Design of a starshade at flight Fresnel numbers in the lab

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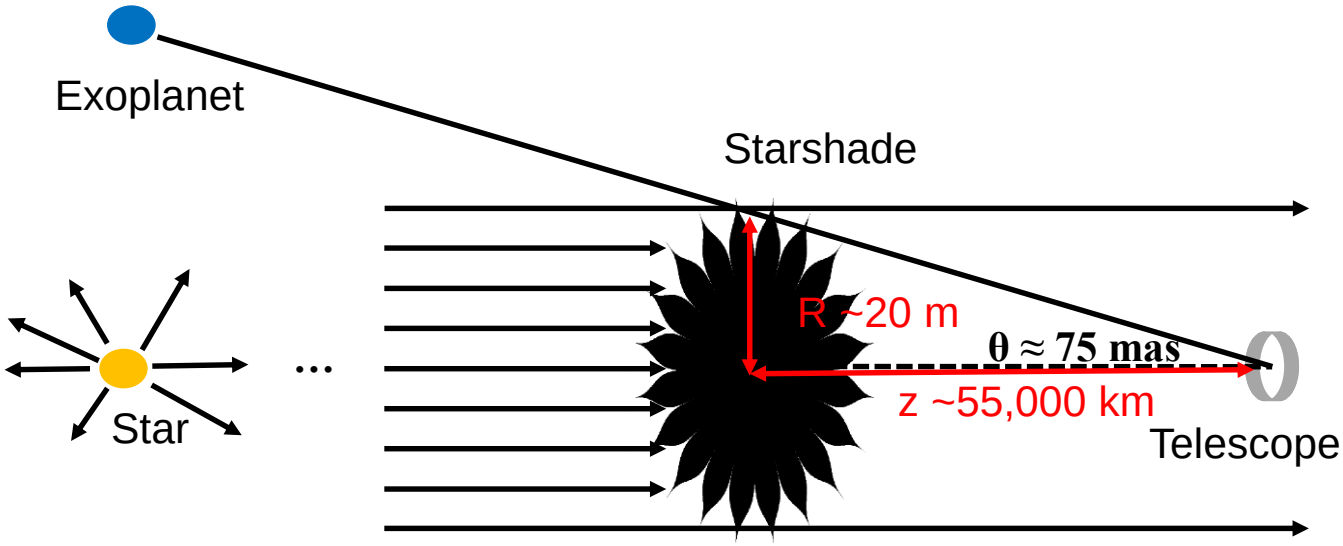
Introduction



- A starshade mission is typically tens of meters across with tens of thousands of kilometer separation → To match very small Inner Working Angle
- Inner Working Angle given by: $\tan\theta = R/z$; Shadow size given by R
- Making full scale ground tests impossible
- Laboratory verification of starshade design is necessary to validate the optical models used to design and predict starshade

Laboratory Scaling

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- The electric field Eocc at a distance z past an starshade mask with an apodization function A(r):

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

r: radius of starshade
ρ: radius of shadow
z: distance between starshade & telescope

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

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

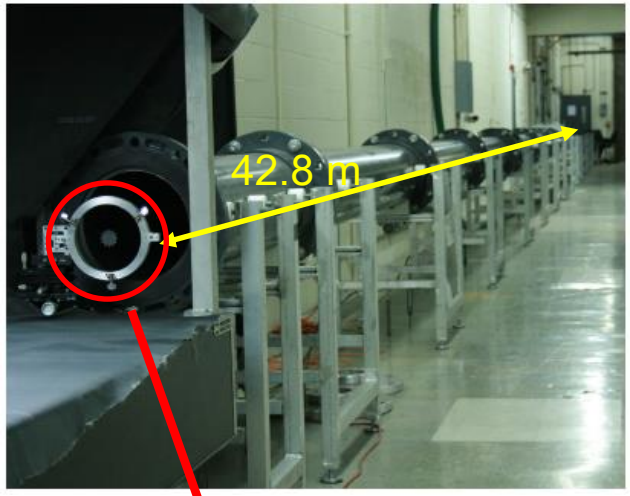
$$E'_{occ} = \frac{2\pi}{i\lambda z'}\int_0^{R'} e^{\frac{\pi i}{\lambda z'}(r'^2+\rho'^2)} J_0\left(\frac{2\pi r'\rho'}{\lambda z'}\right) A'(r') r' dr'$$

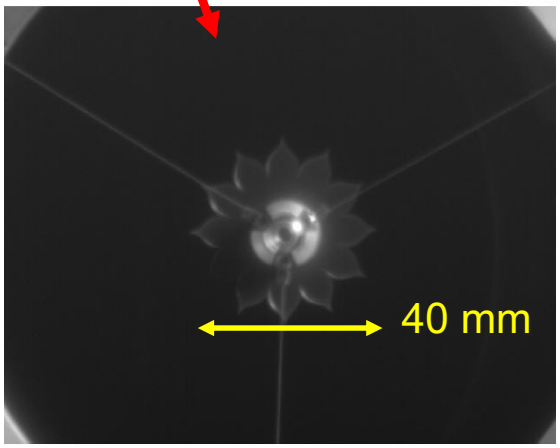
$$\rho' = \frac{\rho}{s}, r' = \frac{r}{s}, A'(r') = A(sr'), z' = z/s^2$$

r ′: radius of scaled starshade in lab
ρ ′: radius of scaled shadow in lab
z ′: distance between scaled starshade & camera
s: scaling factor

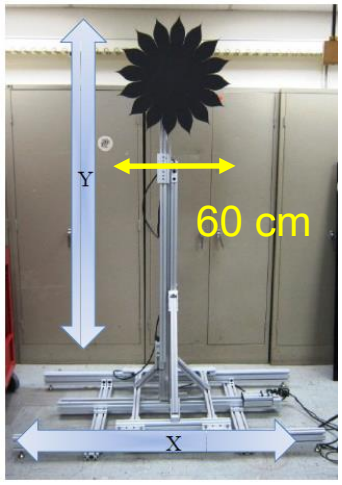
- The electric field at the shadow plane will be identical between space and scaled dimensions

Previous Subscale Laboratory Verification



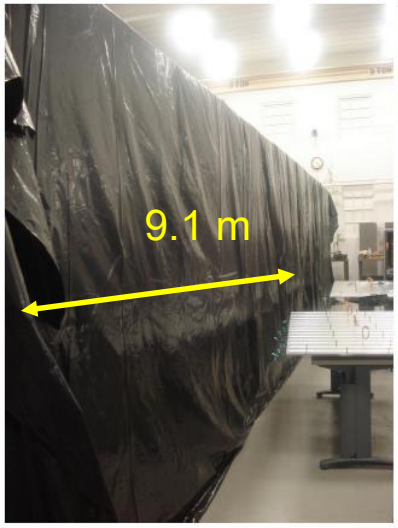


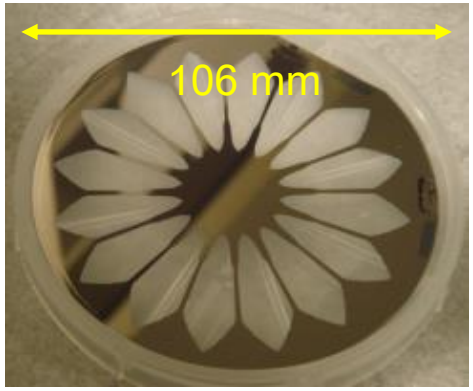
Fresnel Number: 16



Fresnel Number: 150

Northrop Grumman





Fresnel Number: 607

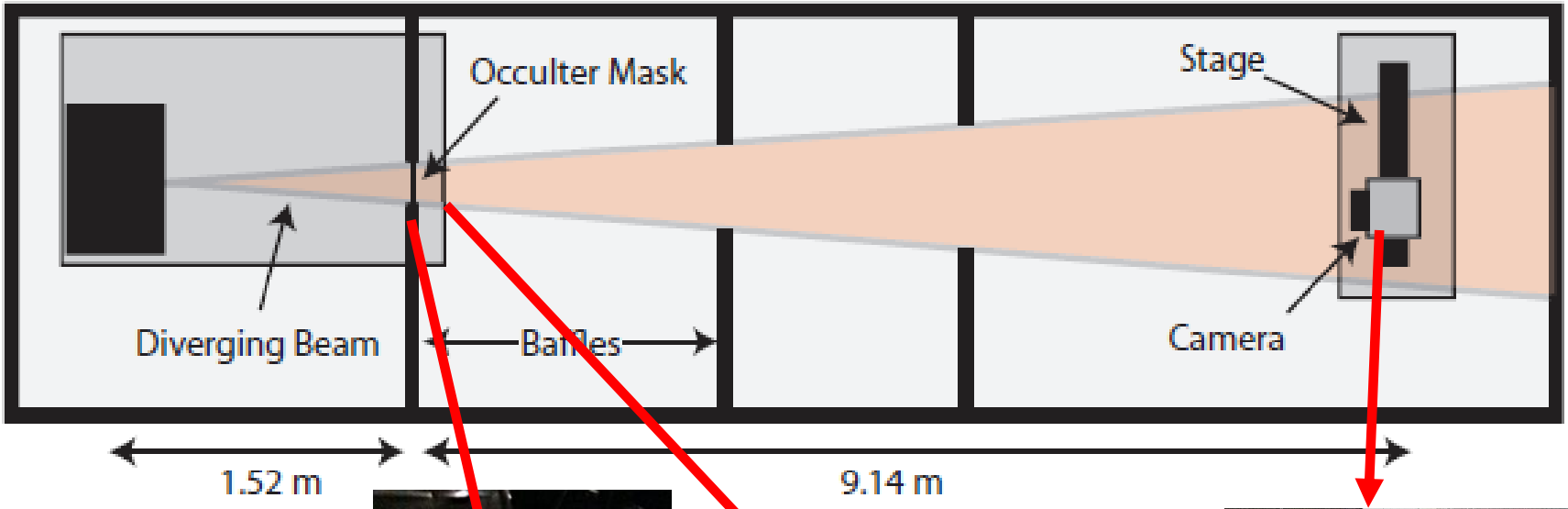
Princeton

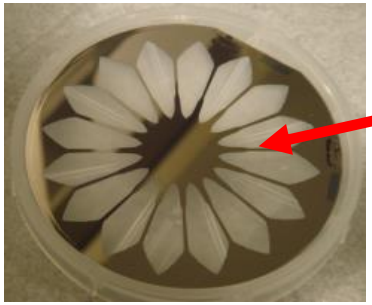
Typical Flight Fresnel Number for Space Mission: 15

