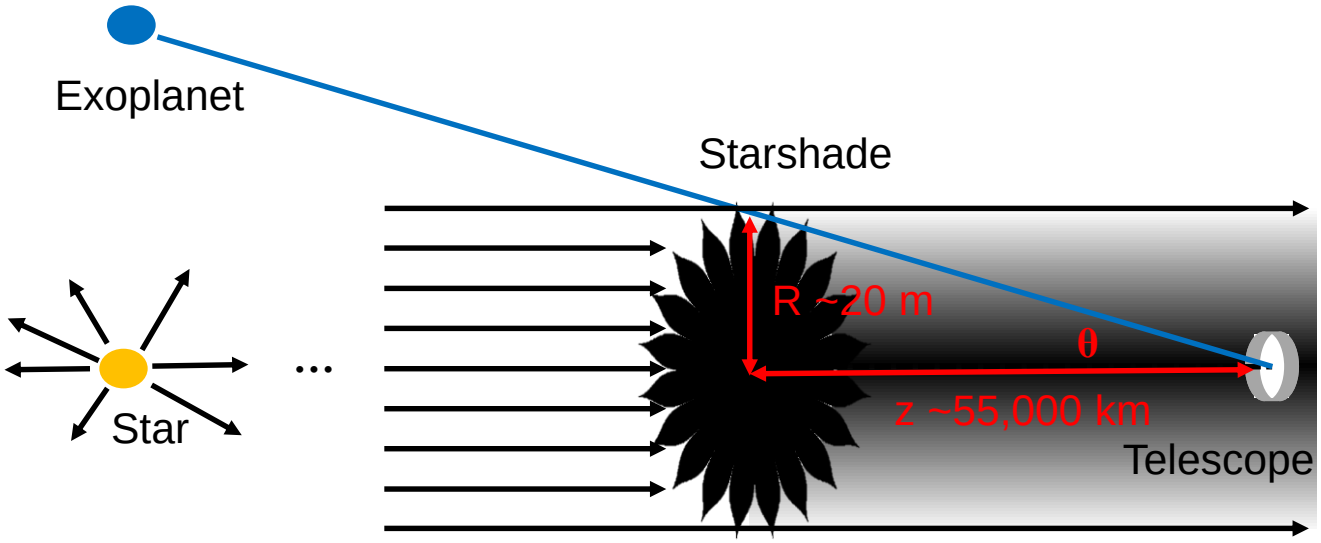
# Optical Demonstrations of a Starshade at Flight Fresnel Number

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

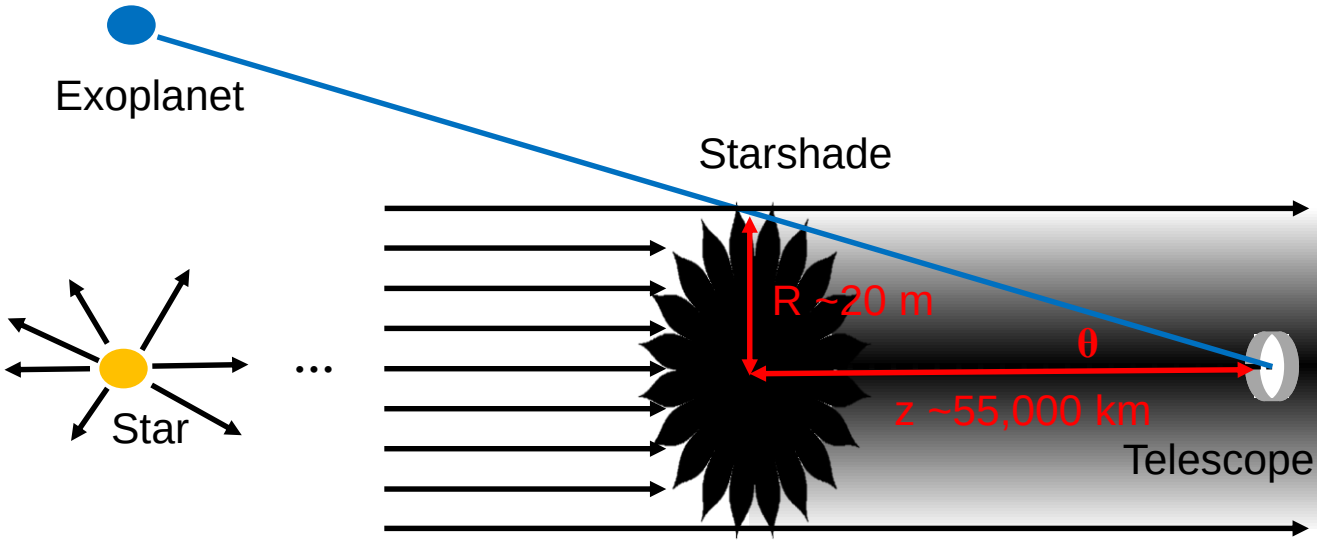
[1]Princeton University
[2]NASA Ames Research Center

