Technology Challenges for Starshade Missions

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How to Find Our Nearest Neighbors

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Sources for this report

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- Astro2010 white papers - Lo et. al., Levine et. al.
  - http://www8.nationalacademies.org/astro2010/DetailFileDisplay.aspx?id=525
    http://www8.nationalacademies.org/astro2010/DetailFileDisplay.aspx?id=488
- ExoPAG 3, Jan 2011 - Kasdin and Lawson
  - http://exep.jpl.nasa.gov/files/exep/1_Kasdin_ExoPAG_Jan2011_v2.pdf
    http://exep.jpl.nasa.gov/files/exep/6 ExoPAG_LawsonRev5.pdf
- ExoPAG 4, June 2011 - Lawson
  - http://exep.jpl.nasa.gov/files/exep/Lawson-Occulter-Rev4.pdf
- ExEP Technology Plan Appendix Fall 2011
  - http://exep.jpl.nasa.gov/files/exep/2011Appendix_Fall.pdf

- Starshade ≡ External Occulter

Technology Areas for Starshades

- ➔ • Optical Diffraction → Model validation & verification
- ➔ • Deployment accuracy/reliability & verification
- ~ • Thermal and vibrational distortion & verification
- OK • Thruster performance and reliability
- ~ • Slew-trajectory and Alignment control & verification
- OK • Punctures (micrometeoroids)
- ~ • Telescope pointing & verification
- ➔ • Solar stray light from edges & plumes & verification

Optical Diffraction

Diffraction is governed by the perimeter shape as projected into the plane perpendicular to the line of sight; **nothing else matters**

Toughest requirements:

- Petal shape accuracy: ~10^{-5} (25µm/2.5m) on ripples ~0.5-2 cyc/m
  - Manufacturing tolerances → perimeter structure with metering spars
  - Thermal deformation tolerance for up to ±50°C (TBR) → low-CTE spars
  - Large sheets across petal are slack (not tensioned against metering structure)
- Petal rigid displacements ~mm

Modest engineering challenge

- In-plane dynamic deformations
  - Tolerant of short transients; truss quickly damps

Easy tolerances

- Very insensitive to petals bending out-of-plane

Optical Diffraction Verification

- For a flagship TPF mission, optical performance testing on the ground at full size (prototype or flight starshade) is impossible
  - Starshade-telescope separation is 2-6 Earth diameters
- The only practical flight verification method is analysis
  - Precise survey of deployed petals' shape and position
  - Diffraction calculations validated by experiment
- Scalar diffraction calculations are now widely trusted because of mutual agreement of several algorithms
  - Still need experimental validation
  - Need vector field diffraction calculations?

Deployment accuracy/reliability

- Petal deployment tolerance ~ ±1mm at root and ±25 mm at tip
  - RF dish deployments commonly achieve this
- Petal shape stability with stow/deploy cycles
  - Structures that control shape are not stressed in stowed configuration
- Single-petal deployment failure threatens the mission
  - Technology demos and analysis are in work
- Need demos to validate ground deployment tests as a predictor of flight deployment reliability

Thermal and vibrational distortion

- Shaklan SPIE paper and ExoPAG talk
  - http://dx.doi.org/10.1117/12.857591
    http://exep.jpl.nasa.gov/files/exep/17. Error Budgeting and Tolerancing by Shaklan.pdf
- Most bending and twisting causes starlight leakage only quadratically or higher, with cm- or meter-scale tolerances
- Some shape tolerances are very tight ~10 µm
- Mixture of design and testing needed to control manufacturing and deployment accuracy and on-orbit stability
- Some thought has been given to actively controlling edge shape

Starshade manufacturing tolerances

http://exep.jpl.nasa.gov/files/exep/17.%20Error%20Budgeting%20and%20Tolerancing%20by%20Shaklan.pdf

