A starshade petal error budget for exo-earth detection and characterization

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Overview

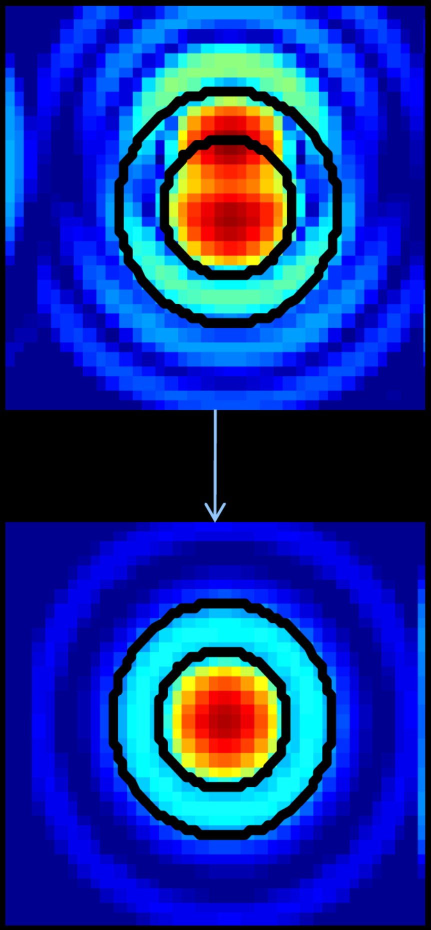
- Build upon last year's work: development of error budget tools and strawman error budget.
- Focus on engineering requirements
- Make it easier: spin the starshade to smear out the speckles.
- Four cases:
  - TDEM starshade (32 m), 90 and 75 mas
  - THEIA starshade (40 m) 75 and 60 mas

Science Requirements

- From many studies
- Δmag = 26
- IWA <100
- Mean scatter < 10^{-10}
- SNR > 4
- Requires r.m.s. of speckle noise floor to be < 10^{-11}
- Evaluate in IWA swath, width matched to core of PSF

Spinning the Starshade

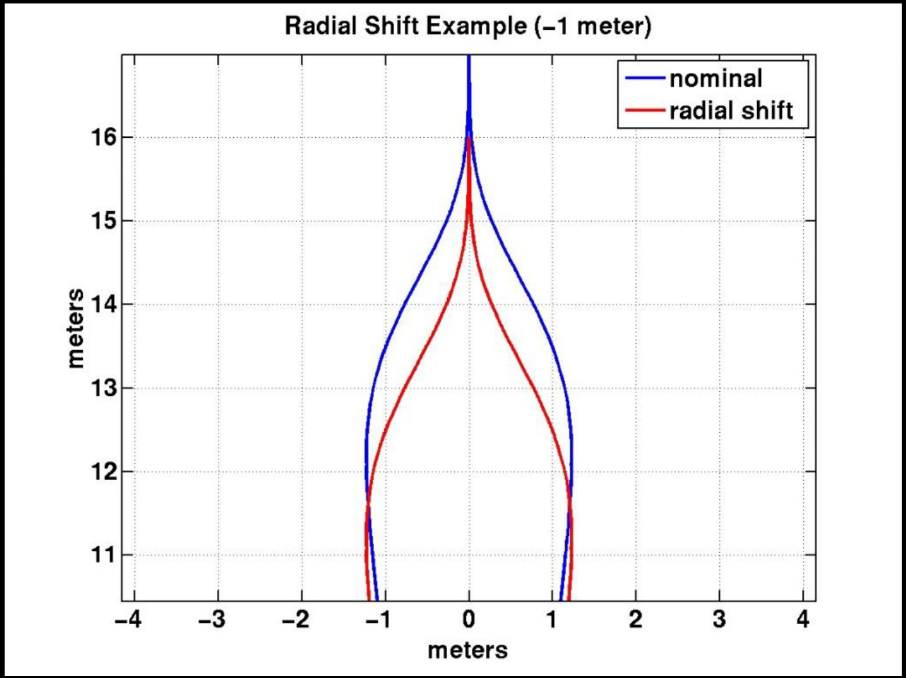
- Local errors, e.g. a displaced petal, scatter into speckles in the image plane.
- Speckles look like planets.
  - Speckle requirement is 1e-11 contrast.
- Spinning the starshade smears the speckles into annuli.
  - Background requirement is 1e-10.
- This leads to a 3x relaxation of requirements.
- Same requirements apply to planet detection and characterization since limited by zodi and exozodi rather than instrument.
- Spin rate: up to 12 rev/hr, limited by retargeting fuel (assumed 1 kg per 90 deg turn)