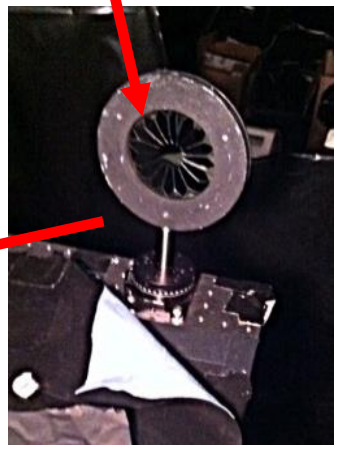
Ref. R. Samuele et al. 2009, 2010
T. Glassman et al. 2013,2014

Ref. E. Cady et al. 2009,2010
D. Sirbu et al. 2013,2014

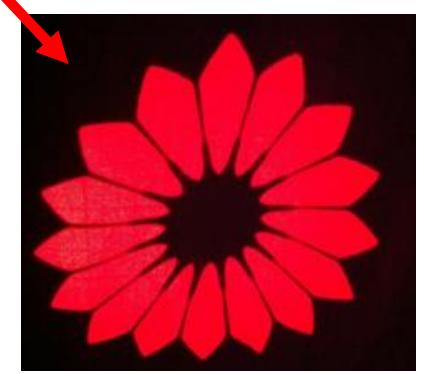
Previous Experimental Setup at Princeton



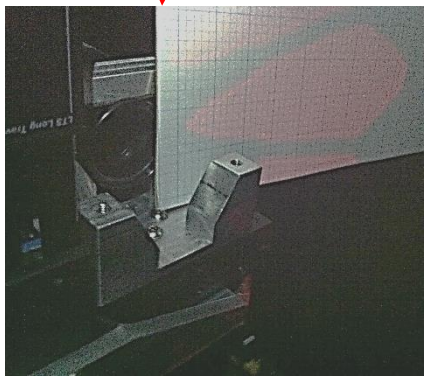




Manufactured Mask
Fresnel Number: 607
(Made at MDL at JPL)



Transparent
light



Camera

Ref. E. Cady et al. 2009
D. Sirbu et al. 2014

Previous Result at Princeton

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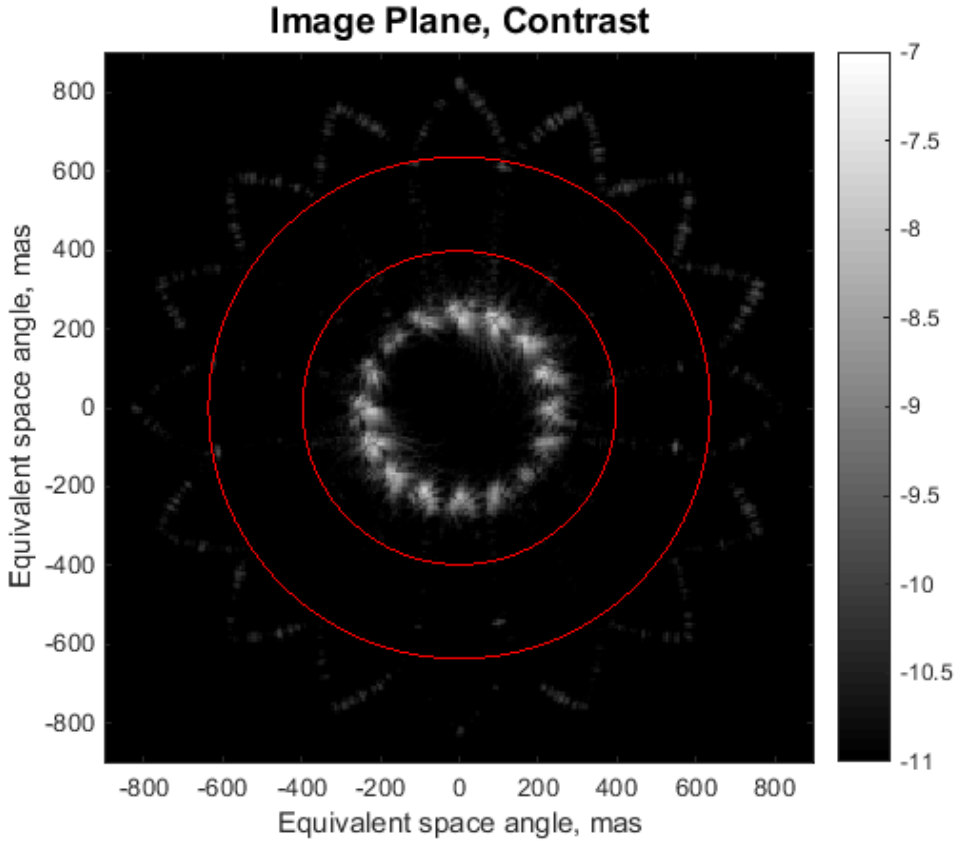
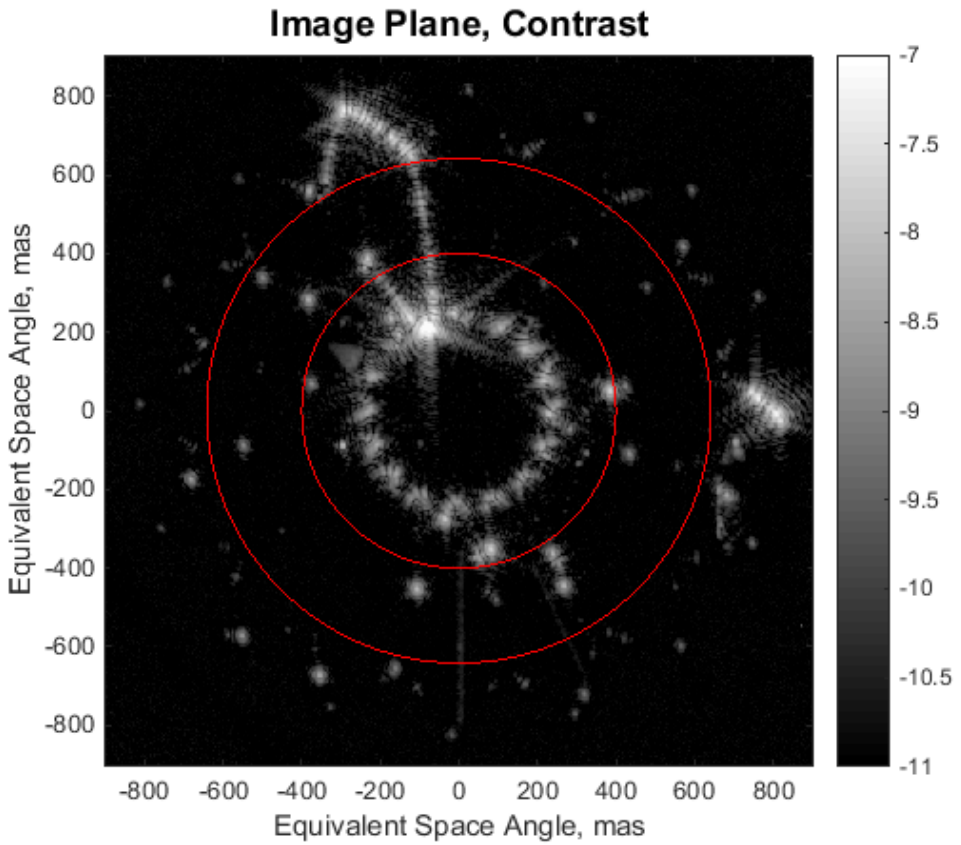
Simulation



Experiment



- Effect of the Fresnel number, that we effectively have a much larger telescope and are over-resolving the starshade.
- The dominant affect causing the bright edges is a manufacturing error