# 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: $\tan\theta = R/z$ ; 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

# Introduction




- 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

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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
$\rho$: 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 ($R^2/\lambda z$)

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

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

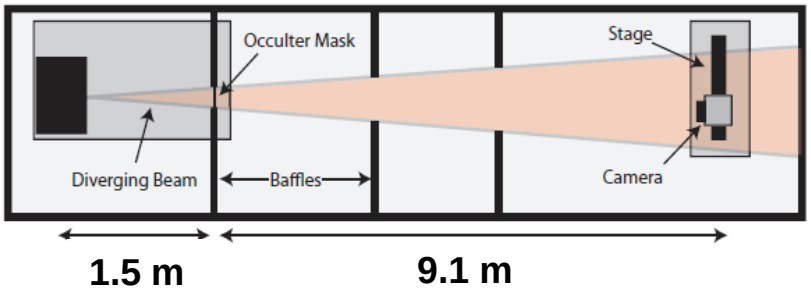
$r'$: radius of scaled starshade in lab
$\rho'$: radius of scaled shadow in lab
$z'$: distance between scaled starshade & camera
$s$: scaling factor

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

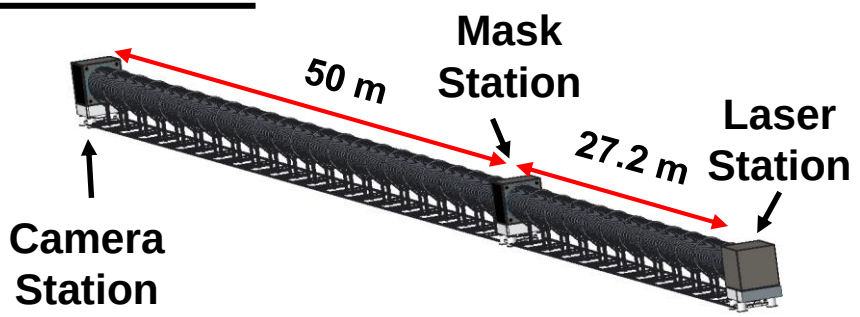
# Objective of New Experiment

- 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 | Starshade 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 |



