Jet Propulsion Laboratory
California Institute of Technology

# Starshade Design and Error Budget Tutorial

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SSWG Telecon
February 3, 2016

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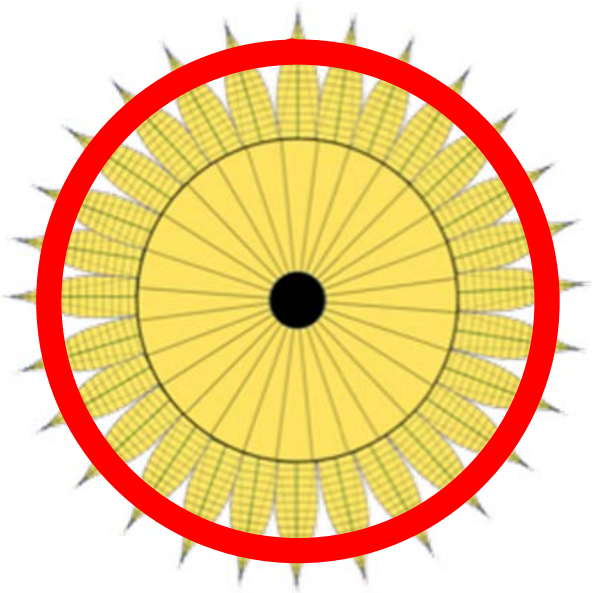
# We Tolerance a Spinning Starshade





A local defect looks like a planet.

A spinning defect does not look like a planet and contributes to the photometric but not the systematic noise floor.

Spinning also mitigates local heating due to shadowing.

We tolerance against a photometric noise floor of 1e-10.

The systematic noise floor is related to 1) Formation Flying, 2) Solar Glint, and 3) Front-side illumination.

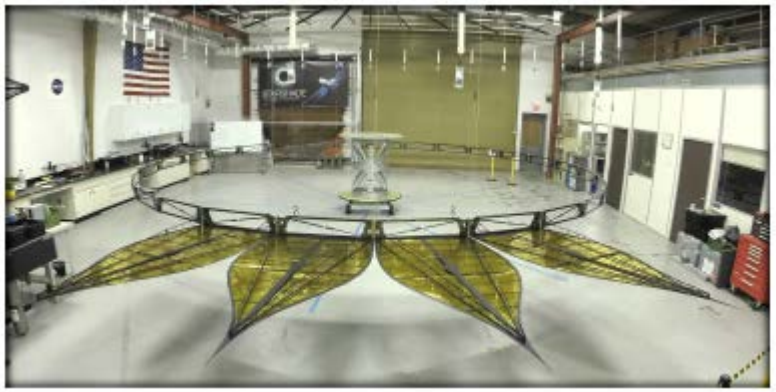
It will be stable and calibratable.

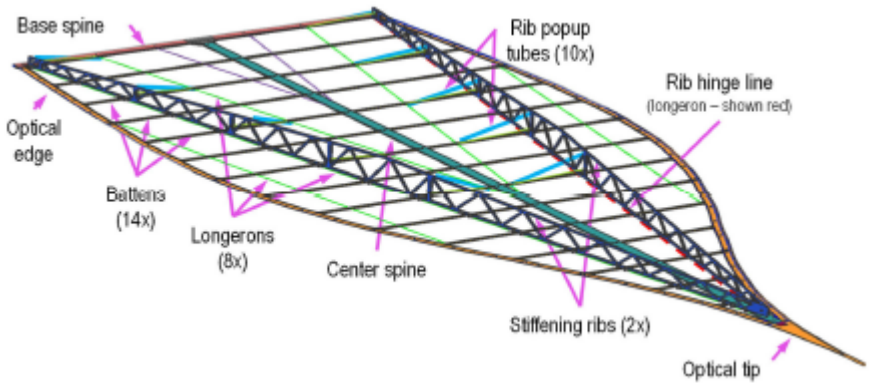
# Main Terms of Starshade Shape Error Budget



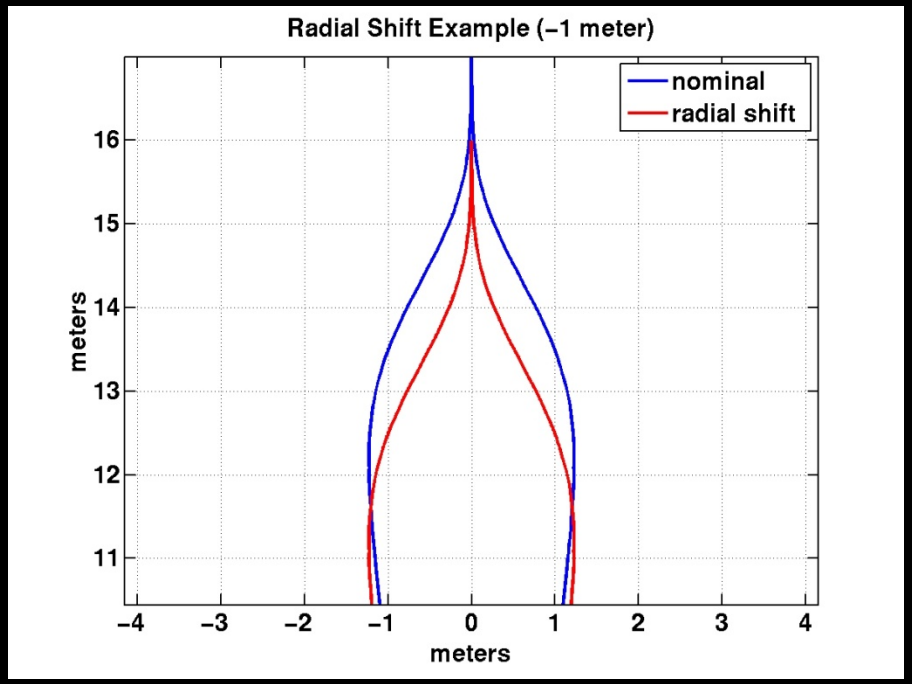
**Table 6.4-1.** Modeled starshade error budget terms.

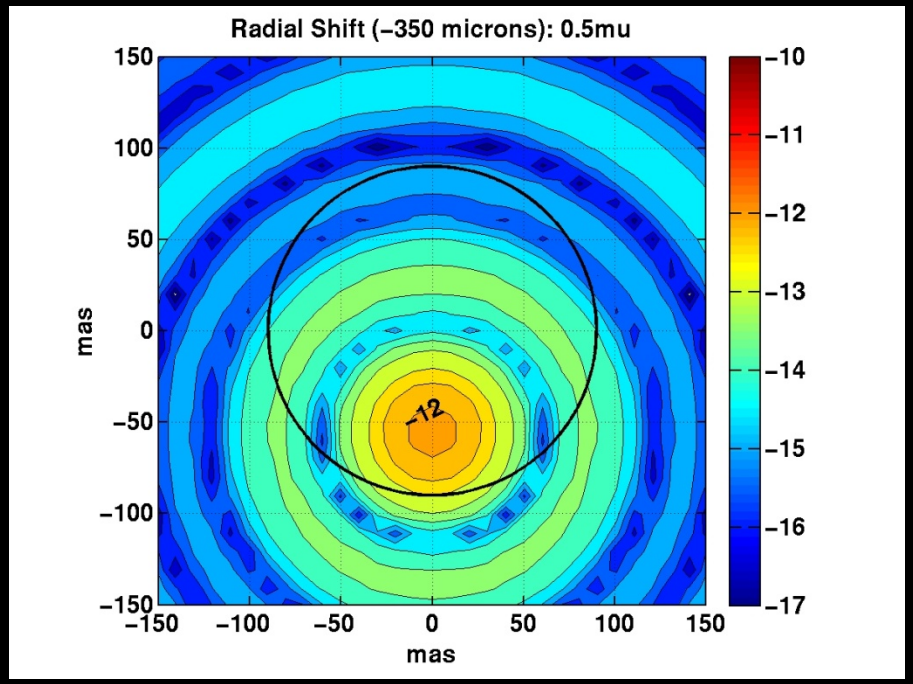
| Manufacture/ Deployment | Description |
|---|---|
| Petal Position | Radial, lateral, in-plane clocking, rotation about spine |
| Segment Shape | 0.5, 1, 2, 3, 4, cycle sine and cosine |
| Segment Placement | Tangential, normal, in-plane clocking |
| Tip Segment Placement | Radial, azimuthal, in-plane 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 |