Ref. D. Sirbu 2014 Thesis

Previous Result at Princeton

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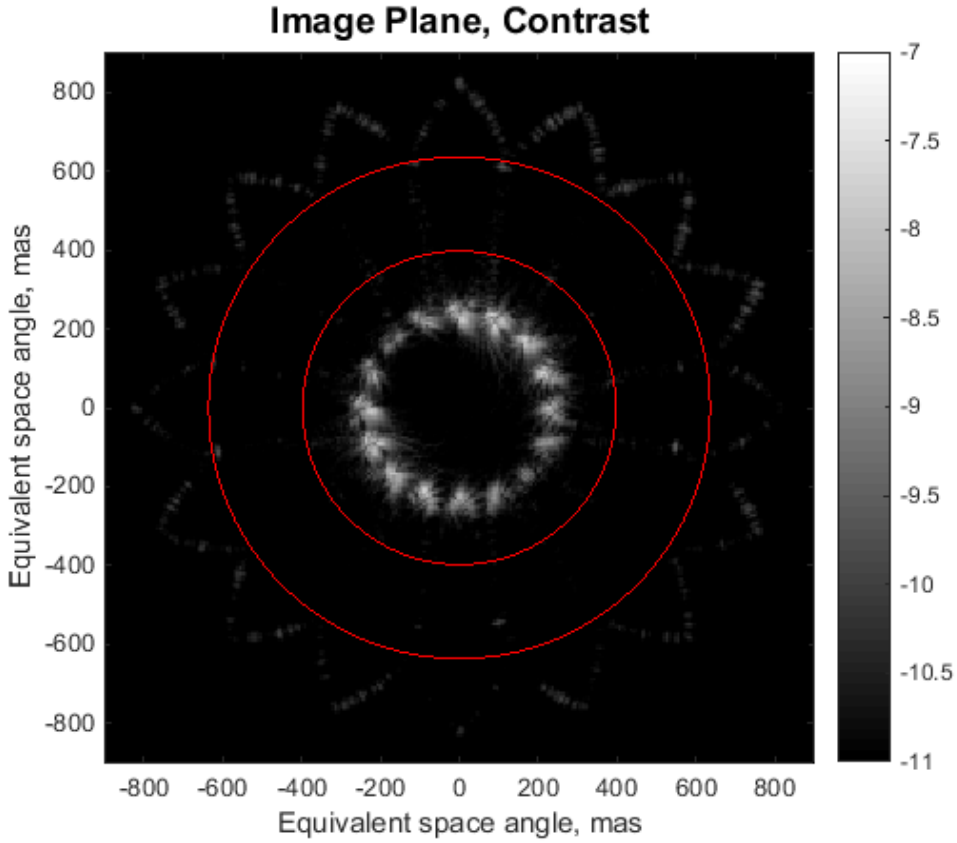
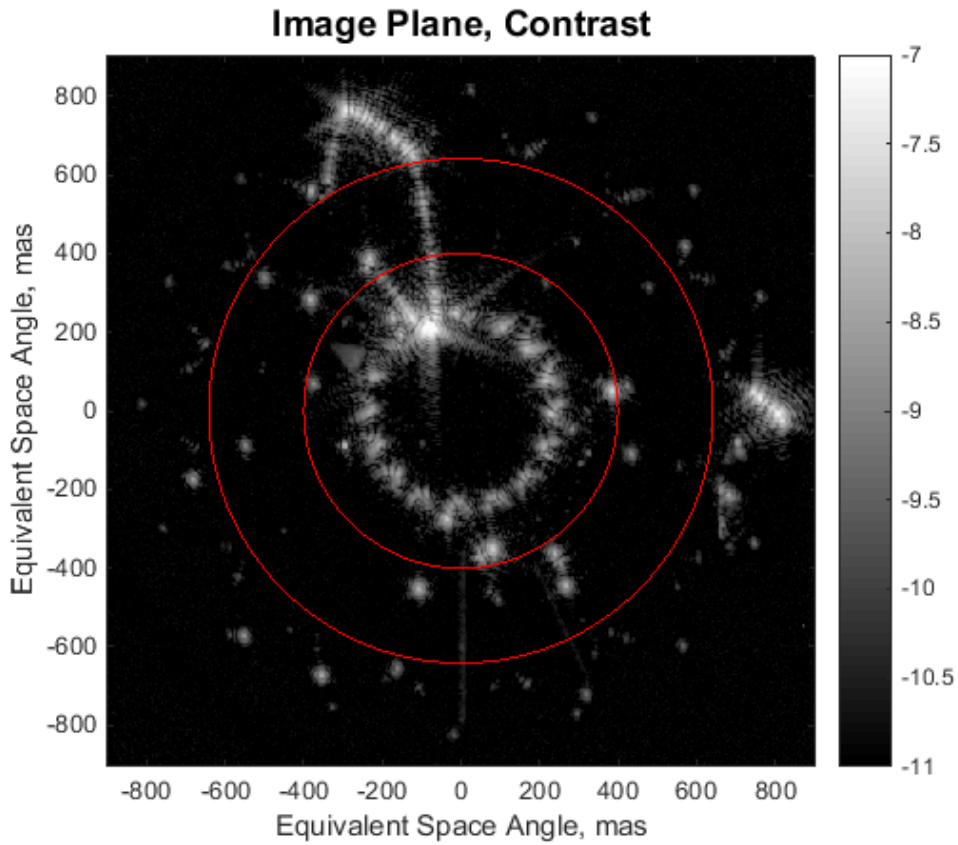
Simulation



Supp.	Contrast
-5.99	-12.49

Experiment



Supp.	Contrast
-5.15	-11.47

Ref. D. Sirbu 2014 Thesis

Previous Result at Princeton

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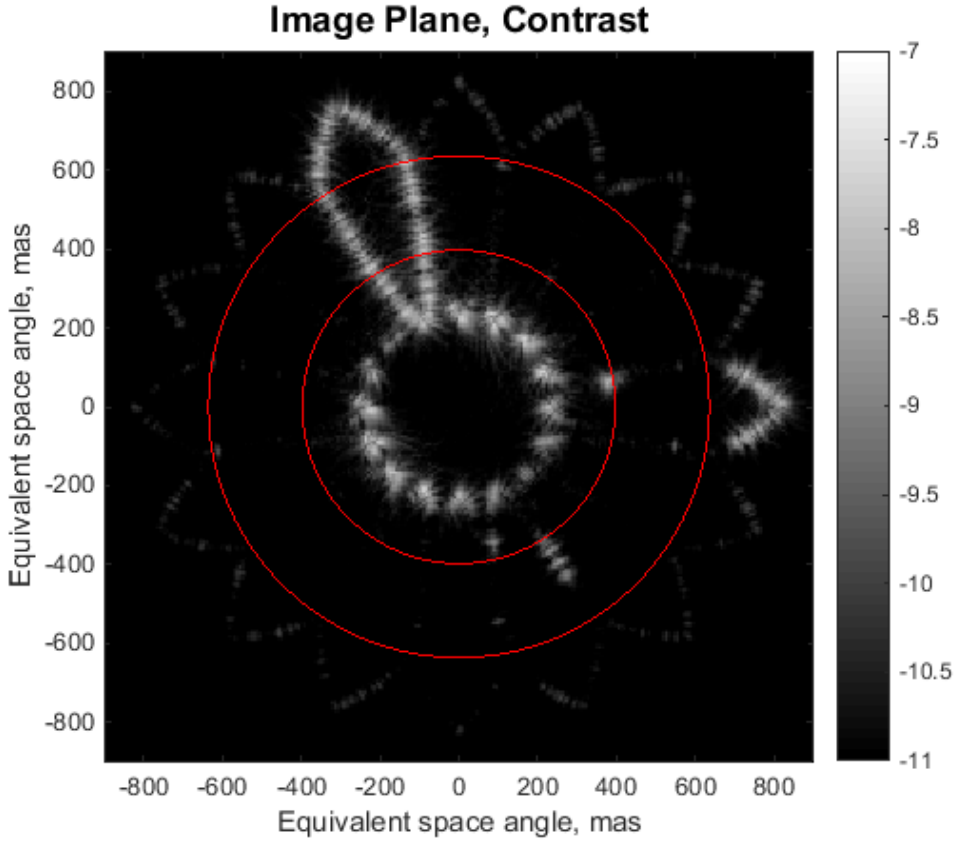
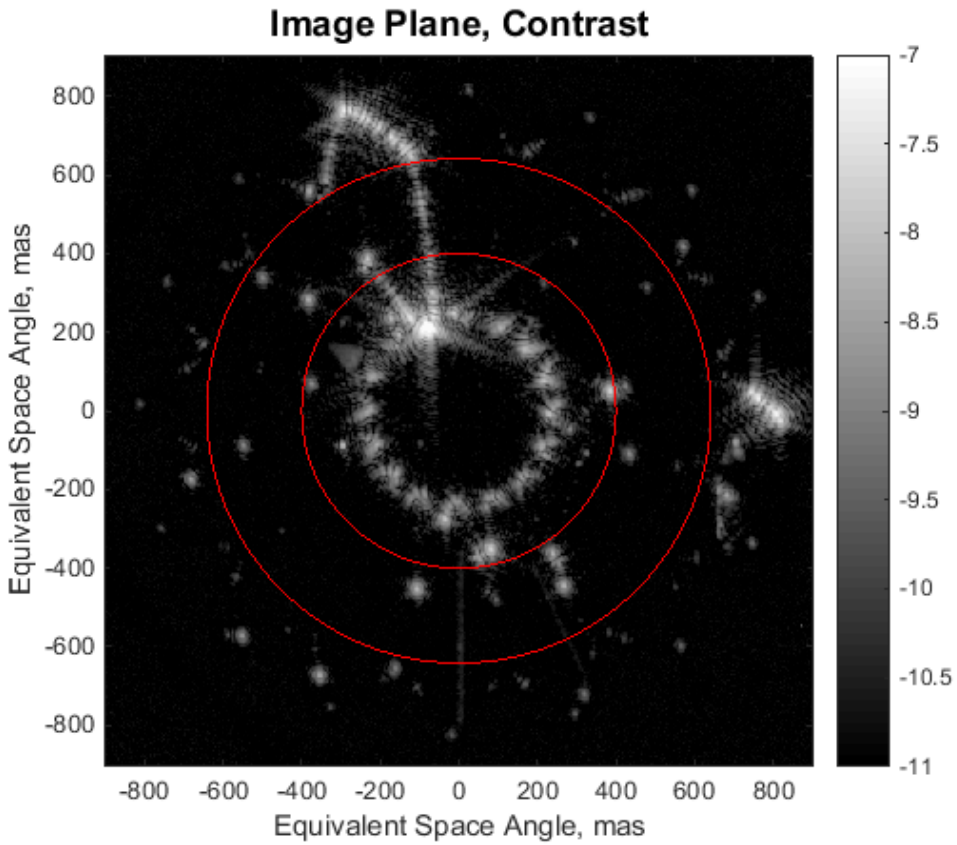
Simulation with defect petal



