Princeton Progress and Opportunities in Starshade Optical Testing

N. Jeremy Kasdin[1], Yunjong Kim[1], Dan Sirbu[2], Michael Galvin[1], Robert J. Vanderbei[1]

[1]Princeton University
[2]NASA Ames Research Center

Starshade Work at Princeton

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

Laboratory Scaling

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

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

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 maintains 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

Original Princeton Testbed

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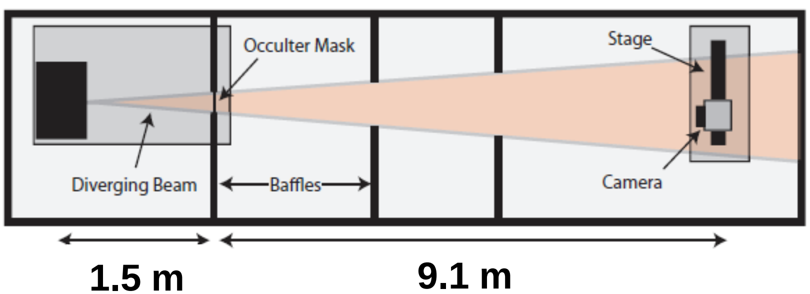
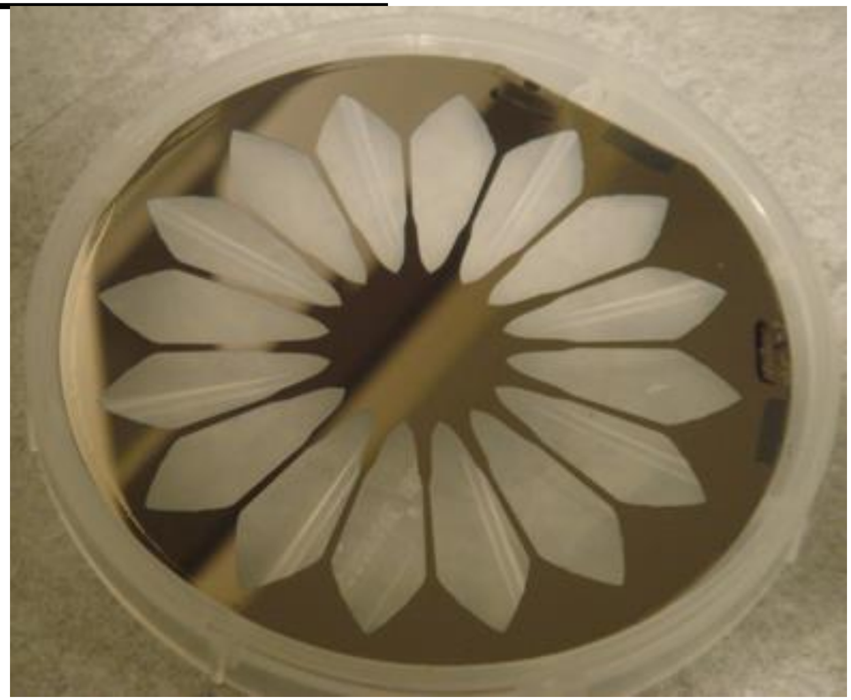
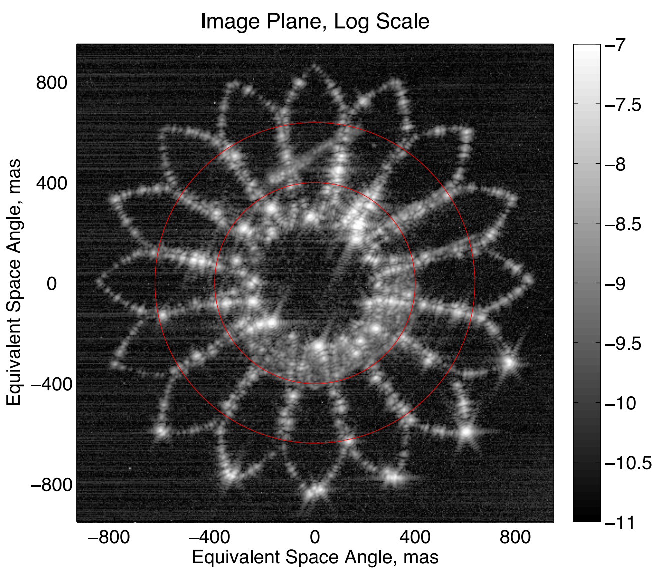
Design	Occulter Radius	Separation	Telescope Diameter	Fresnel Number
THEIA	20 m	55,000 km	4 m	12.1
O3	15 m	21,000 km	1.1 m	17.9
Previous Exp.	188 m	97,000 km	17 m	607.3



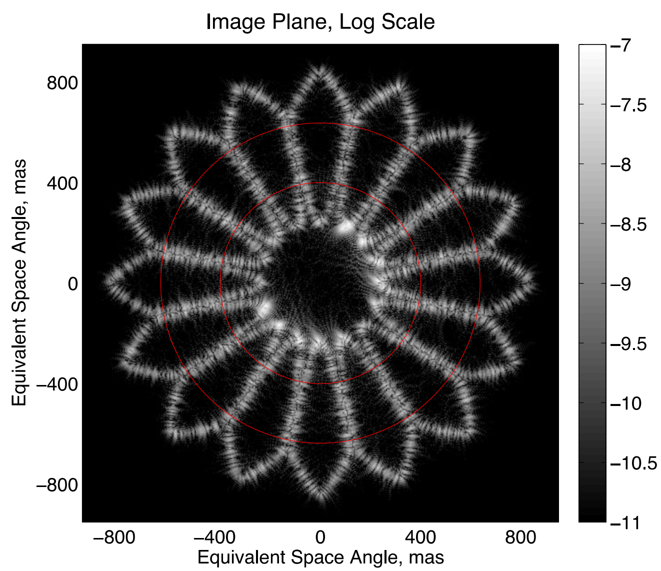


Original Princeton Testbed

Combined Errors



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



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

Final result with 2 micron manufacturing resolution

$\longrightarrow$ Largest sources of performance degradation are manufacturing feature size and edge perturbations