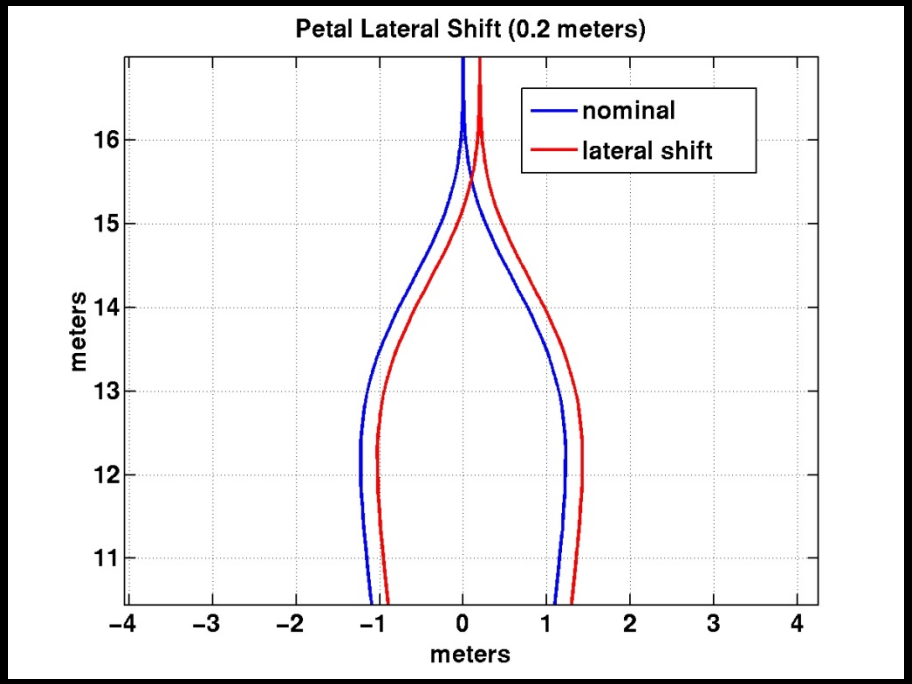


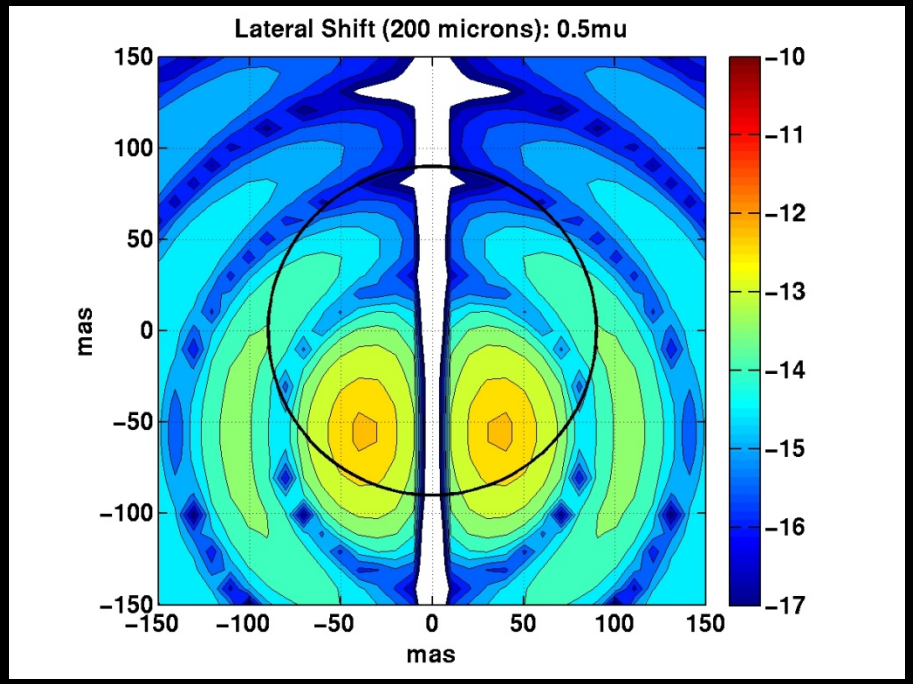
# 2010 Example: Radial Shift



# 2010 Example: Lateral Shift



# Example local and global perturbation



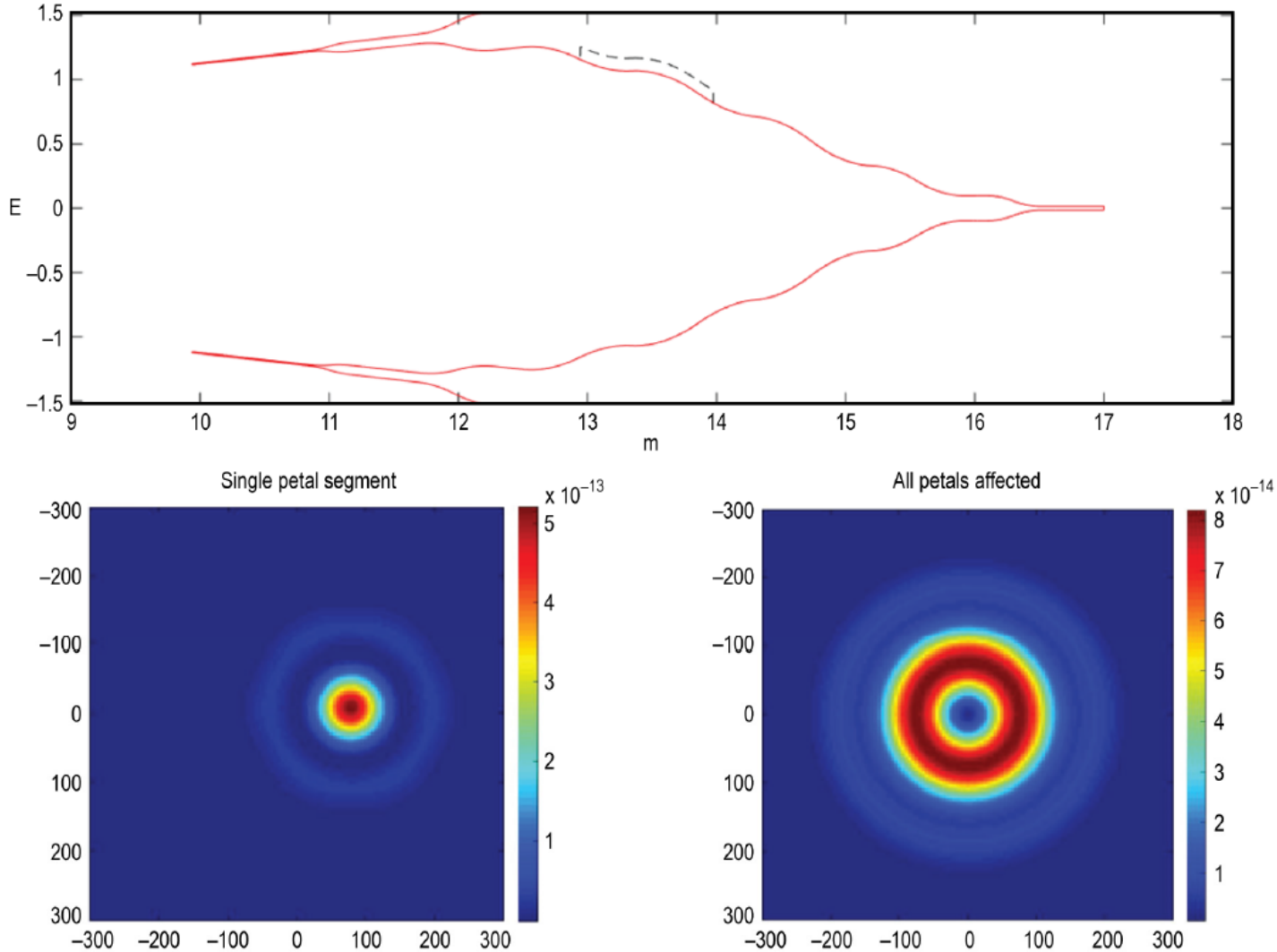
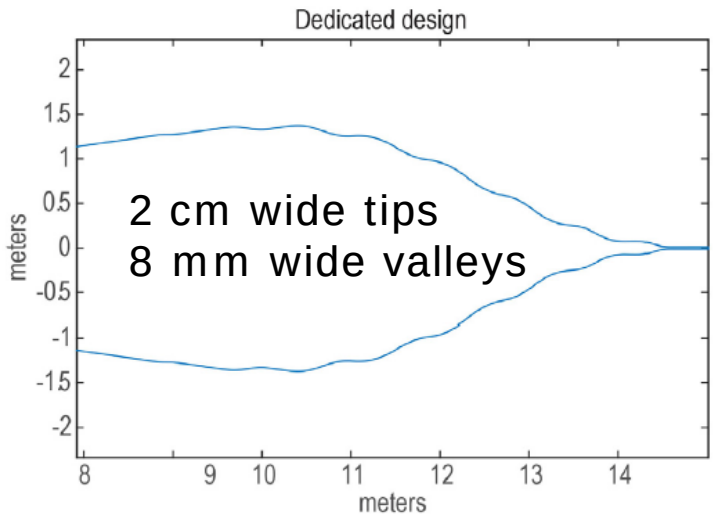
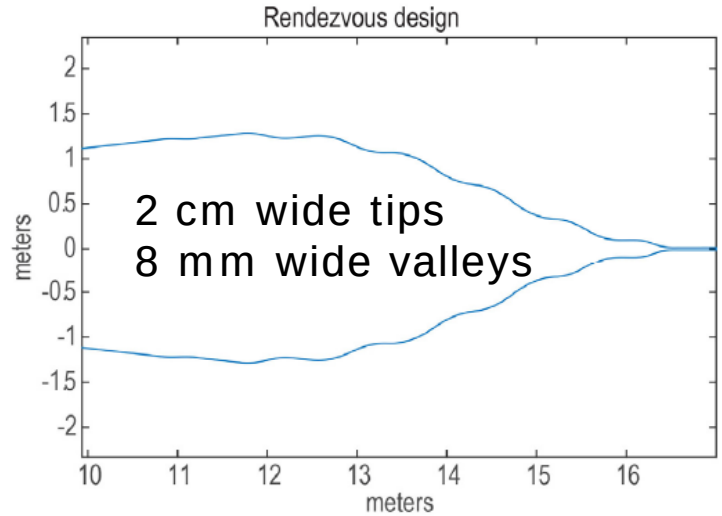


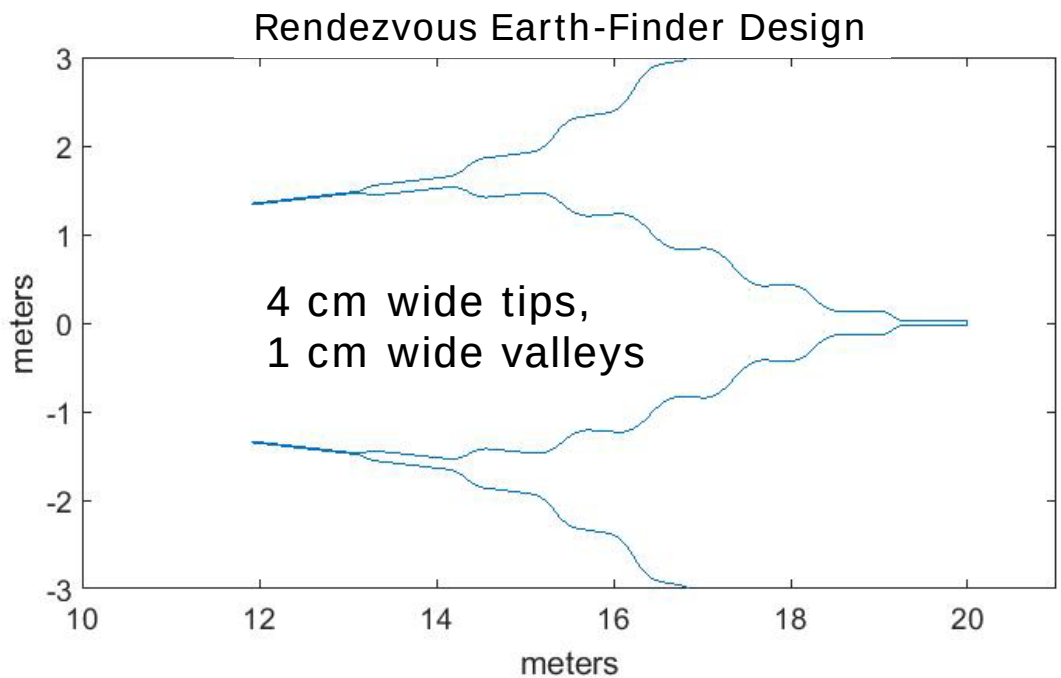

**Figure 6.4-1.** Example of a local petal perturbation; a 1-m long petal segment is displaced normal to the petal axis. The perturbation is shown enlarged 1000× relative to the displacement in the tolerancing analysis. Axes in the image plane are milliarcseconds. Colors are image plane contrast. Note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

# Starshade Petal Designs







# Example from Error Budget Spreadsheet

## Manufacturing Allocation for Rendezvous Design (JY21)



| | | Random rms | Global tolerance | units | Mean Contrast from Random 600 | 650 | 700 | 750 | |
|---|---|---|---|---|---|---|---|---|---|
| Petal Clocking | x | 2.00E-04 | 2.00E-04 | Rad | 2.78E-13 | 3.43E-13 | 3.90E-13 | 4.20E-13 | 4.59E |
| Petal Tip Clip | x | 0.20 | 0.2 | mm | 1.74E-13 | 1.61E-13 | 1.50E-13 | 1.39E-13 | 1.32E |
| Petal Radial | | 0.2 | 0.2 | mm | 4.53E-13 | 5.43E-13 | 6.86E-13 | 7.96E-13 | 9.42E |
| Quadratic Bend Out-of-Plane | | 2 | 2 | mm | 2.04E-16 | 1.56E-16 | 1.18E-16 | 7.92E-17 | 1.54E |
| Petal Tangential | | 0.15 | 0.2 | mm | 1.35E-12 | 1.38E-12 | 1.38E-12 | 1.37E-12 | 1.36E |
| Out of Plane Bend Linear | | 2 | 2 | mm | 1.85E-15 | 1.98E-15 | 1.84E-15 | 1.43E-15 | 1.30E |
| Quadratic In-Plane Bend | | 1 | 1 | mm | 1.31E-15 | 1.80E-15 | 2.43E-15 | 3.18E-15 | 4.13E |
| **Spatial frequency** | x | | | | | | | | |
| **.5 cyde per segment1 sine** | | 10 | 10 | um | **1.18E-13** | **1.27E-13** | **1.42E-13** | **1.48E-13** | **1.56E** |
| **1 cyde per segment1 sine** | | 10 | 10 | um | **8.43E-14** | **7.54E-14** | **7.15E-14** | **6.37E-14** | **5.85E** |
| **2 cyde per segment1 sine** | | 10 | 5 | um | **1.35E-14** | **1.30E-14** | **1.31E-14** | **1.22E-14** | **1.16E** |
| **3 cyde per segment1 sine** | | 10 | 5 | um | **5.58E-15** | **5.45E-15** | **5.53E-15** | **5.19E-15** | **4.96E** |
| .5 cyde per segment2 sine | | 10 | 10 | um | 1.30E-13 | 1.39E-13 | 1.52E-13 | 1.56E-13 | 1.64E |
| 1 cyde per segment2 sine | | 10 | 10 | um | 1.16E-13 | 1.03E-13 | 9.50E-14 | 8.34E-14 | 7.55E |
| 2 cyde per segment2 sine | | 10 | 5 | um | 1.73E-14 | 1.68E-14 | 1.67E-14 | 1.55E-14 | 1.47E |
| 3 cyde per segment2 sine | | 10 | 5 | um | 7.17E-15 | 7.07E-15 | 7.11E-15 | 6.65E-15 | 6.34E |
| **.5 cyde per segment3 sine** | | 10 | **10** | um | **1.39E-13** | **1.48E-13** | **1.61E-13** | **1.64E-13** | **1.70E** |
| **1 cyde per segment3 sine** | | 10 | **10** | um | **1.56E-13** | **1.37E-13** | **1.24E-13** | **1.08E-13** | **9.64E** |

# Key Requirements



**Table 6.4-3.** Key requirements for the error budget. Values are 3-sigma tolerances.

| | Dedicated 1.1 m | Contrast × $10^{-11}$ | Rendezvous 2.4 m | Contrast × $10^{-11}$ |
|---|---|---|---|---|
| Manufacture | | | | |
| Petal Segment Shape (Bias) | 14 µm | 1.4 | 22 µm | 0.37 |
| Petal Segment Shape (Random) | 71 µm | 0.5 | 71 µm | 0.26 |
| Petal Segment Placement (Bias) | 4 µm | 0.7 | 7 µm | 0.07 |
| Petal Segment Placement (Random) | 45 µm | 0.6 | 53 µm | 0.47 |
| | | | | |
| Pre-Launch Deployment | | | | |
| Petal Radial Position (Bias) | 150 µm | 6.0 | 200 µm | 0.15 |
| Petal Radial Position (Random) | 450 µm | 0.6 | 450 µm | 0.1 |
| | | | | |
| Post-Launch Deployment | | | | |
| Petal Radial Position (Bias) | 100 µm | 2.7 | 250 µm | 0.23 |
| Petal Radial Position (Random) | 350 µm | 0.4 | 375 µm | 0.06 |
| | | | | |
| Thermal | | | | |
| Disk-Petal Differential Strain (Bias) | 20 ppm | 6.0 | 40 ppm | 0.6 |
| 1–5 Cycle/Petal Width (Bias) | 10 ppm | 1.0 | 30 ppm | 0.2 |
| | | | | |
| Formation Flying | | | | |
| Lateral Displacement | 1 m | 2.9 | 1 m | 1.1 |
| Longitudinal Displacement | 250 km | 2.5 | 250 km | 0.43 |

# Error Budget Requirements and Allocations



**Table 6.4-2.** Starshade contrast requirements.

| Requirement | Dedicated 1.1 m | Rendezvous 2.4 m |
|---|---|---|
| Photometric Floor | $5\times10^{-10}$ | $1\times10^{-10}$ |
| Systematic Floor | $4\times10^{-11}$ | $4\times10^{-11}$ |