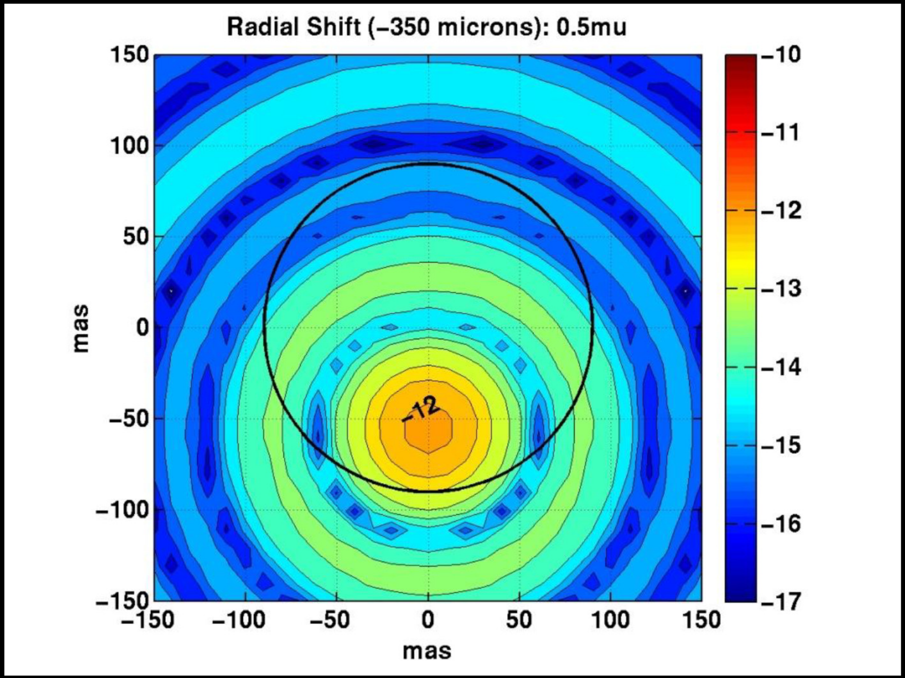


Error Budget Methodology

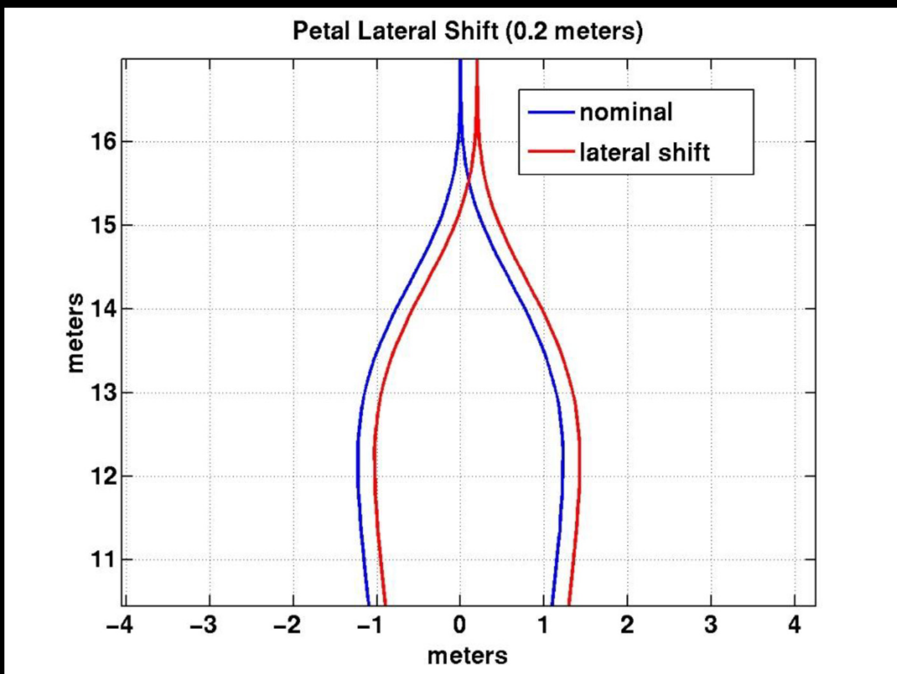
- Optical Models based on Fresnel propagation. Combination of analytic and Fourier-based slit calculations.
- Evaluate effect of perturbations in the image plane in a swath centered at IWA.
- Treat perturbations as independent.
- Sum up scatter from perturbations