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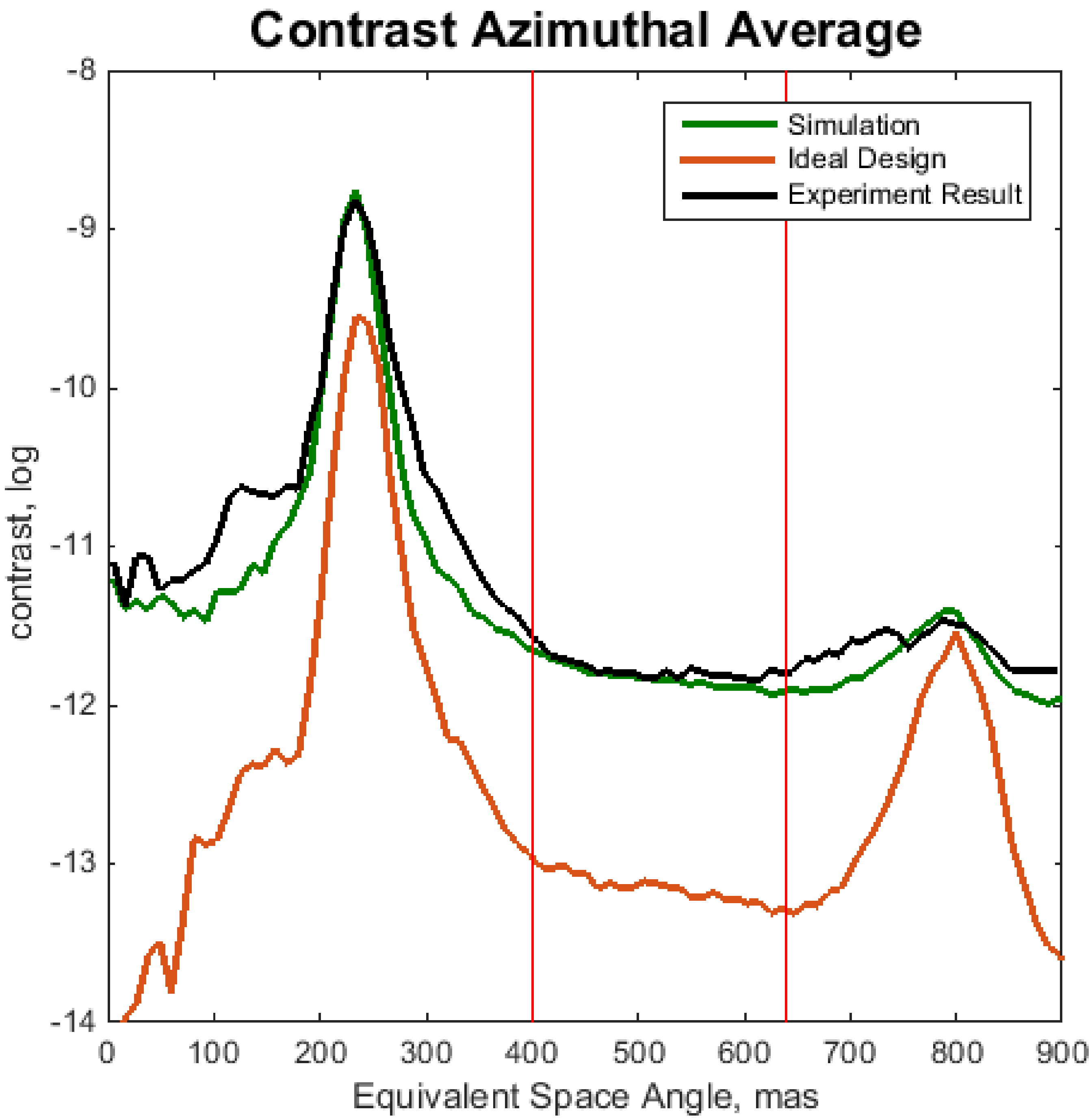
Equivalent space angle, mas



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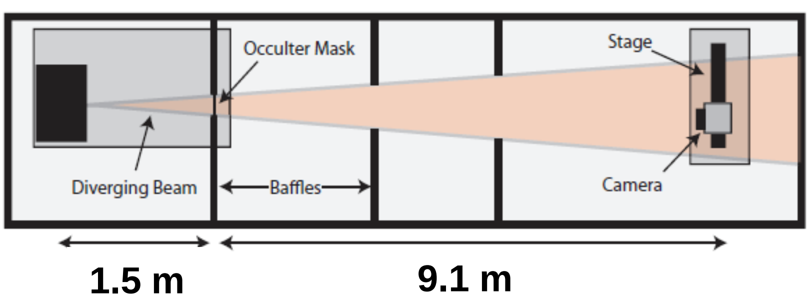
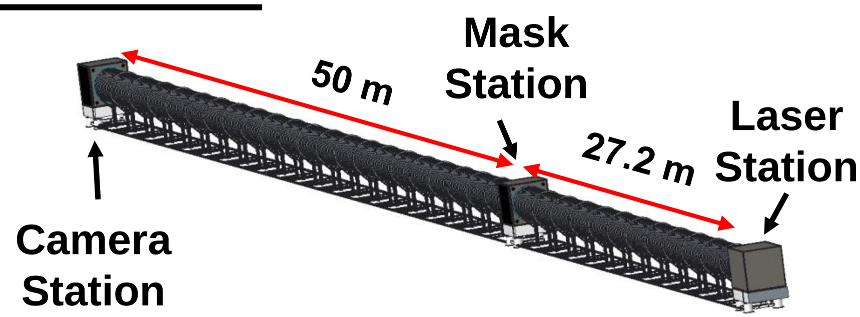
Objective of New Experiment

- 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)

