Jet Propulsion Laboratory
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Starshade Technology Requirements from Exo-S Rendezvous Concept Study

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SSWG Telecon
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Starshade Design

- Design a starshade with the following characteristics:

Starshade Parameter
Inner Disk Diameter
Petal Length
Petal Shape
Distance

Impact
Heritage from Antennas
Launch Configuration, Development Timeline
Stiffness, shape, Development Timeline
Fuel, Retarget Time

Instrument Performancce
Small Inner Working Angle
Deep Limiting sensitivity
Large Bandpass

Planet Finding Performance
Obscurational Completeness
Photometric Completeness
Observational efficiency

- The following pages explain the interdependencies and show how we arrived at the Dedicated and Rendezvous Designs

The shape of the starshade can be tuned to optimize science and limit complexity.

Starshade Design: Setting the IWA and Limiting Sensitivity

RV's: Need IWA ≤ 100 mas in characterization band

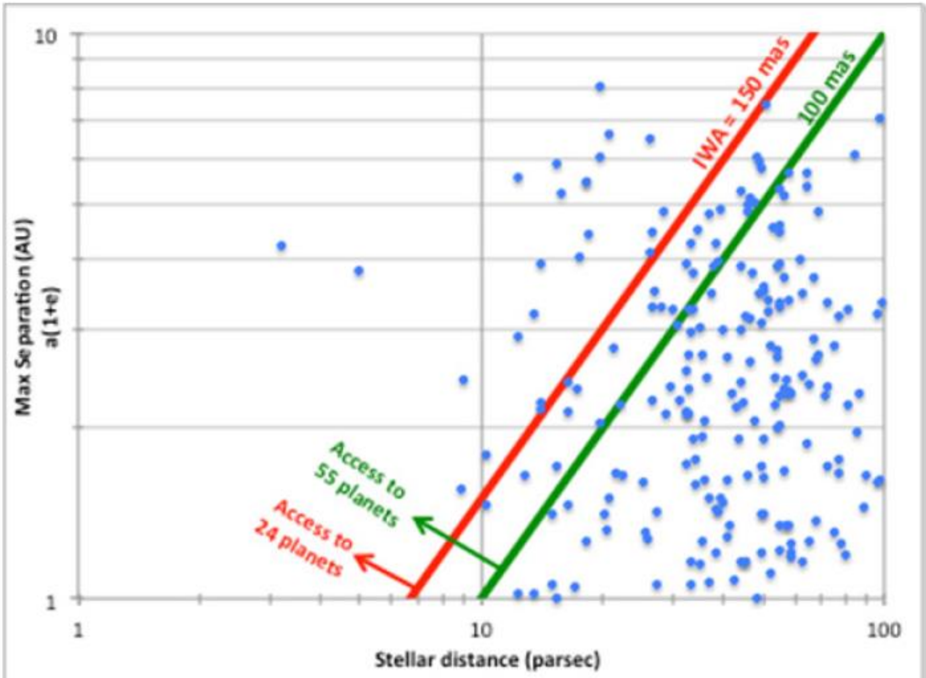


Figure 4.3-2. Access to sufficient known giant planet candidates, to left of IWA contours, requires 100 mas IWA.

Earth's in HZ: Need IWA ≤75 mas and limDmag ≥ 26

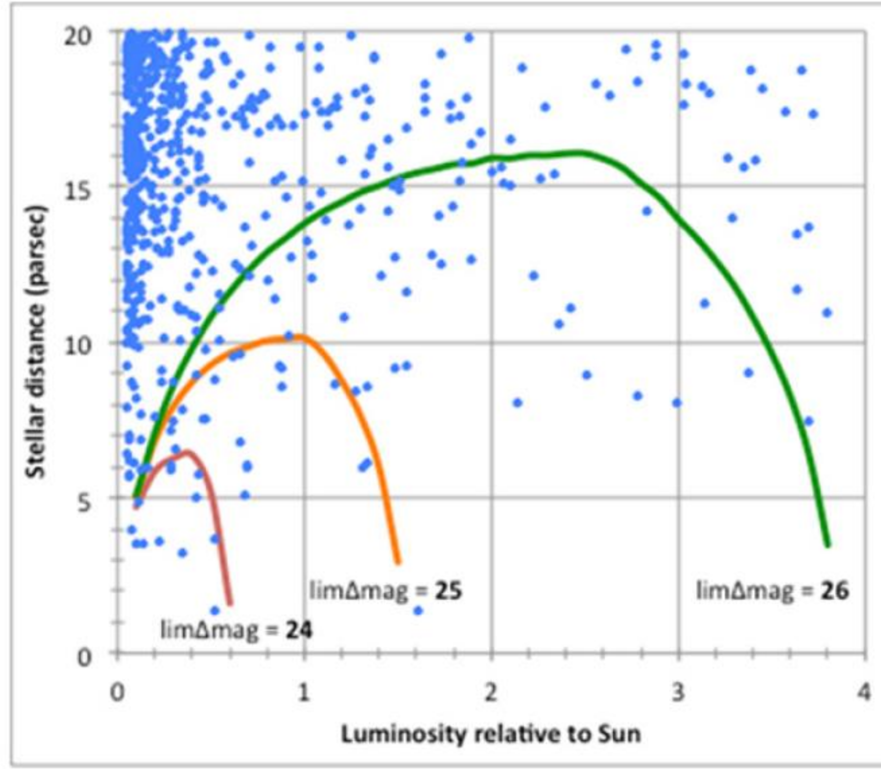


Figure 4.3-3. Access to 50 Earth candidate stars requires limΔmag=26 and IWA=75 mas. Candidates are below contours of ≥ 25% search completeness at varying Δmag.

IWA and limiting sensitivity are selected to enable robust programs in both RV characterization and Earth-twin detection.

Starshade Design: Bandpass/Diameter Trade

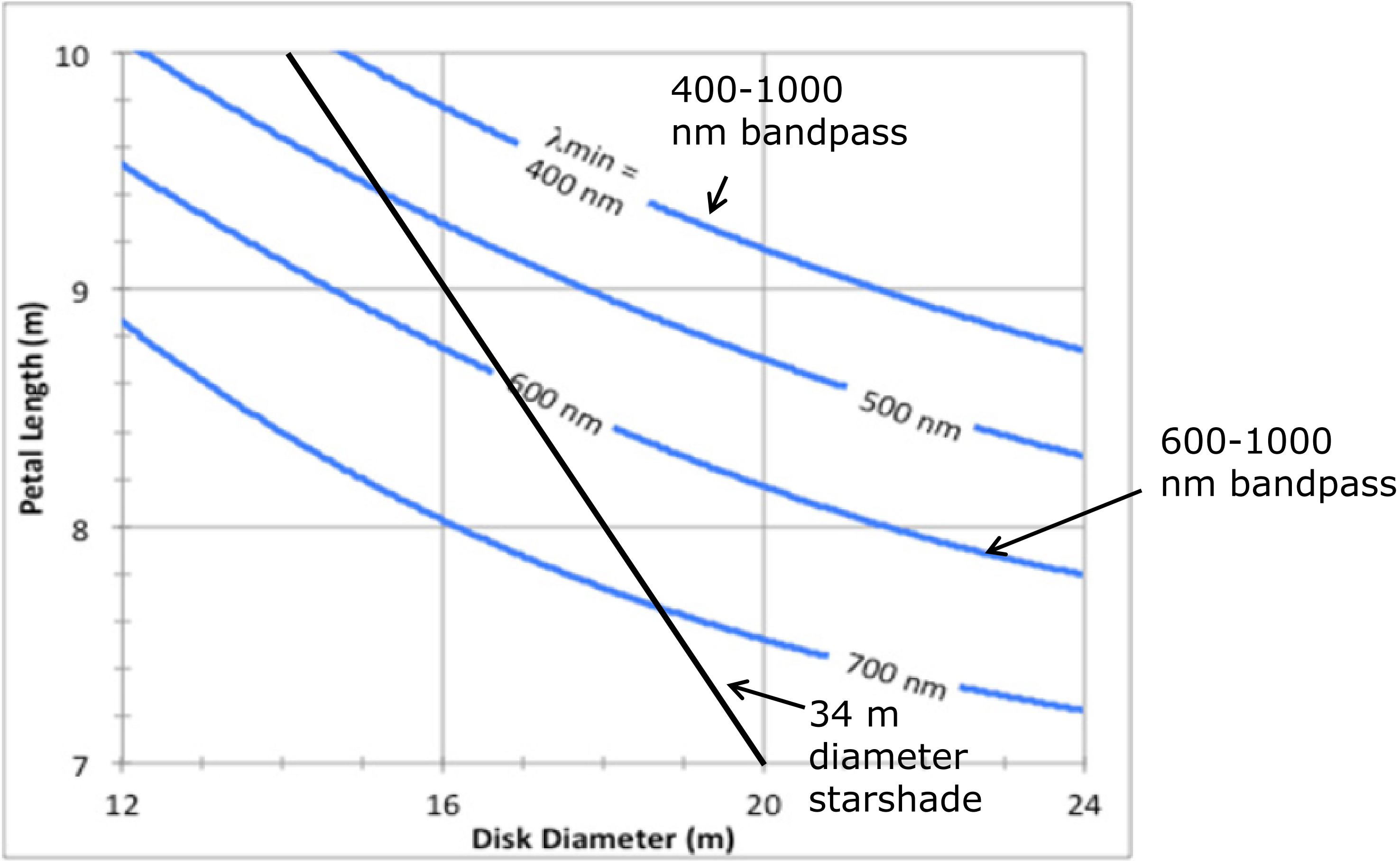
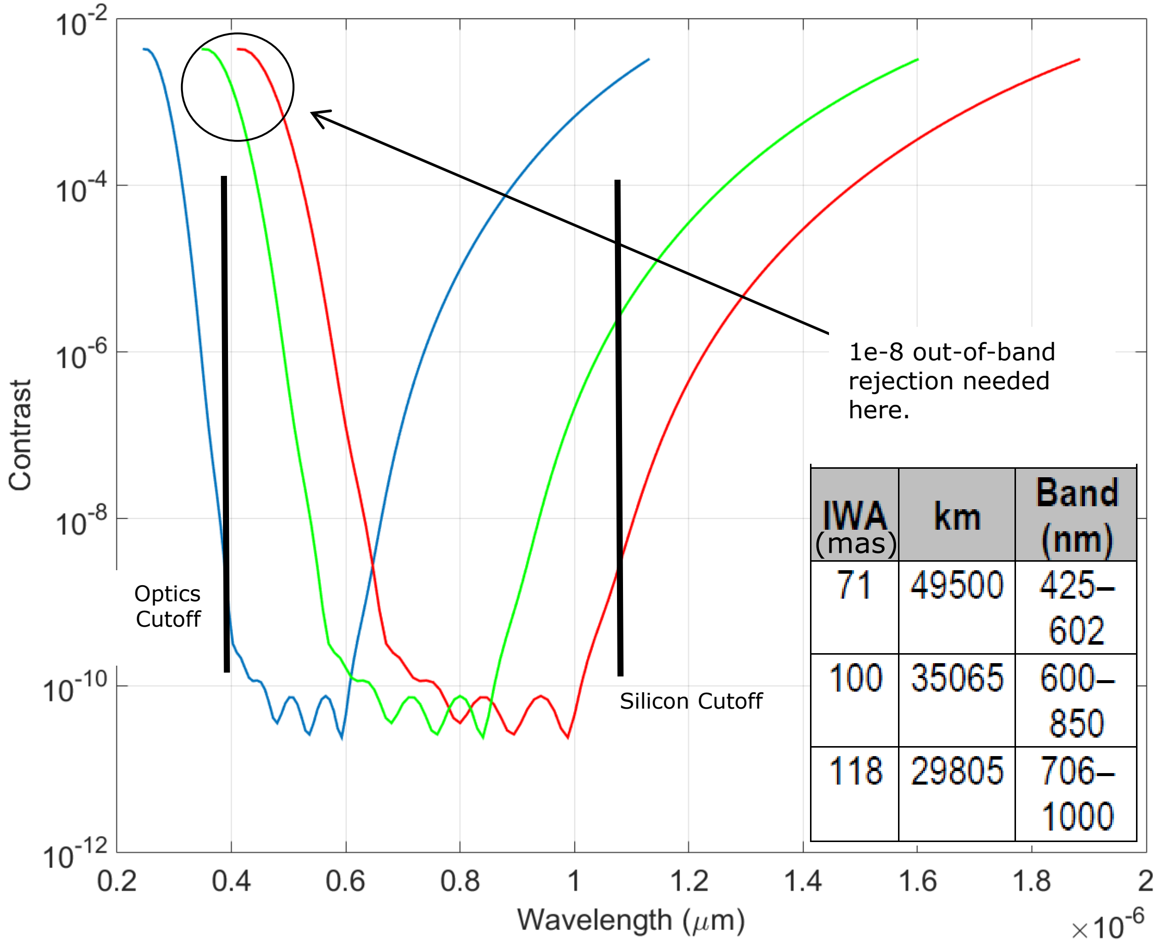