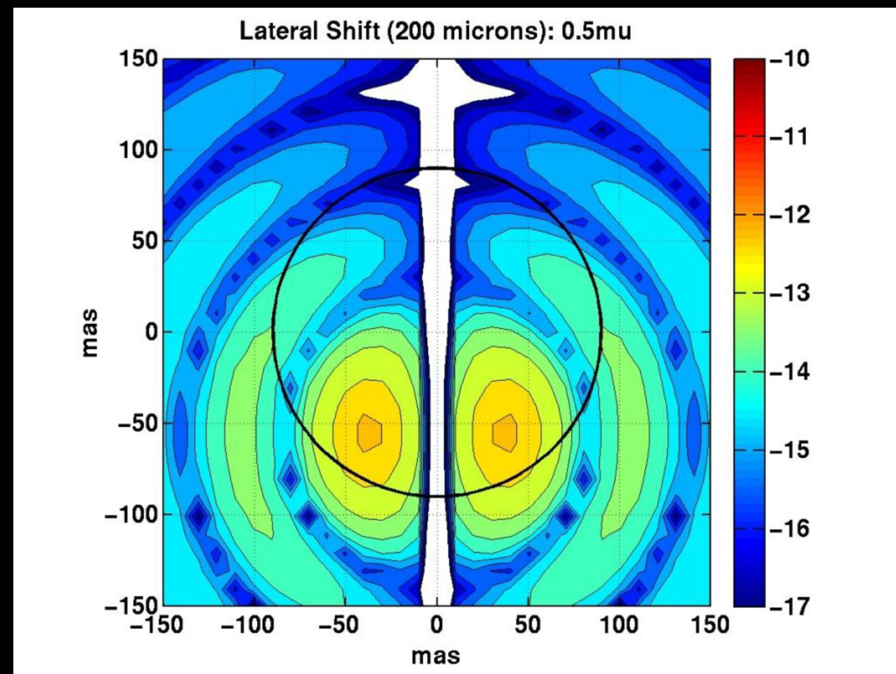
2010 Example: Radial Shift



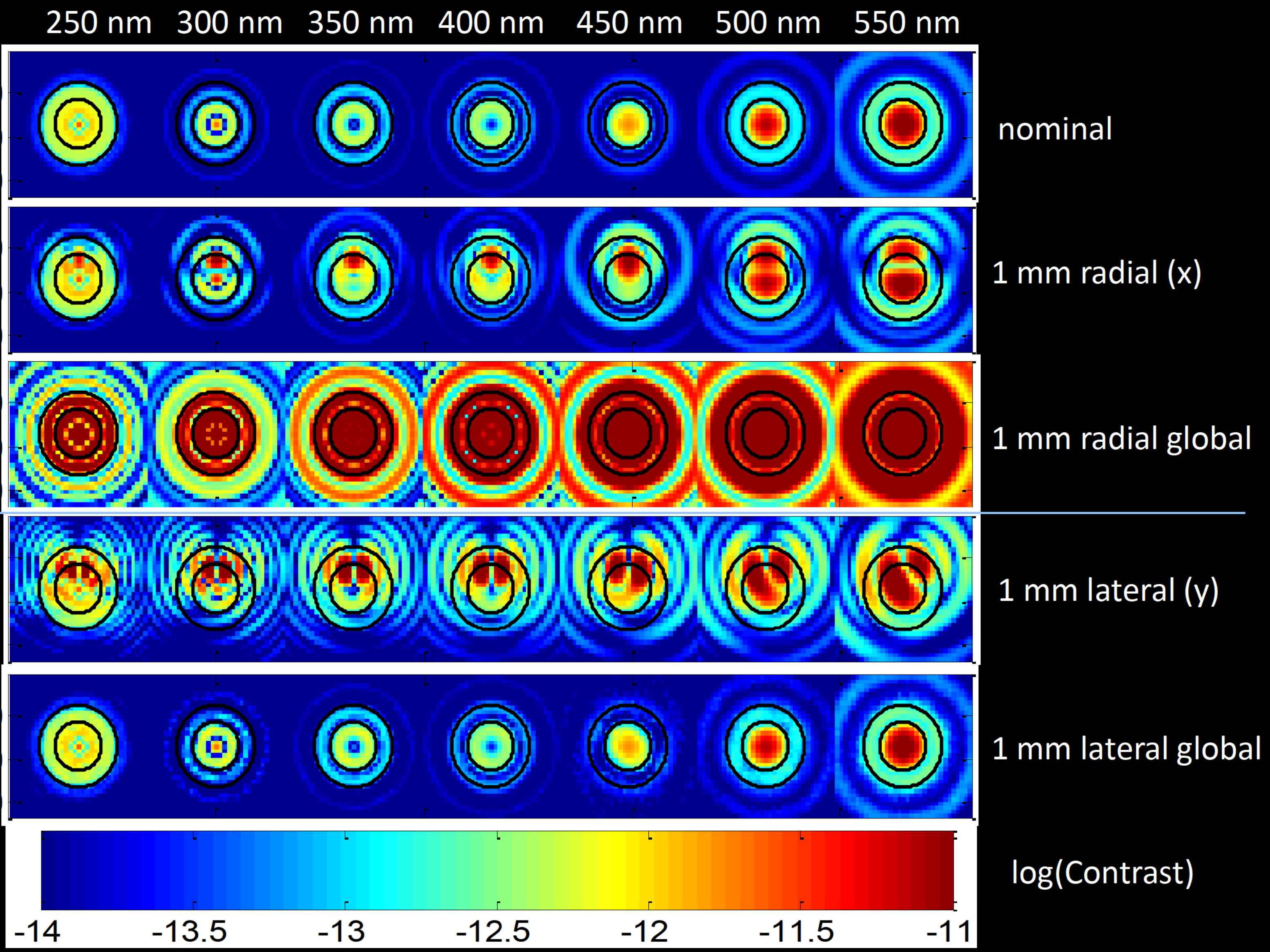


2010 Example: Lateral Shift





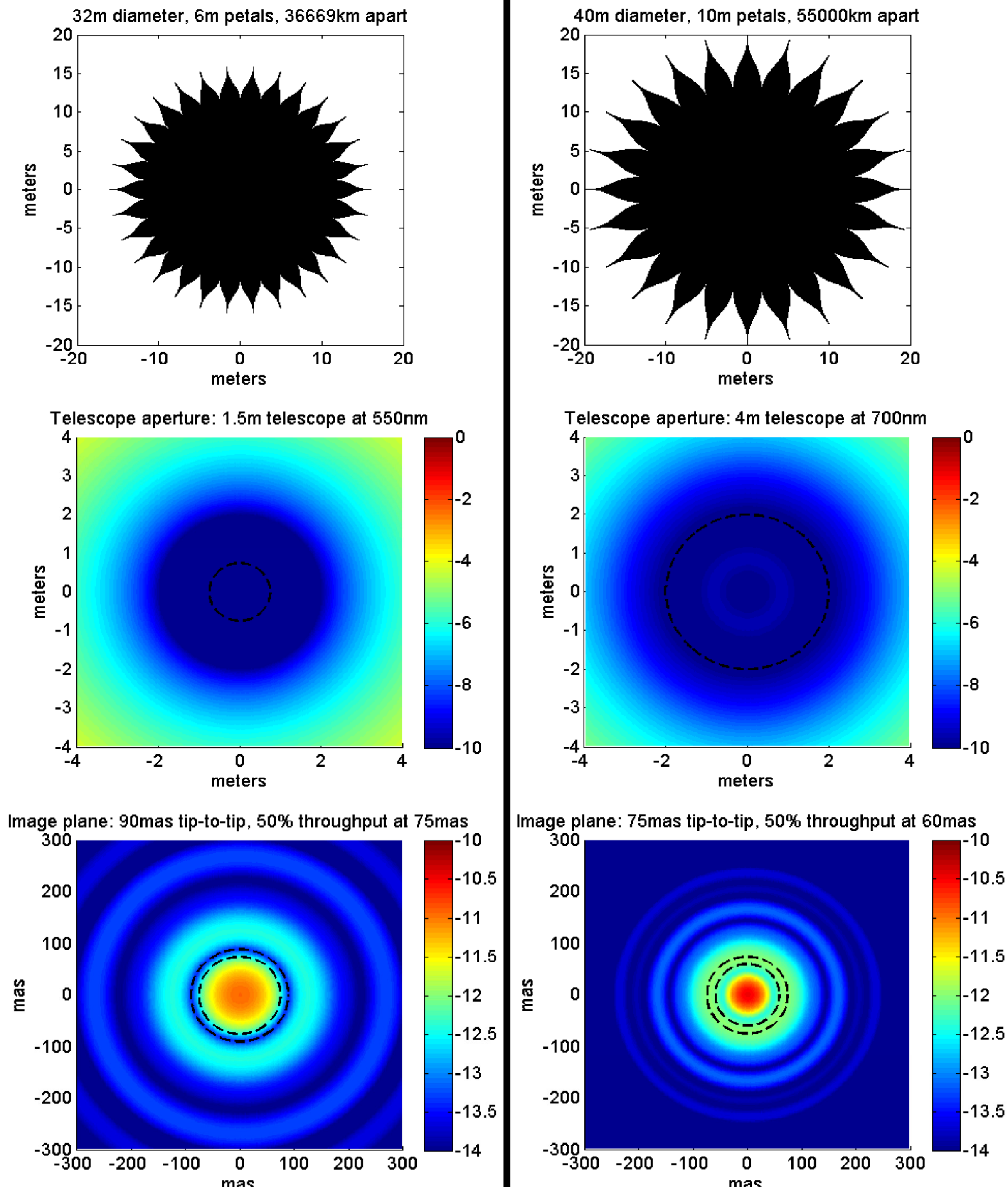
2010 Example: Single-Petal and Global Perturbations