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	2.4 m	14.5

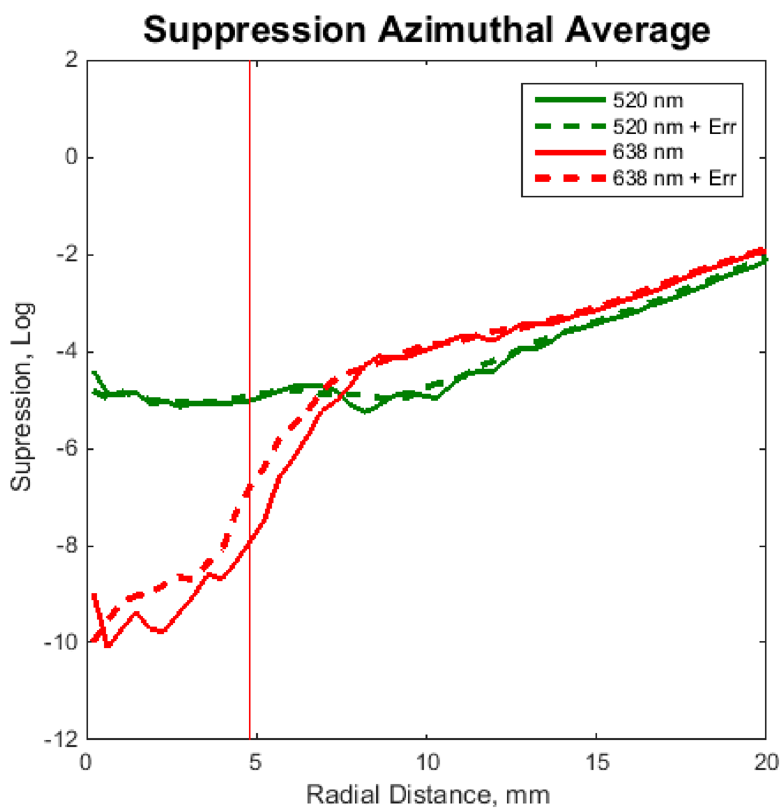


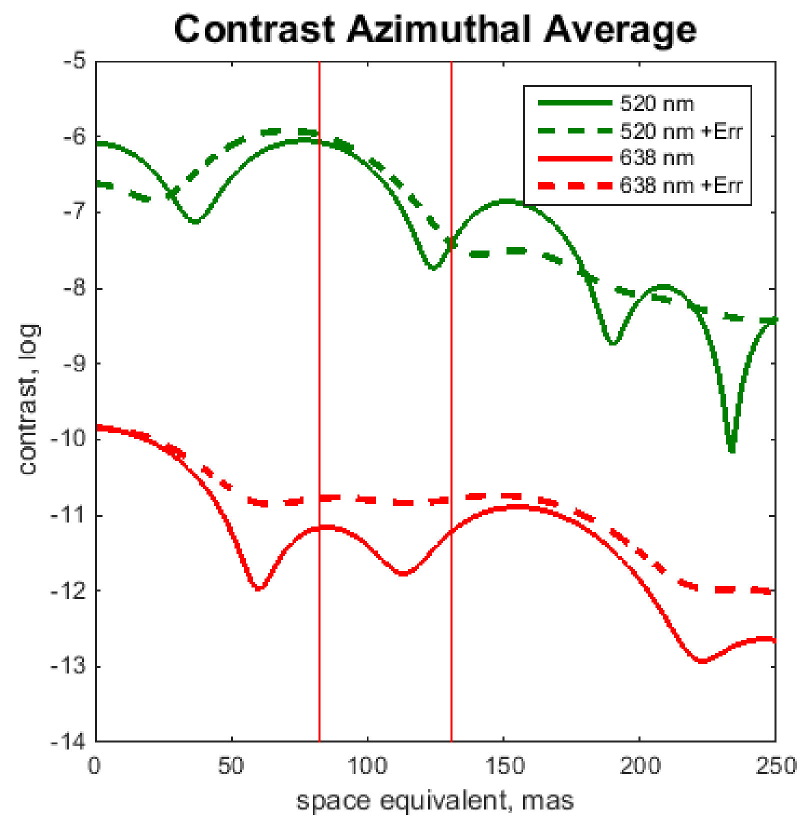
Previous Testbed



New Testbed

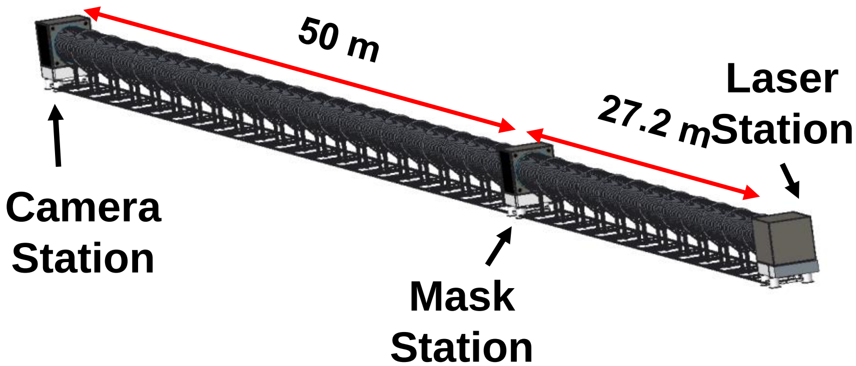
Expected Performance

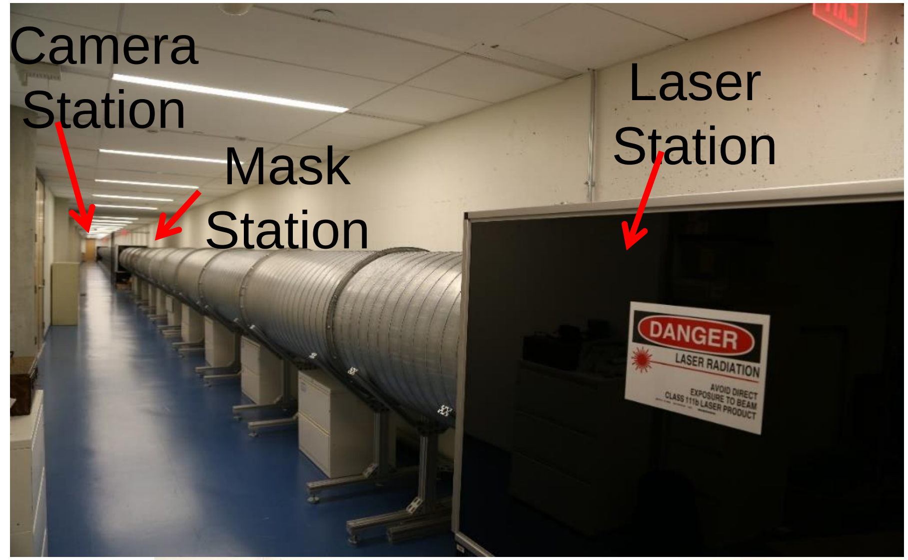


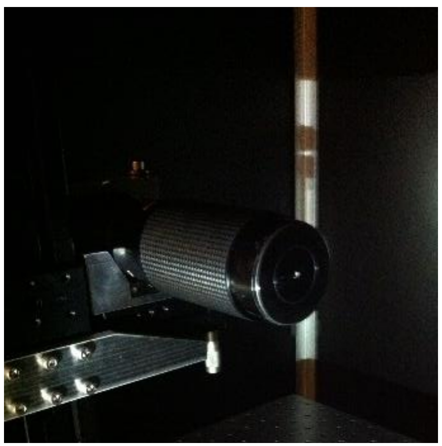


Error Parameter	Feature Size	Edge Perturbation	Beam Misalignment	Pinhole Aberration	Mask Tilt	Camera Aberration
Budget	0.5 um	0.1 um	1.0 mm	60 nm	1 deg	60 nm