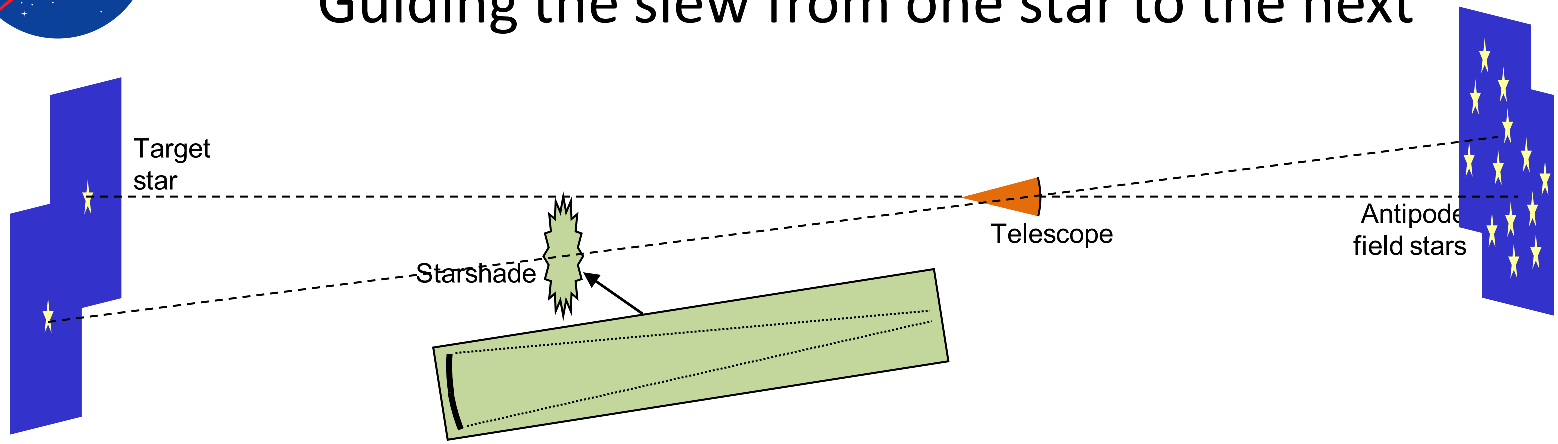
No.	Perturbati on	Single Petal 1-sigma	Global tolerance	Units	r.m.s. contrast	Global Mean Contrast
1	Proporti onal width	2.50E-05	2.00E-05	n/a	**2.6E-12**	**1.6E-12**
2	Tip clip	4	4	mm	2.6E-13	3.3E-13
3	Radial shift	0.25	0.20	mm	**2.2E-12**	**1.4E-12**
4	Quadrati c out-of-plane bend	150	75	mm	2.0E-14	7.0E-15
5	lateral shift	0.15	1	mm	**1.9E-12**	6.5E-15
6	In plane rotati on	2	2	mm at ti p	9.8E-13	7.4E-17
7	In plane quadrati c bend	5	5	mm at ti p	1.4E-13	4.8E-17
8	Symmetric sine wave 1 cycles	25	25	um	1.9E-13	1.8E-13
9	Symmetric sine wave 2 cycles	5	10	um	6.1E-14	2.4E-13
10	Symmetric sine wave 4 cycles	3	1	um	**3.1E-12**	4.7E-13
11	Symmetric sine wave 8 cycles	4	2	um	3.7E-14	1.3E-14
12	Symmetric sine wave 12 cycles	5	5	um	1.3E-14	1.9E-14
13	Symmetric sine wave 16 cycles	25	10	um	1.5E-13	3.4E-14
14	Syymmetric sine wave 20 cycles	25	10	um	9.2E-14	2.0E-14
15	Anti symmetric sine wave 4 cycles	10	50	um	3.9E-13	5.6E-16
16	In plane ellipti cal truss deform.	n/a	0.02	eccentricity	1.6E-16	1.8E-16

Thruster performance and reliability

- Mission requirement $\Delta v \approx 10$ km/sec
- High I_{sp} thrusters are the best option for long slews
- NEXT thruster from NASA Glenn has demonstrated
  - Over 664-kg xenon throughput (2× reqt)
  - 25×10^6 N-s of total impulse (1× reqt), and
  - >38,000 hours (0.87× reqt)
  - http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080047732_2008047267.pdf
- Station keeping during observation
  - Options include hydrazine and PPT thrusters
  - Ion thrusters not compatible
- These are mature enough for now
  → no technology development needed in this area