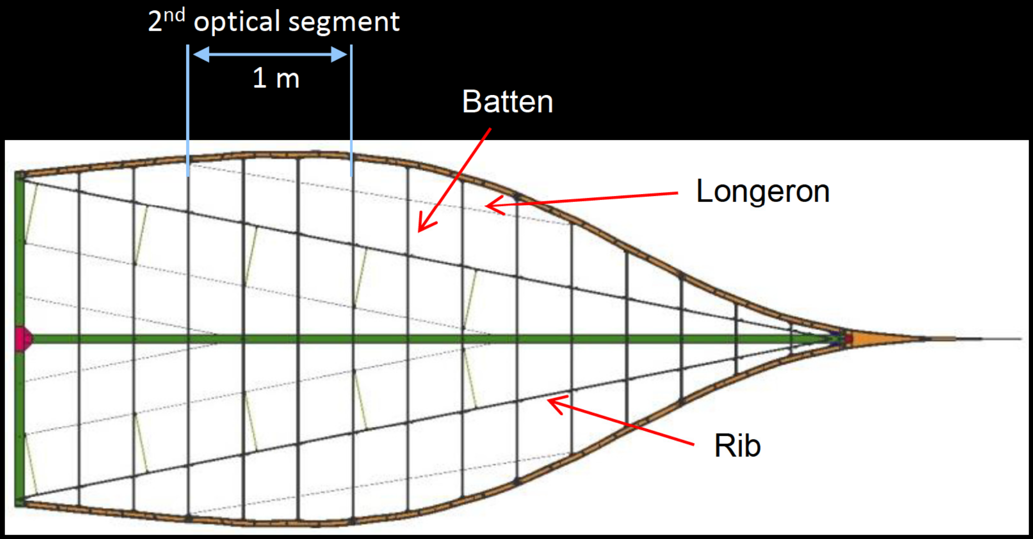
Starshade Mission Designs

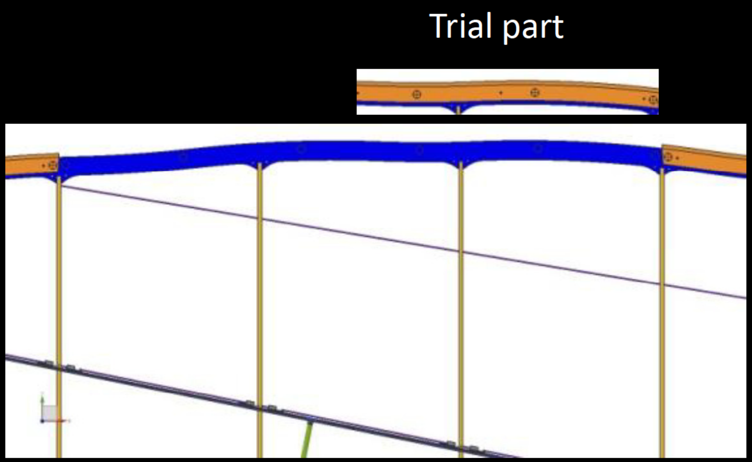
Table 1. Starshade and Telescope Parameters

	TDEM	THEIA
Tip-to-Tip diameter	32 m	40 m
Central Disk Diameter	20 m	20 m
Petal length	6 m	10 m
Number of petals	30	24
Petal Base gap width	1.1 mm	1.5 mm
Petal Tip width	2.6 mm	4 mm
Max petal width	2.34 m	3.275 m
Distance to Telescope	36,700 km	55,000 km
Telescope Diameter	1.5 m	4 m
50% throughput WA	75 mas	60 mas
100% throughput WA	90 mas	75 mas
Bandpass at nominal Distance	250-550 nm	250-700 nm


32m diameter, 6m petals, 36669km apart
40m diameter, 10m petals, 55000km apart
meters
meters
Telescope aperture: 1.5m telescope at 550nm
Telescope aperture: 4m telescope at 700nm
meters
meters
Image plane: 90mas tip-to-tip, 50% throughput at 75mas
Image plane: 75mas tip-to-tip, 50% throughput at 60mas
mas
mas

Petal Manufacture





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Petal Manufacture

Conservative Assumptions

- Assume all errors are global – common to all petals.
  - Except those that have no global impact.
- Assume worst case wavelength
  - 550 nm for TDEM, 700 nm for THEIA
- Assume edge segments max out +/- against tolerance.
- Assume worst case for each tolerance envelope (see following slide).