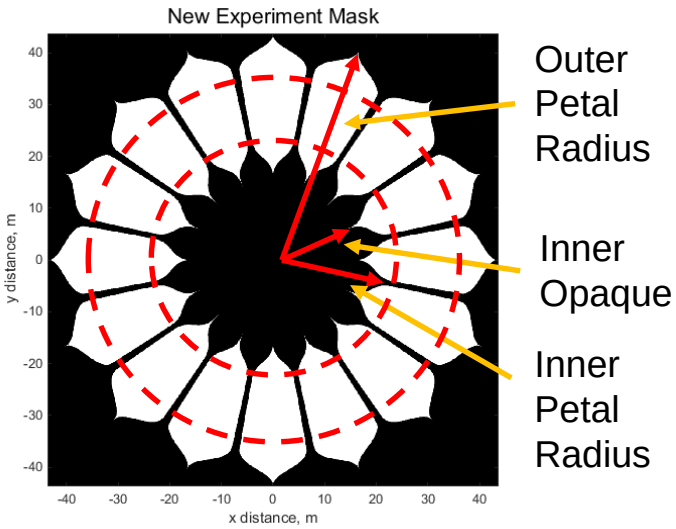

Previous Testbed



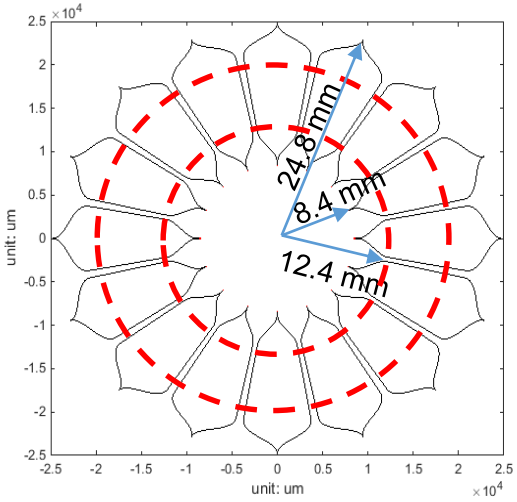

New Testbed

# Design Parameter

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

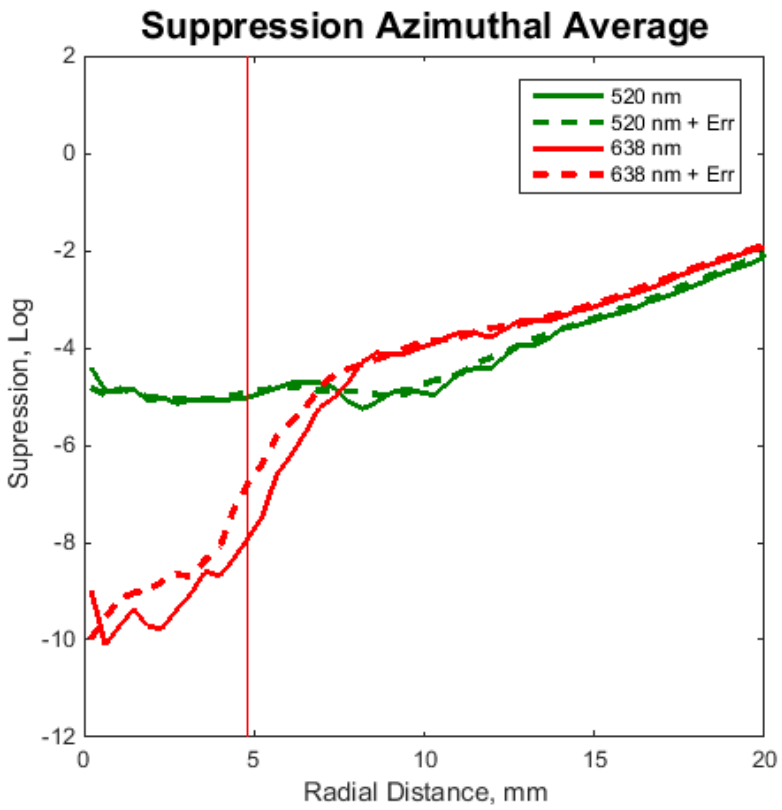


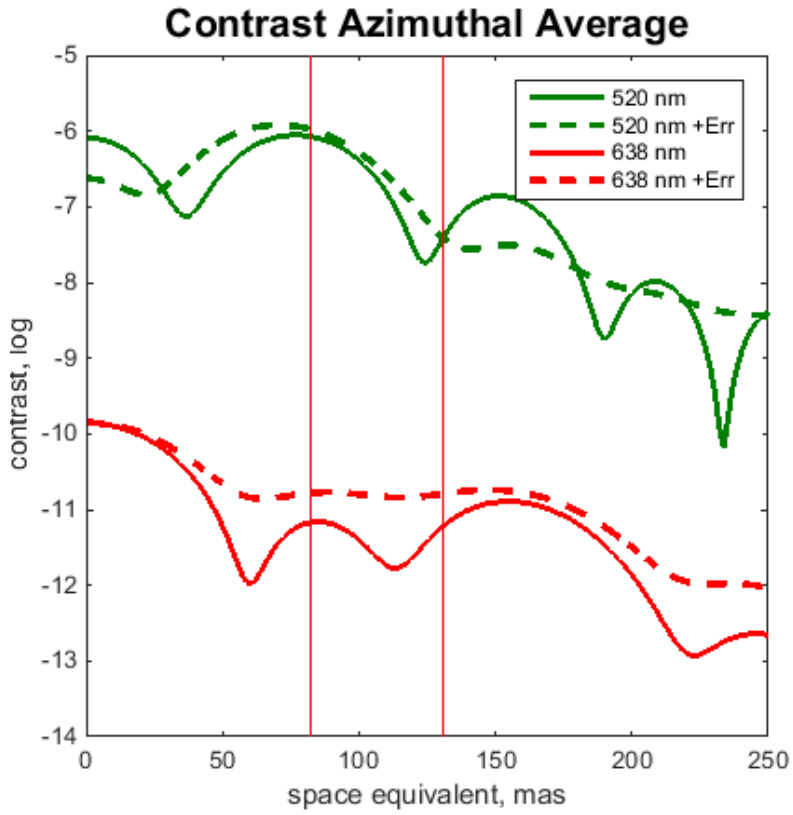

Space Scale Mask




Lab Scale Mask

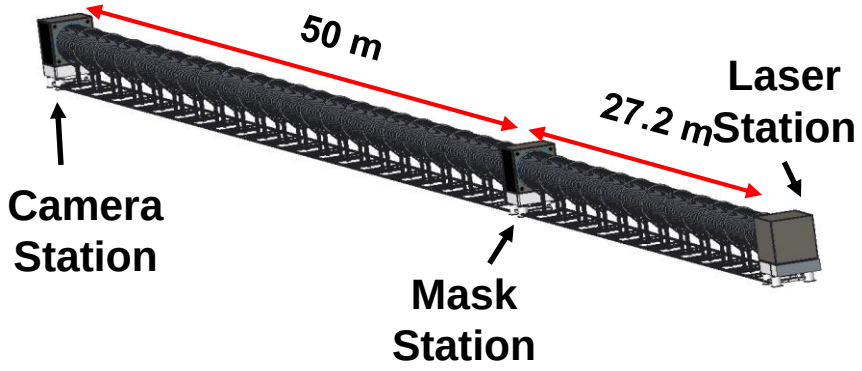
# Expected Performance



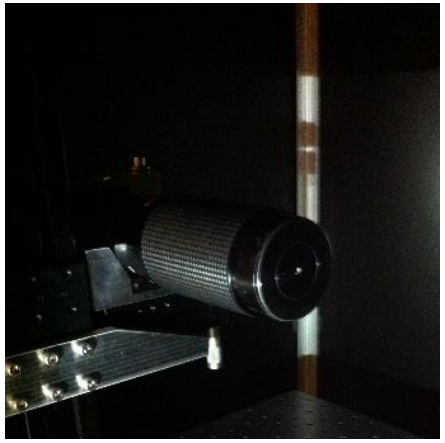




| Error Parameter | Feature Size | Edge Perturbation | Beam Misalignment | Pinhole Aberration | Mask Tilt | Camera Aberration |
|---|---|---|---|---|---|---|
| Budget | 0.5 um | 0.1 um | 1.0 mm | 60 nm | 1 deg | 60 nm |