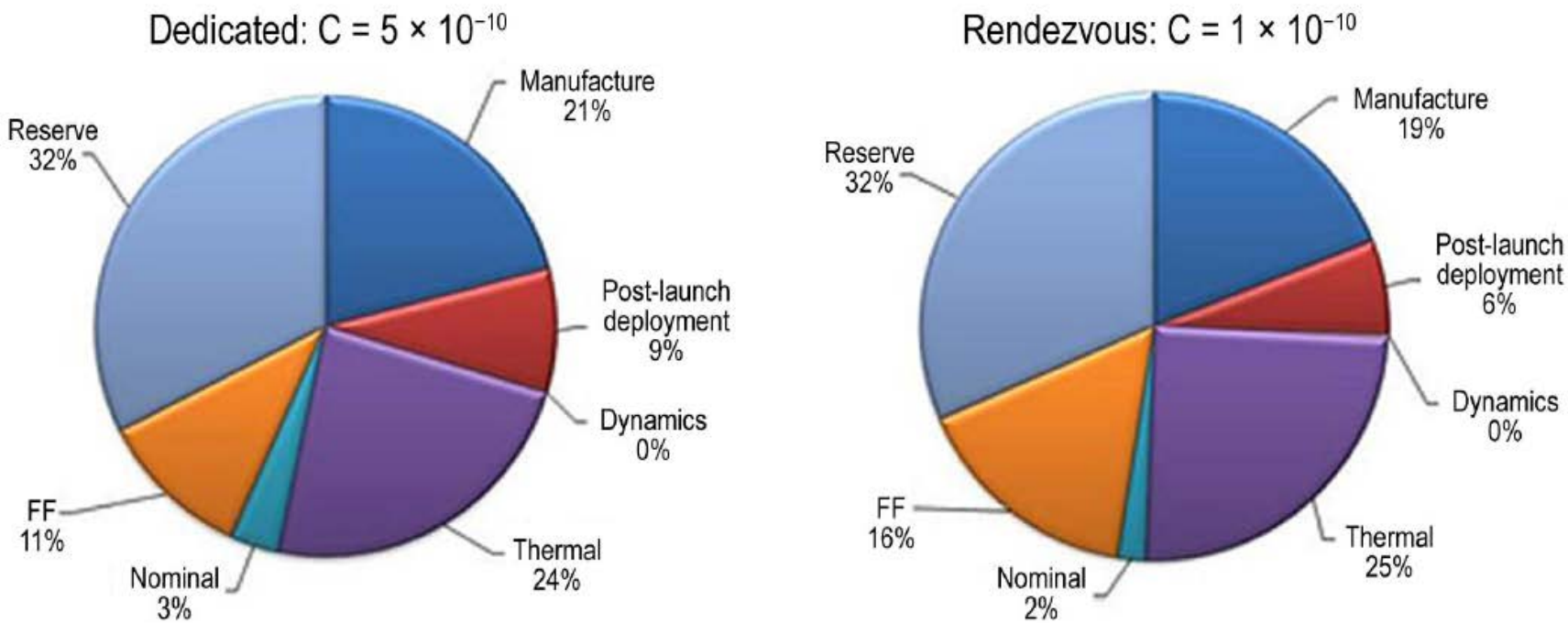



**Figure 6.4-3.** Overall photometric error budget for the Dedicated and Rendezvous missions.

# Manufacturing Error Budget



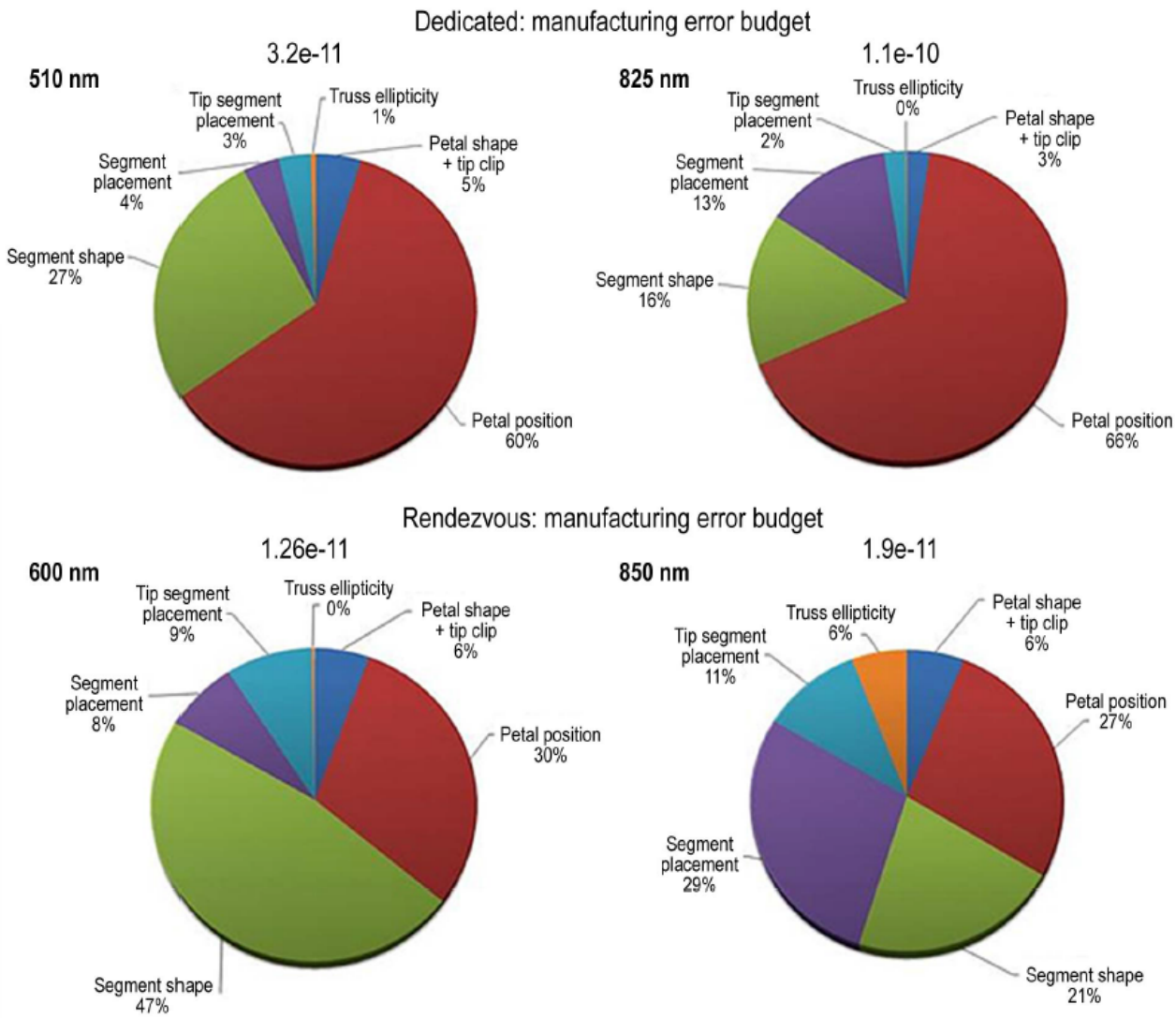



**Figure 6.4-2.** Allocation of errors to the manufacturing error budget. *Top*: Starshade for the Dedication Mission. *Bottom*: Starshade for the Rendezvous Mission. *Left*: Shortest wavelength of the mid-range bandpass. *Right*: Longest wavelength of the bandpass. Values above the pie charts indicate total contrast for these manufacturing terms.

# Experiment vs. Requirement



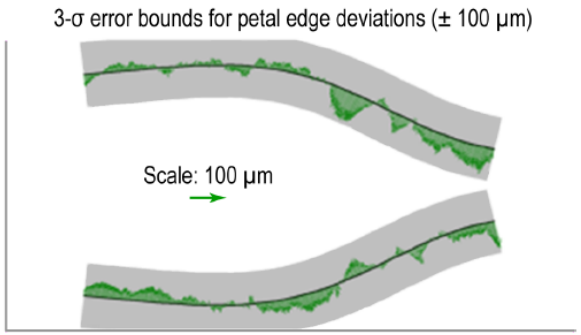
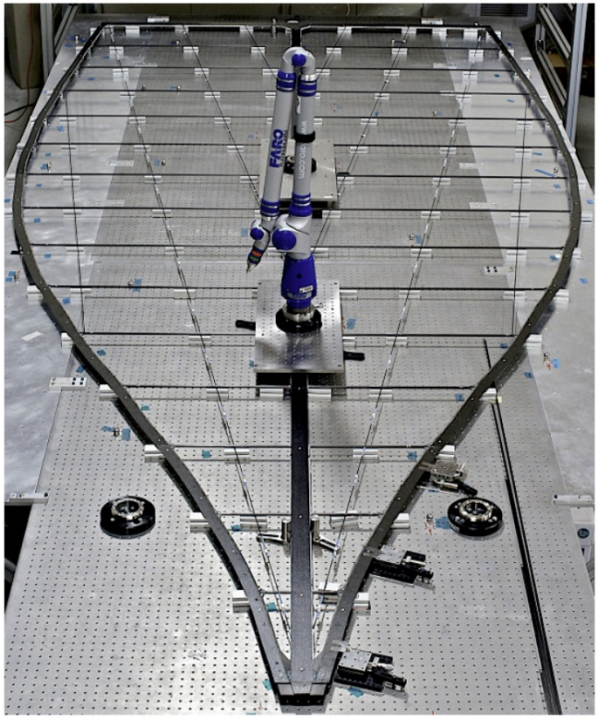


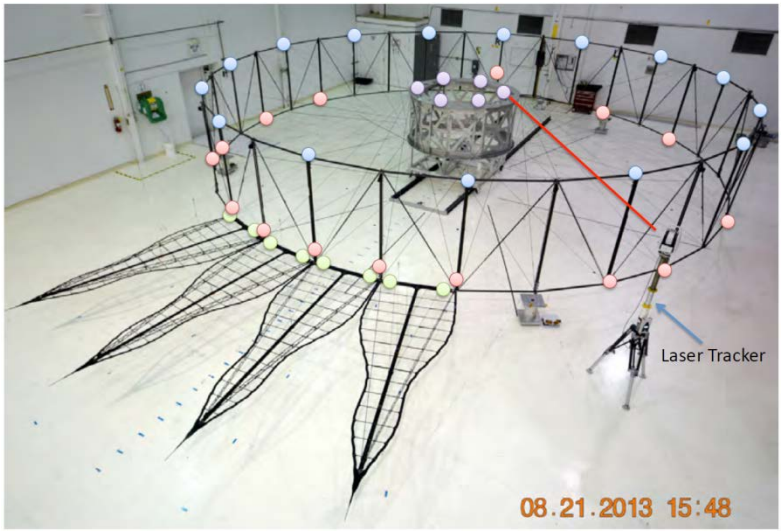

**Figure 9.4-2.** Measured petal shape error (green arrows) vs. 100 μm tolerance for $1 \times 10^{-10}$ imaging (gray band) shows full compliance with the allocated tolerance.

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

| Key Technology | Demonstra-tion | 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-10 Final Report




Kasdin TDEM-11 Final Report

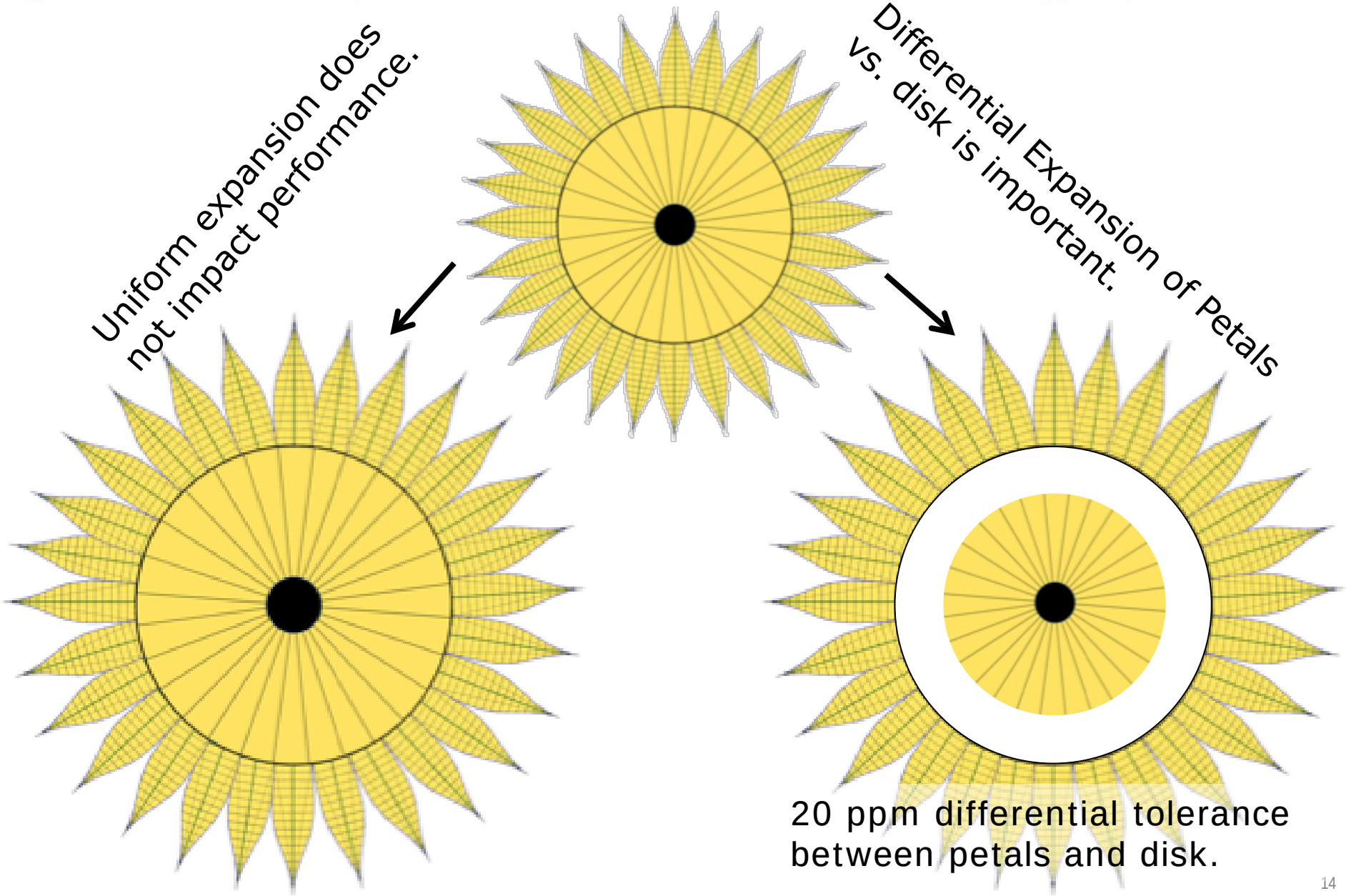
# Exo-S Rendezvous vs. Rendezvous Earth-Finder



| | Rendezvous | Rendezvous E-F |
|---|---|---|
| **Pre-Launch Deployment** | | |
| Petal Radial Position (Bias) | 200 um | 200 um |
| **Post-Launch Deployment** | | |
| Petal Radial Position (Bias) | 250 um | 200 um |
| **Thermal** | | |
| Disk-Petal Differential Strain (Bias) | 20 ppm | 13 ppm |
| Tip segment strain | 500 ppm | 250 ppm |

