Optical Demonstrations of a Starshade at Flight Fresnel Number

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Introduction

A starshade mission is typically tens of meters across with tens of thousands of kilometer separation → Very small Inner Working Angle (IWA)

IWA given by: \( \tan \theta = \frac{R}{z} \); Shadow size given by R

Impossible to make full scale ground test

Laboratory verification of starshade design is necessary to validate the optical models used to design and predict starshade
• Contrast: The ratio of the peak of the stellar point spread function to the halo at the planet location

• Suppression: Normalized shadow intensity at the telescope pupil plane
Laboratory Scaling

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

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

- 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 ($R^2/\lambda z$)

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

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

- 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
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)

<table>
<thead>
<tr>
<th>Design</th>
<th>Starshade 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>
</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>
</tr>
</tbody>
</table>
### Design Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Space Scale</th>
<th>Lab Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation Z</td>
<td>55,000 km</td>
<td>50 m</td>
</tr>
<tr>
<td>Outer Petal Radius</td>
<td>43.7 m</td>
<td>24.8 mm</td>
</tr>
<tr>
<td>Inner Petal Radius</td>
<td>21.9 m</td>
<td>12.4 mm</td>
</tr>
<tr>
<td>Inner Opaque</td>
<td>14.9 m</td>
<td>8.4 mm</td>
</tr>
<tr>
<td>Petal Length</td>
<td>7 m</td>
<td>3.9 mm</td>
</tr>
<tr>
<td>Shadow Diameter</td>
<td>6 m</td>
<td>9.6 mm</td>
</tr>
<tr>
<td>Telescope Diameter</td>
<td>2.4 m</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>lambda range</td>
<td>630 nm</td>
<td>630 nm</td>
</tr>
<tr>
<td></td>
<td>640 nm</td>
<td>640 nm</td>
</tr>
<tr>
<td>Fresnel Number@600 nm</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Suppression Constraint</td>
<td>$10^{-10}$</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

#### Diagrams

**Space Scale Mask**

- Outer Petal Radius
- Inner Opaque
- Inner Petal Radius

**Lab Scale Mask**

- Outer Petal Radius
- Inner Opaque
- Inner Petal Radius
# Expected Performance

<table>
<thead>
<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>
</thead>
<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>
</tr>
</tbody>
</table>
Testbed Setup

Camera Station  

50 m  

Laser Station  

Mask Station  

Camera Station  

27.2 m  

Laser Station  

Mask Station  

Camera Station  

Mask Station  

(Manufactured by the MDL of the JPL)  

Laser Station
Beam Propagation – 520 nm
Out of Band Contrast – 520 nm

- Check the alignment status of camera and mask
- Exposure time: 500 sec

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</table>
Out of Band Suppression – 520 nm

- Suppression reached a limit due to stray light
- Exposure time: 3000 sec

Zoom-In Center region

Stray light

Raw data

Simulation

Experiment

Profile
Beam Propagation – 638 nm

Camera Station  
Mask Station  
Laser Station

Frick Testbed - LASER Propagation (638 nm & 520 nm)

Beam Propagation – 638 nm

Camera Station  
Mask Station  
Laser Station

11/19
Contrast at Designed Aperture – 638 nm

- Inner petal region is brighter than as we expected
- Exposure time: 3000 sec
- Error in simulation is the same as for the 520 nm case
Contrast at Large Aperture – 638 nm

- Shadow diameter: 9.6 mm / EPD: 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
Suppression – 638 nm

- Suppression reached a limit due to stray light
- Exposure time: 3000 sec
Source Change

638 nm
Single mode fiber
w/o pinhole

15 μm pinhole
Lens
633 nm laser

633 nm
Diverging lens +
15 μm pinhole
Contrast Improvement

- Difference
  - Alignment Status
  - Beam Quality
  - Laser Power
  - Stray Light

Large Aperture (Diameter 13.6 mm)

Designed Aperture (Diameter 3.8 mm)

638 nm

633 nm

Mask defects
Contrast − 633 nm

- Inner petal region is brighter than as we expected
- Exposure time: 3000 sec
- Contrast $10^{-9}$ is a limit of current mask quality

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<td>0.1 mm</td>
<td>60 nm</td>
<td>1 deg</td>
<td>60 nm</td>
</tr>
</tbody>
</table>
Suppression – 633 nm

- Suppression reached a limit due to mask defect
- Removed major stray source
- Another error source appeared
- Exposure time: 3000 sec
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
Thank you for your attention!
Appendix
Contrast – 633 nm

![Image Plane, Contrast for different time intervals: 50s, 500s, 3000s, 10000s, 30000s.](image)

**Contrast Azimuthal Average**

- **50s**
- **500s**
- **3000s**
- **10000s**
- **30000s**
Camera Mount Replacement
Bright point on petal 15 in experiment image is matched to the microscope Image of 15-1 and 15-2.
New Mask at Previous Testbed

**Contrast Azimuthal Average**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.2</td>
<td>-5.4</td>
<td>-6.1</td>
</tr>
</tbody>
</table>

**Feature**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0.5 um</td>
<td>0.5 um</td>
<td>0.1 mm</td>
<td>60 nm</td>
<td>1 deg</td>
<td>60 nm</td>
</tr>
</tbody>
</table>
Divergent Beam Scaling

<table>
<thead>
<tr>
<th>labZ (z’, m)</th>
<th>Mask Radius (r'', mm)</th>
<th>Dark Radius (ρ'', mm)</th>
<th>Margin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.6</td>
<td>13.0</td>
<td>3.6</td>
<td>± 1.7</td>
</tr>
<tr>
<td>50</td>
<td>12.4</td>
<td>4.8</td>
<td>± 2.9</td>
</tr>
<tr>
<td>60</td>
<td>10.8</td>
<td>6.6</td>
<td>± 4.7</td>
</tr>
<tr>
<td>65</td>
<td>9.5</td>
<td>8.2</td>
<td>± 6.3</td>
</tr>
<tr>
<td>70</td>
<td>7.6</td>
<td>11.1</td>
<td>± 9.2</td>
</tr>
</tbody>
</table>

Camera Radius: 1.9 mm
Ideal Simulation

638 nm

520 nm
**All Error Combined Simulation**

<table>
<thead>
<tr>
<th>Error Parameter</th>
<th>Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature Accuracy</td>
<td>0.5 μm</td>
</tr>
<tr>
<td>Edge Perturbation</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>Optics Aberrations</td>
<td>λ/10 ≈ 60 nm</td>
</tr>
<tr>
<td>Diagonal Beam Misalignment</td>
<td>1 mm</td>
</tr>
<tr>
<td>Mask Tilt</td>
<td>1°</td>
</tr>
<tr>
<td>Camera Aberrations</td>
<td>60 nm</td>
</tr>
</tbody>
</table>

![Graphs showing error parameters](image1)

638 nm  
520 nm
Simulation Result of JPL

Suppression

Contrast