Figure 4.4-1. Starshade dimensions vs. bandpass lower limits. The starshade has: an upper bandpass limit of 1,000 nm, 100 mas IWA, limΔmag =26, 3.1-m shadow.

Larger instantaneous bandwidth comes from longer petals, larger truss, or both.

Starshade Design: Rendezvous Observing Bandpasses

To guide using WFIRST coronagraph instruments – without adding an IR camera – the Starshade must leak blue light while forming a dark shadow in red light.



IWA (mas)	km	Band (nm)
71	49500	425–602
100	35065	600–850
118	29805	706–1000

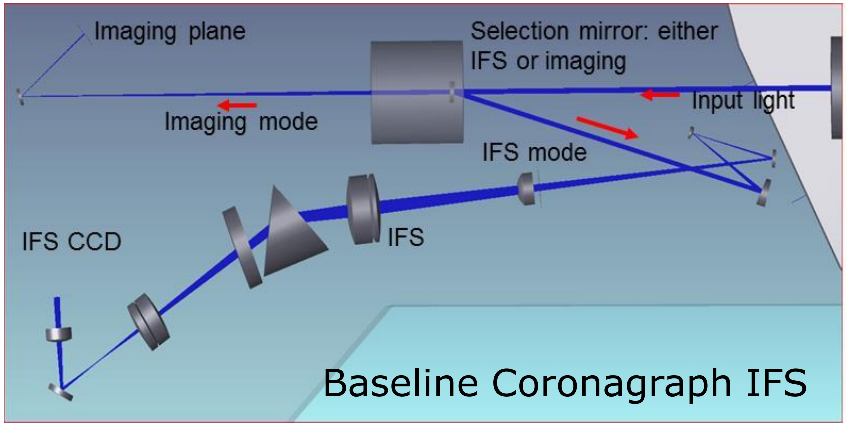
Figure 11. Bandpass for the Rendezvous mission for three different starshade-telescope distances. When positioned for observation in the red and guiding in the blue (red curve), rejection of 1e-8 is required below ~500 nm.

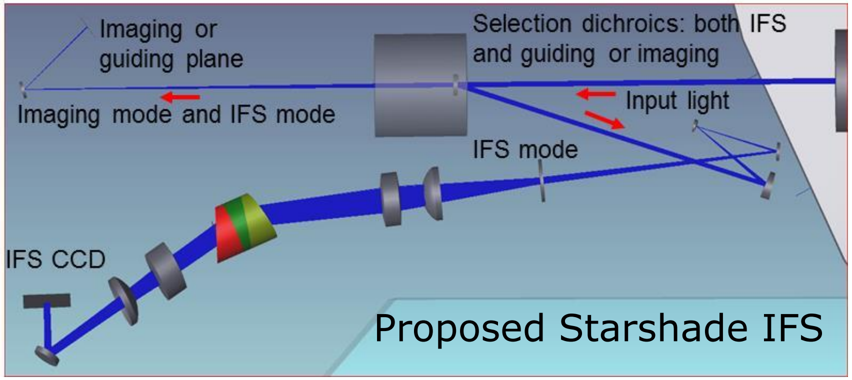
- Blue: starshade farther from telescope
  - Detection in imaging channel, guiding in IFS
- Red: starshade closer to telescope
  - Characterization on IFS, guiding with imaging channel.
- Implications
  - Starshade designed to have a bandpass
  - Out-of-band rejection requirements on bandpass filters

Starshade-Ready WFIRST Instrument: IFS

1Kx1K EMCCD 201 1.6K x 1.6K EMCCD 207

	Coronagraph			Starshade		
λ center	660	770	890	515	725	855
λ min	600	700	810	425	600	706
λ max	720	840	970	600	850	1000
pixels per spectrum	25.2			48.2		
Instantaneous BW	18%			34%		
F#	870			1135		
Lenslet pitch (μm)	164			214		
Samples across PSF	3.4	4.0	4.6	2.8	3.9	4.6
Radial FOV (as)	0.82			1.1		
Spectral resolution	70+/-5			70+/-5		
Magnification	1:1			1:1.23		
Lenslet format	76x76			76x76		
Lenslet array width	11.7 mm			15.0 mm		





- Footprint doesn't change.
- Field is improved
- Bandwidth is improved.
- Larger detector used.

Starshade Ready WFIRST Instrument: Filter Wheels

Mask/filter wheel	SPC (Imaging)	SPC (IFS)	HLS (Imaging)	Starshade (IFS and Imaging)	Baseline Filter Wheel Positions Req'd	Starshade-ready Filter Wheel Positions Req'd
Pupil Mask	1	3	open	open	5	5
Focal Plane Mask	2	9	2	open	14	14
Lyot Mask	1	1	1	open	4	4
Field Stop Mask	open	open	2	open	3	3
Color Filters	2	3	2	open	8	8
IFS/Guide select/dark /pupil	1	1	1	4	5	9

The table shows the number of masks or filters required in each configuration at each location in the optical beamtrain.