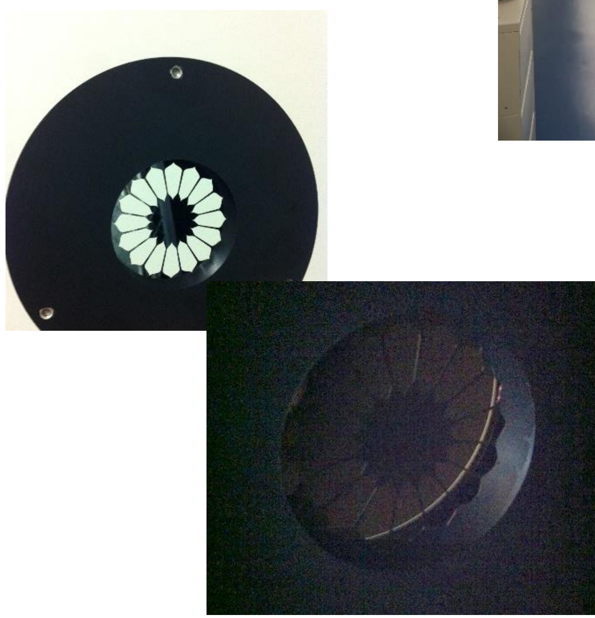
Testbed Setup



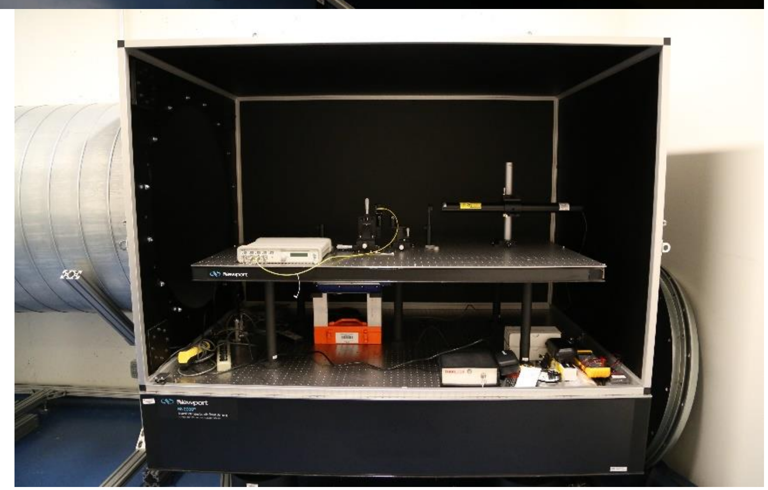




Camera Station

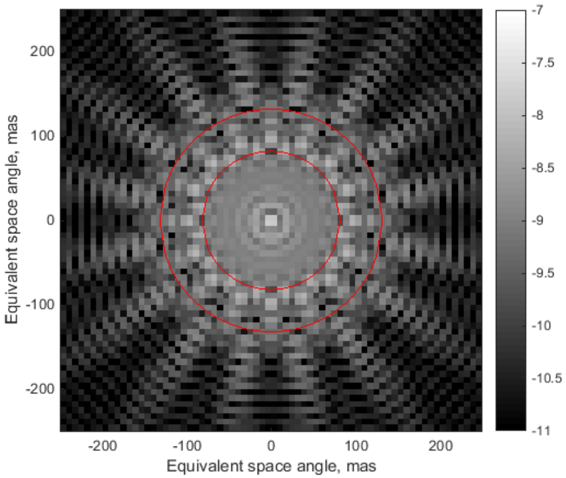


Mask Station (Manufactured by the MDL of the JPL)