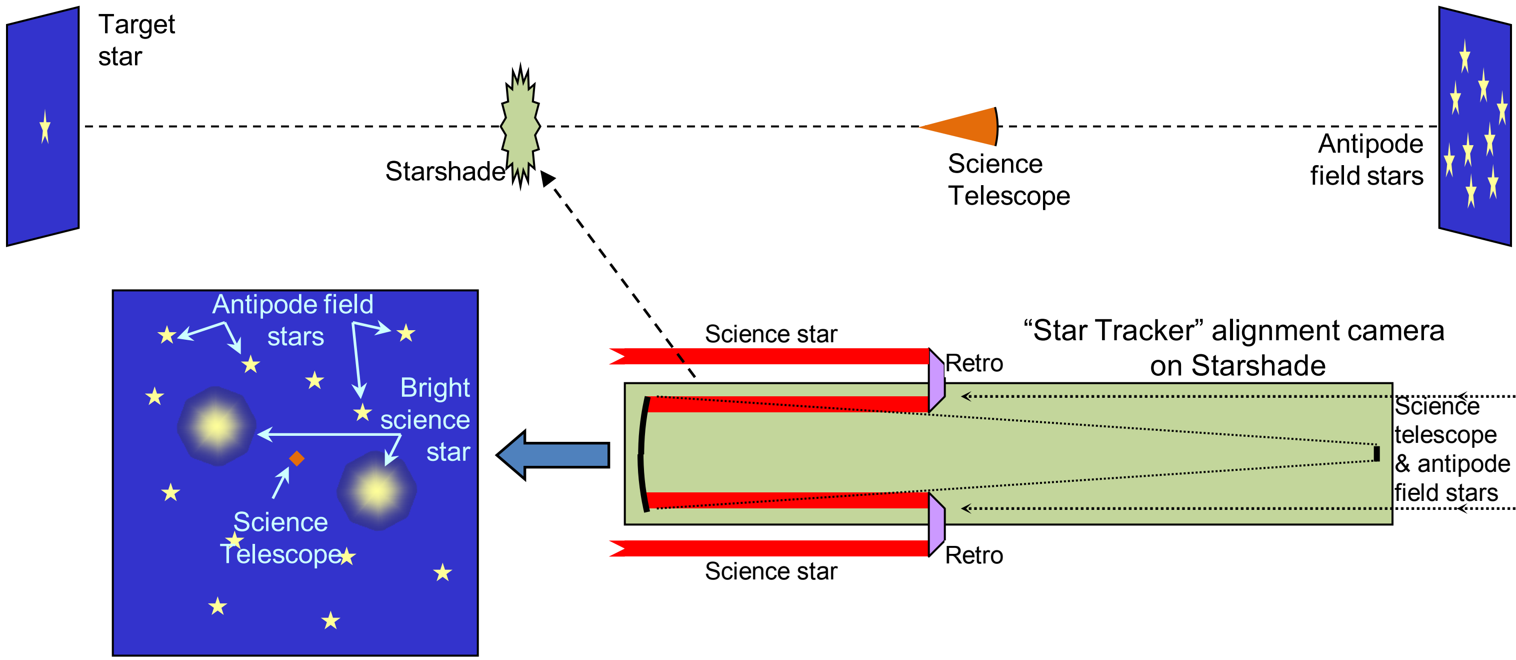
Slew-trajectory control

Guiding the slew from one star to the next



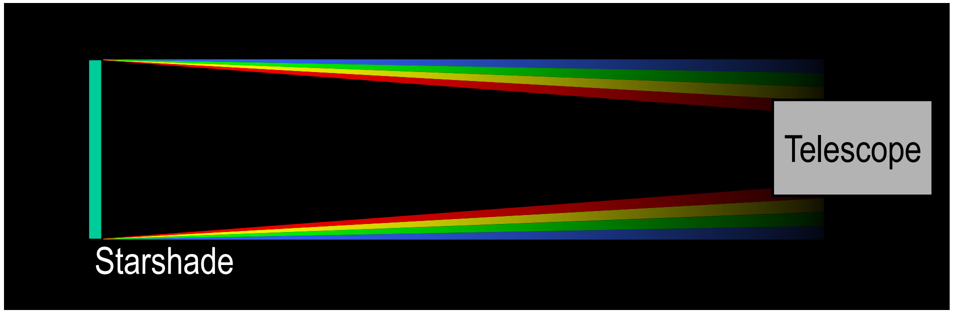
- Large “star tracker” (20-30 cm dia) on starshade observes distant telescope (sunlight glint) surrounded by the background star field
- Navigate to put telescope at the right RA/Dec
- Telescope is the one that moves at up to 9”/minute
  - Blinking beacon on telescope might speed identification during formation initialization, but has its own challenges