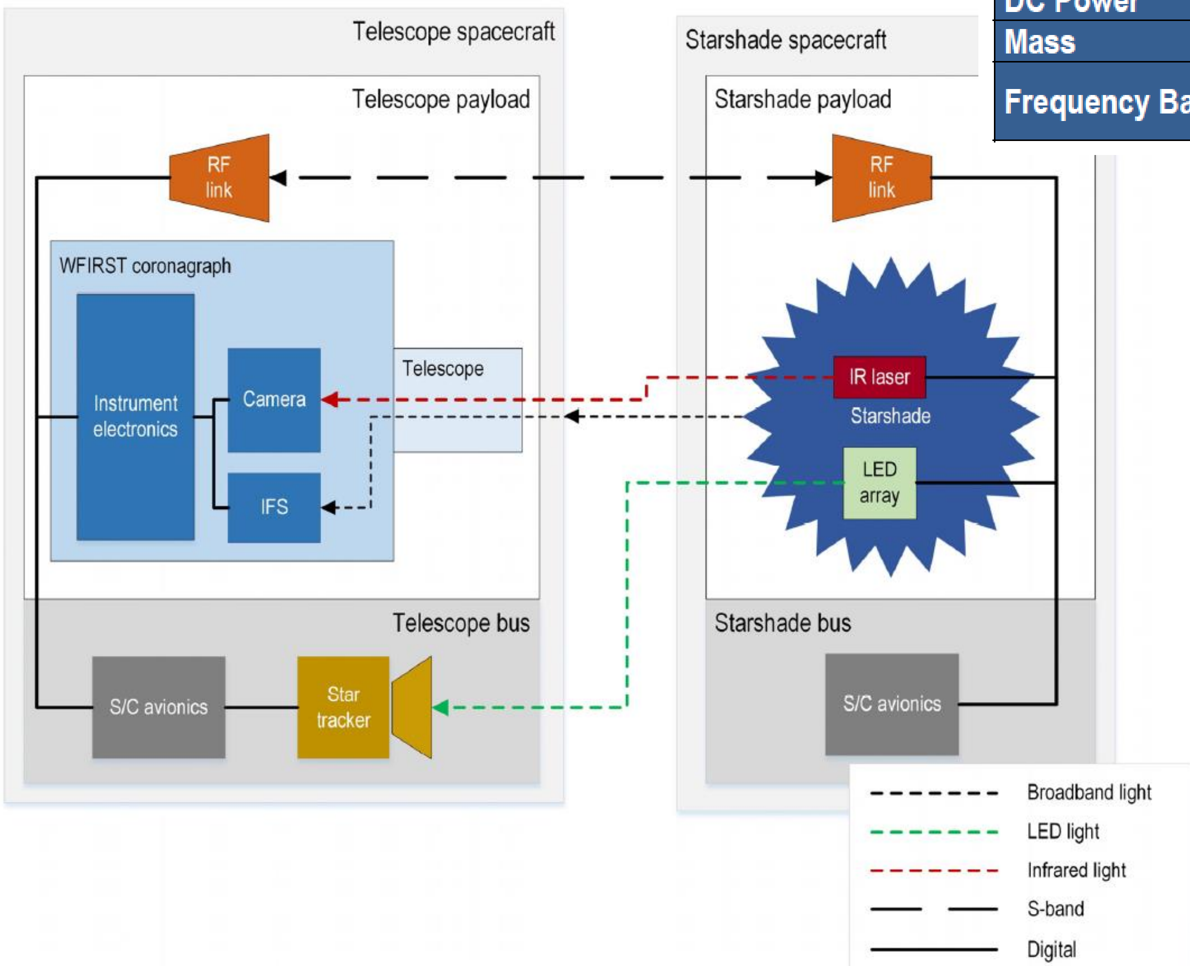
In the baseline coronagraph design, the IFS select-wheel houses a mirror and two lenses, matching the three coronagraph set-ups. For Starshade, 4 dichroic filters are needed to select red/green/blue bands for either direct imaging or characterization in 34% spectral bands.

Starshade Ready WFIRST: Formation Flying

An S-Band radio/ranging system is required to communicate with the Starshade. It has been flown on GRAIL.

Table 8.4-4. Telescope S-band subsystem characteristics.

Range Accuracy	<3.5 m
Minimum Data Rate	100 bps
DC Power	29.5 W
Mass	5.3 kg
Frequency Bands	2025–2110 MHz, 2200–2290 MHz

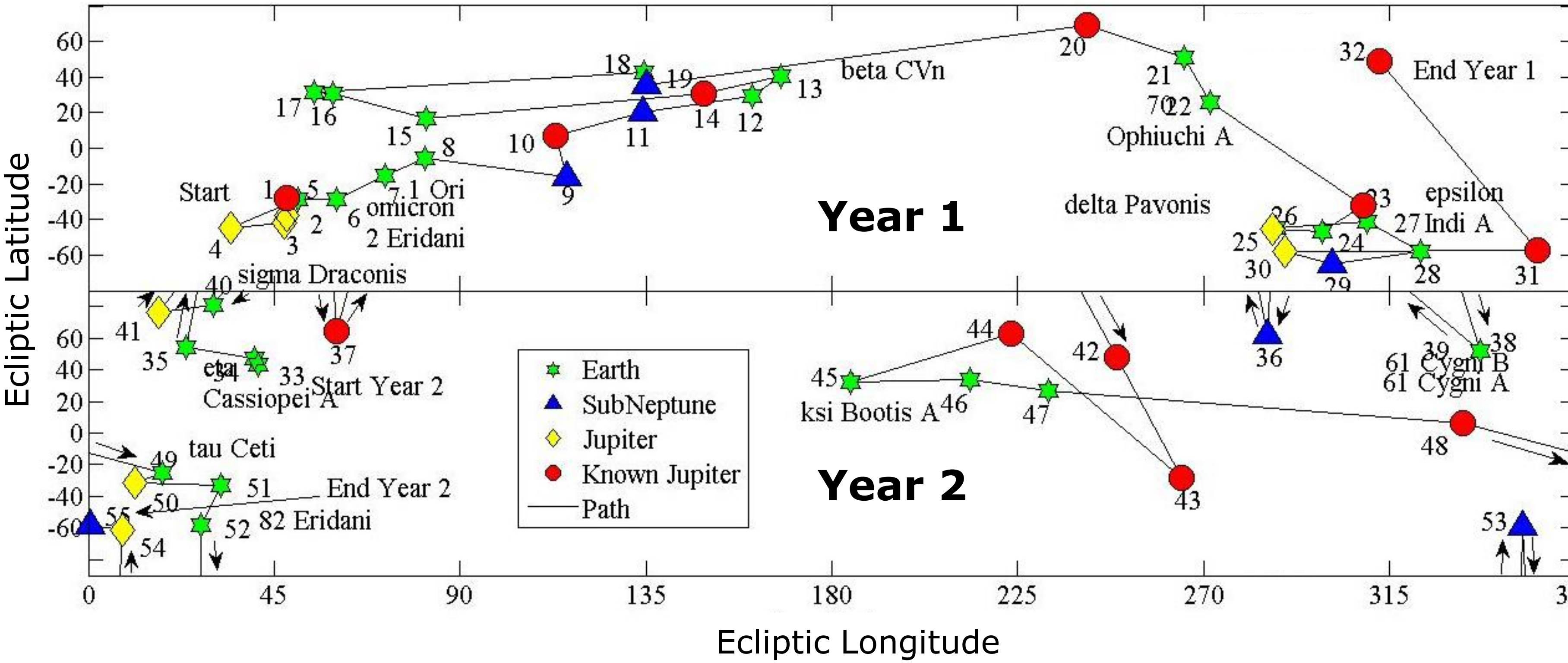


Observing Sequence: Rendezvous Mission

Based on chemical propulsion system

This is a 2-year sequence, 55 targets, ΔV = 1266 m/s

Targets: 12 known RVs, 28 Earth twins, 7 sub-Neptune, 8 Jupiters



Telescope Time Utilized: **9%**. This was a strategic decision to maximize the number of targets while still getting many spectra of giant planets. For the Dedicated mission, telescope utilization is **25%** (Cases 1 and 2).

The program is consistent with low overall utilization of the telescope allowing other science to be performed.

Mission Summary

- Mission
  - 3 year mission, 2 years for discovery, 1 year for follow-up
  - L2 orbit
  - Chemical Propulsion
- Sensitivity to Exo-Earth levels.
  - <1e-10 contrast
  - 100 mas in the central band
  - 34% instantaneous bandpass, tunable 425-1000 nm
- Starshade
  - 34 m tip-to-tip diameter
  - Distance 30,000 – 50,000 km
- WFIRST
  - Utilize WFIRST cameras (no new cameras for starshade)
    - Requires both cameras to be working simultaneously
  - Use no more than 25% of WFIRST time during 2 year discovery mission

Measurement and Mission Requirements

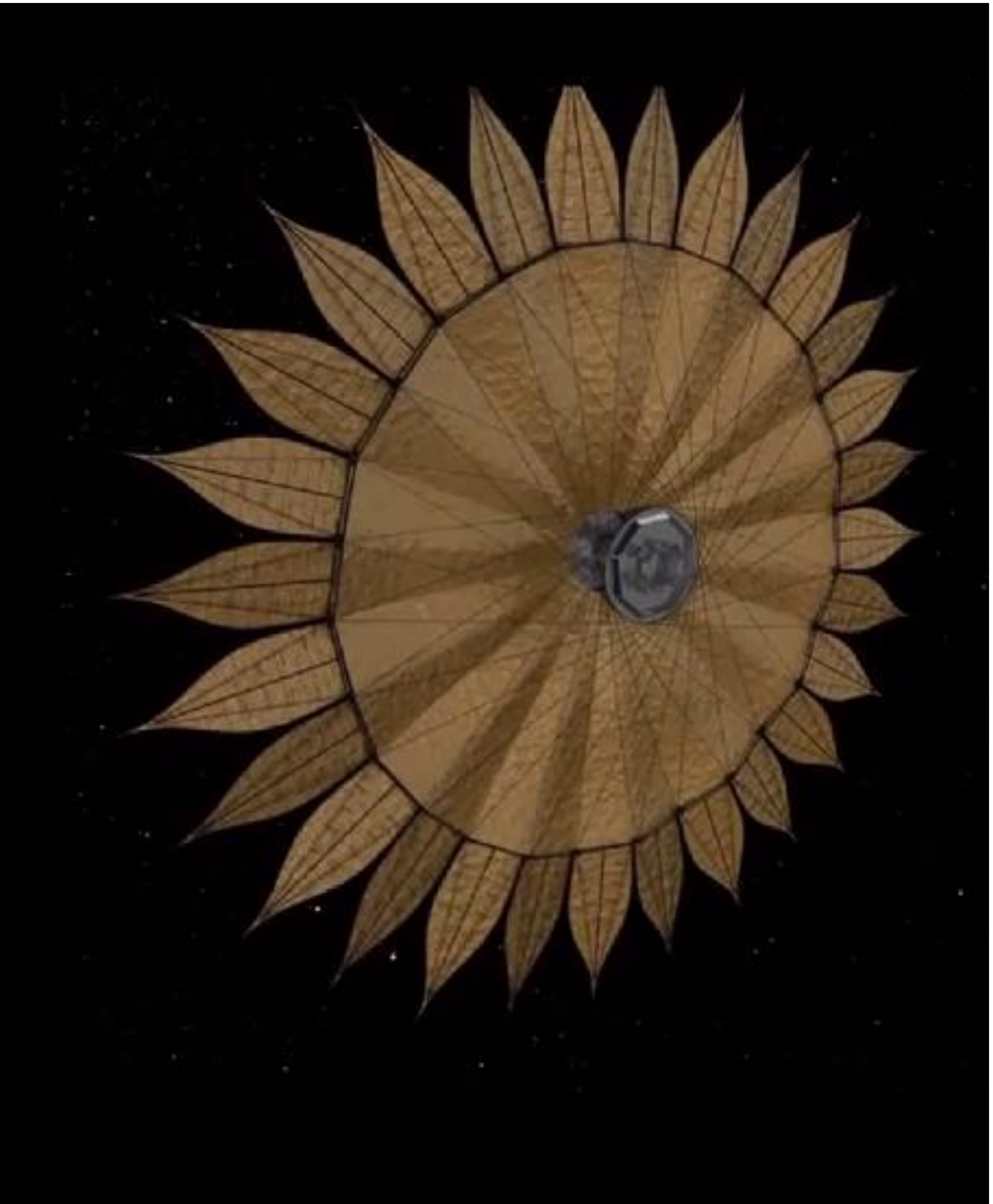
Table 8.1-1. Dedicated Mission design requirements