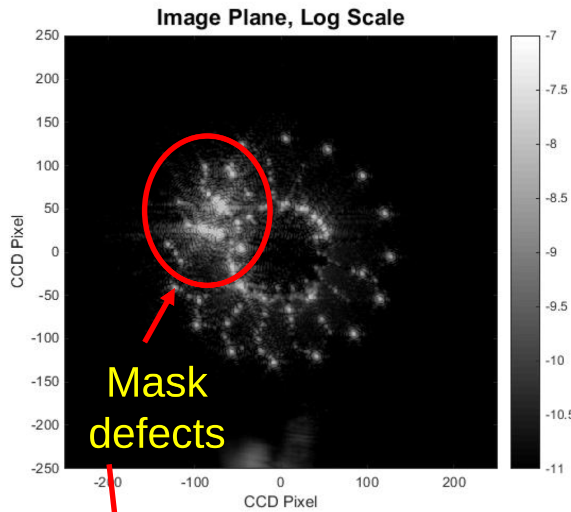


Laser Station

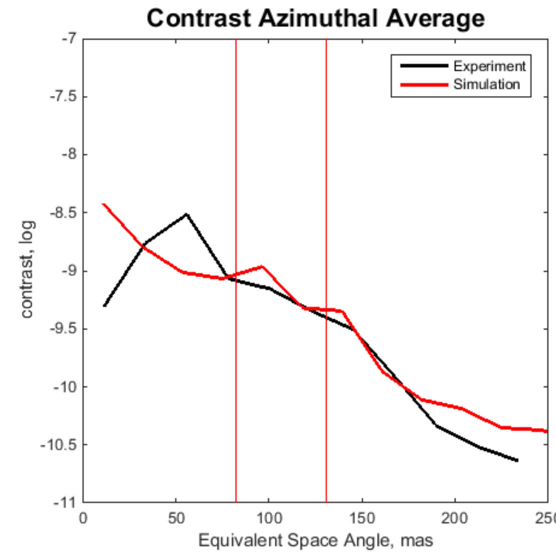
Contrast at Large Aperture – 638 nm



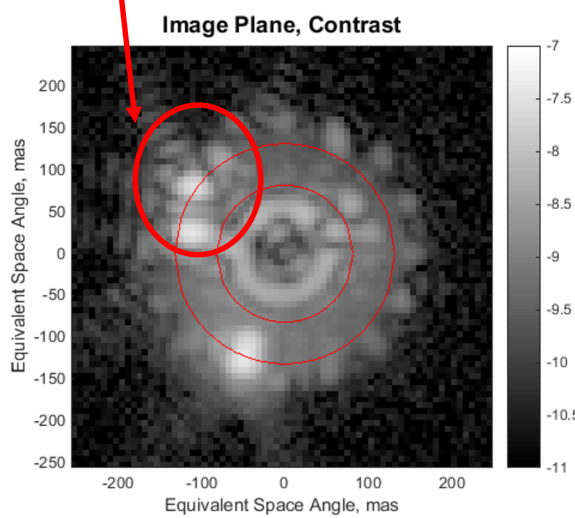
Ideal Simulation



Previous Testbed



Large Aperture
(Diameter 13.6 mm)



New Testbed

- 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

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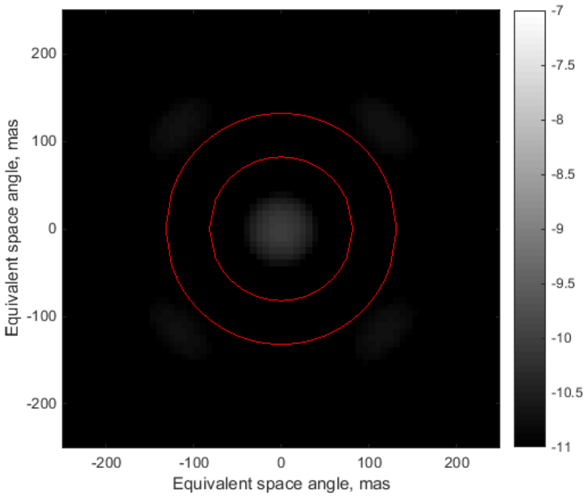
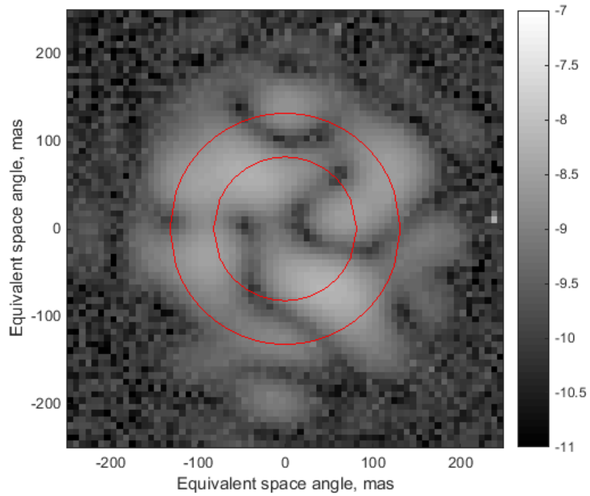
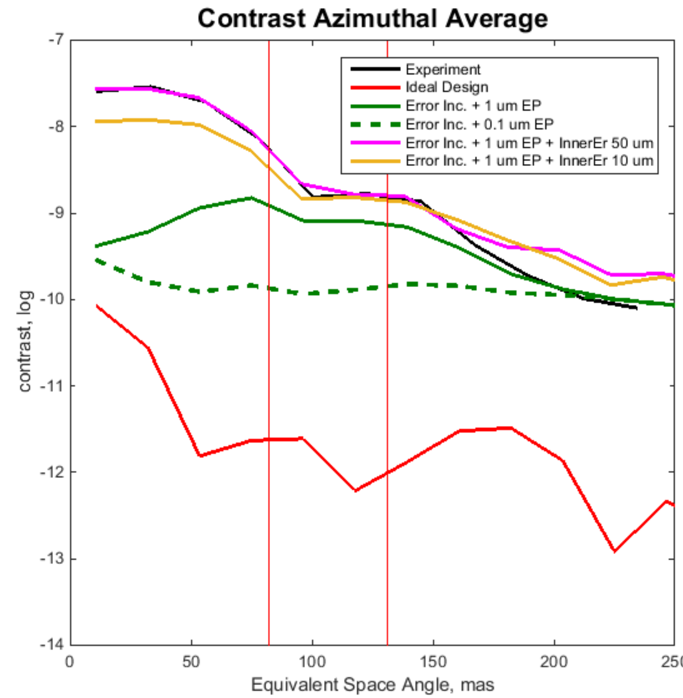
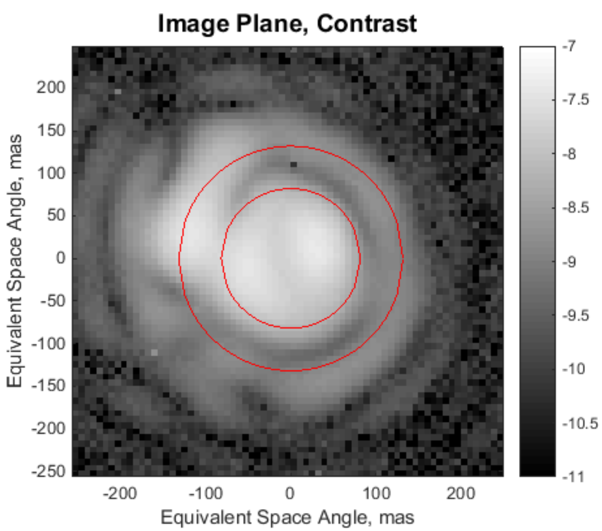


Ideal Simulation

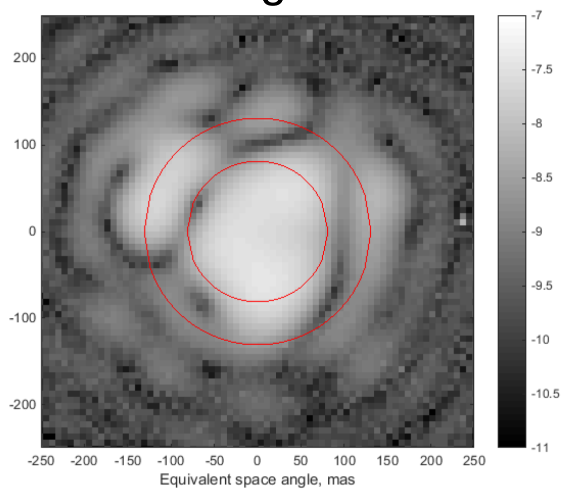


Error Included + 1um Edge Pert.