# Testbed Setup

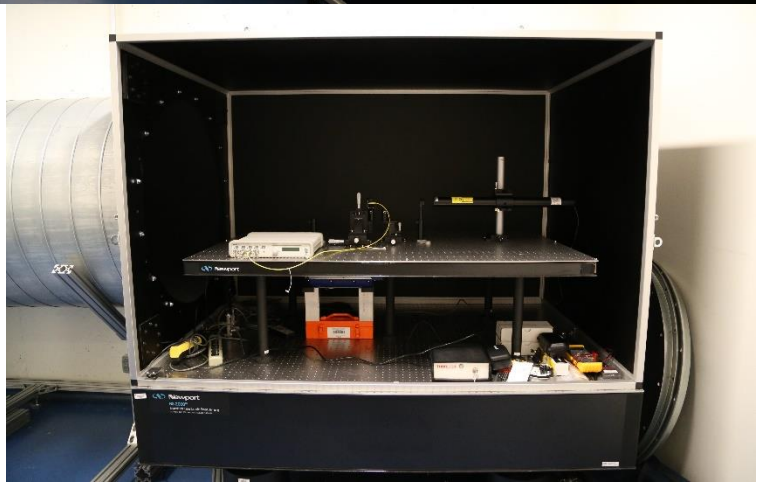






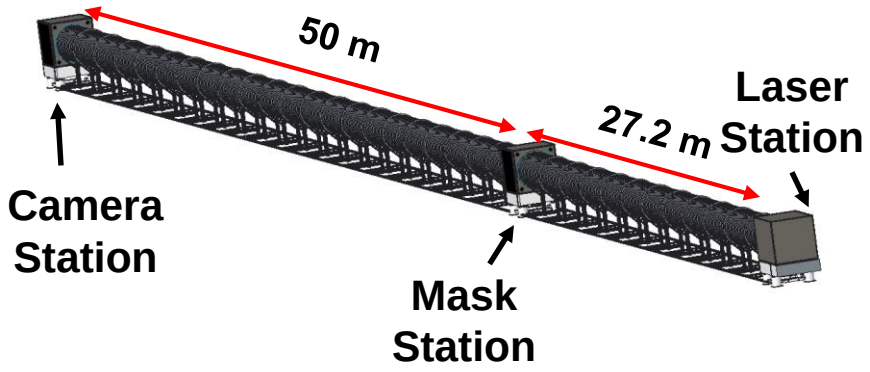
Camera Station

Mask Station (Manufactured by the MDL of the JPL)