Perturbation	Global to Random ratio
Proportional width or petal tilt	2.4
Tip clip	2.0
Radial shift	2.3
Quadratic out-of-plane bend	1.8
1 cycle/petal	8.2
2 cycle/petal	5.2
3 cycle/petal	8.2
4 cycle/petal	5.5
5 cycle/petal	3.6
6 cycle/petal	1.6
Displ. of segment 10-11 meters	2.6
Displ. of segment 11-12 meters	2.3
Displ. of segment 12-13 meters	2.1
Displ. of segment 13-14 meters	2.0
Displ. of segment 14-15 meters	1.8

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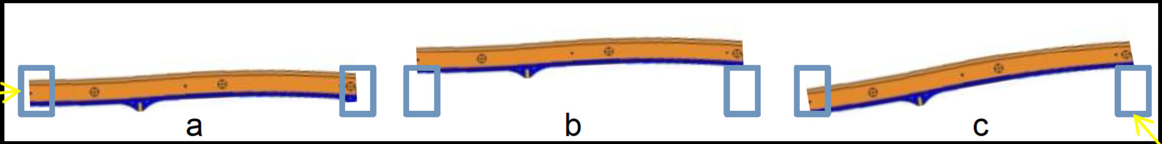
Use Worst Case for Tolerancing

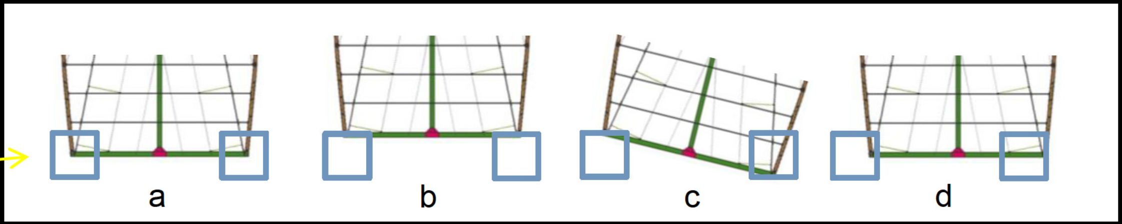
25 um tall box.



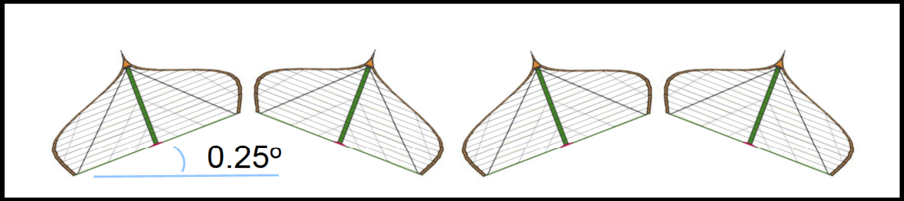
Width can be > 50 um.

Edge segment placement
Case (b) scatters 2-3 x more light than case (c).

1 mm square box

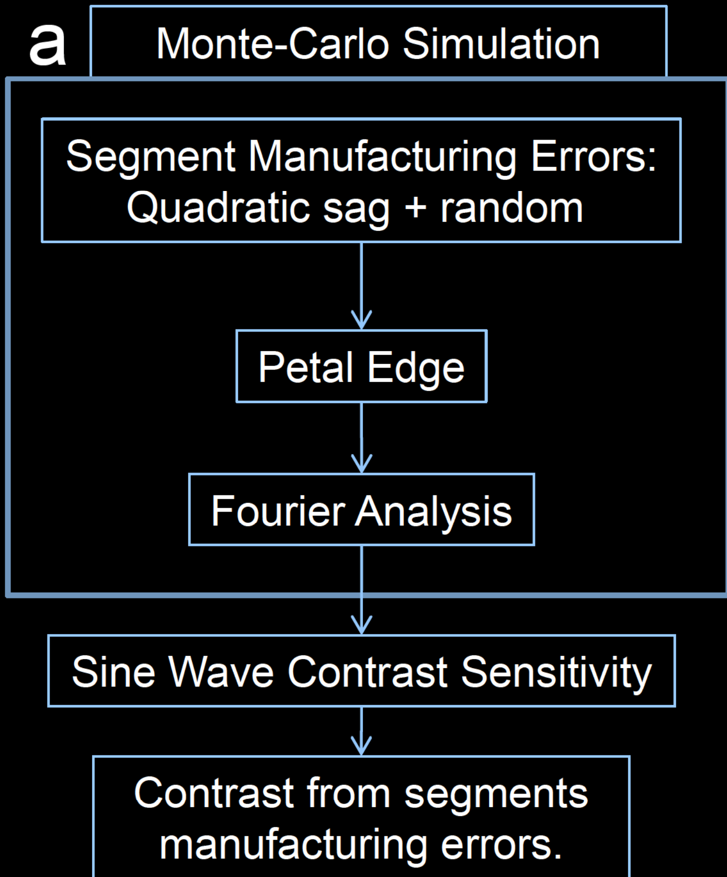


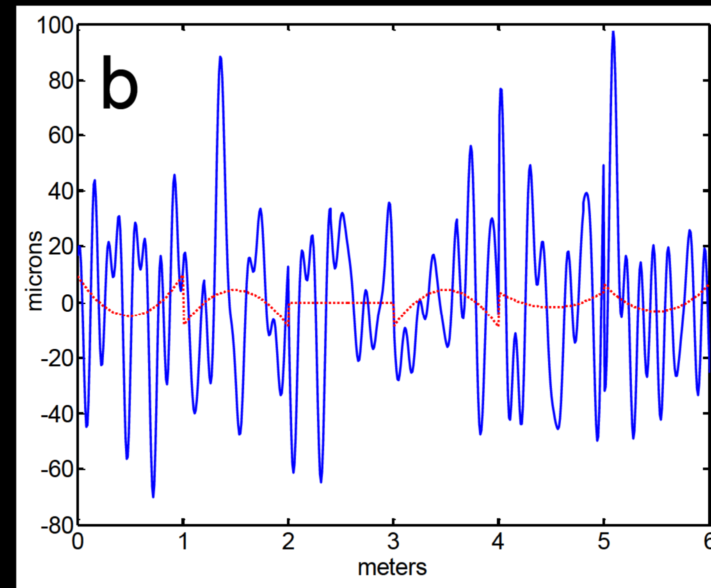
Petal positioning relative to ideal.
Case (b) scatters 4x more light than (c).
Case (d) has no global effect.