# Disk vs. Petal CTE





# Thermal Modeling Results



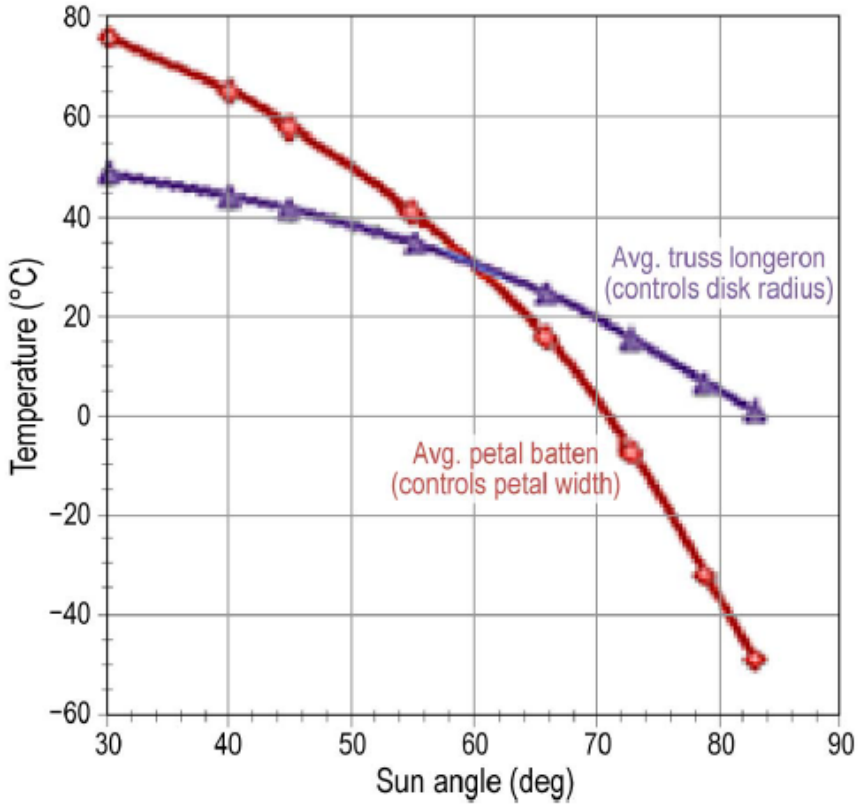



**Figure 6.2-20.** Temperature predicts for truss longerons and petal battens over full range of operating Sun angles. The maximum 83°Sun angle corresponds to 7° from petal plane.

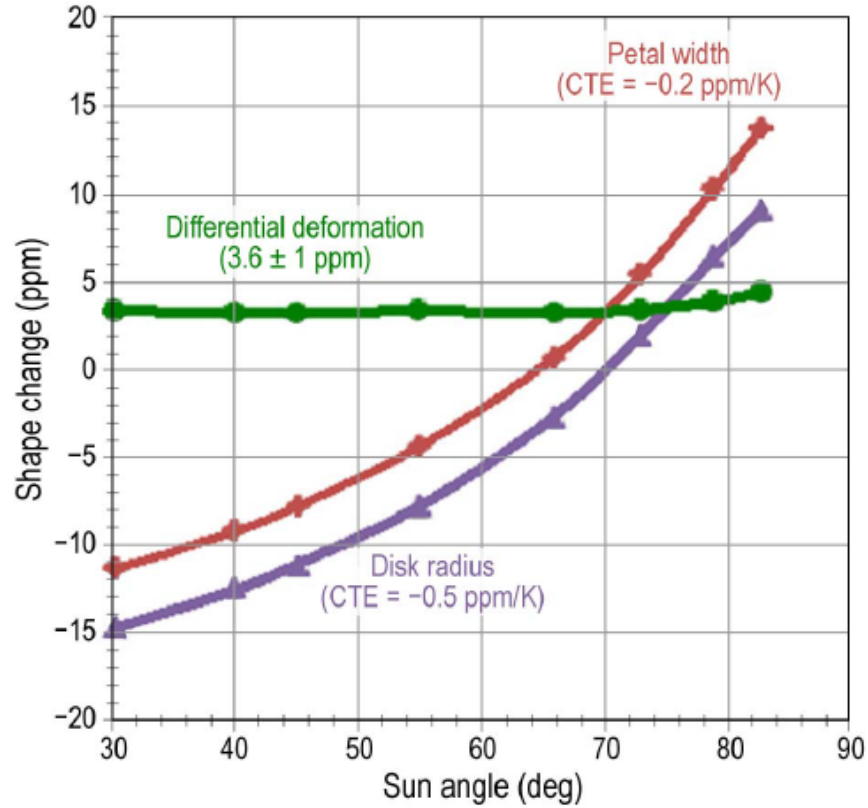



**Figure 6.2-21**. Uniform thermal deformations to petal width, disk radius and the differential between the two. A bias of 3.6 ppm is indicated.

The petals change temperature more than the inner disk. To reduce differential expansion we design petals to have a smaller CTE than the disk.

# Thermal Requirement Tolerancing



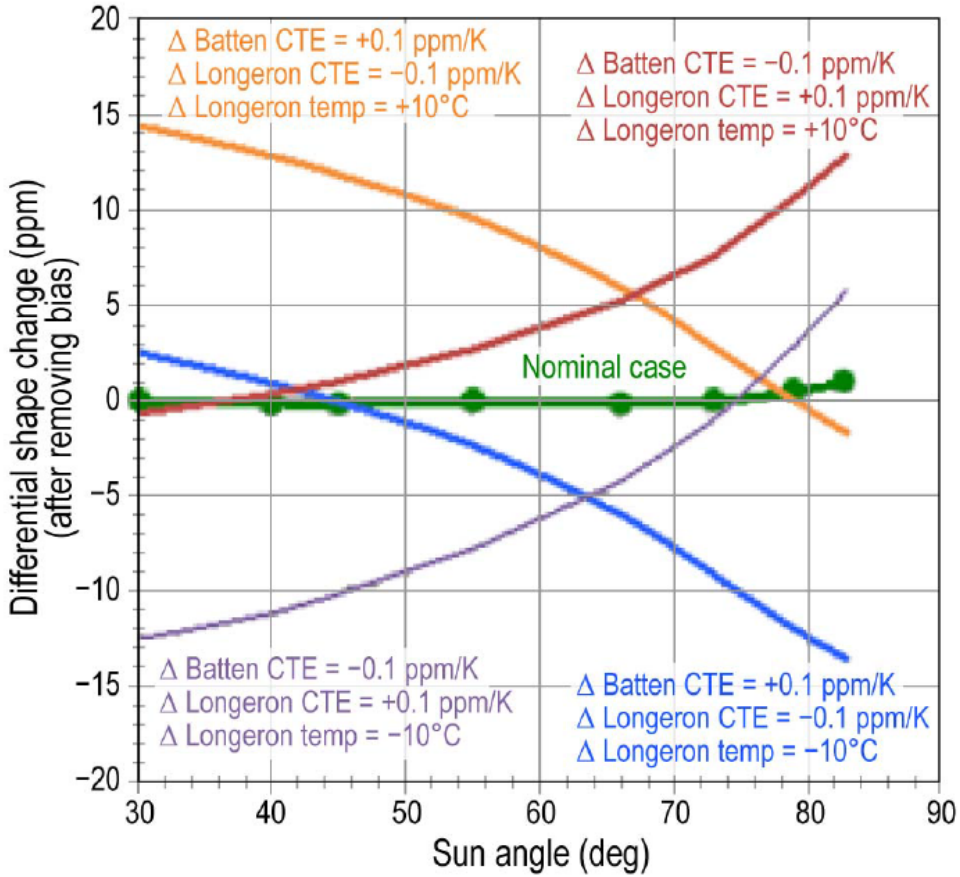



**Figure 6.2-22**. Residual differential deformation after removing the bias term, for nominal CTE and temperatures plus combinations of longeron CTE and temperature error.

This chart shows combinations of CTE error on battens, longerons, and Temperature errors, that do not exceed the 20 ppm differential expansion requirement.

# Solar Edge Glint



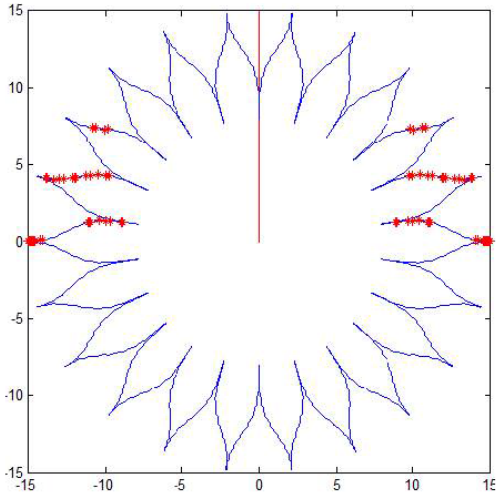
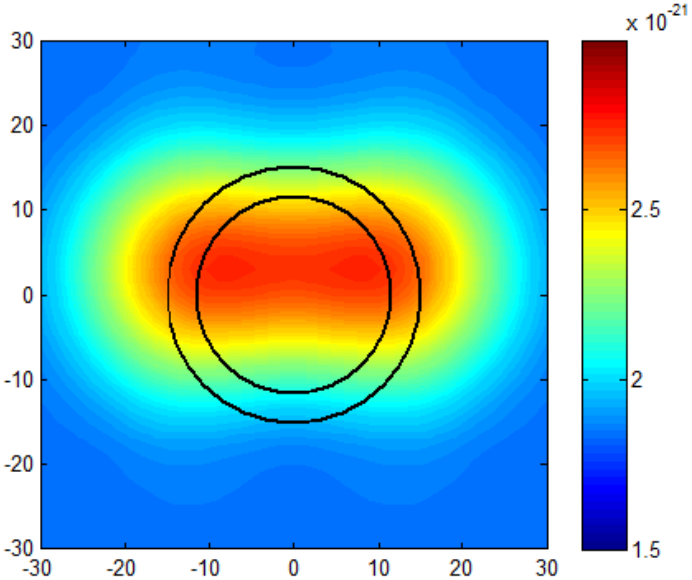


**Figure 9.1-1.** Lit-up edge regions. Red symbols indicate where specularly reflected and diffracted sunlight originates. The Sun is 30° into paper at top of figure (60° solar incidence). Units



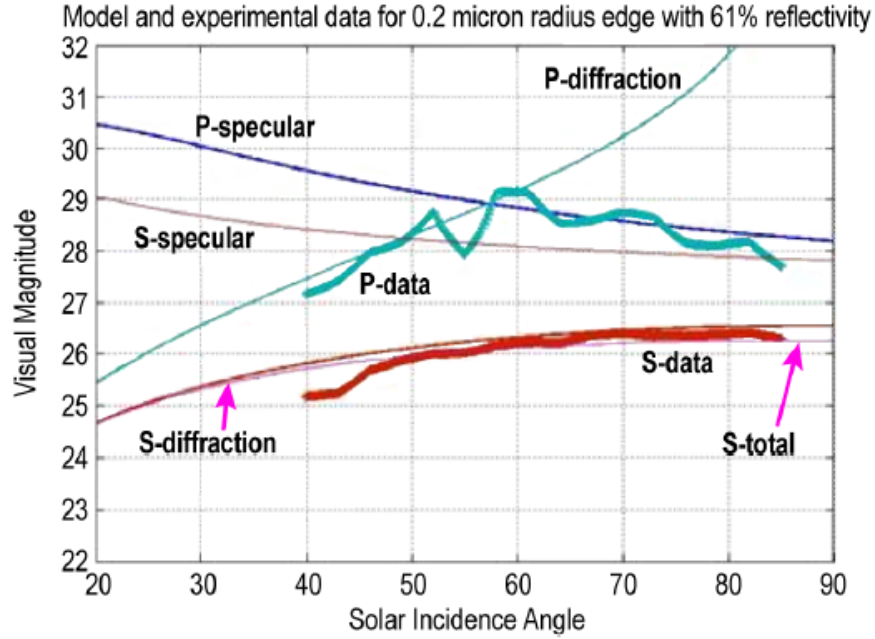




**Figure 9.1-2.** Model predictions compared to stainless steel razor blade measurements (not baseline design), for total light diffracted and specularly reflected by the starshade edge.