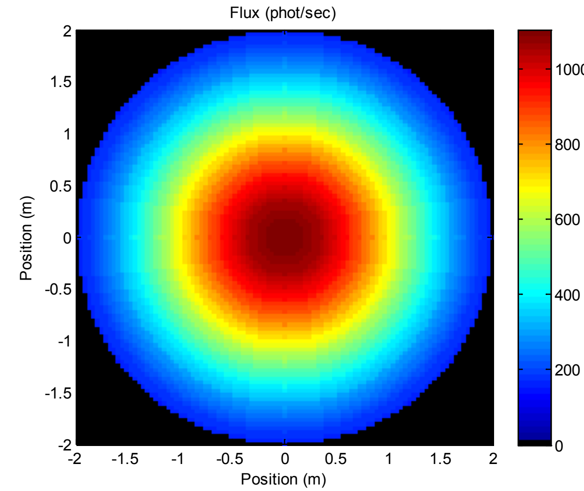
Acquiring the shadow



- Casting starshade's shadow on the science telescope
  - Retroreflectors make the "star tracker" into a sextant
  - Compare the science star (behind the alignment camera) to the science telescope (in front) on the same detector
  - Steer science star images vs. telescope, within 100 mas

Alignment control during observations





- Requirement for telescope centering in shadow within ±1 m
- Occulter position error is sensed by HgCdTe camera that images the pupil
  - Uncertainty 1.3mm per axis in 1 sec, mag 6 star

Table 1. Shadow sensor parameters	
Pixel size in pupil	4 cm
Pupil diameter	4 m
CCD QE	80%
Optical throughput	54.2%
Wavelengths	1.5-2.3 µm
Solid angle	30"x30"
Dark rate	0.004 /sec
Read noise	14
Thermal emission	61 /sec

- Differential gravity and solar pressure are very feeble
  → Control loop time is typically > 200s
- Huge SNR surplus, which we can spend tuning the control loop for minimum fuel consumption

Punctures through starshade fabric

- Single hole: r=0.5cm, λ=550 nm, D=80,000 km
  $$\delta I = (\pi r^2/\lambda D)^2 = 3.2\times 10^{-12}$$
- Single layer fabric, many holes: r=0.5 mm, density ρ = 100/m^2 (e.g. 10 cm grid)
  $$\delta I = (\pi r^2 \rho)^2 = 6.2\times 10^{-9} \text{ (square of area fill factor)}$$
  - All that light appears in the focal plane right in the middle of the starshade – not where planets are
- With punctures through a multilayer fabric, optical field phase is scrambled at each layer → all random
  $$\delta I = (\pi r^2/\lambda D)^2 (\rho \lambda D) = 1.4\times 10^{-12}$$
  - Appears all over the starshade, not beyond
- Punctures look pretty benign

Telescope pointing

- With star suppressed, we need good pointing so that
  - The planet is not smeared
  - The star position is known well enough for planet orbit determination
- Unlike coronagraphs, our best guide star is blocked before reaching the telescope
- Possible mitigation alternatives:
  - Field stars surrounding the exoplanet science star
  - Deliberate leakage by pinholes – partial transmission

Solar stray light from edges & plumes

- Looking for faint planet light past starshade edges, thrusters spray propellant across those lines of sight
- Sunlight on the plumes causes unknown stray light
- Sunlight on edges of starshade petals is adjacent to planet pixels
  - If edge scatter of sunlight ≤ exozodi, then radius of curvature <7µm (like a commercial razor blade)
  - Can relax by ~5× with some sensitivity loss near sunward edges