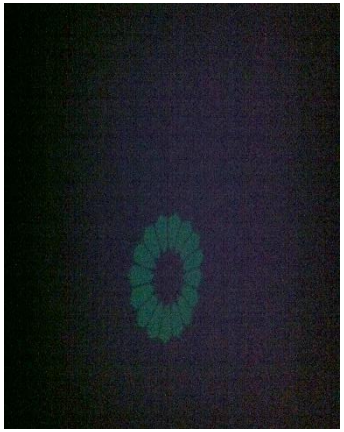
Laser Station

# Beam Propagation – 520 nm

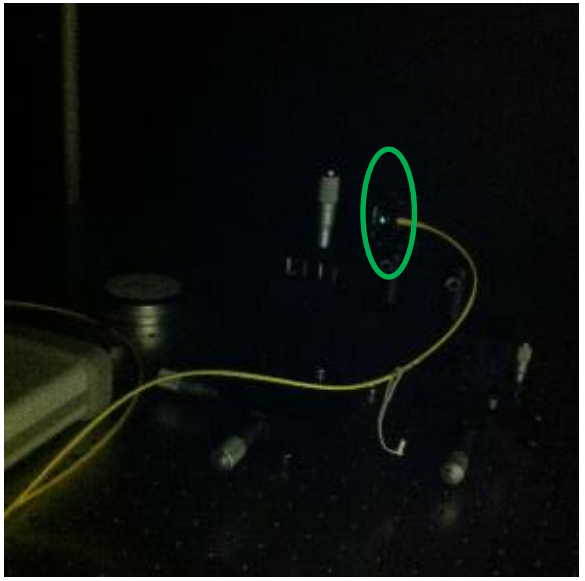




Camera Station

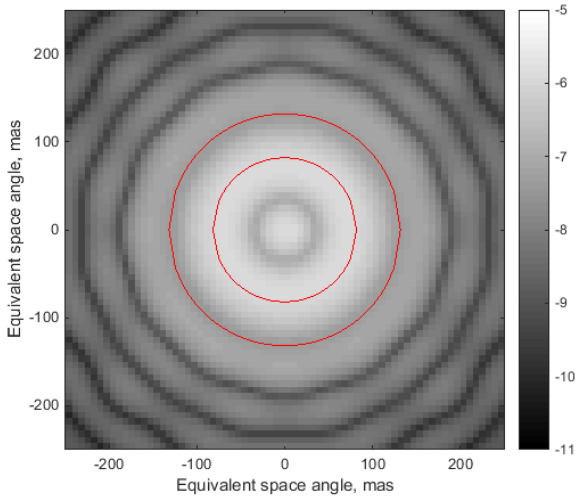


Mask Station

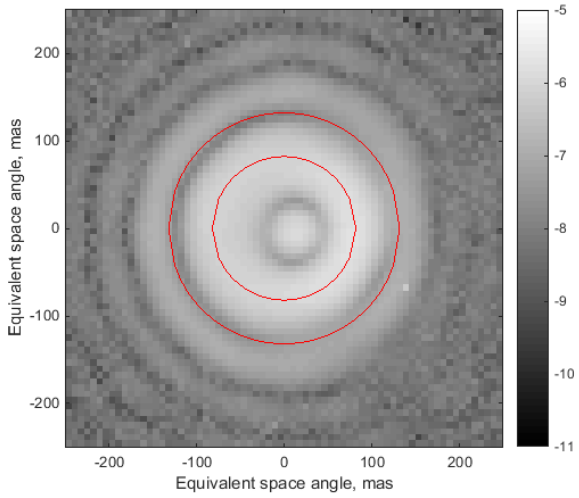


Laser Station

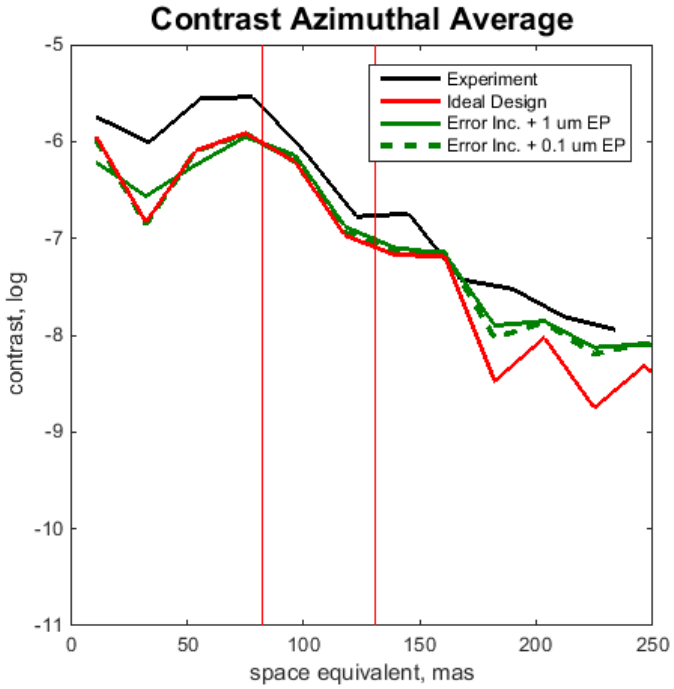
# Out of Band Contrast – 520 nm

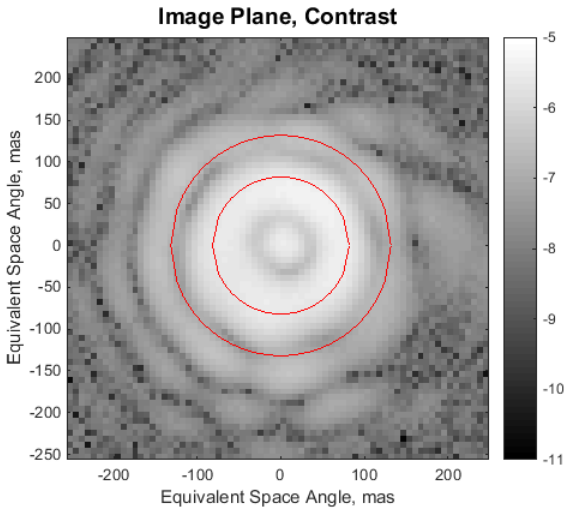