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

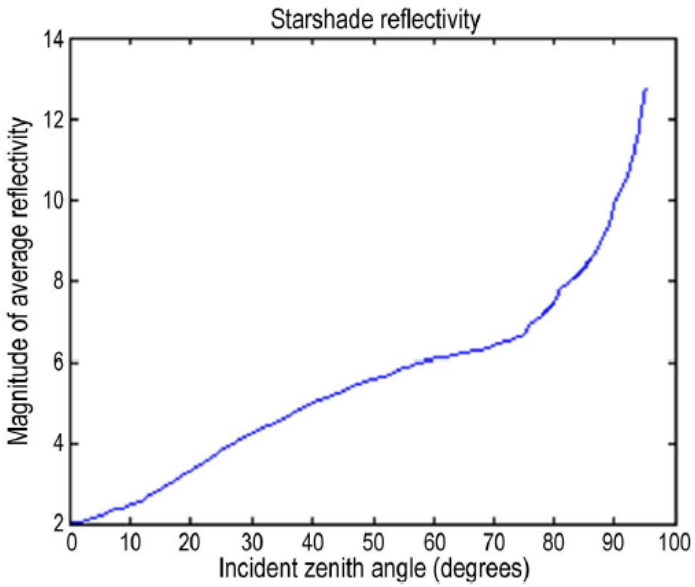



**Figure 6.4-4.** Average reflectivity of the starshade for a range of incident angles relative to the starshade normal.

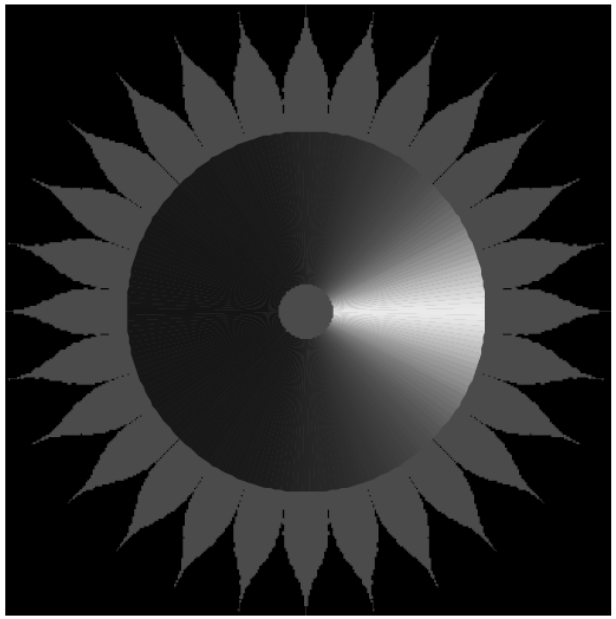


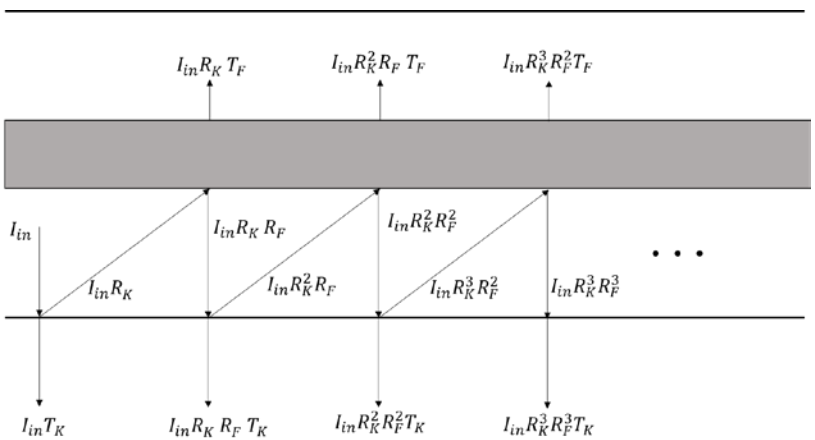
**Figure 6.4-5.** Starshade illumination from a point source 12° off axis.

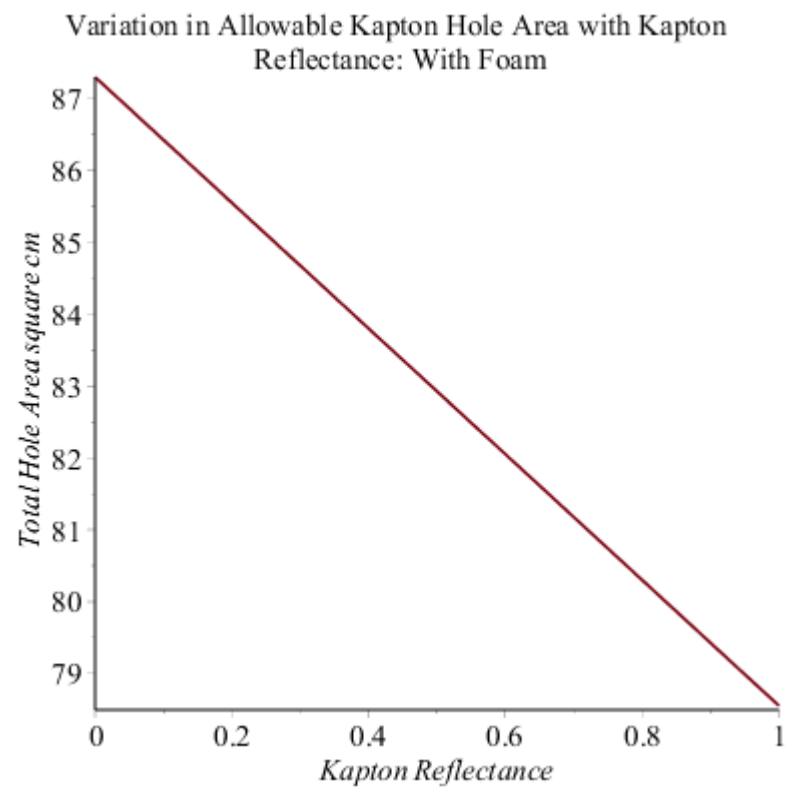
# Solar Light Leakage



- 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.

# Integrated Modeling Example: Petal Shape



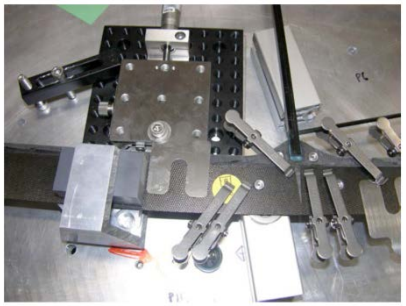
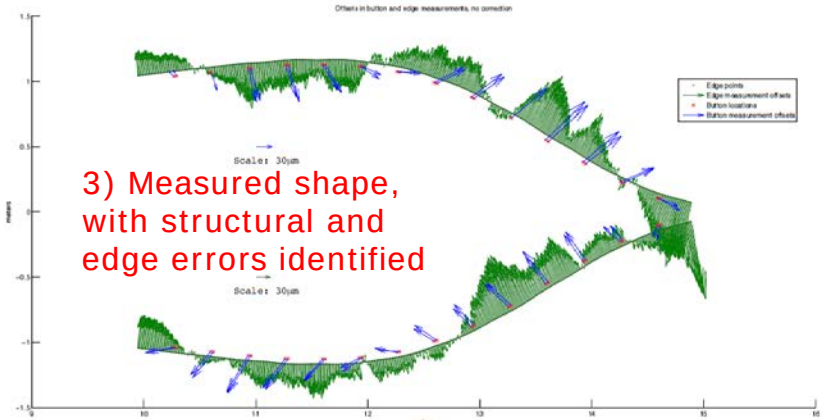


FIGURE 13. End of edge section showing translation stage and shim attachment used to adjust edge. Also shown are the metal clips and left, the aluminum and grey plastic spacer are part of the pneumatic clamp.

1) Manufacture of Petal to Flight Dimension Tolerance

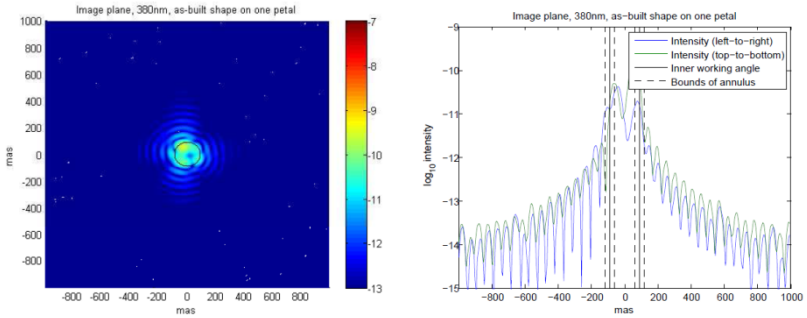
FIGURE 16. Setup of the petal on the tables at Allied. The black and grey bags are bearing-filled bags that load the petal to maintain contact with the extrusion pieces.

2) Measure shape on precision CMM



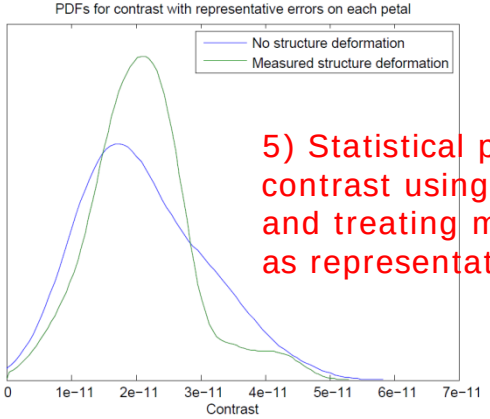

3) Measured shape, with structural and edge errors identified

4) Optical model propagates light assuming measured petal shape.




(a) Worst-Case PSF (b) PSF Cross Section

FIGURE 29. (*Left*) The image-plane intensity profile at 380nm for an occulter with 30 random petals, plotted on a log scale. The inner working angle is shown with a solid circle. While the occulter is assumed to be spinning, this represents an instantaneous snapshot of the intensity. (*Right*) A cross section of the point-spread function showing the designed inner working angle and the boundaries of the annulus used for contrast calculation.




5) Statistical predictions of contrast using optical model and treating measured shape as representative of all petals.

FIGURE 30. Distribution of worst-case mean contrast, assuming random errors consistent with the placed segments are applied to each segment on each petal independently. The two cases shown are with and without the overall petal deformation seen in the petal as built.

# Integrated Modeling Example: Thermal Gradients



Thermal Model: Batten Temperatures at different Sun Angles

↓

Fit uniform expansion term (carried separately in error budget) and determine amplitude of residual non-uniform term.

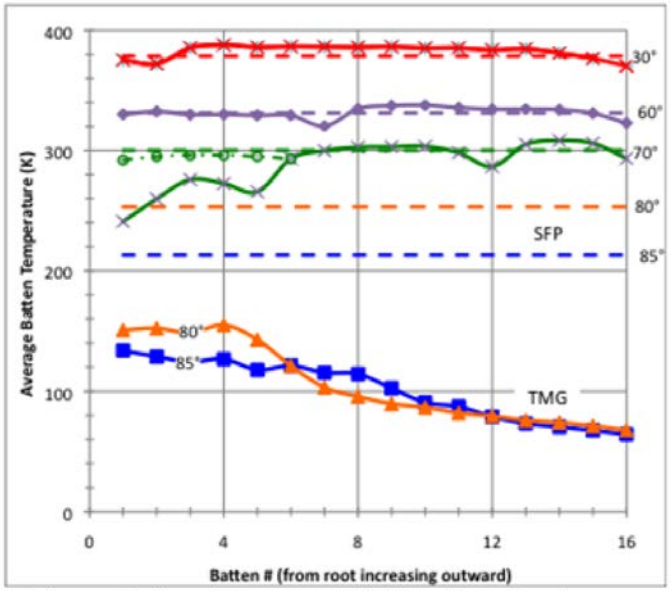



Figure 4. Steady state predictions for effective emissivity = 0.1.