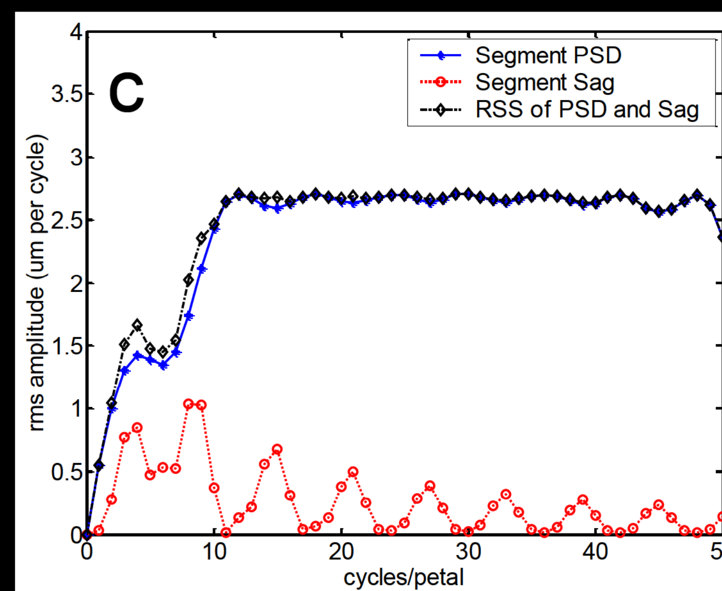


Petals tilted out of plane.

Segment Scatter

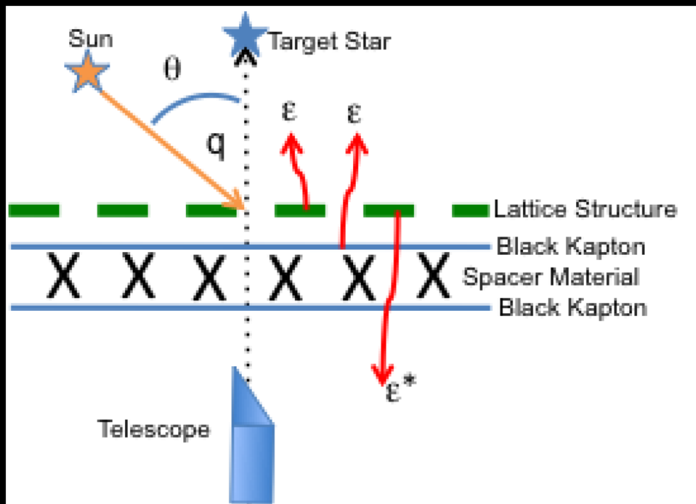


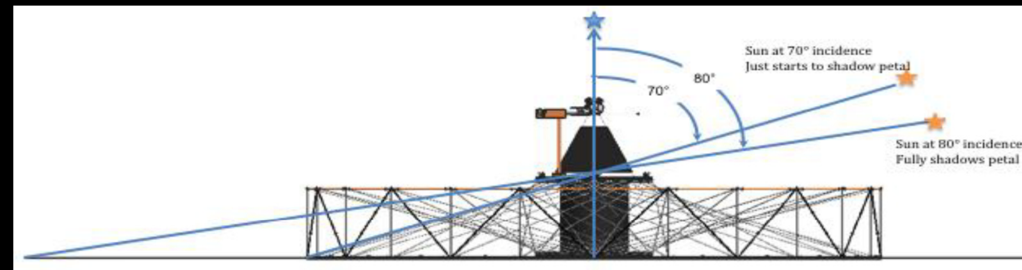




a) Monte-Carlo simulation that generates petal edges from 6 segments each having a flat PSD from 1-8 cycles/petal and a quadratic sag.
b) An example petal edge without segment positioning errors.
c) Fourier Analysis. Petal sag contributes mainly in the 3-9 cycle/petal region, while PSD errors contribute mainly above 10 cycles.

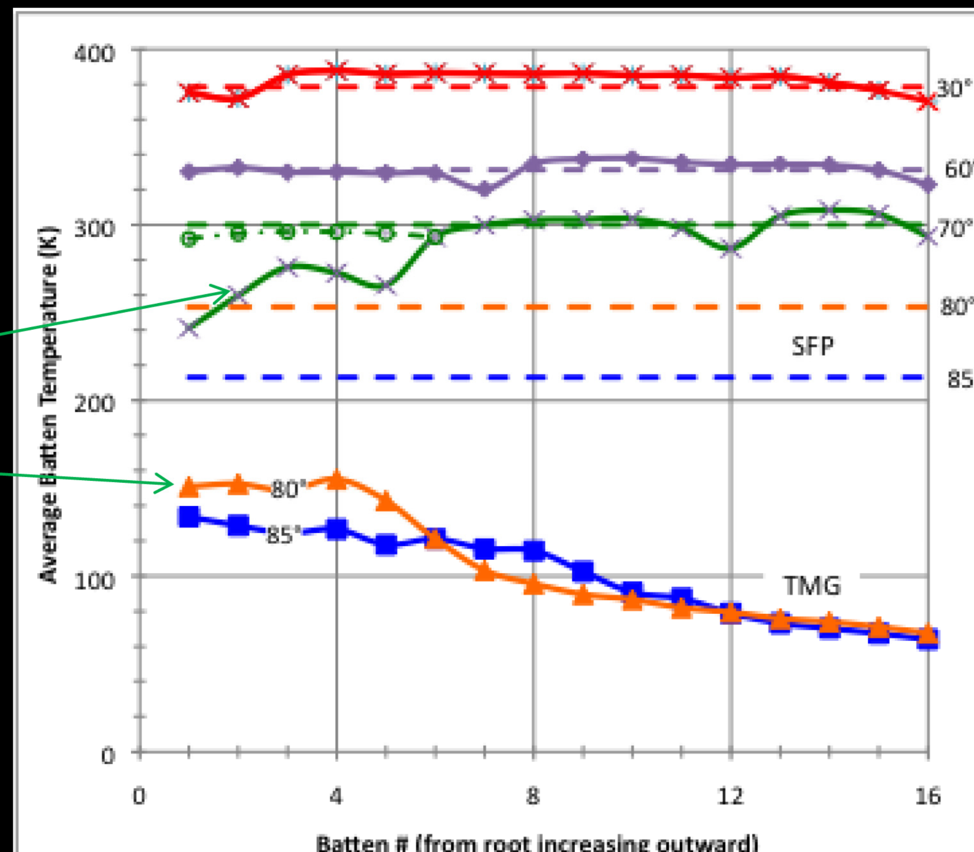
Thermal Modeling
Steady-state (non-spinning) predicts