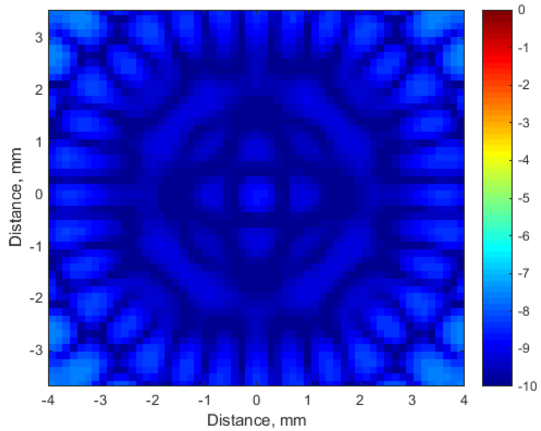
Experiment



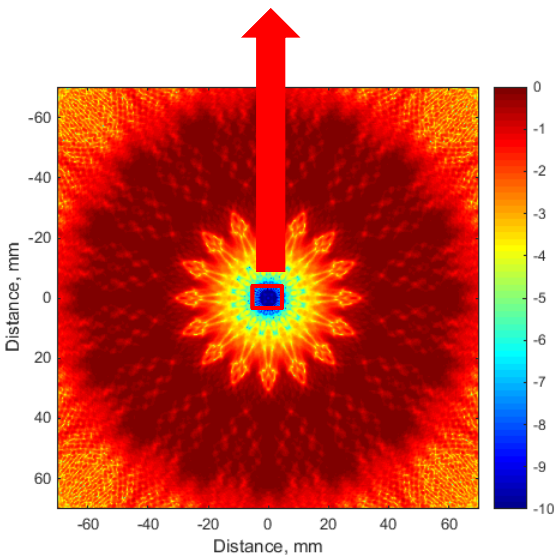
Error Included + 1um EP. + 50 um Inner

- 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

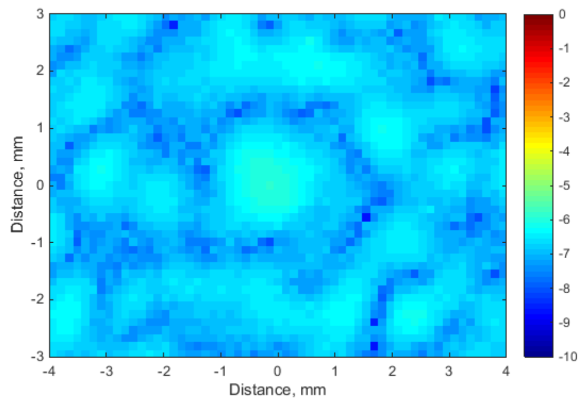
Suppression – 633 nm



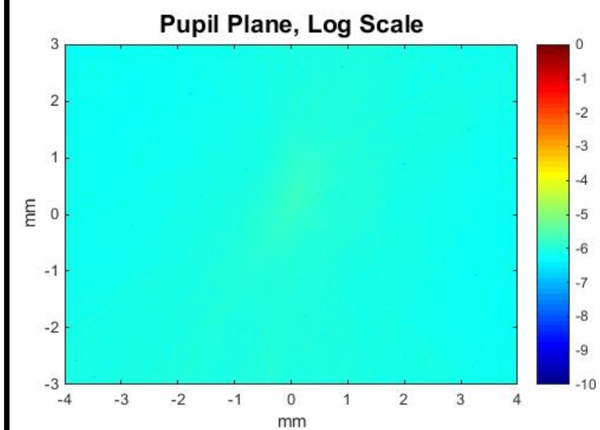
Zoom-In Center region



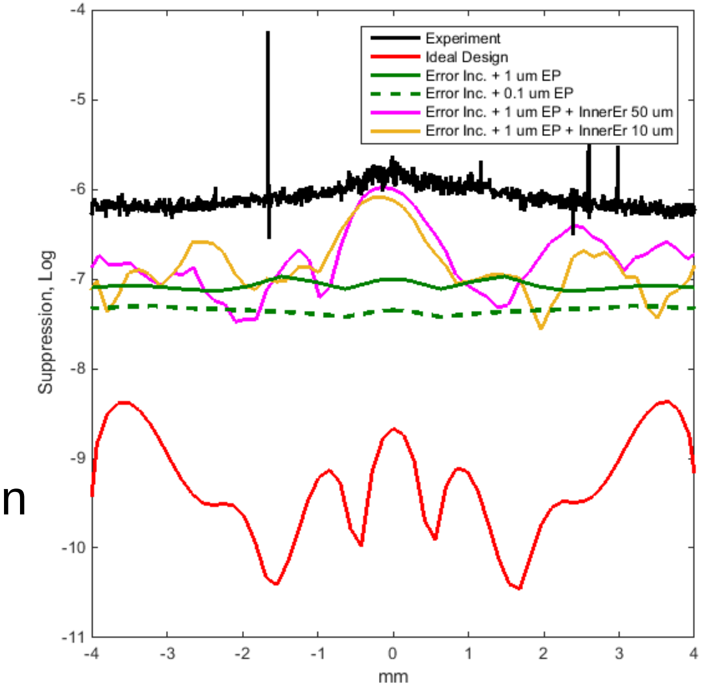
Ideal Simulation



Error Inc. + 1um EP.
+ 50 um Inner Pert. Simulation

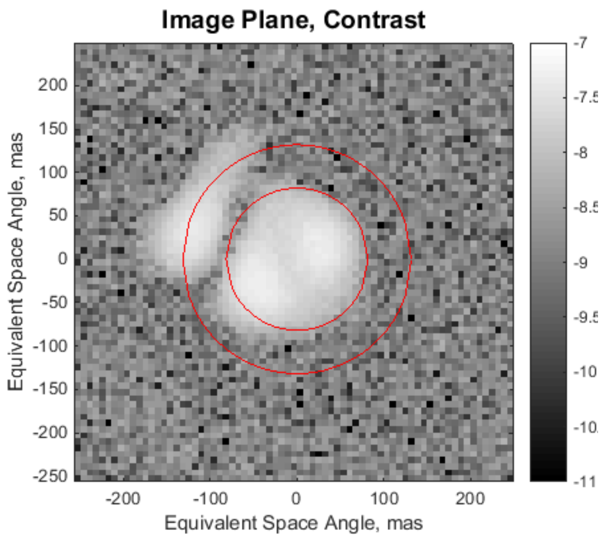


Experiment

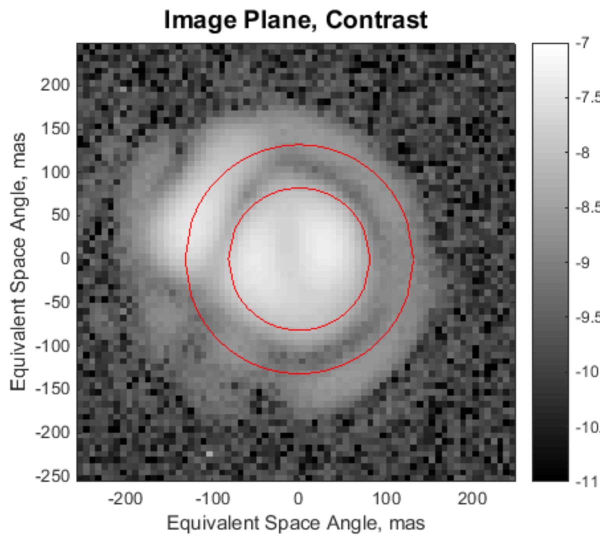


- Suppression reached a limit due to mask defect and stray light
- Gap between experiment and simulation with inner error will be the camera noise