Sine Waves on Edge amplitude a

↓

Optical Propagation Model

↓

Contrast C in Image plane

↓

Sensitivity dC/da

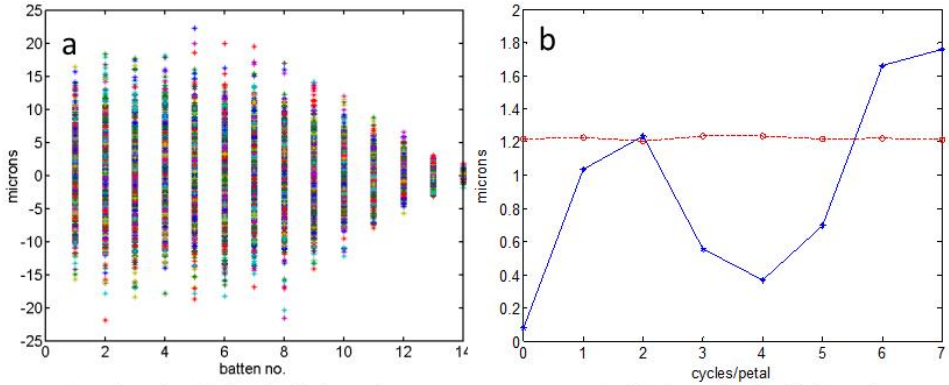
Monte Carlo Simulation of non-uniform Batten Temperatures

↓

Mechanical Deformation Model

↓

Fourier Analysis into Sine Waves on Petal Width



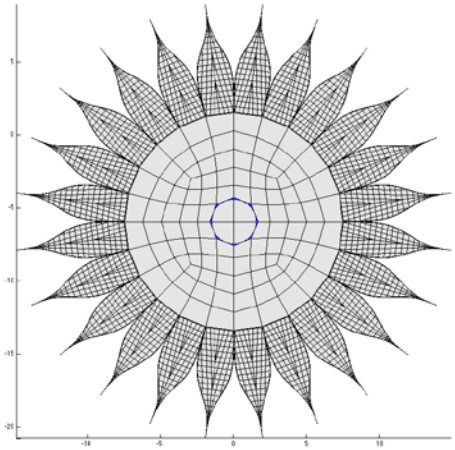

Random thermal variation simulation and r.m.s. power spectrum. a) This shows the distribution of 1000 realizations of the change in length of the 14 battens that control the TDEM petal width. We assumed a standard deviation of 2.5 ppm leading to a maximum deviation of about +/- 7.5 ppm or +/- 18 um. b) The solid curve with star markers is the FFT of one realization normalized to show the r.m.s. variation in a 1 cycle/petal bandwidth. The dashed curve with circle markers shows the average of 1000 realizations, a white spectrum with 1.2 um r.m.s. per cycle.

→ Contrast predictions

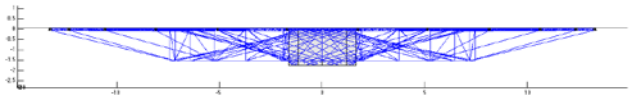
# Integrated Modeling Example: CIELO Model

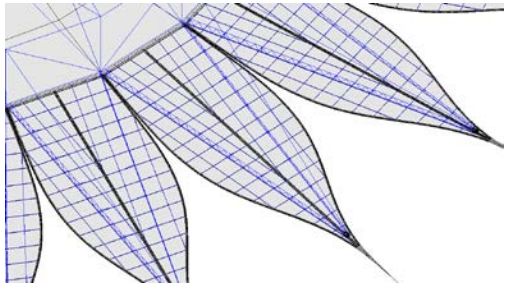
## CIELO = JPL integrated modeling tool, Hoff et al, SPIE 8127 (2011).



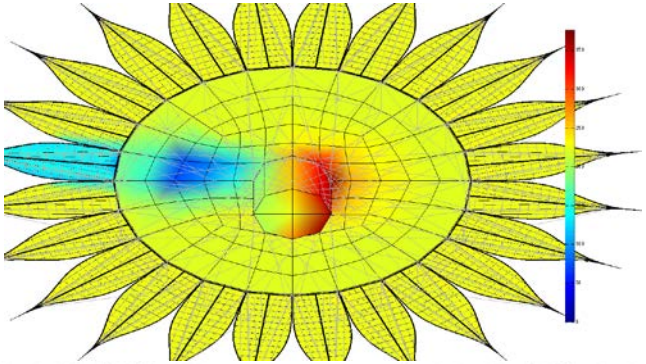


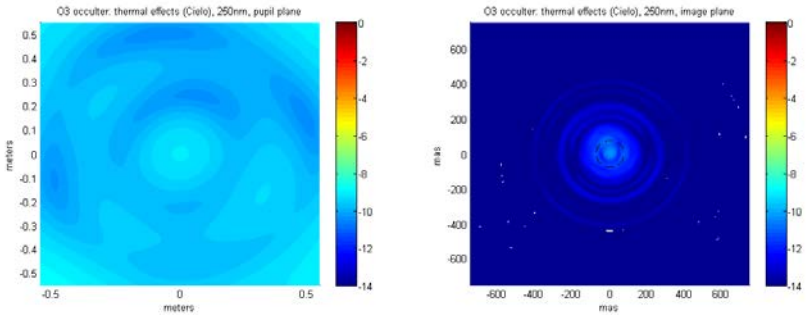
Model particulars:
210k radiation exchange elements
170k thermal degrees of freedom
1M structural degrees of freedom



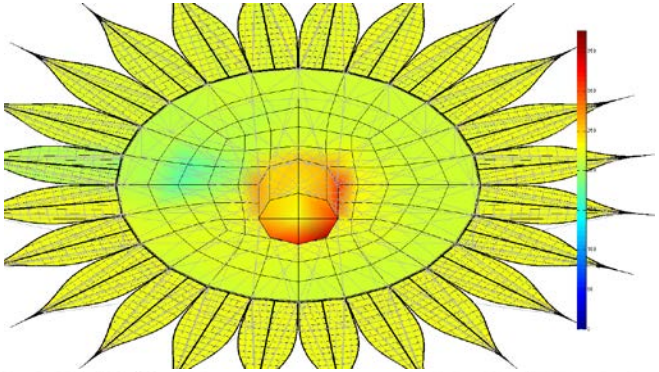


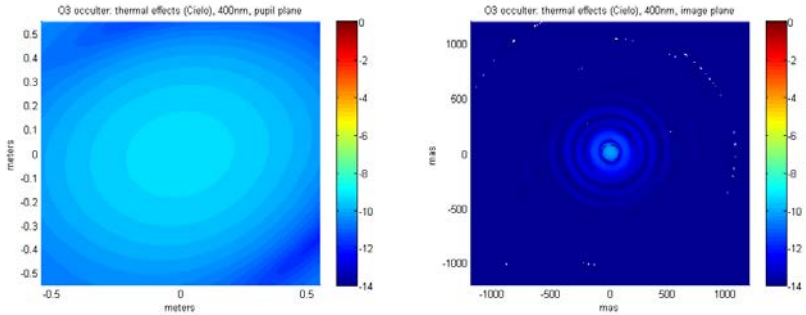
Occulter at 5 deg Grazing Angle to Sun
Steady-State Temperature Solution (°K)






Occulter at 5-deg Grazing Angle to Sun Rotating
Simulation – 1 Revolution per 30 Minutes

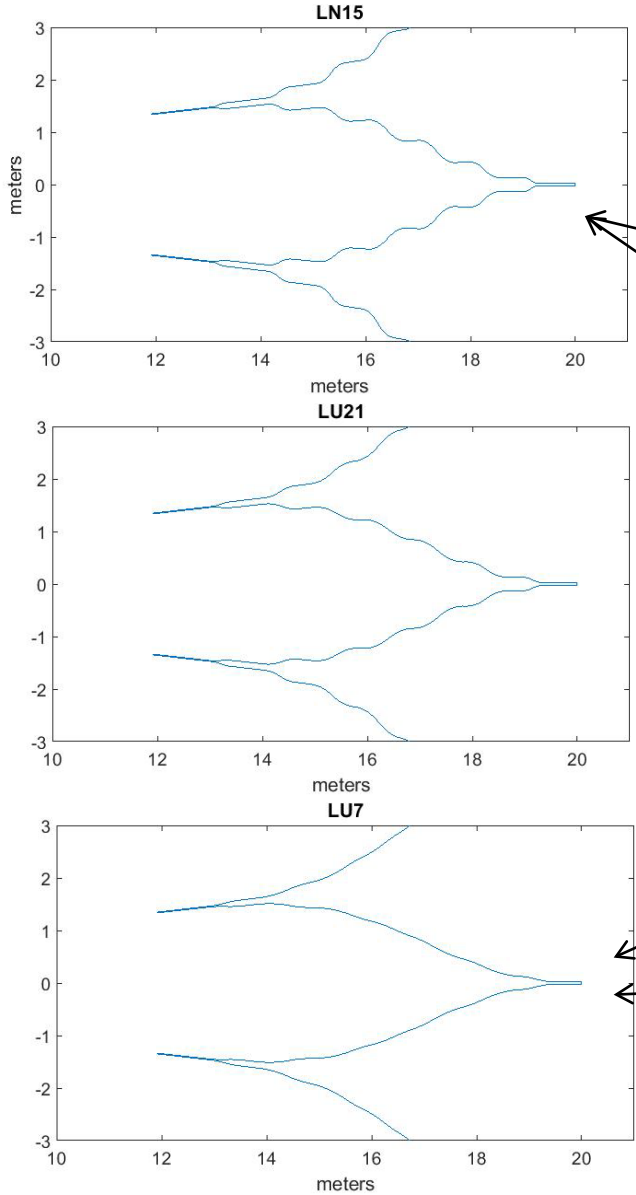




# Backup

# Starshades with Different Edge Smoothness






*All three designs are 40 m diameter with 8-m petals, IWA = 50 mas, Working with a 2.4 m telescope.*

Nominal Contrast * 1e-12

| | 400 nm | 475 nm | 550 nm |
|---|---|---|---|
| **LN15** | 3.8 | 2.3 | 6.9 |
| **LU21** | 3.7 | 2.3 | 7.6 |
| **LU7** | 3.9 | 2.1 | 9.3 |

Sensitivity to 0.5 mm radial petal motion

ΔContrast * 1e-12

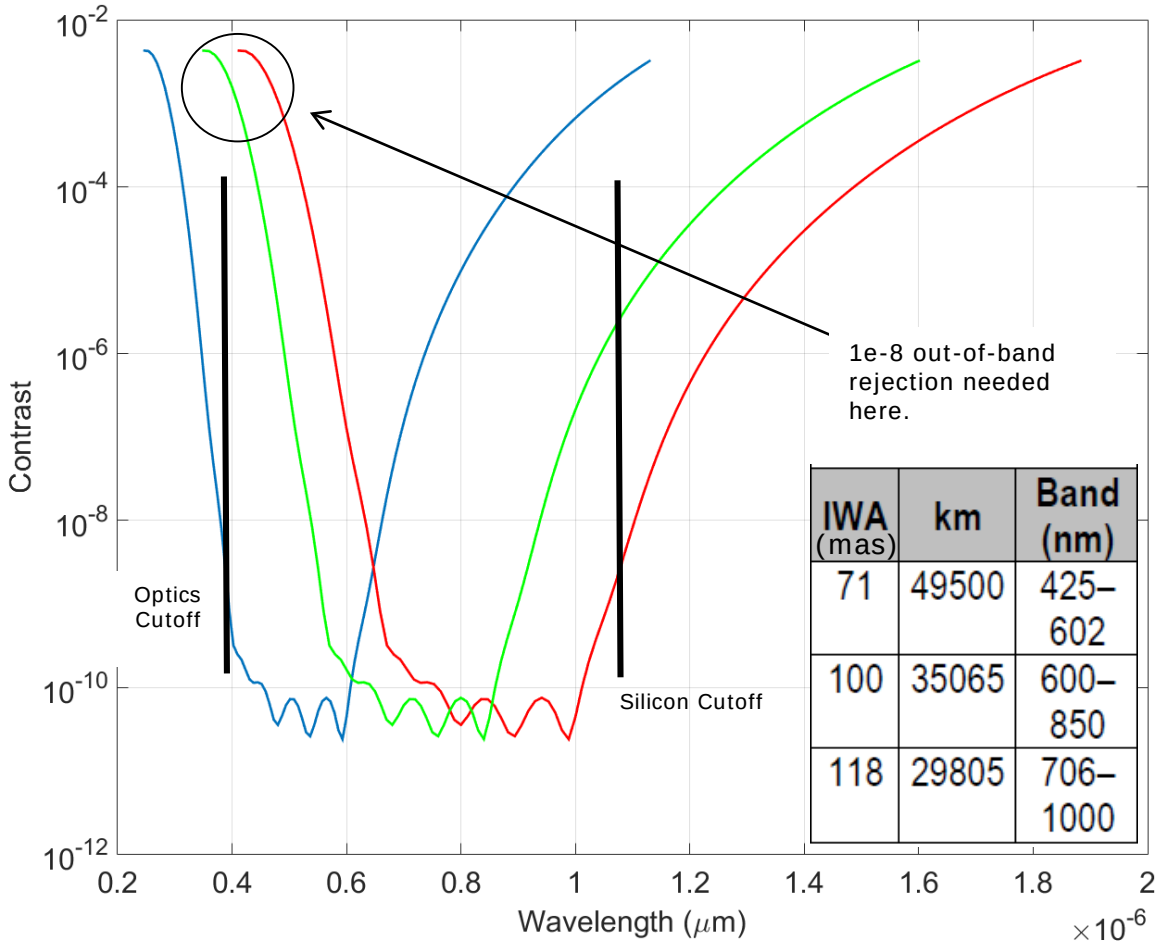
| | 400 nm | 475 nm | 550 nm |
|---|---|---|---|
| **LN15** | 8.5 | 12.5 | 10.1 |
| **LU21** | 8.7 | 12.3 | 8.9 |
| **LU7** | 8.8 | 12.1 | 6.2 |

Table shows change in contrast including mixing with the nominal field.