Ideal Simulation




Error Included +
1um Edge Pert.



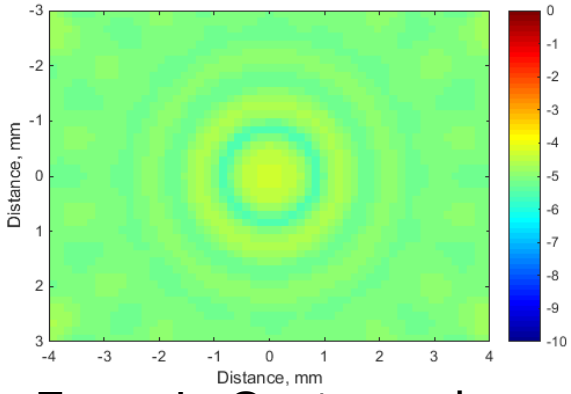




Experiment

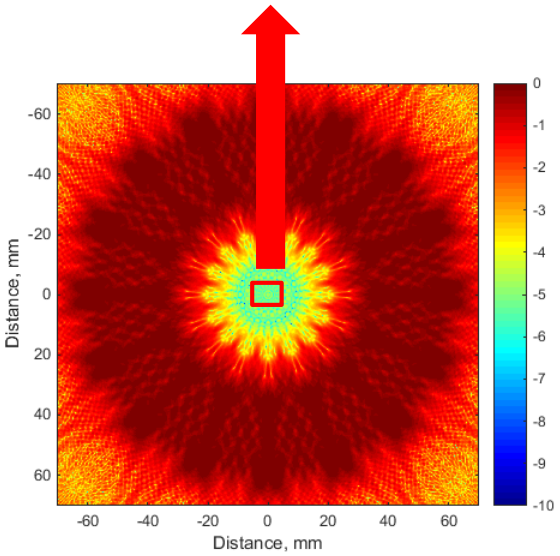
- Check the alignment status of camera and mask
- Exposure time: 500 sec

| Feature Size | Edge Pert. | Beam Disp. | Pinhole Abr. | Mask Tilt | Cam Abr. |
|---|---|---|---|---|---|
| 0.5 um | 0.1 um<br>1.0 um | 0.1 mm | 60 nm | 1 deg | 60 nm |