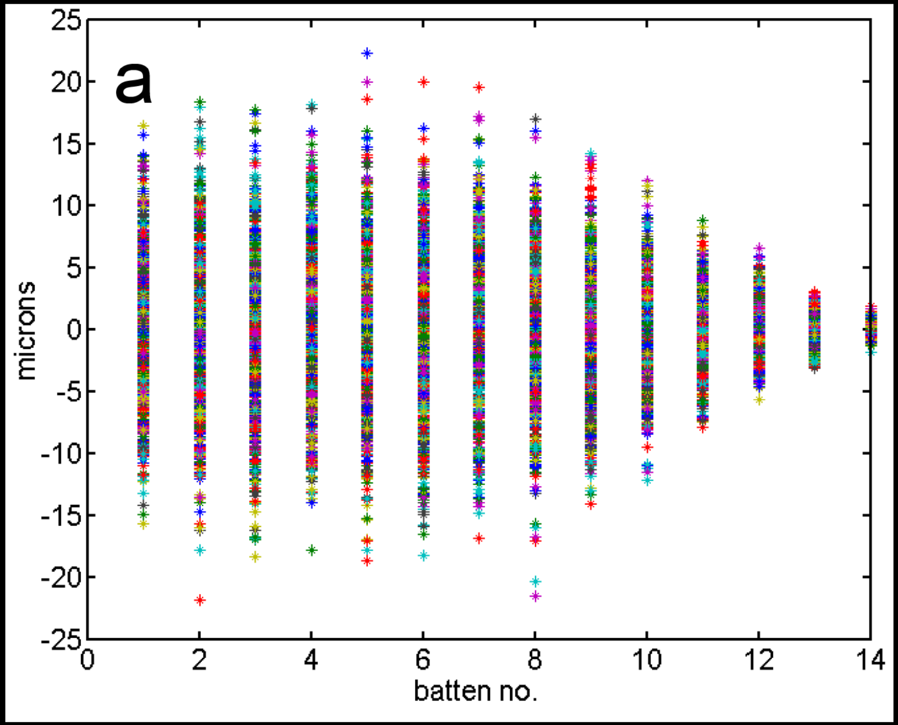
Partial Shadowing from s/c

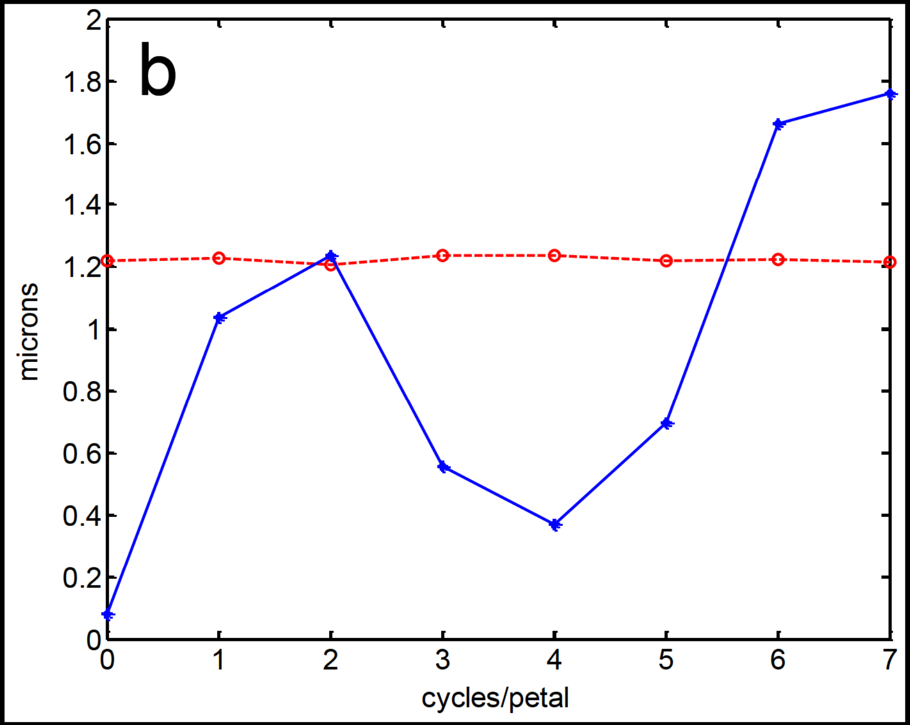
Fully shadowed petal



Dashed lines are analytical predictions in the absense of shadowing.

Random Thermal Variations





1000 realizations of the change in length of the 14 battens that control the TDEM petal width.
σ = 2.5 ppm, roughly +/- 18 um p-v

Blue: FFT of one realization normalized to show the r.m.s. variation in a 1 cycle/petal bandwidth.
Red: average of 1000 realizations, a white spectrum with 1.2 um r.m.s. per cycle.