<table>
<tr><th></th><th colspan="3">Rendezvous Mission Requirements</th></tr>
<tr><th>Measurement Requirements</th><th>Starshade</th><th>Instrument</th><th>Spacecraft & Mission</th></tr>
<tr><td rowspan="4">Planet contrast sensitivity ≤ 4E-11
(limΔmag ≥ 26)</td><td rowspan="4">Manufacturing and deployment requirements (see Section 6.4)
Thermal and structural deformation (see Section 6.4)
Sun angle: 28° to 83° off normal (Section 6.4.6.3)
Hole area < 1 cm²
(Section 6.4.4)</td><td rowspan="3">Formation guide camera requirements (Appendix D)</td><td>WFIRST/AFTA S/C:
Lateral position control: 1 m
(Section 6.3.1, Appendix D.4)</td></tr>
<tr><td>Starshade S/C:
Pointing requirement: 1° 3-σ
(see Appendix D.6)
Spin rate: 1 rev per 3 min
(Section 6.4.2)</td></tr>
<tr><td rowspan="2">Orbit: L2 halo orbit (Section 4.6)</td></tr>
<tr><td rowspan="2">Detector requirements
(see Section 8.4)</td></tr>
<tr><td>Planet detection SNR: ≥ 5</td><td></td><td></td></tr>
<tr><td>Spectral res (Earths or larger) ≥ R10
Spectral res (sub-Neptunes or larger): ≥ R50
Planet characterization SNR: ≥ 10</td><td></td><td>IFS requirements (see Section 8.4)</td><td></td></tr>
<tr><td>Total bandpass = 400–1,000 nm</td><td rowspan="2">Bandpass: partial
(Section 4.4.1)
Inner Disk Structure Dia. 20 m
Petal Length 7 m
Petal #28</td><td>Bandpass: 400–1000 nm (Section 4.3, 2.3)</td><td rowspan="2">Spacecraft separation distances: 30,000 to 50,000 km (Section 6.1 and Appendix D)</td></tr>
<tr><td>IWA ≤ 100 mas</td><td></td></tr>
<tr><td>Spectral res (giants): ≥ R70
Planet characterization SNR: ≥ 10</td><td rowspan="2"></td><td rowspan="2">IFS requirements
Pixel scale: 10 mas/pixel (see Section 8.4)</td><td rowspan="2">Min mission duration: 2 years
(Section 5.3.3)</td></tr>
<tr><td>Planet cross-track position ≤ 0.01 AU</td></tr>
<tr><td>FOV > 10 AU at 10 pc</td><td></td><td>IFS FOV > 3 asec
(Section 8.4.1)</td><td></td></tr>
<tr><td>Measure polarization</td><td></td><td>0°, 45°</td><td></td></tr>
</table>

Technology Drivers

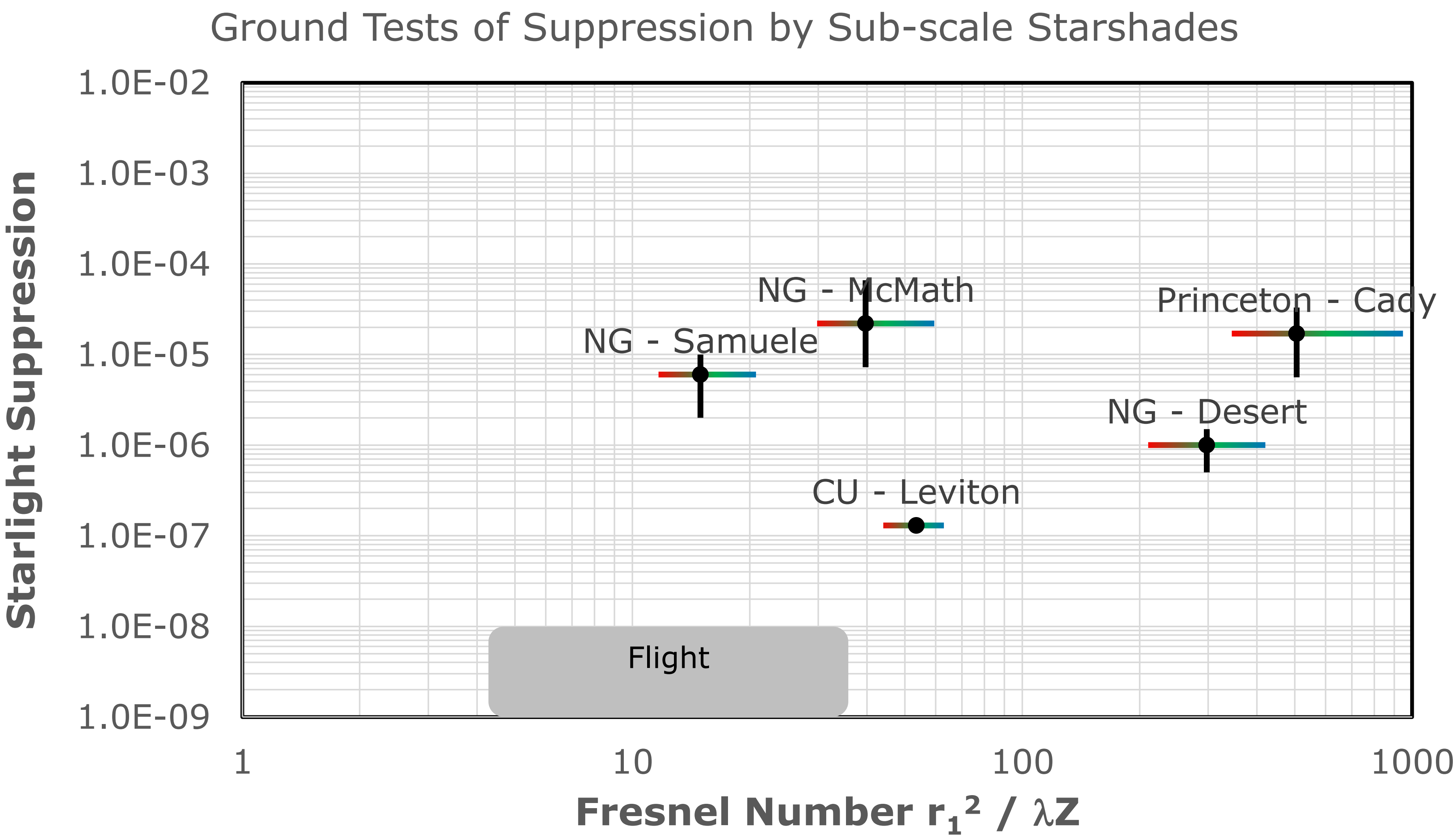
Driver	Impact
Contrast < 1e-10	Sub-scale demonstration Validated optical model Petal shape and position Formation flying precision
Scatter V<27	Limit solar scatter to diffraction from ideal edge Limit reflectivity of telescope-facing surface Limit holes from micrometeoroids
Survive Launch	Petal Launch restraint and controlled release

Starshade Driving Technologies



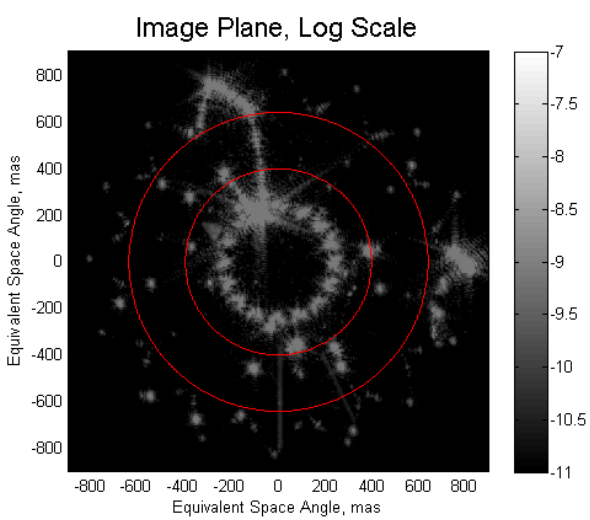
1. *Contrast performance demonstrations and optical model validation*
2. *Controlling solar glint*
3. *Lateral formation-flying sensing accuracy*
4. *Precision petal fabrication*
5. *Inner disk deployment*
   a. *Precision Deployment*
   b. *Optical shield*
   c. *Thin-film solar cells (Rendezvous Extended Study)*
6. *Petal launch restraint and controlled release*

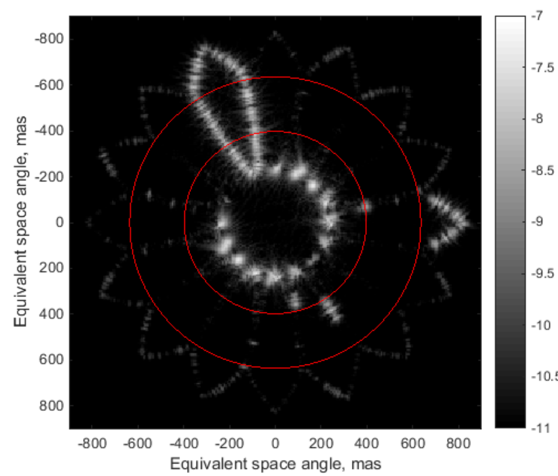
Contrast Performance Demo and Optical Model Validation



Contrast Performance Demo and Optical Model Validation

- Requirement:
  - Demonstrate < 1e-9 contrast and suppression in a scaled flight-like geometry (Correct Fresnel Number F~10-15)
- Status:
  - Laboratory experimentation at large Fresnel Number F>100
  - High contrast < 1e-10, poor suppression >10-6
    - The scattered light is highly resolved around the starshade
- Plan:
  - TDEM funding Princeton testbed for proper geometry
  - First results expected mid-2016
- Key challenge: accurately manufacturing the mask with < 0.5 um features.





