Princeton Progress and Opportunities in Starshade Optical Testing

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Starshade Work at Princeton

- Optimal Design and Analysis
- Starshade Petal Precision Manufacturing (TDEM)
- Starshade Precision Petal Deployment (TDE M)
- Optical Verification in Laboratory (TDEM)
- Formation Flying Sensing and Control (TDEM)
Laboratory Scaling

- The electric field $E_{occ}$ at a distance $z$ past an starshade mask with an apodization function $A(r)$:

$$E_{occ} = \frac{2\pi}{i\lambda z} \int_0^R \frac{\pi i}{e^{\lambda r^2 + \rho^2}} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) A(r) r dr$$

- Scaling Objective: Maintaining an identical shadow intensity to that expected in space by maintaining constant Fresnel numbers ($R^2/\lambda z$)

- Scaled version that maintains Fresnel number ($R^2/\lambda z$)

$$E'_{occ} = \frac{2\pi}{i\lambda z'} \int_0^{R'} \frac{\pi i}{e^{\lambda r'^2 + \rho'^2}} J_0 \left( \frac{2\pi r' \rho'}{\lambda z'} \right) A'(r') r' dr'$$

$$\rho' = \frac{\rho}{s}, r' = \frac{r}{s}, A'(r') = A(sr'), z' = z/s^2$$

- The electric field at the shadow plane will be identical between space and scaled dimensions

$r$: radius of starshade
$\rho$: radius of shadow
$z$: distance between starshade & telescope

$r'$: radius of scaled starshade in lab
$\rho'$: radius of scaled shadow in lab
$z'$: distance between scaled starshade & camera
$s$: scaling factor
## Original Princeton Testbed

<table>
<thead>
<tr>
<th>Design</th>
<th>Occulter Radius</th>
<th>Separation</th>
<th>Telescope Diameter</th>
<th>Fresnel Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>THEIA</td>
<td>20 m</td>
<td>55,000 km</td>
<td>4 m</td>
<td>12.1</td>
</tr>
<tr>
<td>O3</td>
<td>15 m</td>
<td>21,000 km</td>
<td>1.1 m</td>
<td>17.9</td>
</tr>
<tr>
<td>Previous Exp.</td>
<td>188 m</td>
<td>97,000 km</td>
<td>17 m</td>
<td>607.3</td>
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![Diagram of experimental setup with labels for Diverging Beam, Occulter Mask, Raffle, and Camera. Dimensions 1.5 m and 9.1 m are indicated.]
Original Princeton Testbed

Combined Errors

Measured
Pupil Suppression: $10^{-4.82}$

2D Propagation
Pupil Suppression: $10^{-4.85}$

→ Largest sources of performance degradation are manufacturing feature size and edge perturbations

Final result with 2 micron manufacturing resolution
Contrast Azimuthal Average

-8
-9
-10
-11
-12
-13
-14
0 100 200 300 400 500 600 700 800 900
Equivalent Space Angle, mas

contrast, log

Simulation
Ideal Design
Experiment Result

Feature
Size
Edge Pert.
Beam Disp
Opt.
Abr.
Wave.
Abr.
Tilt Camera
Abr.

0.55 um
0.05 um
2.2 mm
60 nm
0 nm
5 deg
30 nm

Results with better mask
**Objective of New Experiment**

- Upgrade the previous experimental facility that allows testing a scaled starshade at flight – like Fresnel numbers
- Total beam path: 77.2 m
- Design a mask to satisfy requirement (suppression < 1e-9, contrast < 1e-11)

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</tr>
<tr>
<td>New Exp.</td>
<td>21.9 m</td>
<td>55,000 km</td>
<td>2.4 m</td>
<td>14.5</td>
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![Diagram of testbeds](image)
## Expected Performance

<table>
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<tr>
<th>Error Parameter</th>
<th>Feature Size</th>
<th>Edge Perturbation</th>
<th>Beam Misalignment</th>
<th>Pinhole Aberration</th>
<th>Mask Tilt</th>
<th>Camera Aberration</th>
</tr>
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<tbody>
<tr>
<td>Budget</td>
<td>0.5 um</td>
<td>0.1 um</td>
<td>1.0 mm</td>
<td>60 nm</td>
<td>1 deg</td>
<td>60 nm</td>
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</table>
Camera Station

Mask Station

Laser Station

Testbed Setup

50 m

27.2 m

Camera Station

Mask Station

Laser Station

(Manufactured by the MDL of the JPL)
Contrast at Large Aperture – 638 nm

- Shadow diameter: 9.6 mm
- Pinhole Diameter: 13.6 mm
- More light is incident to the camera → The contrast is worse than with the smaller designed aperture
- Mask defects can be seen clearly because of a much larger camera over-resolving image
Contrast – 633 nm

- Add inner part error around ± 100 um inner peak
- It looks like there’s a bright source around the inner petal area
- Curves do not include defects
Suppression – 633 nm

- Suppression reached a limit due to mask defect and stray light
- Gap between experiment and simulation with inner error will be the camera noise
Contrast Stability – 633 nm

Image Plane, Contrast

Equivalent Space Angle, mas

-250 -150 0 150 250

-11 -10.5 -10 -9.5 -9 -8.5 -8 -7.5 -7

50s

500s

3000s

10000s

30000s

Contrast Azimuthal Average

Equivalent Space Angle, mas

0 50 100 150 200 250

Contrast, log

-12 -11.5 -11 -10.5 -10 -9.5 -9 -8.5 -8 -7.5 -7
Summary

- We achieved a first light result for a starshade at flight Fresnel number 14.5 with $10^{-9}$ contrast and $10^{-6}$ suppression at 633 nm.
- From the analysis the inner petal region is brighter than design.
- Limiting factor of current setup is mask defects, accuracy and stray light.
- Images extremely stable on the times scales measured indicating turbulence is not a problem.
- The effect of wavefront error and beam drift was negligible.
- We are installing EMCCD and checking stray light source.
- We hope to get $10^{-9}$ suppression and $< 10^{-11}$ contrast at working bandpass from a new mask.
- Once fully functional, lab can be used to test a variety of masks with different defects to compare to models.
Starshade Modeling Reconciliation activity: NG, JPL, CU, and Princeton modeled the NG Desert tests.

Ultimately got to excellent agreement but still some work to do.
Three Questions from Stuart

- Is the testbed big enough?
- Does it allow us to test a variety of scales?
- Is a larger testbed necessary?

First question:

Yes because it works on scalar diffraction, exactly like the full starshade.

And Yes because it is large enough to do meaningful sensitivity testing and inform the error budget and model uncertainties.

Second question:

Yes, because we can change wavelength, diameter, Fresnel number over factors of 2 - 4.

Third question:

No. Larger testbeds, up to 10 km, may help improve the model uncertainty, but it is already good at 77 m.
Thank you!