Supp.	Contrast
-5.68	-12.01

Experiment



Supp.	Contrast
-5.15	-11.47

Previous Result at Princeton

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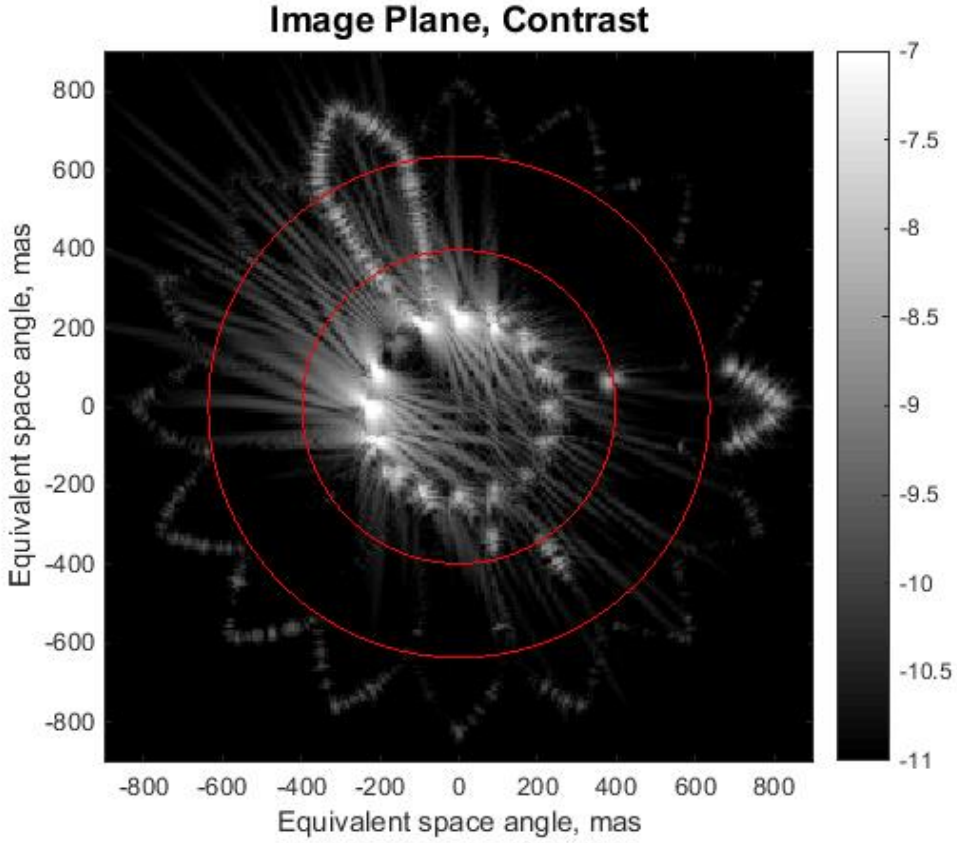
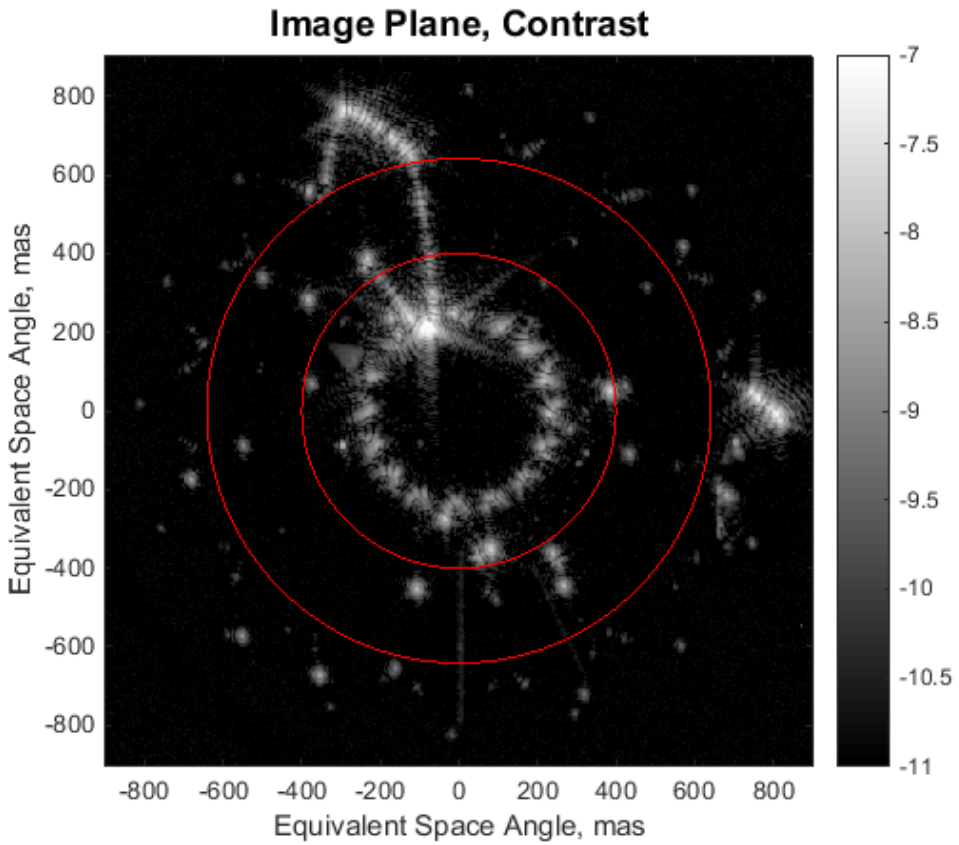
Simulation with defect petal



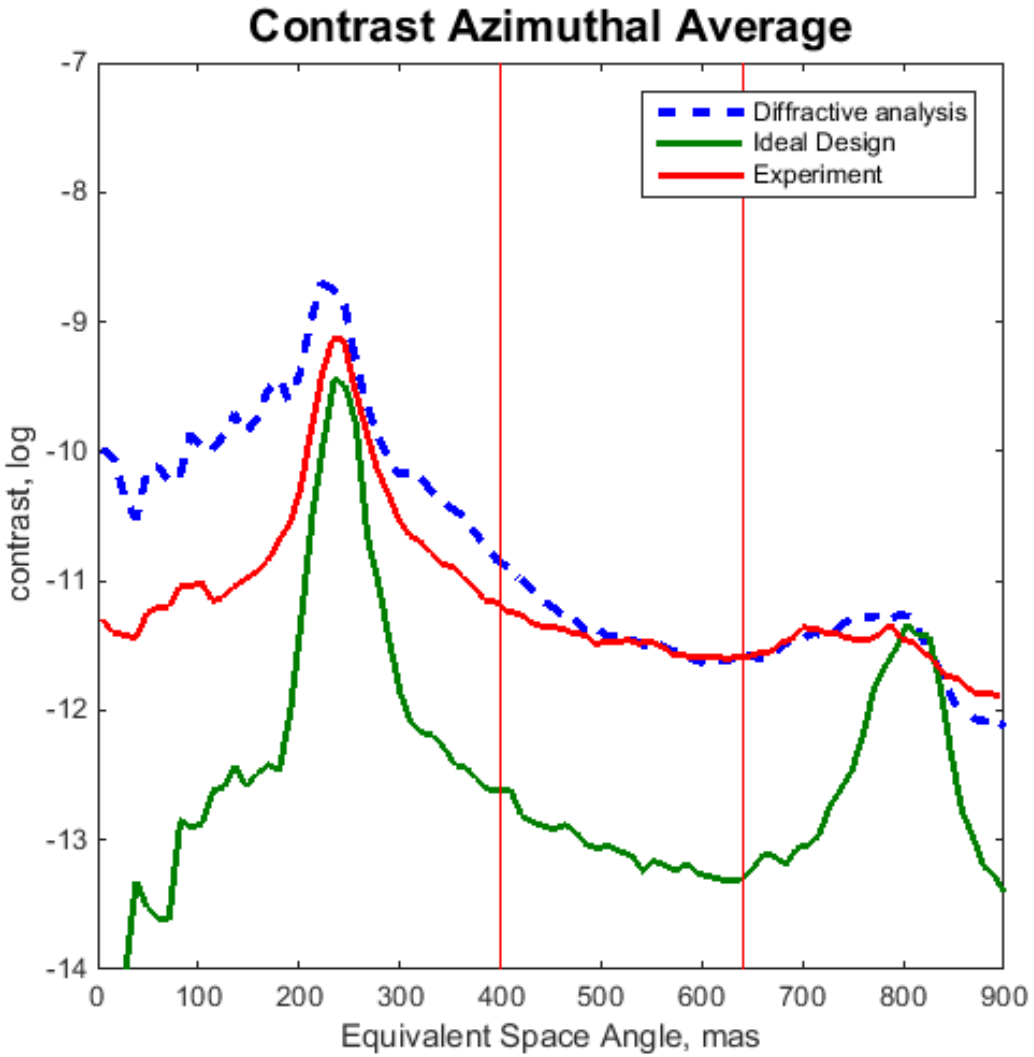
Supp.	Contrast
-5.52	-11.35

Experiment



Supp.	Contrast
-5.15	-11.47

Previous Result at Princeton



- Achieved contrast in lab of 10^{-11} and suppression of $10^{-5.1}$ (Design Contrast:10^{-13} Design Suppression -$10^{-6.6}$)
- Limitations of the experiment
  - Manufacturing accuracy
  - Camera noise
- Condition of diffractive analysis

Feature Size	Edge Pert.	Beam Disp	Opt. Abr
0.55 um	0.05 um	3.7 mm	60 nm

- Mask manufacturing accuracy of better than 0.5 microns

Objective of New Experiment

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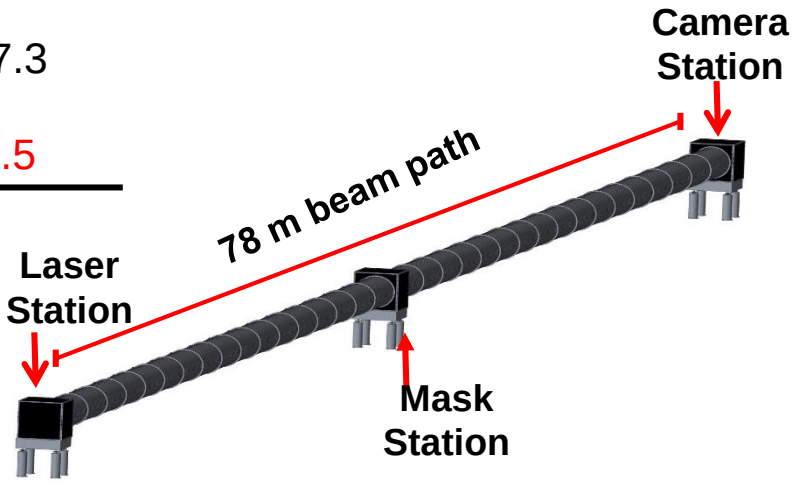
- Upgrade the previous experimental facility that allows testing a scaled starshade at flight –like Fresnel numbers
- Total beam path: 78 m
- Design a mask to satisfy requirement (suppression < 1e-9 , contrast < 1e-11)