# 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 |

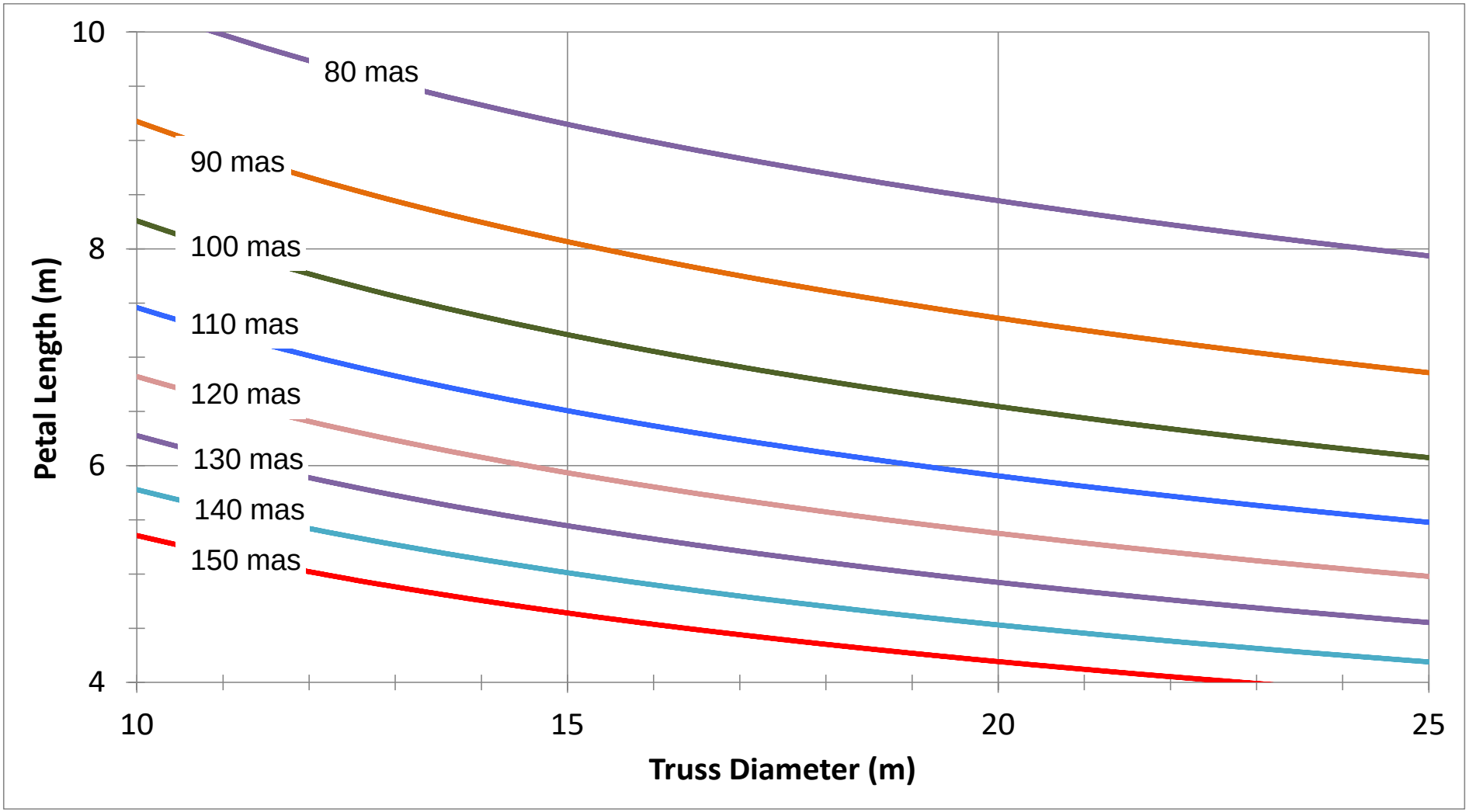
**Figure 11. Bandpass for the Rendezvous mission for three different starshade-telescope distances. When positioned for observation in the red and guiding in the blue (red curve), rejection of 1e-8 is required below ~500 nm.**