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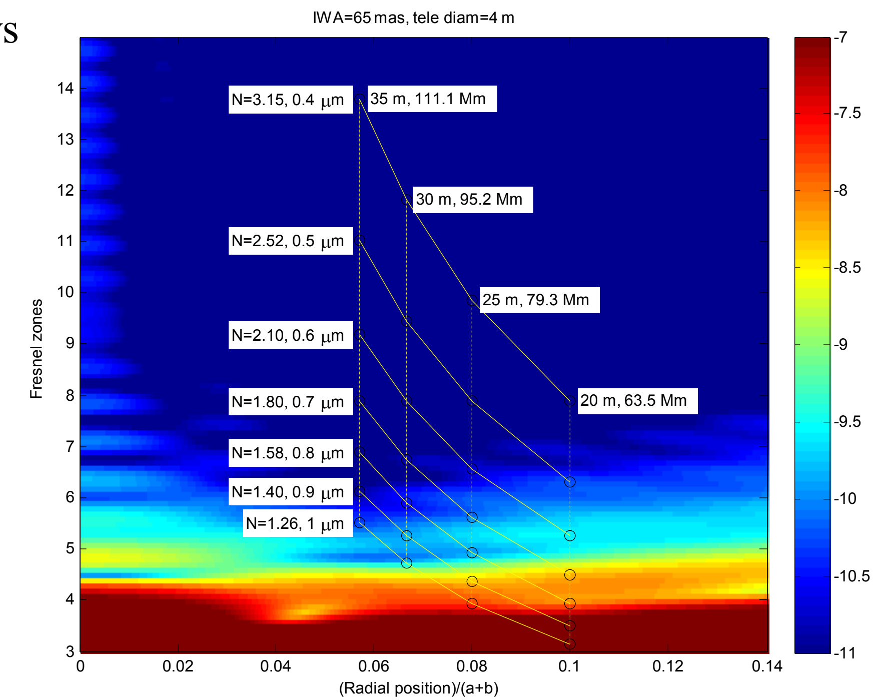
Sizing Rules of Thumb

- $R = F\lambda/\alpha$ (radius of starshade)
- $D = F\lambda/\alpha^2$ (telescope-starshade distance)
- Starshade scaling

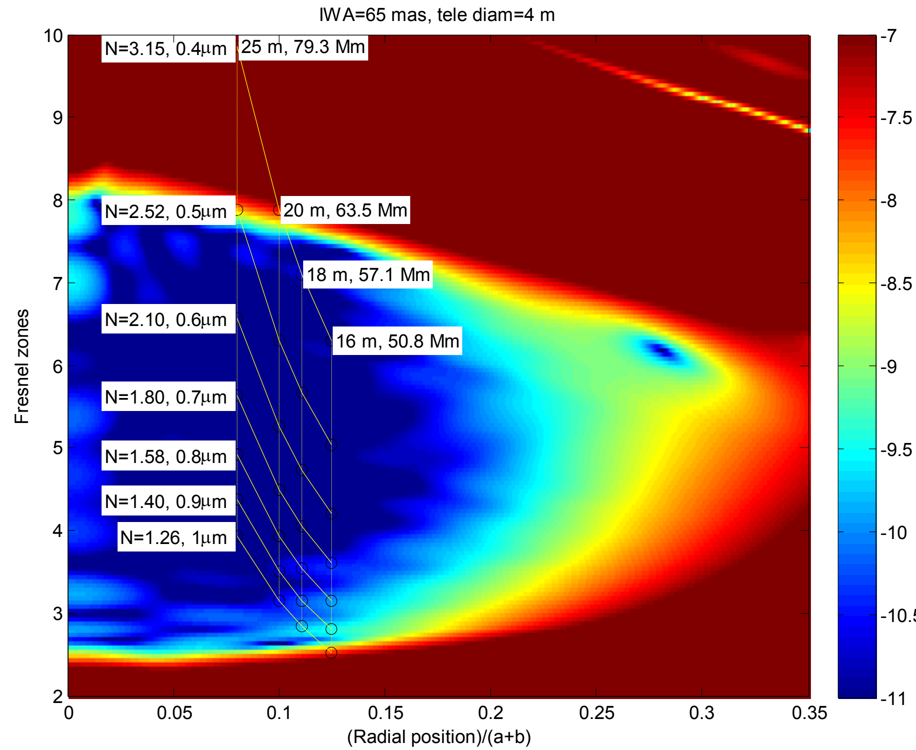
Hypergaussian starshade, 65 mas

- 25m starshade allows planet detection at 0.6μm at 50 mas
- Allows spectral characterization to λ=0.8μm at 65 mas, λ= 1μm at 81 mas



Scaling for optimized starshade

- Petal shape optimization yields good suppression at smaller F~2.5
- Optimizer was allowed to sacrifice suppression outside prime passband → Stellar diffraction rises at large F as well
  - Bounds the exoplanet science in the UV
  - Larger telescopes have reduced λ range



- Deep hole begins at F~2.5 → Can use a smaller starshade
- Stops at F~8 → Limited flexibility to change the IWA by using different starshade distances
  - Exoplanet sensitivity is bounded at UV end
  - Re-optimization could extend wavelength range