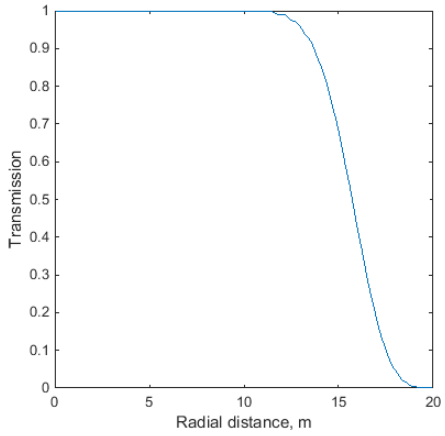
Design	Occulter Radius	Separation	Telescope Diameter	Fresnel Number
THEIA	20 m	55,000 km	4 m	12.1
O3	15 m	21,000 km	1.1 m	17.9
Previous Exp.	188 m	97,000 km	17 m	607.3
New Exp.	21.9 m	55,000 km	4 m	14.5



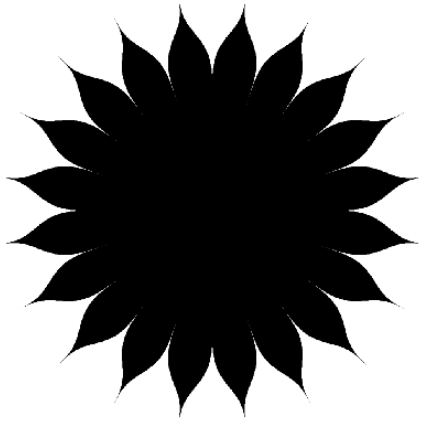
Starshade Design Process

- Starshade for space mission

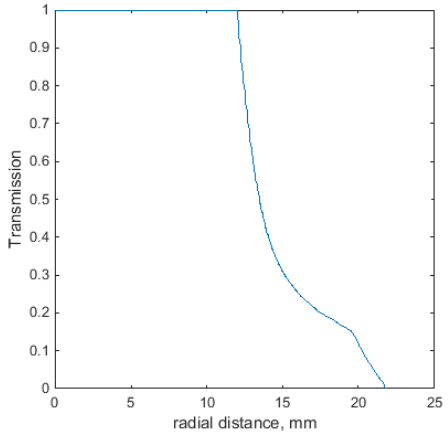
Ref. D. Sirbu 2014 Thesis



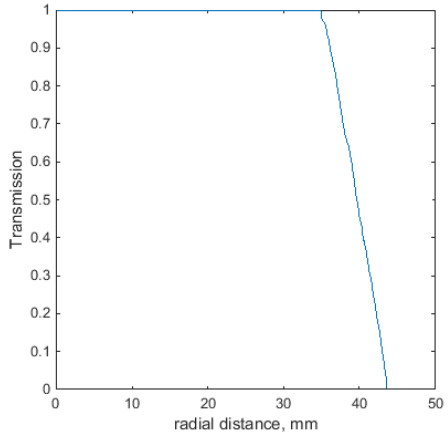
Profile



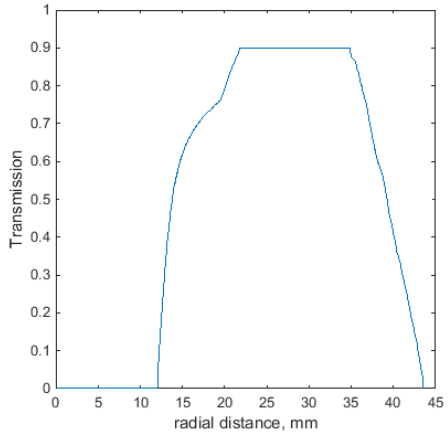
- Starshade for lab experiment



Inner Profile



Outer Profile



Total Profile

Starshade Design Process for New Lab

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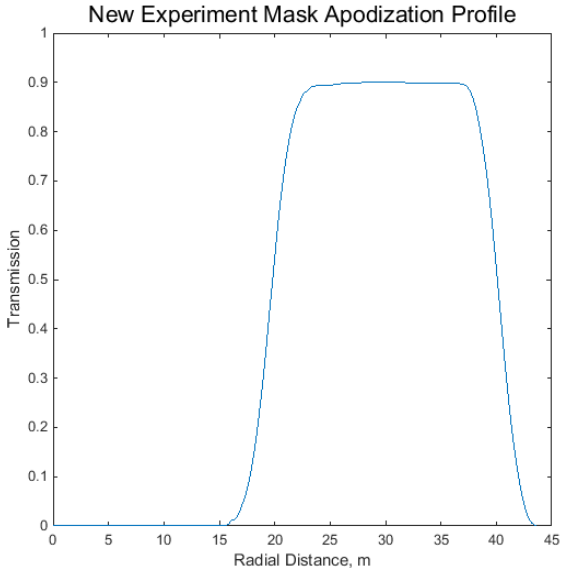
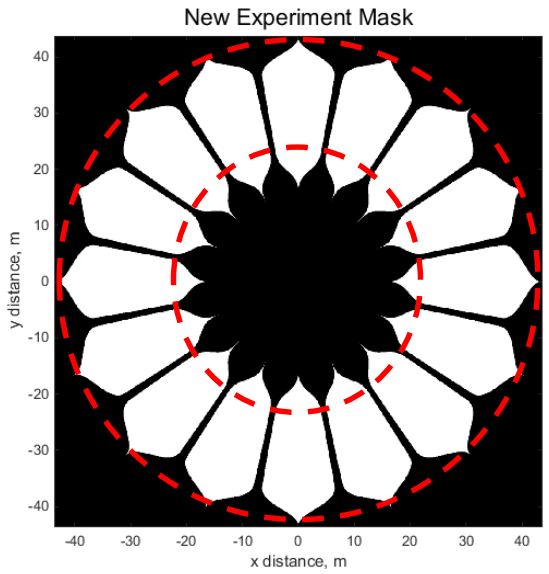
Parameter	Space Scale
Separation	55,000 km
Outer radius	43.7 m
Inner radius	21.9 m
Outer opaque	35.0 m
Inner opaque	14.9 m
Shadow Diameter	6 m
Telescope Diameter	4 m
Smoothness	0.1
lambda range	500 – 850 nm
Fresnel Number@600 nm	14.5
Suppression constraint	10^{-11}





Starshade Design Process for New Lab

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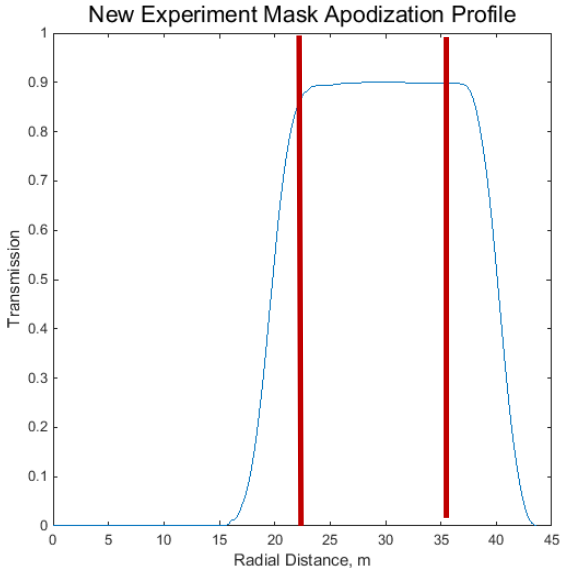