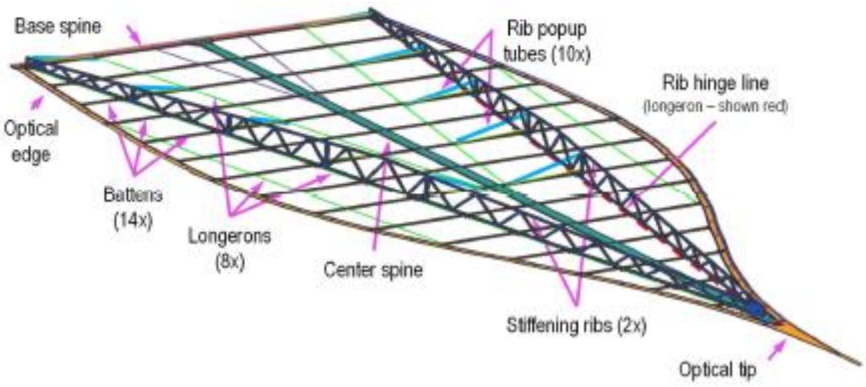
Example of Model Validation on a defective starshade mask on the Princeton 11 m testbed.

Kim & Kasdin, 2015

Detailed Starshade Error Budget

Table 6.4-1. Modeled starshade error budget terms.

Manufacture/ Deployment	Description
Petal Position	Radial, lateral, in-plane clocking, rotation about spine
Segment Shape	0.5, 1, 2, 3, 4, cycle sine and cosine
Segment Placement	Tangential, normal, in-plane clocking
Tip Segment Placement	Radial, azimuthal, in-plane clocking
Truss Ellipticity	In-plane elliptical deformation
Petal Shape + Tip Clip	In-plane and out-of-plane bending, broken tip
Thermal	**Description**
Uniform Petal Expansion	Petal multiplicative shape change
Uniform Truss Expansion	Radially displaces petals
Radial Gradient	Petal base to tip gradient (length and width)
Harmonic Gradient	1, 2, 3, 4, 5 cycles/petal (width only)
Formation Flying	**Description**
Lateral Displacement	Decentration of telescope from center of shadow
Longitudinal Displacement	Position of telescope along line-of-sight to starshade
Other	**Description**
Solar Glint	Sunlight glinting off of petal edges
Surface Scatter	Earthshine, etc. scattering from telescope-facing surface
Holes	Starlight leakage from micrometeoroids



Example local and global perturbation

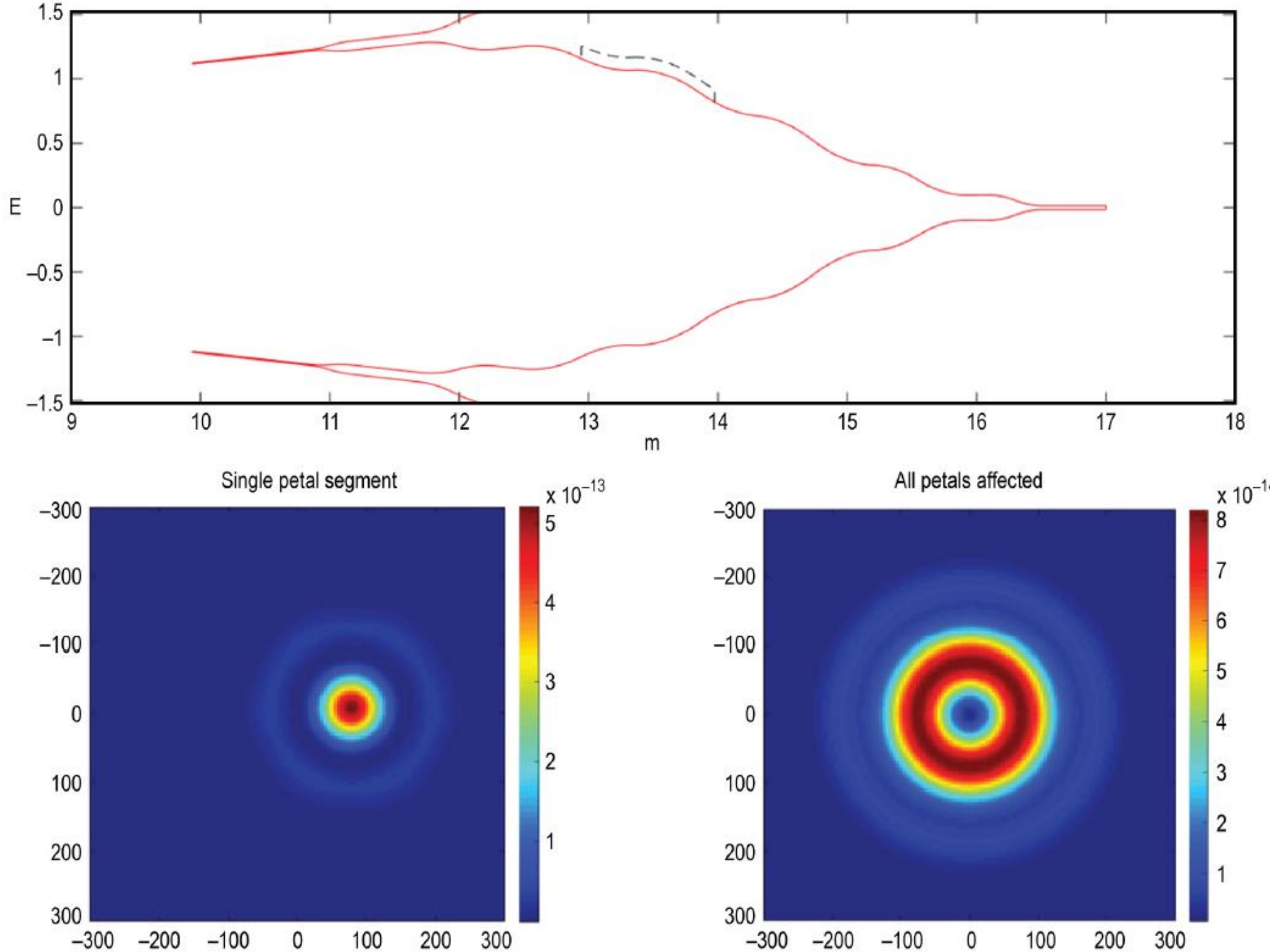


Figure 6.4-1. Example of a local petal perturbation; a 1-m long petal segment is displaced normal to the petal axis. The perturbation is shown enlarged 1000× relative to the displacement in the tolerancing analysis. Axes in the image plane are milliarcseconds. Colors are image plane contrast. Note that the perturbation in a single petal appears off-axis, compared to the on-axis appearance of random amplitude errors distributed amongst the petals

Error Budget Requirements and Allocations

Table 6.4-2. Starshade contrast requirements.

Requirement	Dedicated 1.1 m	Rendezvous 2.4 m
Photometric Floor	5×10^{-10}	1×10^{-10}
Systematic Floor	4×10^{-11}	4×10^{-11}