Thermal Analysis:

uniform, gradient, and random variation across a petal

Deformation Type	Worse-case parameters	Max temp deviation with unc'ty (K)	Max deformation (ppm)	Tolerance Allocation (ppm)	Margin against allocation (%)	Notes
Uniform - proportional width	$\varepsilon^* = 0.1$ $\theta = 30°$ to $85°$	100	20	35	43	ΔT is relative to reference temp. set midway between extremes
Non-uniform - monotonic gradient	$\varepsilon^* = 0.7$ $\theta = 80°$	30	6	15	60	Allocation applies at extreme temp. points
Non-uniform - semi random	$\varepsilon^* = 0.7$ $\theta = 70°$	15	3	7.5	60	Allocation applies as envelope about average batten temp.

	Manufact.	Deployed Shape	Deployed Position	Thermal	Dynamic/ Form. Fly	Incoherent	Description	Units
Proportional width	x	x		x			Prescribed width is $w(\rho)$, actual width is $\varepsilon w(\rho)$	ppm
Tip clip	x						Tip segment length is too short or too long.	mm
Segment azimuthal displacement	x	x					Edge segments are displaced making local petal width too wide or narrow	mm
Segment in-plane rotation	x	x					Edge segments are rotated in plane relatve to nominal local petal shape	radians
Base-to-tip thermal gradient				x			The base is warmer than the tip causing differential petal growth	ppm
Random batten length change				x			Shadowing and spinning cause the battens to grow and contract	ppm
In plane quadratic bend		x		x			Petal center line is shifted in plane by $a(\rho-\rho_0)^2$, where ρ_0 is the radial	mm at tip
Out of plane quadratic bend		x		x			Petal center line is shifted out of plane by $b(\rho-\rho_0)^2$, where ρ_0 is the	mm at tip
Radial Shift			x	x			Petal is moved radially, in plane.	mm
Lateral Shift			x	x			Petal is moved normal to center line, in plane.	mm
In plane rotation			x				Petal center line is rotated in plane, starting at petal base.	mm at tip
Rotation about petal spine			x				Petal rotates about its center line. Effect is equivalent to prop. Width.	deg
Truss Deformation			x				Elliptical and higher order deviations from ideal circular shape	mm
Truss modes					x		Deformation of truss due to dynamic perturbations (e.g. thrusters).	mm
Petal modes					x		Deformation of petals due to dynamic perturbations.	mm
Lateral Formation Flying					x		Starshade shifts laterally relative to star-telescope line-of-site	m
Incoherent contributions						x	Solar scatter from edge RoC and roughness, holes, solar scatter in	um, PSD

	TDEM Design 6 m petals, 32 m tip-to-tip 1.5 m diam. telescope		THEIA Design 10 m petals, 40 m tip-to-tip 4 m diam. telescope		
	90 mas	75 mas	75 mas	60 mas	3-sigma
MANUFACTURE					
Proportional width	10	5	10	10	ppm
Segment placement	12.5	8	25	25	um
Segment shape	75	60	75	75	um
Contrast	**1.6E-11**	**1.5E-11**	**4.2E-12**	**8.9E-12**	
DEPLOYED SHAPE					
Proportional width	5	5	5	5	ppm
Segment displacement	5	3.5	5	5	um
In-plane Quadratic bend	1	1	2	2	mm at tip
Out of plane quadratic bend	10	10	20	20	mm at tip
Contrast	**2.0E-12**	**5.7E-12**	**3.1E-13**	**1.2E-12**	
DEPLOYED POSITION					
Radial Shift	0.50	0.24	0.50	0.50	mm
Lateral Shift	0.50	0.24	0.50	0.50	mm
Rotation about petal spine	0.25	0.25	0.25	0.25	deg
Elliptical truss def.	1.00	0.75	1.00	1.00	mm
Contrast	**2.2E-11**	**2.5E-11**	**1.3E-11**	**2.3E-11**	
THERMAL					
Proportional width	35	15	35	35	ppm
Base to tip gradient	30	30	30	30	ppm
Random batten length	7.5	7.5	7.5	7.5	ppm
In-plane Quadratic bend	1	1	2	2	mm at tip
Out of plane quadratic bend	10	10	20	20	mm at tip
Radial Shift	0.2	0.13	0.2	0.2	mm
Lateral Shift	0.2	0.13	0.2	0.2	mm
Contrast	**1.3E-11**	**1.8E-11**	**4.8E-12**	**8.3E-12**	
FORMATION FLYING	1	0.25	1	1	m
Contrast	**3.3E-12**	**4.5E-12**	**2.0E-12**	**4.7E-12**	
DYNAMICS ALLOCATION	**5.0E-12**	**5.0E-12**	**5.0E-12**	**5.0E-12**	
EDGE SCATTER ALLOCATION	**2.0E-11**	**2.0E-11**	**2.0E-11**	**2.0E-11**	
RESERVE	**1.8E-11**	**6.8E-12**	**5.1E-11**	**2.9E-11**	
TOTAL	**1.0E-10**	**1.0E-10**	**1.0E-10**	**1.0E-10**	

Conclusions

- Requirements for building a high-performance starshade petal are achievable with current technology
  - Build segments to 25 um rms, attach them within a 25 um window.
  - Edge RoC should be ~ 50 um. Technique for achieving this is under study. A matter of material choice and processing.
- Requirements for positioning the petals appear to be achievable within current technology
  - 1 mm deployment window on a 20 m diameter truss.
- We have made many conservative (worst-case) assumptions. Simulations show that performance loss due to petal manufacture is expected to be minimal.
- Thermal performance has signficant margin even without spinning.
- By spinning the starshade, performance is limited by photometric rather than systematic scatter. This applies to both characterization and detection.

Future Work

- Measure the new TDEM petal and model scatter
- Perform deployment tests to show that +/- 0.5 mm is achievable with our design.
- Complete thermal analysis of spinning starshade and analyze the performance margin (expected to be substantial).
- Perform dynamics analysis.
- Include Model Uncertainty Factors and perform material uniformity studies.