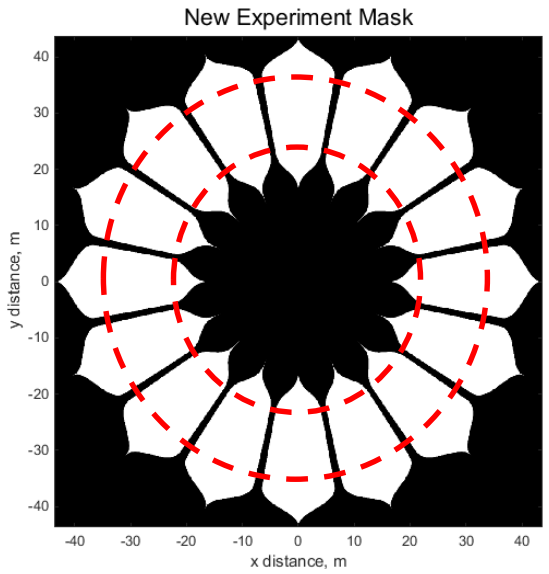

Starshade Design Process for New Lab

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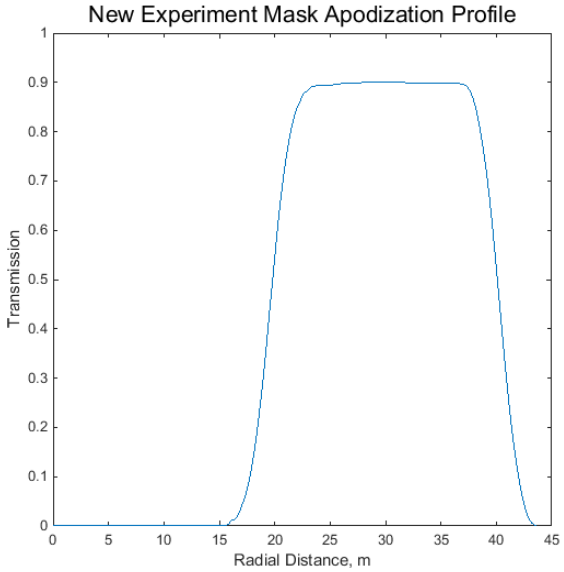
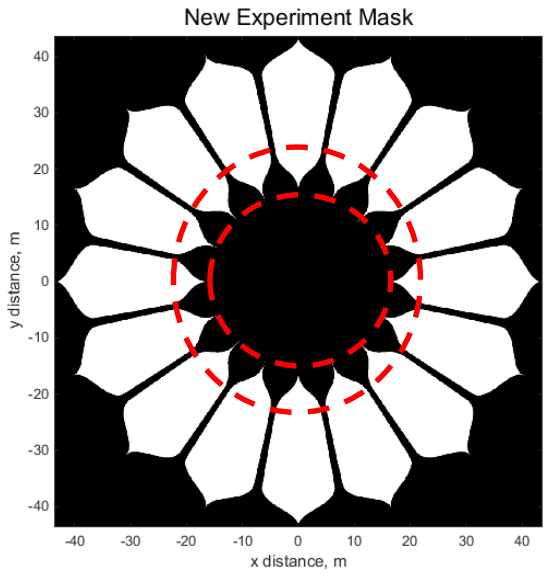
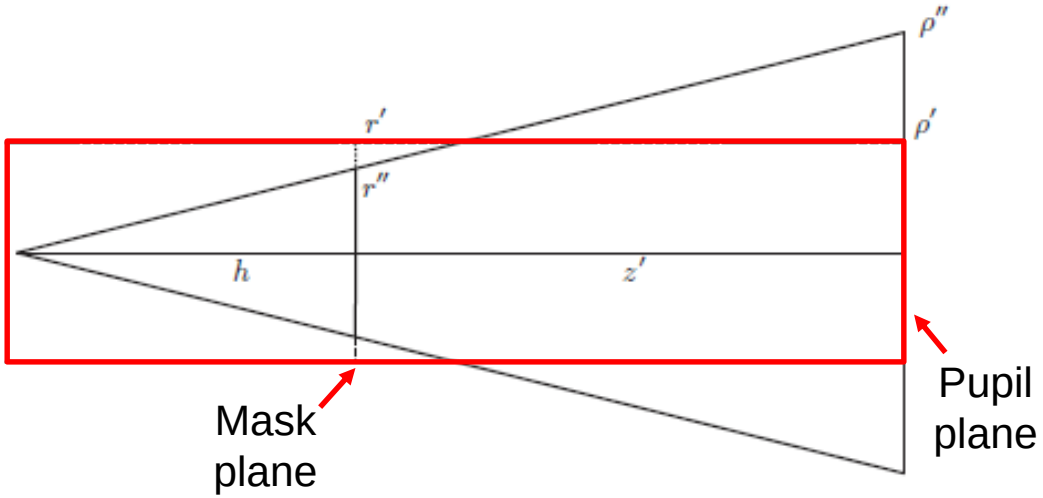
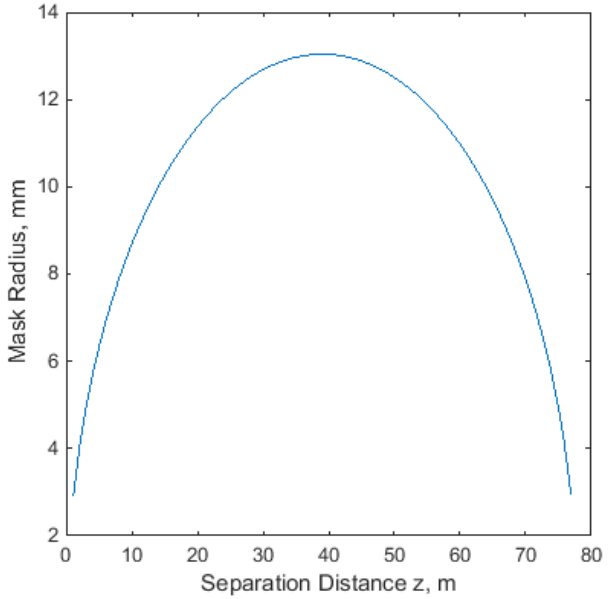


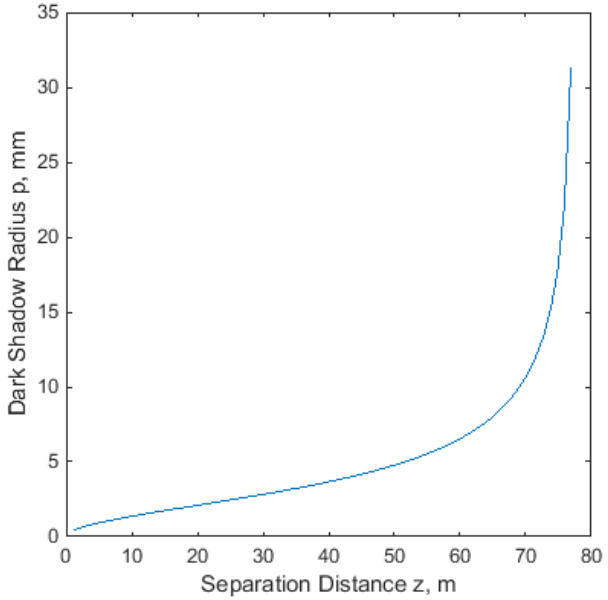


Divergent Beam Scaling



labZ (m)	Mask Radius (mm)	Dark Radius (mm)	Margin (mm)
39	13.0	3.6	± 1.9
50	12.5	4.8	± 3.1
60	11.0	6.5	± 4.8
65	9.7	8.0	± 6.3
70	7.9	10.6	± 8.9





Lab Scale Parameter

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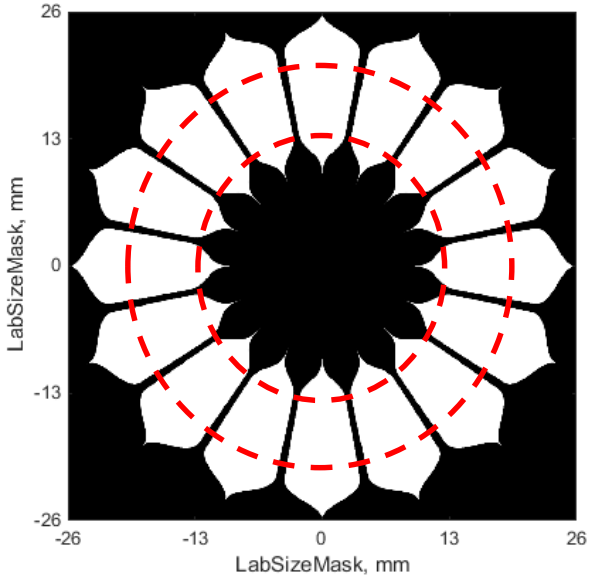
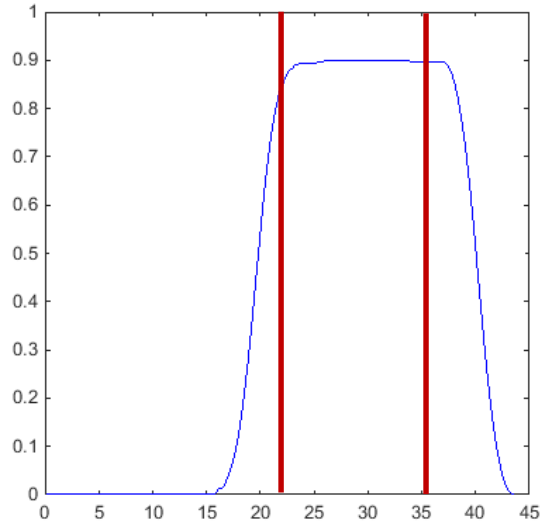
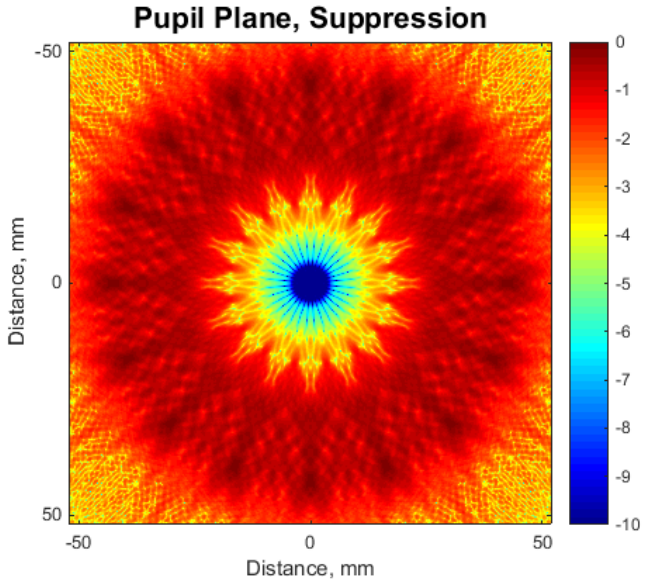
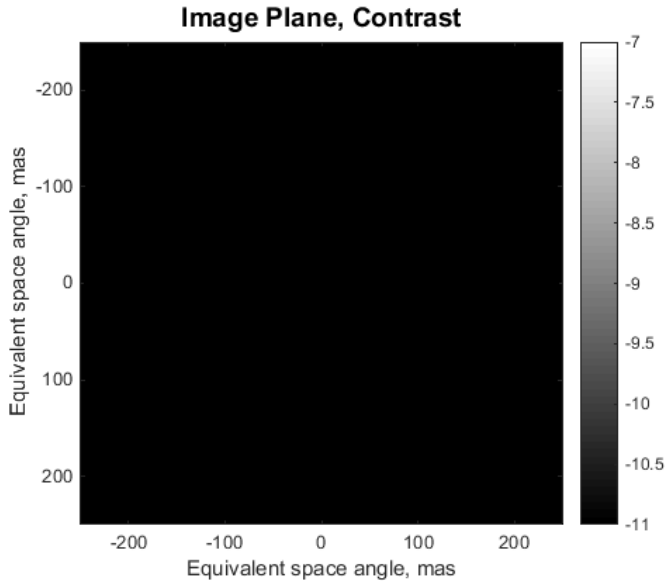
Parameter	Space Scale	Lab Scale
Separation Z	55,000 km	39 m
Outer radius	43.7 m	26 mm
Inner radius	21.9 m	13 mm
Outer opaque	35.0 m	29 mm
Inner opaque	14.9 m	8.8 mm
Shadow diameter	6 m	7.2 mm
Telescope diameter	4 m	3.4 mm
smoothness	0.1	0.1
lambda range	500 – 850 nm	
Fresnel Number @600 nm	14.5	14.5