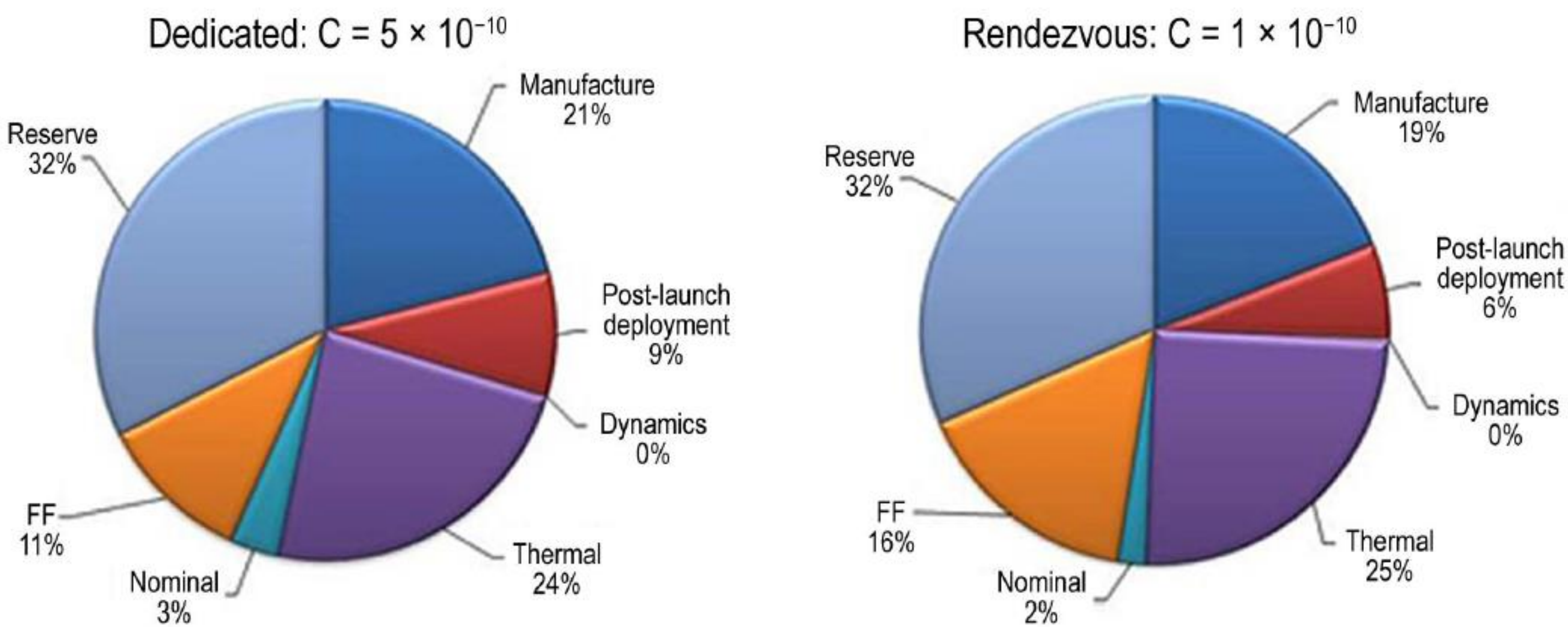


Figure 6.4-3. Overall photometric error budget for the Dedicated and Rendezvous missions.

Solar Edge Glint

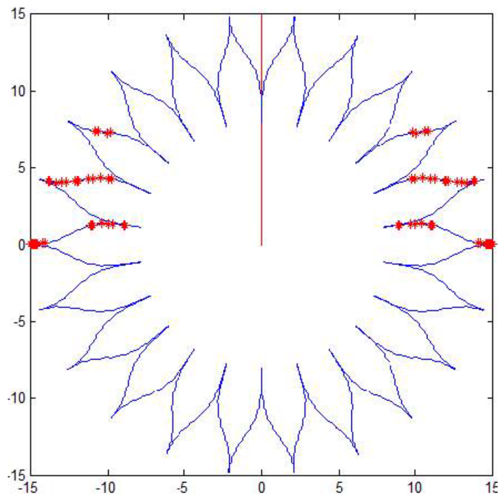
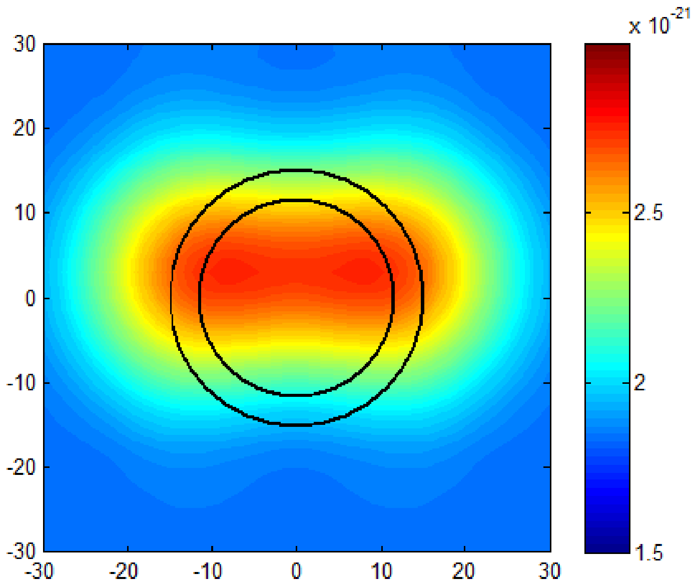


Figure 9.1-1. Lit-up edge regions. Red symbols indicate where specularly reflected and diffracted sunlight originates. The Sun is 30° into paper at top of figure (60° solar incidence). Units



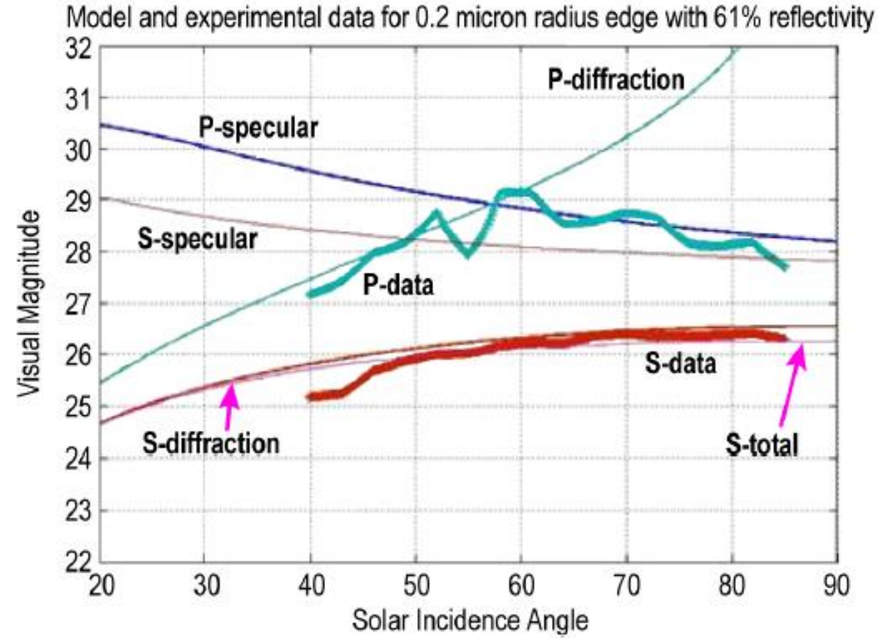


Figure 9.1-2. Model predictions compared to stainless steel razor blade measurements (not baseline design), for total light diffracted and specularly reflected by the starshade edge.

Requirement:
Radius of curvature (in microns)
Reflectivity (in %)
ROC * Refl < 12

Surface Reflectivity

- Black kapton material
- Measured BRDF of coupons
- Computed net reflectivity at telescope after integrating over petals and conical section of disk.

Table 6.4-5. Apparent magnitude of the telescope-facing side of the starshade when illuminated by astronomical objects.

Source	Worst-Case Apparent Magnitude of Starshade
Jupiter	29.7
Mars	29.7
Venus	31.3
Milky Way	29.6

1 zodi is V=28 in a 0.1 arcsec beam

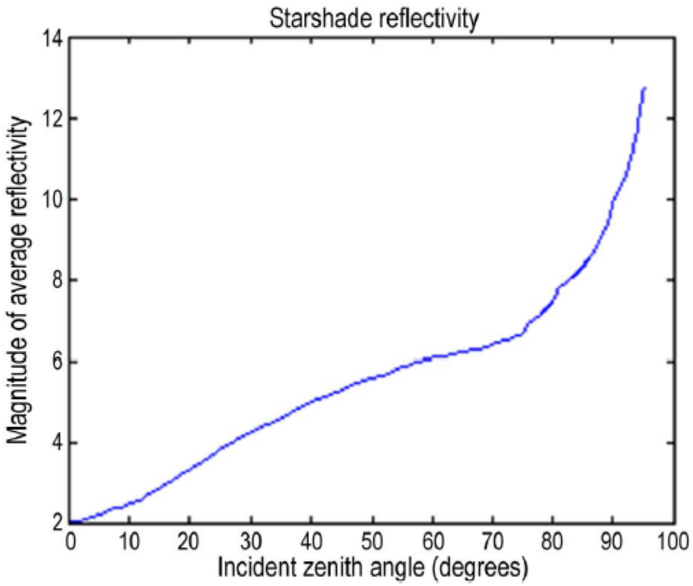


Figure 6.4-4. Average reflectivity of the starshade for a range of incident angles relative to the starshade normal.

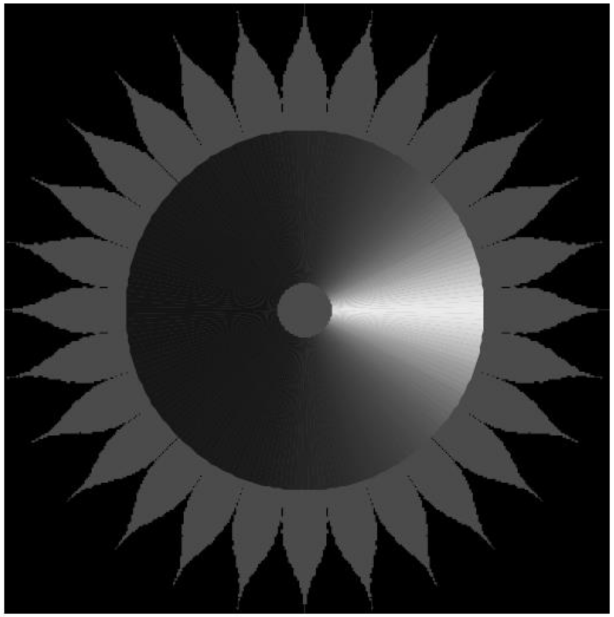
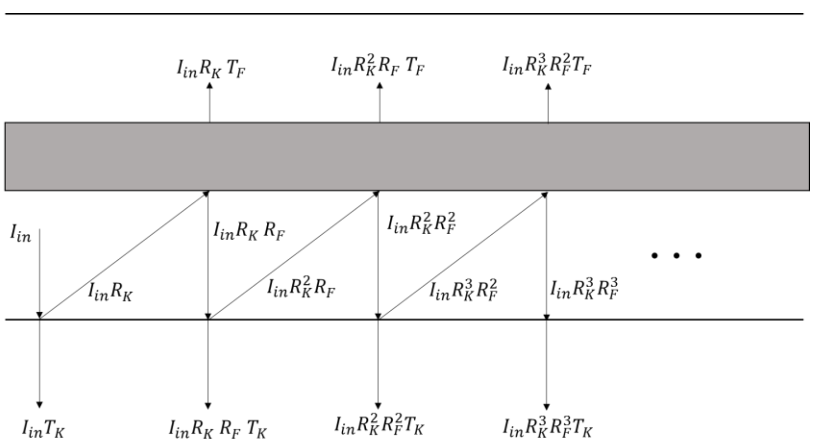