- 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

# Contours of constant IWA

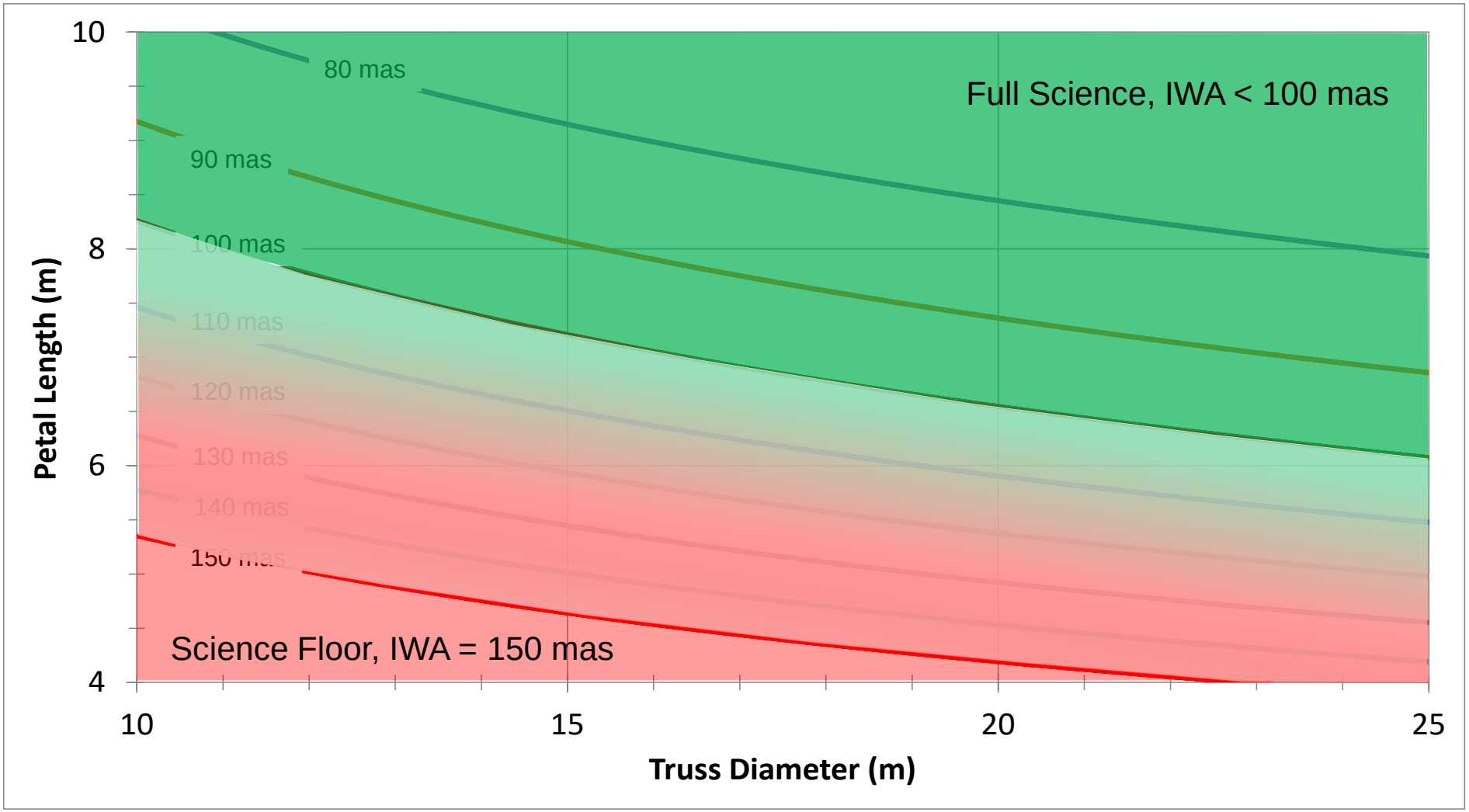


Sensitivity Δmag = 25.1, Bandpass 510-825 nm, Shadow diam = 3.1 m



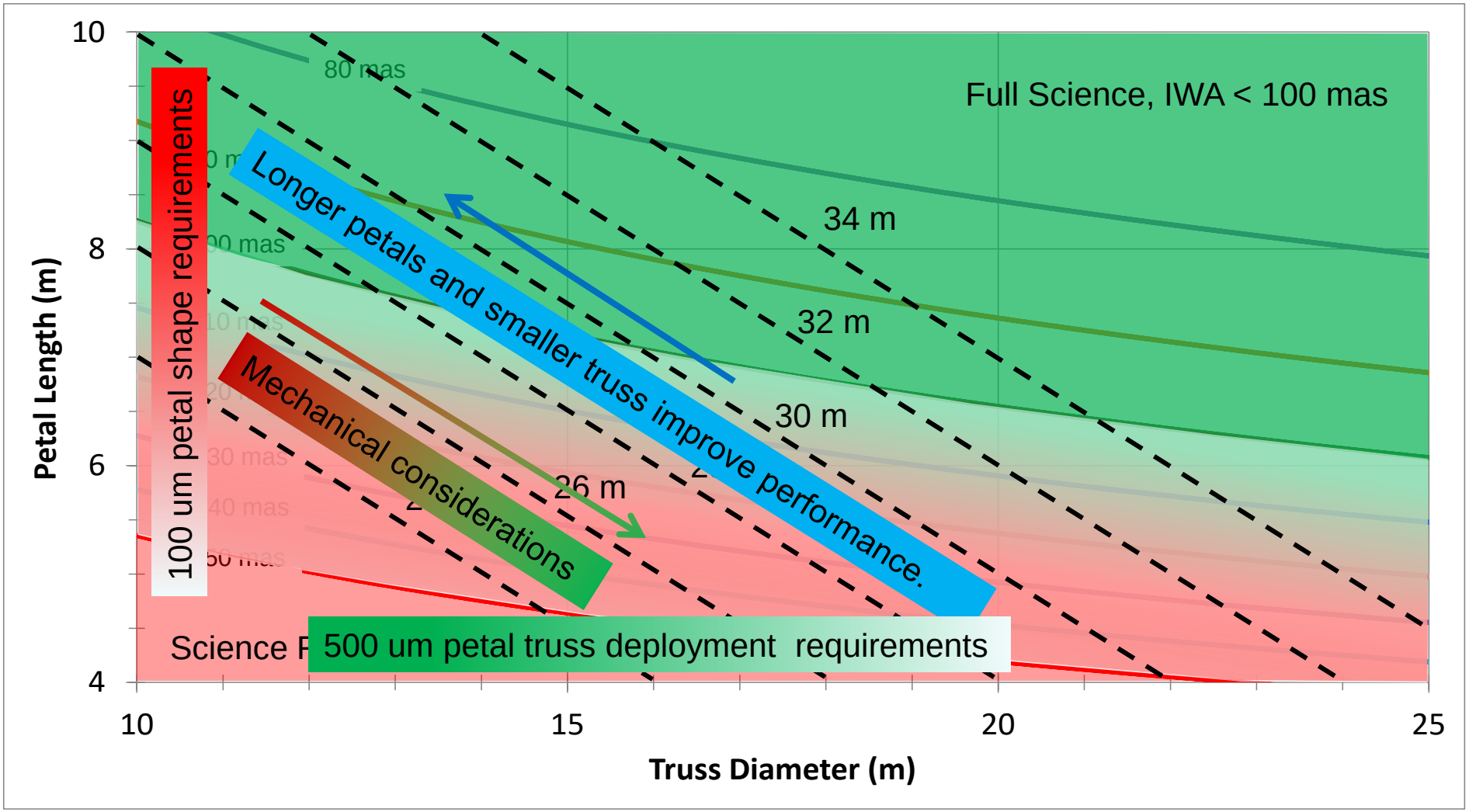
# Goal Science, Floor Science





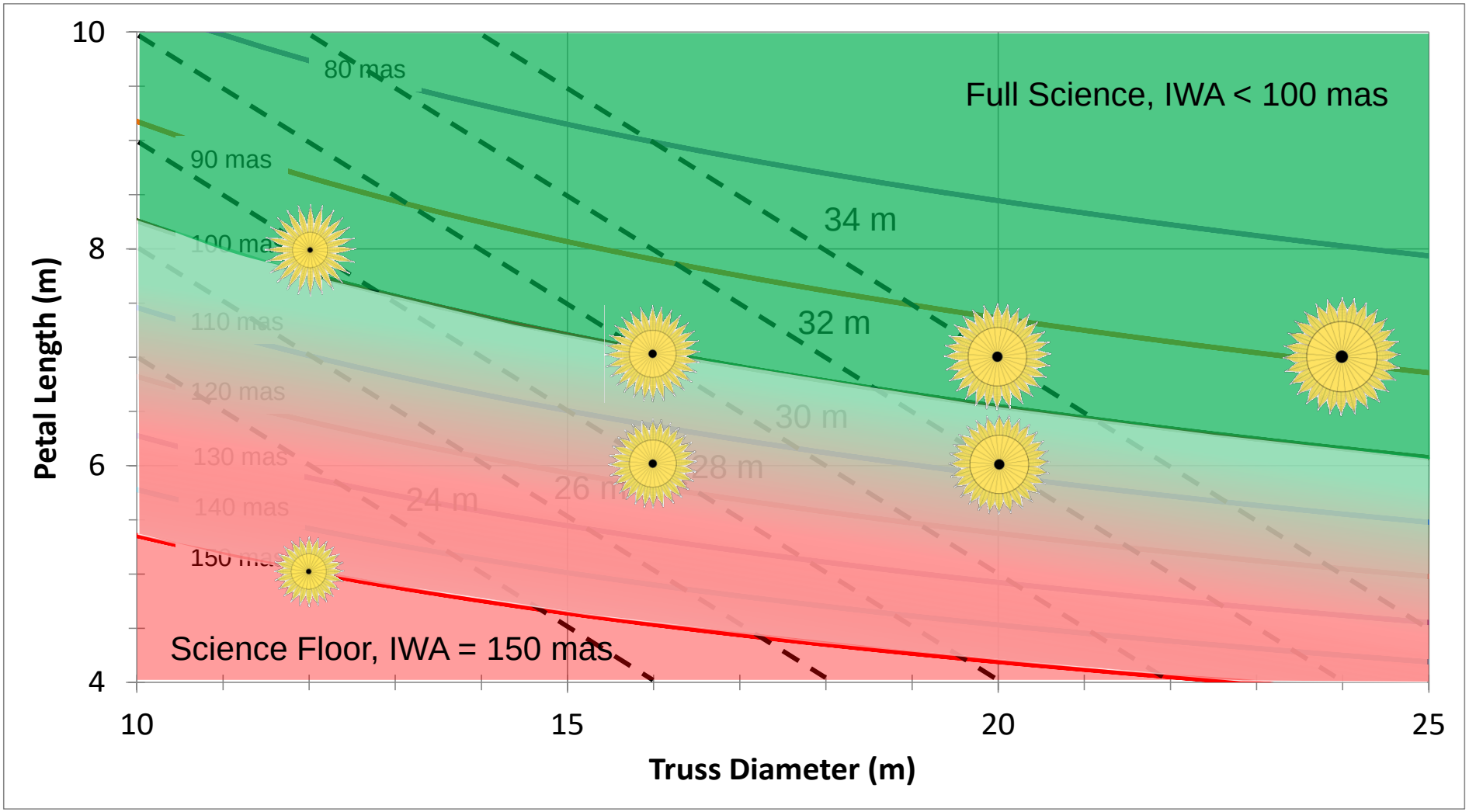
# Contours of Tip-to-Tip Diameter





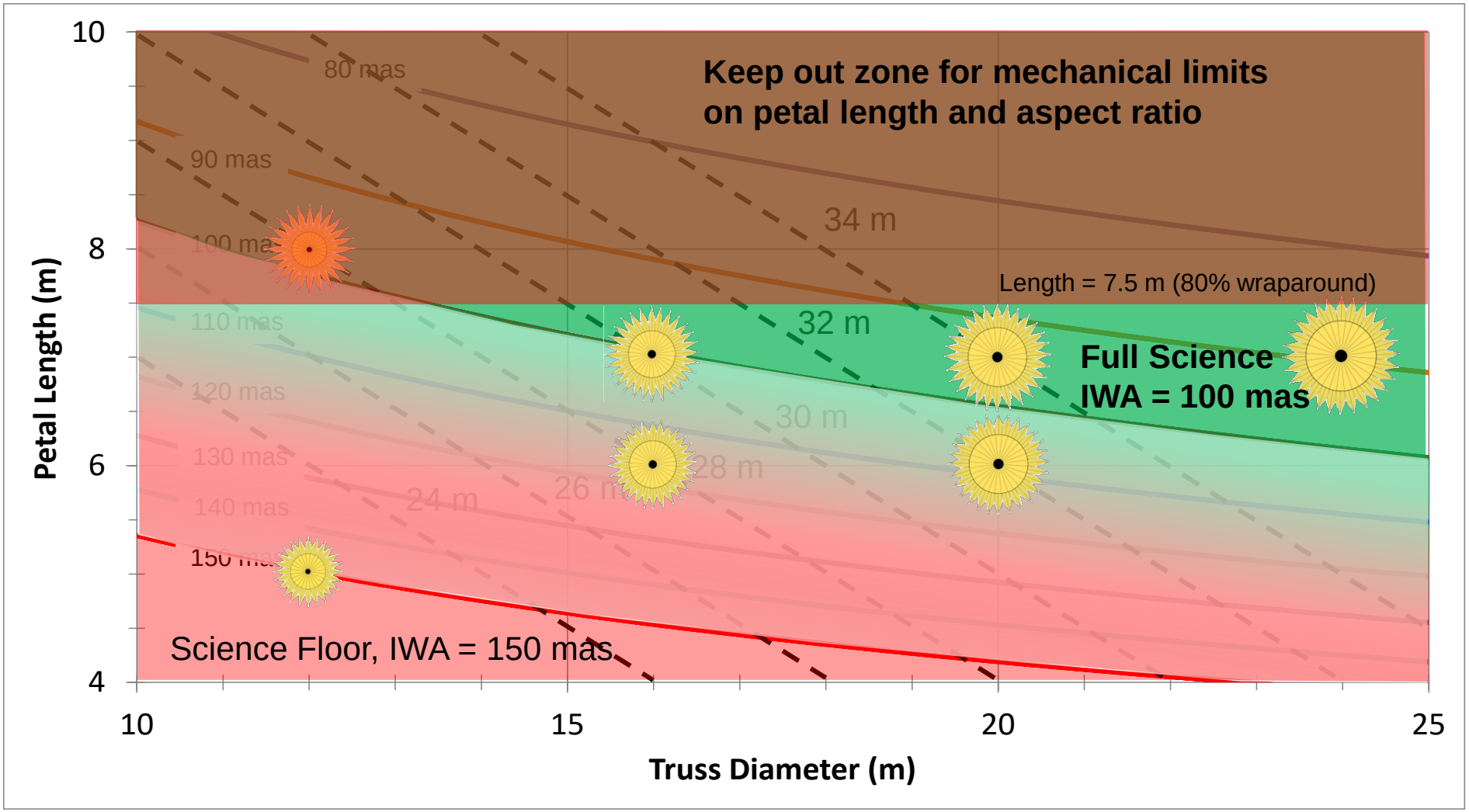
# Starshade Designs





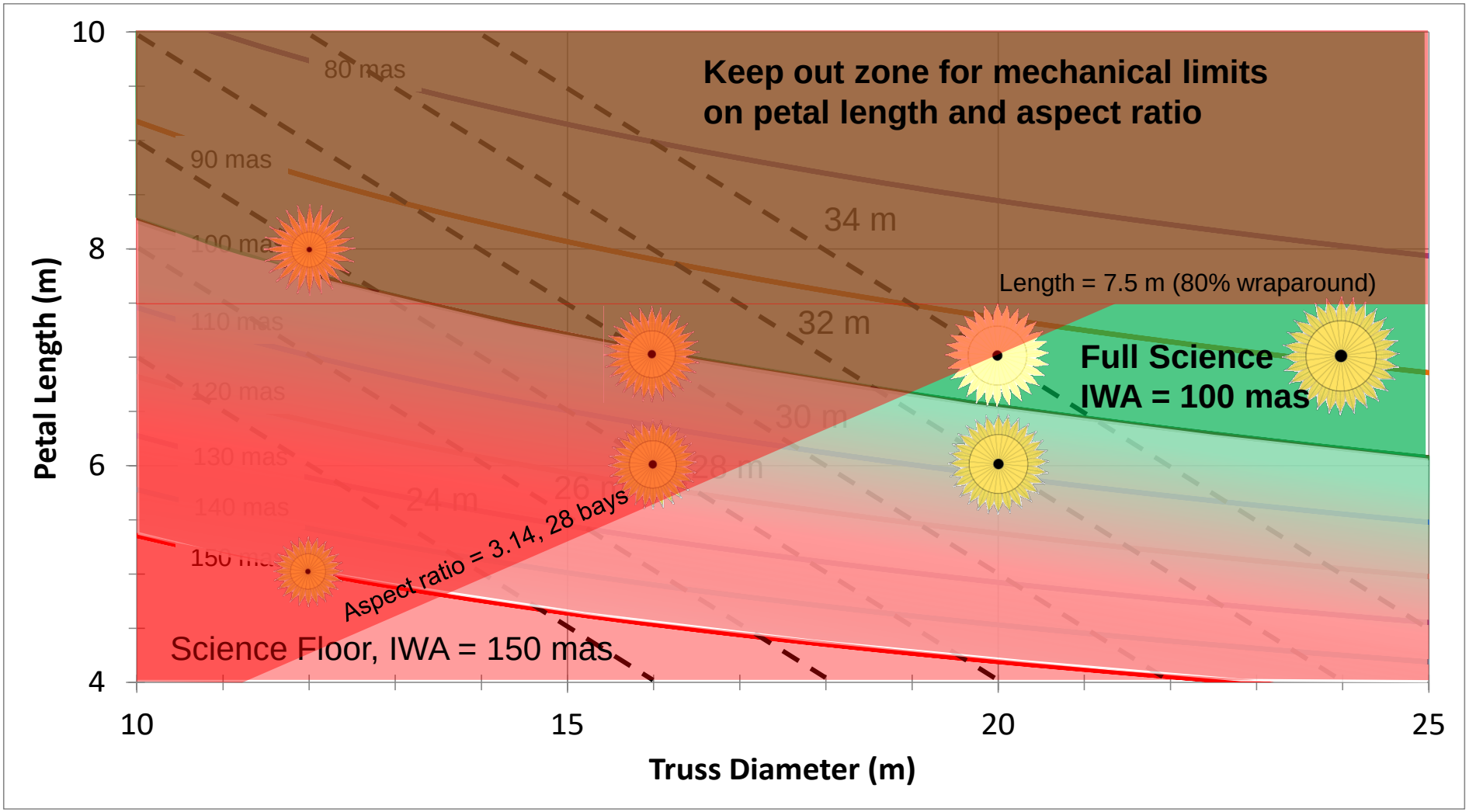
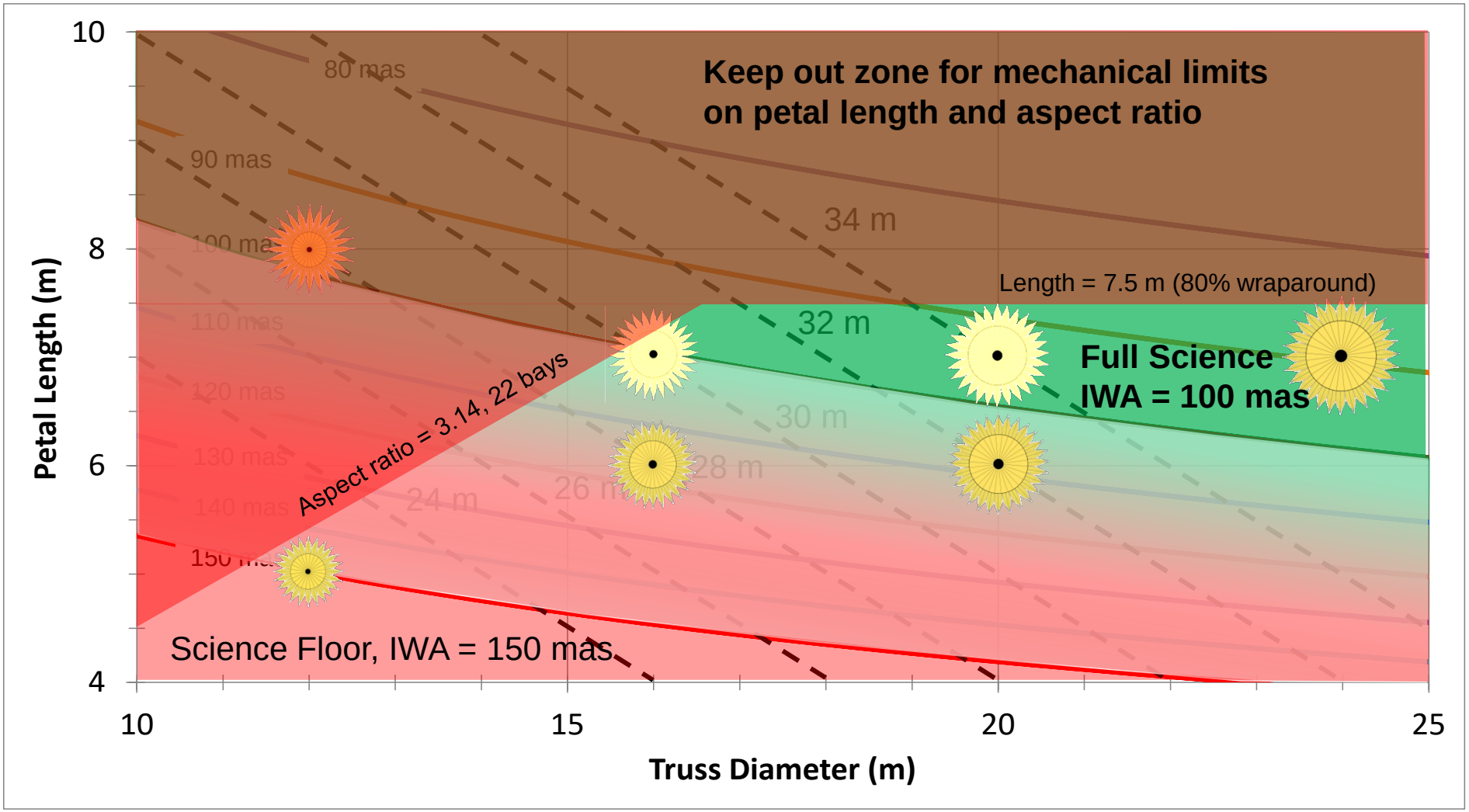
# Mechanical Constraints
# Petal length < 80% of hub circumference





# Mechanical Constraints
# Petal aspect ratio = 3.14, 28 bays





# Mechanical Constraints
# Petal aspect ratio = 3.14, 22 bays