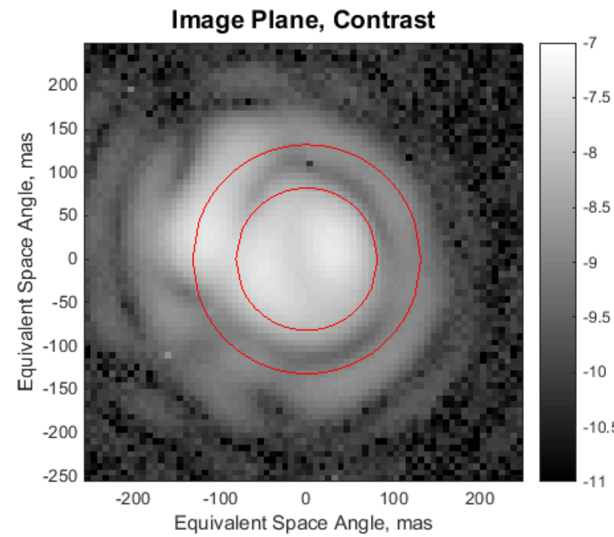
Contrast Stability – 633 nm



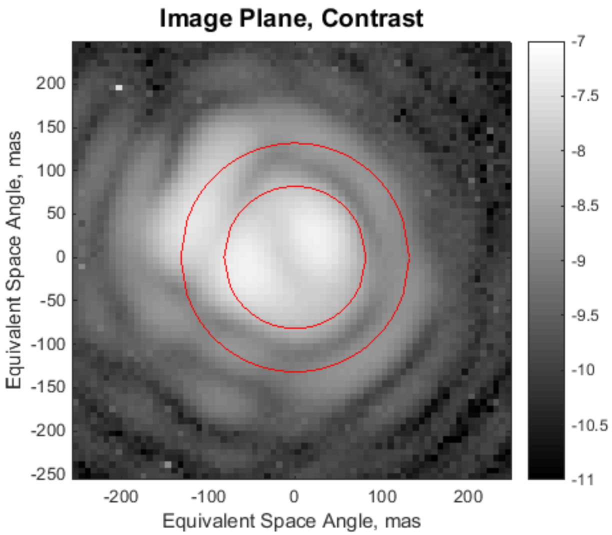
50s



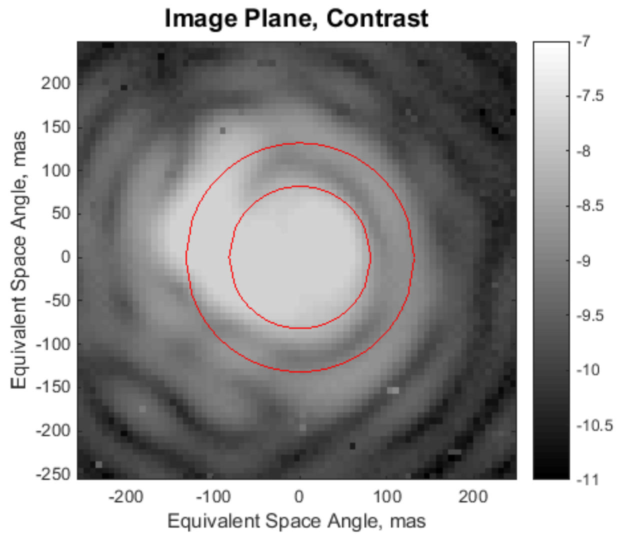
500s



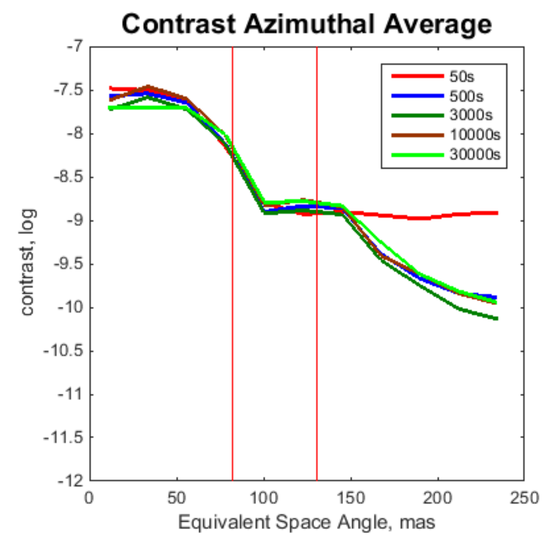
3000s



10000s



30000s



Summary

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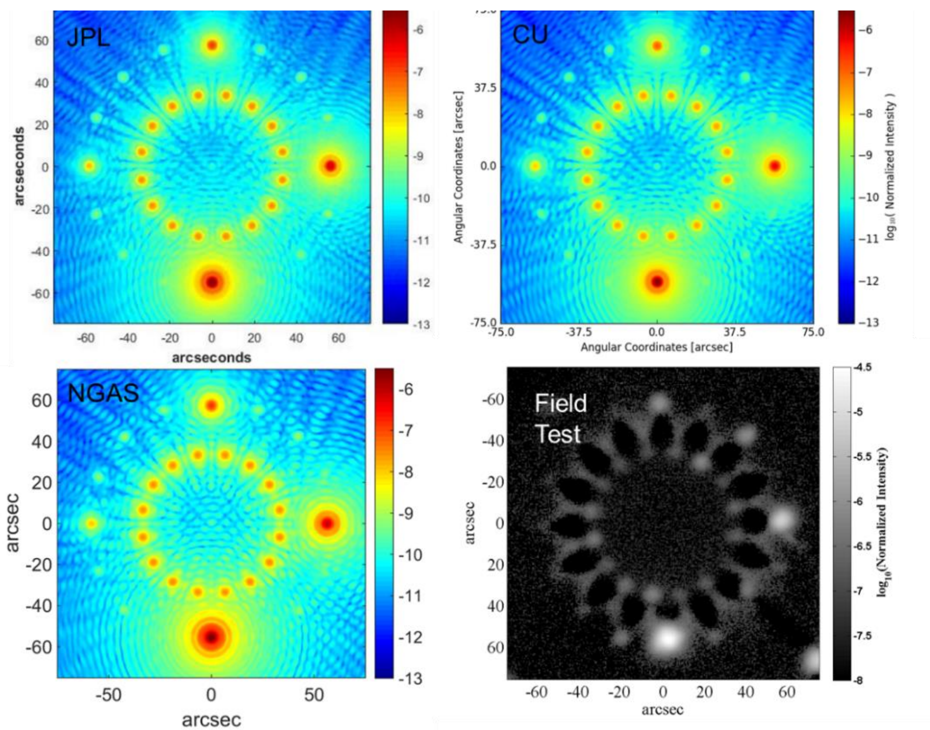
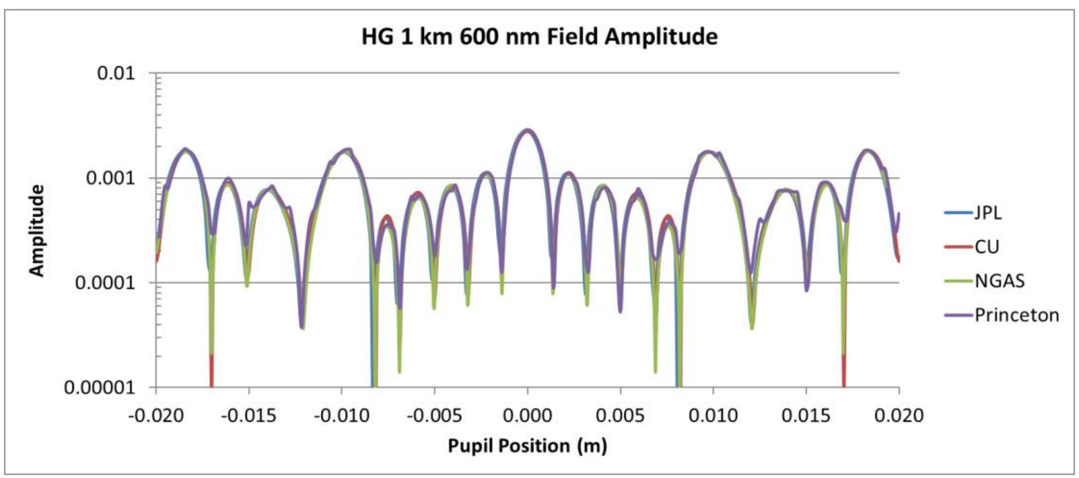
- We achieved a first light result for a starshade at flight Fresnel number 14.5 with 10^{-9} contrast and 10^{-6} suppression at 633 nm
- From the analysis the inner petal region is brighter than design
- Limiting factor of current setup is mask defects, accuracy and stray light
- Images extremely stable 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.





Case	Contrast			Ratio	
	CU	NGAS	JPL	JPL/CU	JPL/NGAS
HG_DISPLACED_EDGES	2.22E-07		2.19E-07	0.99	
	4.89E-07		4.73E-07	0.97	
	7.02E-07		6.97E-07	0.99	