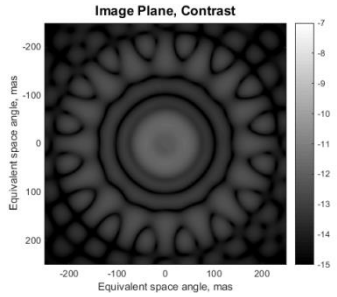


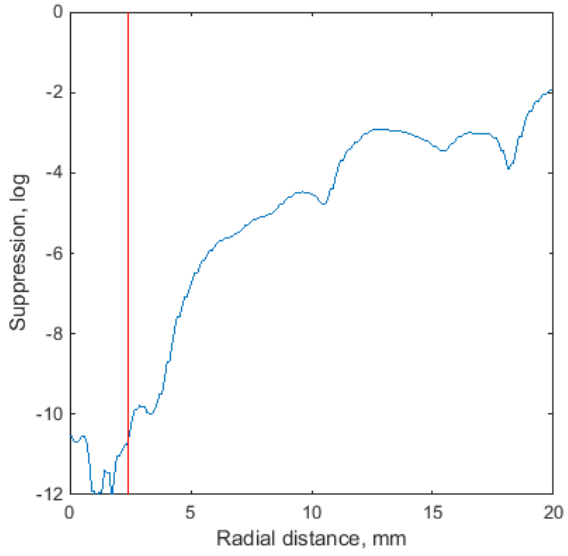
Ideal Simulation

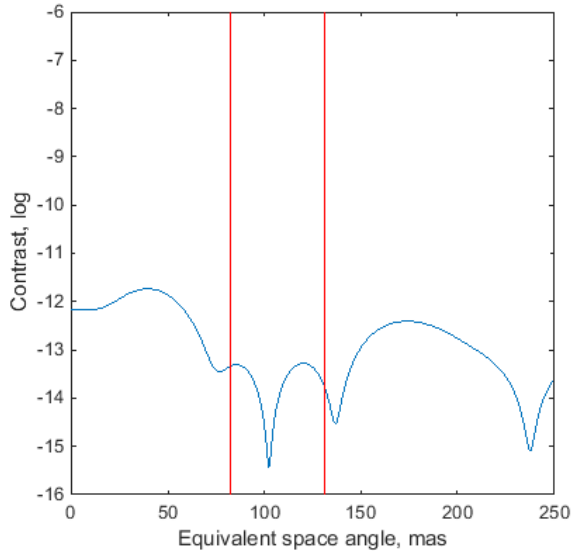




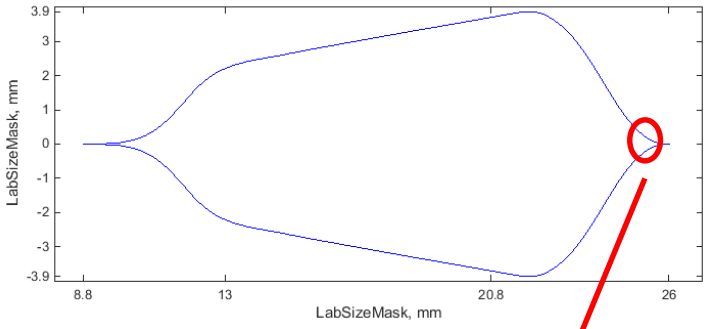
λ = 633 nm

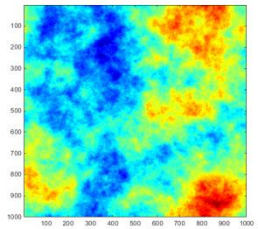






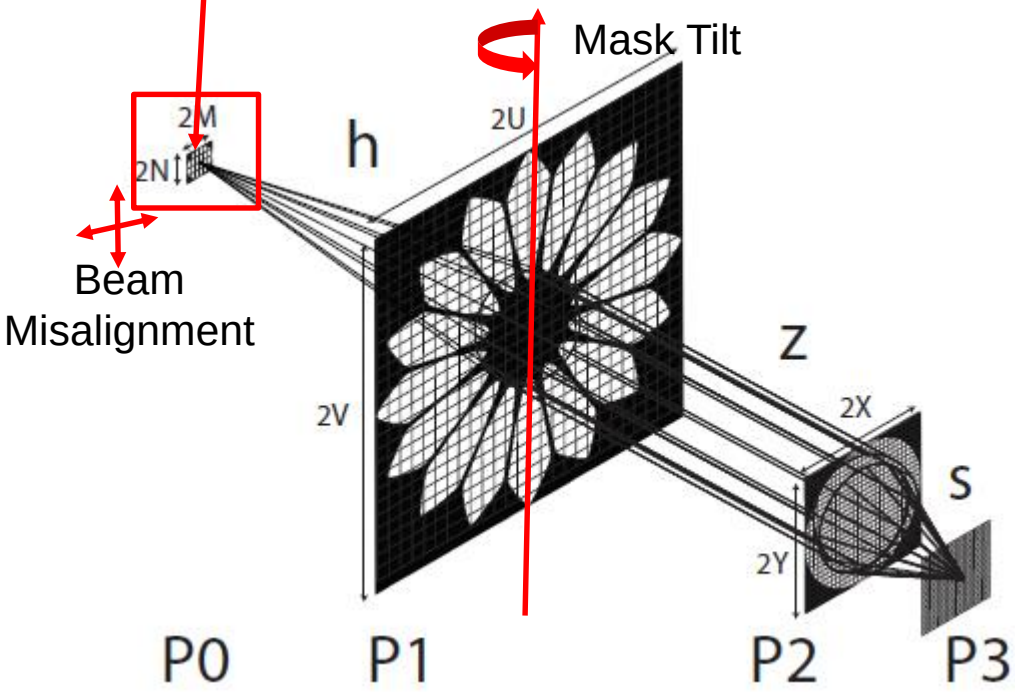
2D Simulation with Sensitivity Analysis





Optics Aberrations

Feature Accuracy

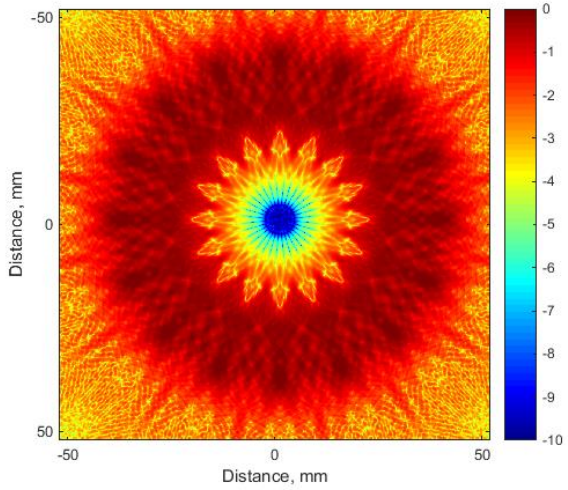


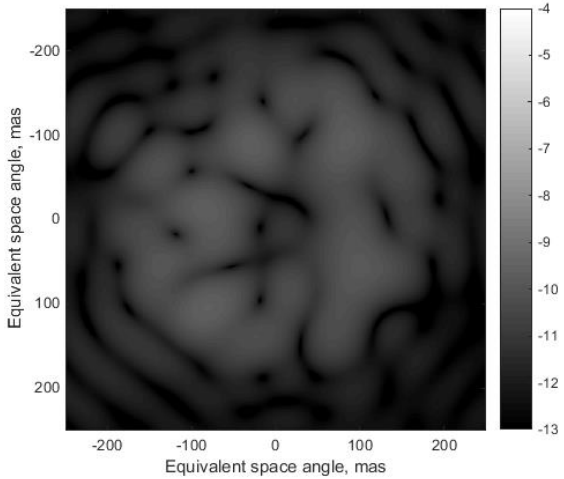
Error Parameter
Feature Accuracy
Edge Perturbation
Optics Aberrations
Diagonal Beam Misalignment
Mask Tilt

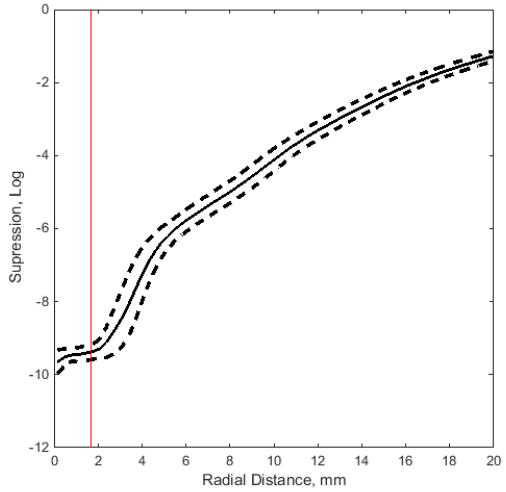
Ref. D. Sirbu 2014 Thesis

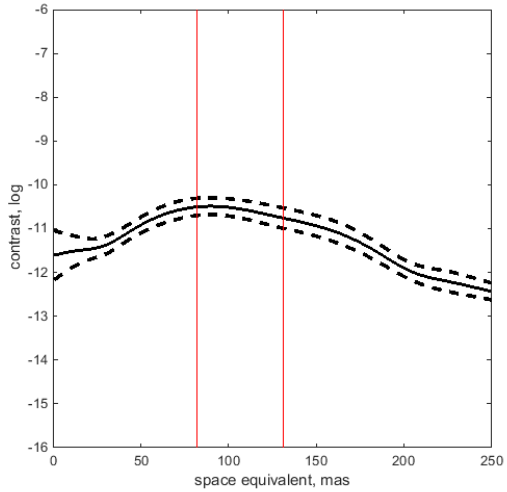
All Error Combined Simulation

Error Parameter	Budget
Feature Accuracy	0.25 μm
Edge Perturbation	0.5 μm
Optics Aberrations	λ/10 ≈ 60 nm
Diagonal Beam Misalignment	2 mm
Mask Tilt	1°

