (after multi-bounces)
Sunlight leakage thru optical shield flaps V > 32

KPP 2 Model validation accuracy ≤ 25% 2 x 10^-11
Flight dev. margin ≥ 100% margin 4 x 10^-11

KPP 4 Lateral Formation Sensing ≤ ± 30 cm

KPP 9

Pre-launch (Mfr., AI&T & storage) ≤ ± 70 μm 1 x 10^-11
On-orbit thermal stability ≤ ± 80 μm 0.8 x 10^-11
KPP Threshold Values
Margin
- KPP Goals
  - Contingency or MUFs
  - Nominal CBE Values/Basis
Pre-launch (Mfr., AI&T & storage) ≤ ± 300 μm 0.1 x 10^-11
KPP 7 41%
KPP 8 100% (4X in contrast)

41% (2X in contrast)
≤ ± 50 μm
25%
≤ ± 40 μm
Mostly TDEM-09 msts.

Key terms are well understood & not a threat to 10% calibration accuracy
## S5 Key Performance Parameters

<table>
<thead>
<tr>
<th>Technology Gaps</th>
<th>KPP #</th>
<th>KPP Specifications</th>
<th>KPP Threshold Values</th>
<th>KPP Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starlight Suppression</td>
<td>1</td>
<td>Demonstrate flight <strong>instrument contrast</strong> performance is viable via small-scale lab-tests</td>
<td>$1 \times 10^{-10}$</td>
<td>$5 \times 10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Validate <strong>contrast model accuracy</strong> relative to flight-like shape errors</td>
<td>$\leq 25%$</td>
<td>$\leq 10%$</td>
</tr>
<tr>
<td>Solar Scatter</td>
<td>3</td>
<td>Verify <strong>solar scatter</strong> lobe brightness visual magnitude</td>
<td>$V \geq 25$ mags</td>
<td>$V \geq 26$ mags</td>
</tr>
<tr>
<td>Lateral Formation Sensing &amp; Control</td>
<td>4</td>
<td>Verify <strong>lateral position sensor accuracy</strong> and that it supports $\pm 1$ m control via simulation</td>
<td>$\leq\pm 30$ cm</td>
<td>$\leq\pm 10$ cm</td>
</tr>
<tr>
<td>Petal Shape</td>
<td>5</td>
<td>Verify <strong>pre-launch accuracy</strong> (manufacture, AI&amp;T, storage)</td>
<td>$\leq 70$ $\mu$m</td>
<td>$\leq 50$ $\mu$m</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Verify on-orbit <strong>thermal stability</strong></td>
<td>$\leq 80$ $\mu$m</td>
<td>$\leq 40$ $\mu$m</td>
</tr>
<tr>
<td>Petal Position</td>
<td>7</td>
<td>Verify <strong>pre-launch accuracy</strong> (manufacture, AI&amp;T, storage)</td>
<td>$\leq 300$ $\mu$m</td>
<td>$\leq 212$ $\mu$m</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Verify on-orbit <strong>thermal stability</strong></td>
<td>$\leq 200$ $\mu$m</td>
<td>$\leq 100$ $\mu$m</td>
</tr>
</tbody>
</table>
Monte Carlo of Contrast Response to CTE Variation with Temperature Mapping

STOP Analysis Results:

<table>
<thead>
<tr>
<th>Sun Angle</th>
<th>Contrast*1e12</th>
</tr>
</thead>
<tbody>
<tr>
<td>83°</td>
<td>0.588</td>
</tr>
<tr>
<td>40°</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Monte-Carlo Analysis Results:

<table>
<thead>
<tr>
<th>Sun Angle</th>
<th>Samples</th>
<th>Prob contrast &lt;=2.5e-12</th>
<th>Mean contrast*1e12</th>
<th>90th percentile *1e12</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>

Requirement is 90% probability that delta contrast is < 2.5E-12
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
  – 1\textsuperscript{st} major mass lateral mode is at 51 Hz (Req’t 10 Hz)
  – 1\textsuperscript{st} 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)
  – 1\textsuperscript{st} major mass lateral mode is at 25 Hz (Req’t 10 Hz)
  – 1\textsuperscript{st} major mass axial mode is at 104 Hz (Req’t 25 Hz)
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:

- Carbon rods along gore hinges, pinned at starshade hub and terminate at truss

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
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

- Carbon rods along gore hinges, pinned at starshade hub and terminate at truss
- 1g offloading deflections in Abaqus model
- ~20x speed
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
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>Shadow clocking orientation has little effect on max/min temps, only moves cold portion of starshade</td>
<td>300 C</td>
</tr>
</tbody>
</table>
| Spinning | Averages temperatures symmetrically around spin axis  
Transient has negligible effect on contrast | 90 C | 65 C / -95 C |
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-isotropy layup from NGAS
    • Optical Edge - Quasi-isotropy layup with the addition of the amorphous metal foil and 5 mil epoxy each side
    • Truss longerons - Quasi-isotropy 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 Distortion Contrast Results

<table>
<thead>
<tr>
<th>Case</th>
<th>CBE Delta Contrast x 1e-12</th>
<th>Max Expected Delta Contrast w/ 100% contingency x 1e-12</th>
<th>Max Expected % of Starshade Allocated Shape Error (3.4 e-11)**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spinning</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 deg*</td>
<td>0.002</td>
<td>0.01</td>
<td>&gt;1%</td>
</tr>
<tr>
<td>78 deg</td>
<td>0.398</td>
<td>1.592</td>
<td>4.6%</td>
</tr>
<tr>
<td>83 deg*</td>
<td>0.655</td>
<td>2.62</td>
<td>7.7%</td>
</tr>
<tr>
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<td></td>
<td></td>
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<tr>
<td>40 deg</td>
<td>0.06</td>
<td>0.24</td>
<td>&gt;1%</td>
</tr>
<tr>
<td>78 deg</td>
<td>0.45</td>
<td>1.81</td>
<td>5.3%</td>
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<tr>
<td>83 deg</td>
<td>0.56</td>
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<td>6.5%**</td>
</tr>
</tbody>
</table>

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

**Summary**

<table>
<thead>
<tr>
<th>Case</th>
<th>CBF Delta Contrast x 1e-12</th>
<th>Max Expected Delta Contrast w/ 100% contingency x 1e-12</th>
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</table>

* 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
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