	5.64E-08		5.40E-08	0.96	
HG_PETAL_CLOCKING	6.66E-06	6.80E-06	6.53E-06	0.98	0.96
	1.14E-05	1.16E-05	1.12E-05	0.98	0.97
	3.16E-06	3.26E-06	3.11E-06	0.99	0.95
	9.65E-07	9.92E-07	9.51E-07	0.99	0.96
HG_SHRUNK_PETALS	1.19E-06	1.16E-06	1.18E-06	0.99	1.02
	6.24E-07	5.93E-07	6.16E-07	0.99	1.04
	1.96E-06	1.92E-06	1.94E-06	0.99	1.01
	2.92E-06	2.85E-06	2.88E-06	0.98	1.01
HG_SINES	8.61E-08	1.12E-07	8.48E-08	0.98	0.76
	1.93E-07	2.52E-07	1.91E-07	0.99	0.76
	2.33E-08	2.59E-08	2.29E-08	0.98	0.88
	4.73E-08	5.23E-08	4.66E-08	0.99	0.89
HG_TRUNCATED_VALLEYS	2.45E-06	2.60E-06	2.43E-06	0.99	0.93
	5.77E-06	5.93E-06	5.66E-06	0.98	0.95
	9.13E-07	9.85E-07	8.95E-07	0.98	0.91
	3.29E-07	3.54E-07	3.25E-07	0.99	0.92
HG_CLIPPED_TIPS	1.30E-07	1.40E-07	1.28E-07	0.99	0.92
	7.64E-07	8.73E-07	7.57E-07	0.99	0.87
	3.46E-06	4.11E-06	3.43E-06	0.99	0.83
	1.38E-08	1.09E-08	1.36E-08	0.99	1.25

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!