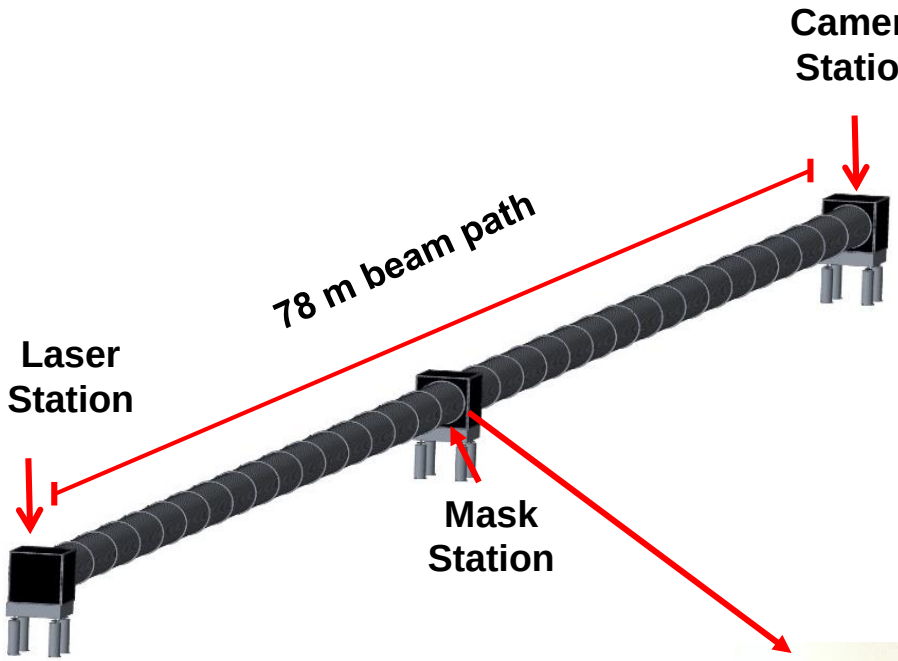


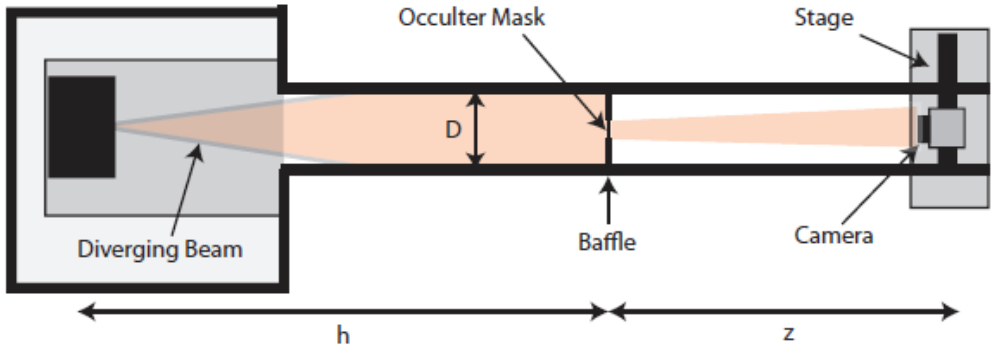


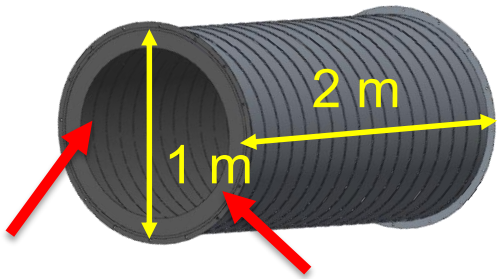




Testbed Design

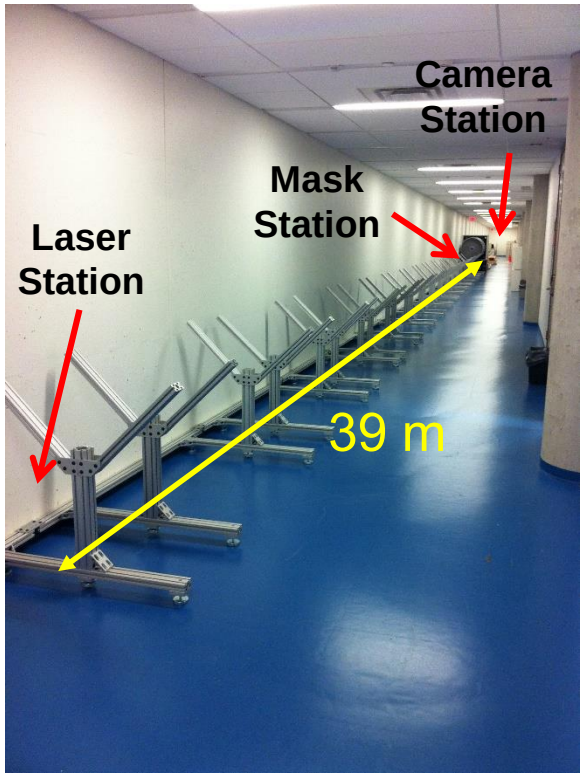






Entire inner surface painted black

Black baffle plates at each segment joint

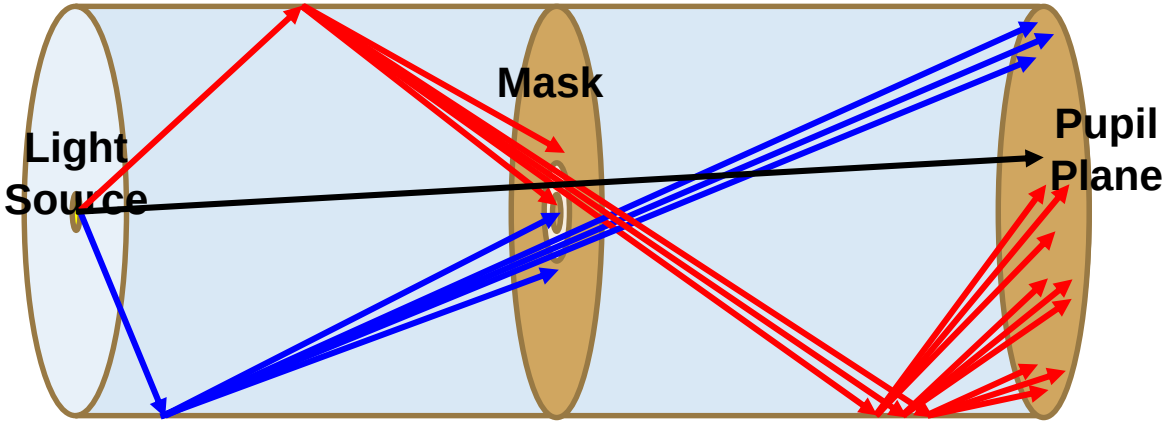


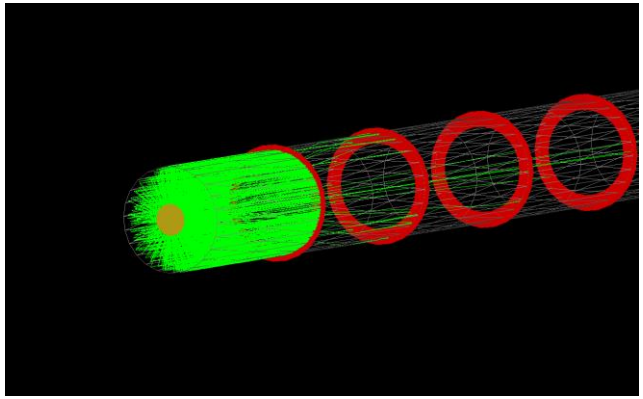
Stray Light Analysis

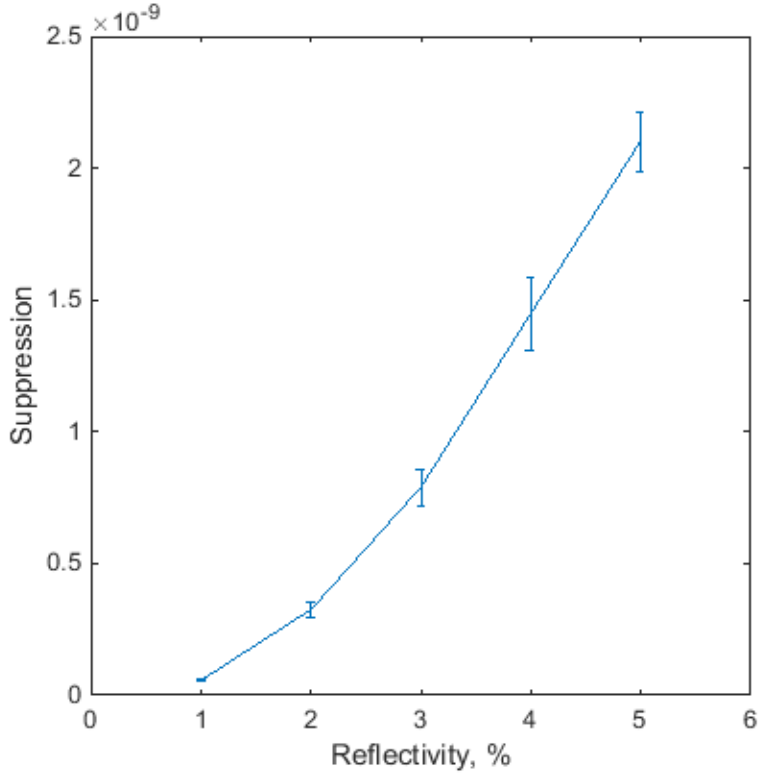
Path 1 : No scattering ; light source → pupil plane, directly

Path 2 : 1st scattering ; light source → tube 1(1st scat) → pupil plane

Path 3 : 2nd scattering ; light source → tube 1(1st scat) → tube 2(2nd scat) → pupil plane







Most of the stray light can be blocked when we set 0.8 m diameter

Summary

PRINCETON UNIVERSITY

- We designed a starshade for scaled experiment in lab and performed error analysis to check the reliability of the design.
- We are in the process of evaluating the sensitivity to wavefront error in the tube and plan to measure the wavefront directly using a wavefront sensor
- We are modifying baffle design to remove stray light due to reflection of the enclosure.
- We expect the entire installation to be completed with first light by mid-December.

Thank you for your attention!