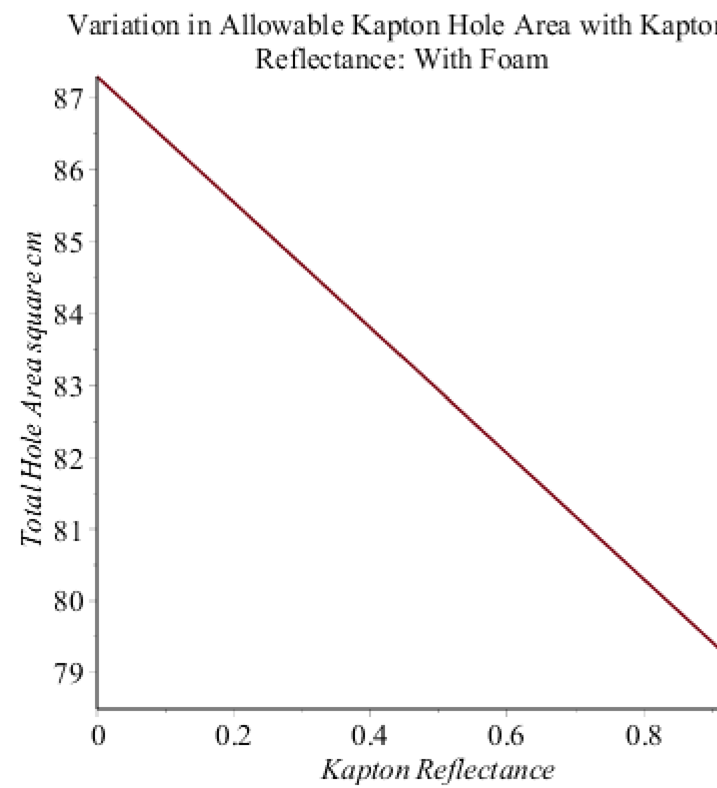
Figure 6.4-5. Starshade illumination from a point source 12° off axis.

Solar Light Leakage

- Micrometeoriods punch holes in the top and bottom surfaces, and through the central layer of foam.
- Sunlight enters the top through the holes, forms a 'bath' of light in the middle, and exits the bottom toward the telescope
- Model of multiple reflections, small leakage, absorption, resembles a lossy optical cavity.

$$I_{out} = \frac{T_K^2 T_F}{(1 - R_F R_K)^2 - R_K^2 T_F^2} I_0$$

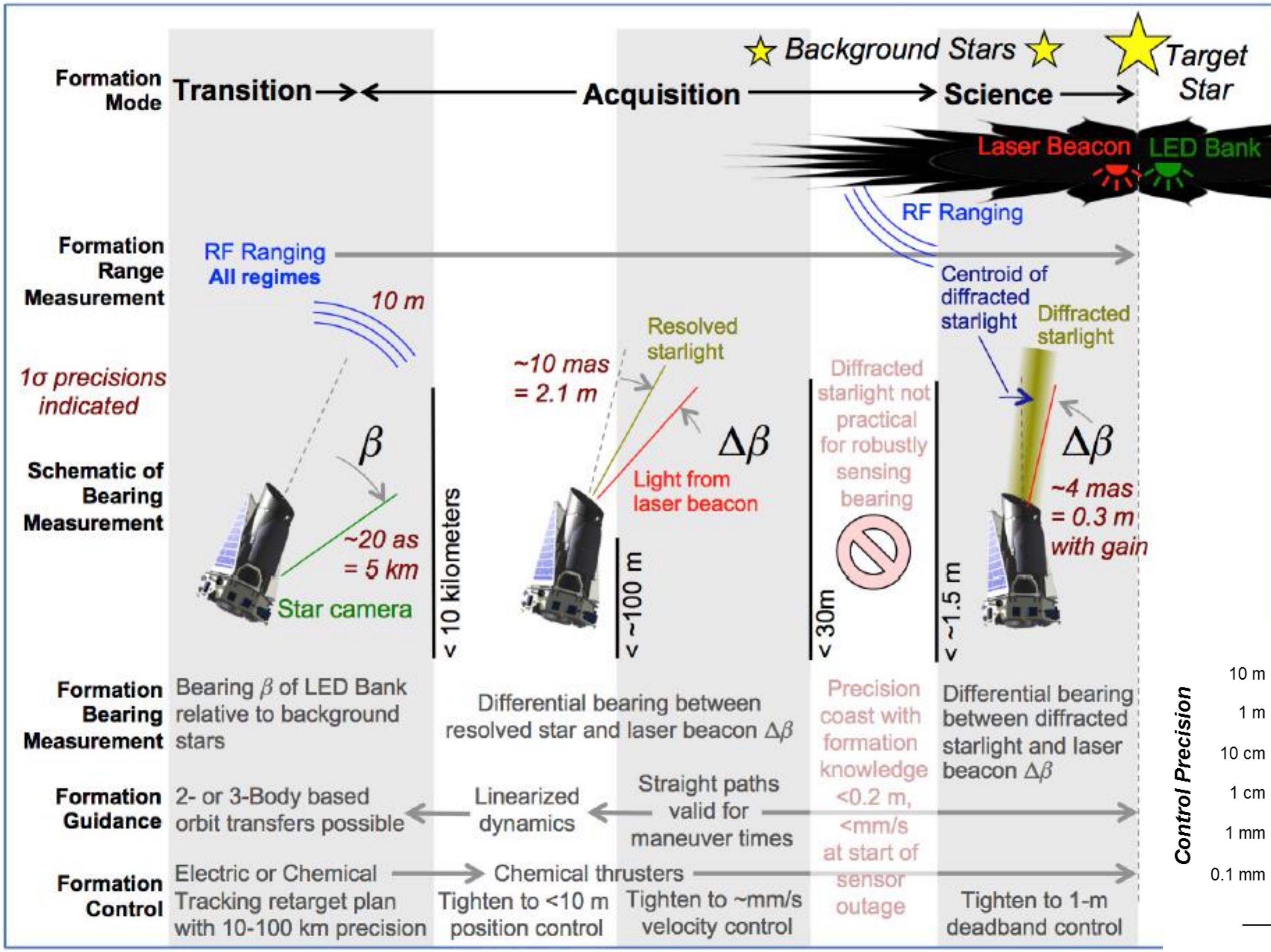




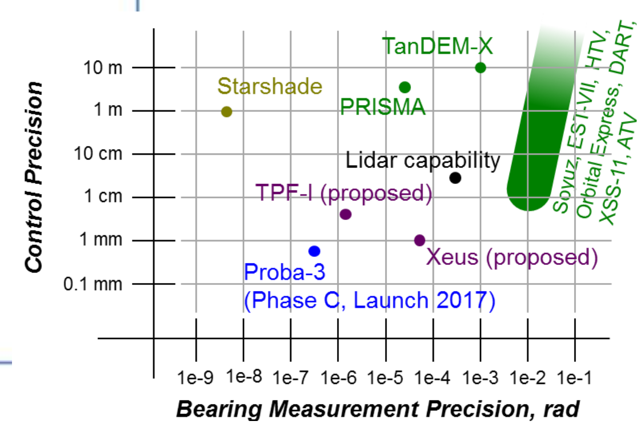
Permissible Hole Area vs. Kapton Reflectance

A plot of hole area vs. Kapton reflectance for $r_F = 0.1$, $t_F = 0.01$, $\alpha = 10$, opaque Kapton, and small hole fraction demonstrating the small, approximately linear response to changes in Kapton reflectance of an optical shield with low-transmittance foam.

Lateral Formation Flying



- Sensing is the key technology for formation flying.
- Control is not regarded as a key issue:
  - Gravity gradients are small
  - Time constants are long
  - Comparable to low-earth orbit docking



Petal Fabrication, Petal Placement

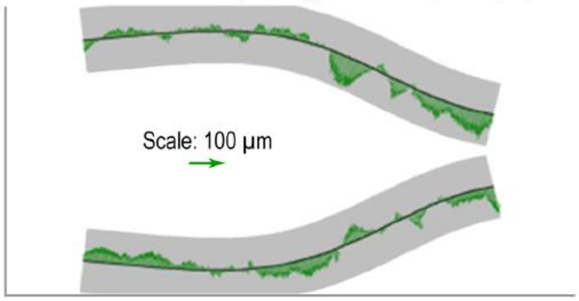
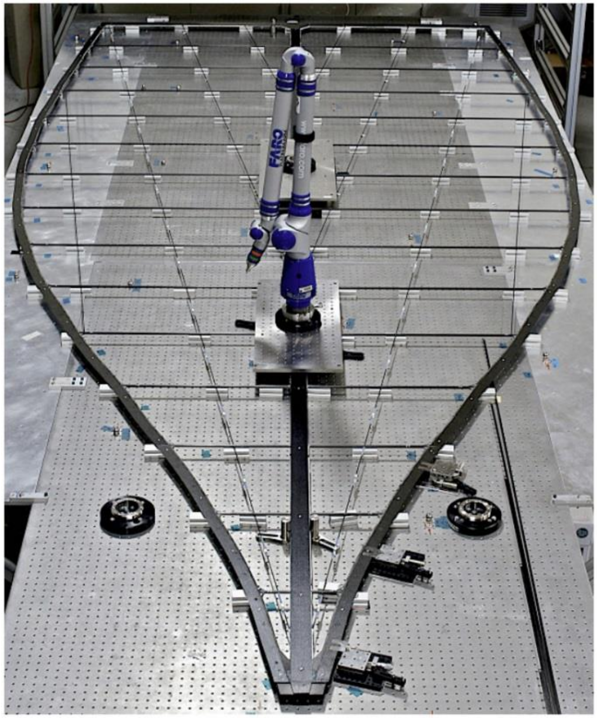


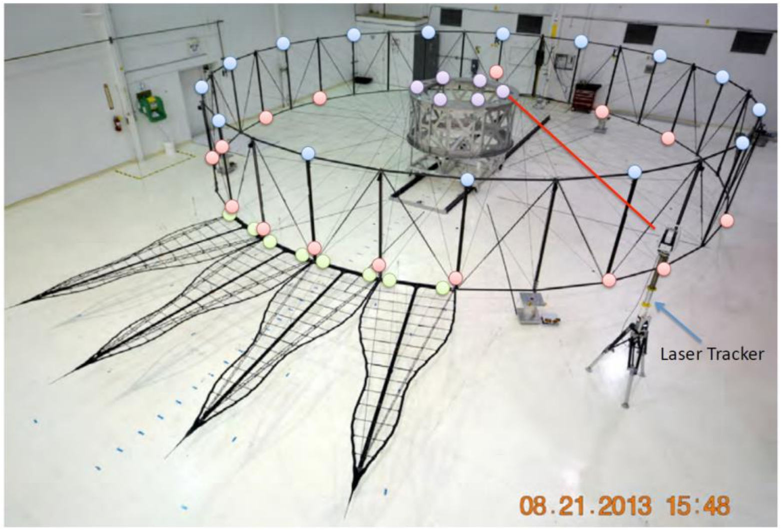
Figure 9.4-2. Measured petal shape error (green arrows) vs. 100 μm tolerance for 1×10^{-10} imaging (gray band) shows full compliance with the allocated tolerance.



Kasdin TDEM-10 Final Report

Table 6.4-4. Comparison of TDEM results with Exo-S requirements.

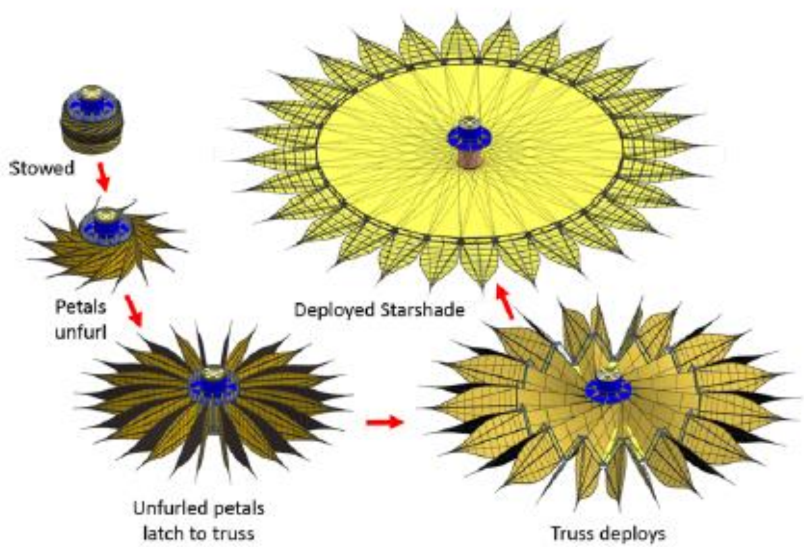
Key Technology	Demonstration	Achieved Tolerance	Required Tolerance
Petal Segment Shape (Random)	TDEM-09	±45 μm	±68 μm
Petal Segment Position (Random)	TDEM-09	±45 μm	±45 μm
Radial Petal Position (Bias)	TDEM-10	±100 μm	±150 μm



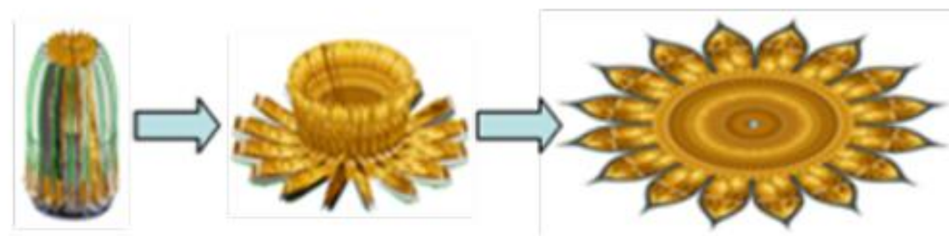
Kasdin TDEM-11 Final Report

Deployment: Optical Shield

Description	Current Capabilities	Needed Capabilities
Demonstrate that a starshade can be autonomously deployed to within its budgeted tolerances after exposure to relevant environments.	Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12m prototype and no optical shield; no environmental testing (Exo-S design).	Demonstrate deployment tolerances are met with flight-like, minimum half-scale inner disk, with simulated petals, optical shield, and interfaces to launch restraint after exposure to relevant environments.



Exo-S starshade deployment concept



NGAS starshade deployment concept

Recent Activities

- 10m inner disk testbed was completed in 2014.
- 2m testbed completed for demonstrating origami shield designs in 2015.
- TDEM-14 awarded for optical shield design and integration into 10m inner disk testbed (Mark Thomson/JPL).

Petal Launch Restraint and Controlled Launch

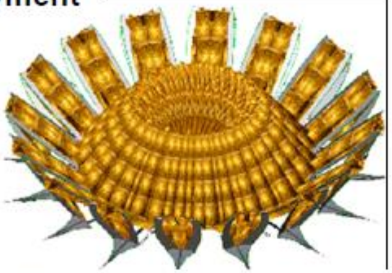
Description	Current Capabilities	Needed Capabilities
Demonstrate petals deploy without edge contact.	Model simulations predict uncontrolled petal unfurling produces edge contact (Exo-S design).	Full-scale controlled petal deployment mechanism demonstrated to secure petals throughout launch and deploy with no edge contact.

Possible Next Steps to Closing Technology Gap

- **Roccor to design and fabricate a full-scale petal unfurling testbed to demonstrate latching and petal interface. (CY16)**
  - Petal spines will be full-scale (7m)
  - NGAS to review designs; possible architecture trade

- **Roccor funded to upgrade the petal unfurling testbed to demonstrate controlled unfurling of full-scale petals (CY17)**

Exo-S unfurling deployment



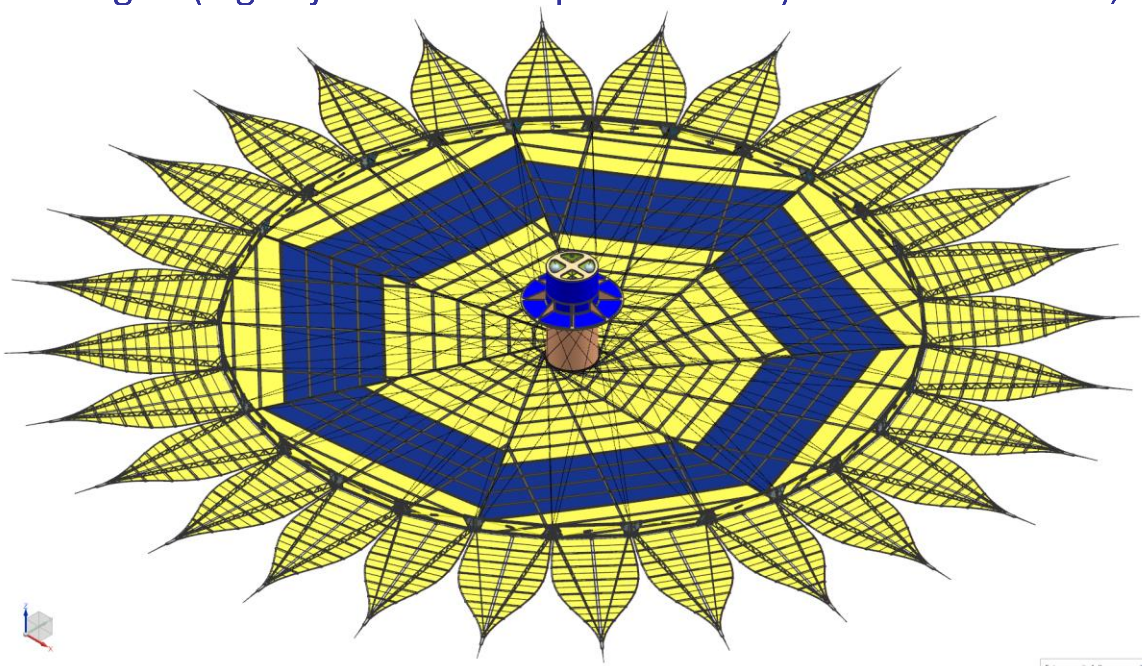
NG radial boom deployment

Recent Activities

SBIR partner Roccor and JPL produce preliminary design for unfurling and petal restraint mechanisms.

Thin-Film Solar Cells (Enhanced Rendezvous Mission)

- Solar Electric Propulsion is an important enhancement to the Rendezvous mission described in the Exo-S report.
  - Enables 5 years of observations
- SEP is TRL-9 (BPT-4000 thrusters).
- We need to generate power without a deployed solar array.
  - Starshade spins
  - Arrays cast shadows resulting in deformation.
- A solution is to integrate solar cells into the starshade.
  - Must not interfere with deployment. Want thin, low mass ceels
- Baseline cell technologies (e.g. 3-junction amorphous silicon) have low efficient, but starshade has ample area.



Summary

- Rendezvous mission science requirements are mapped to technical requirements through detailed error budgets, models, and design reference mission studies.
- The requirements on WFIRST instruments are also understood.
  - Some modifications desired to take full advantage of starshade.
  - Communication/ranging system required. Flight proven, small.
- Much more detailed information is available in the Exo-S report.