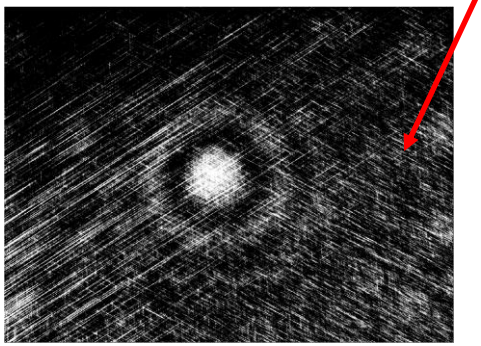
# Out of Band Suppression – 520 nm




Zoom-In Center region

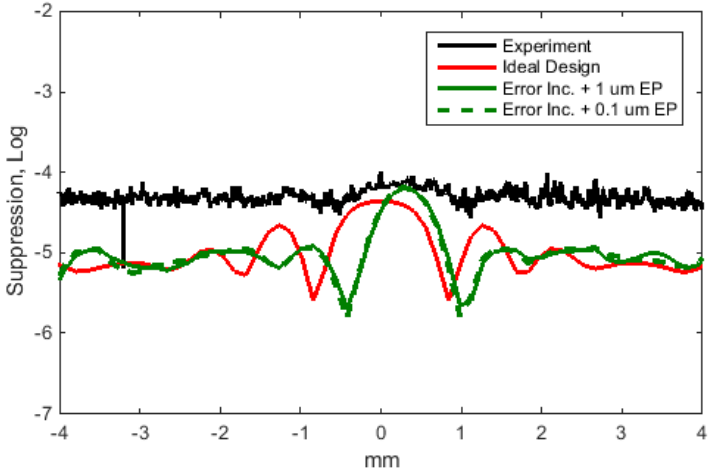



Simulation

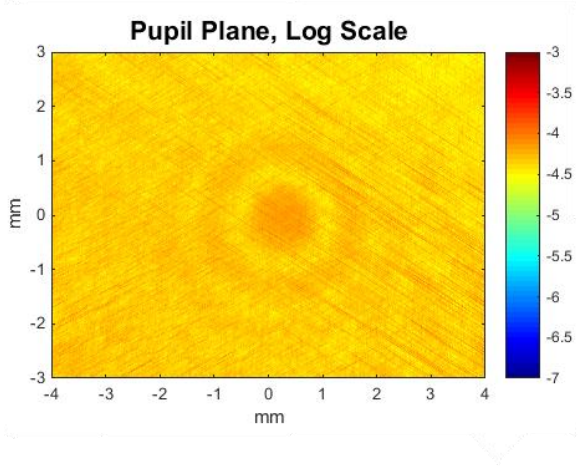


Raw data

Stray light



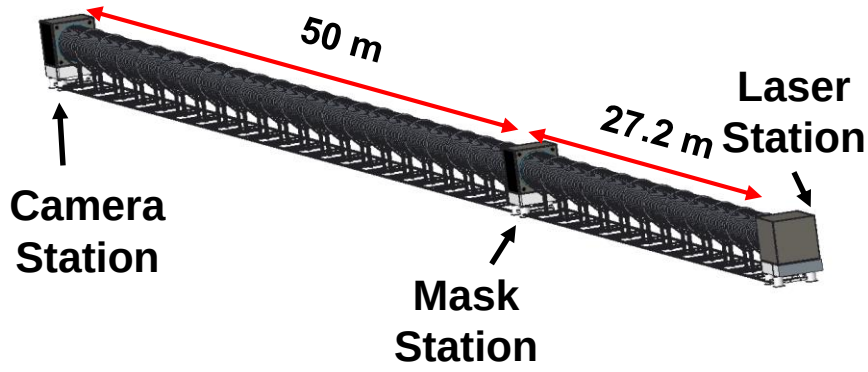

Profile



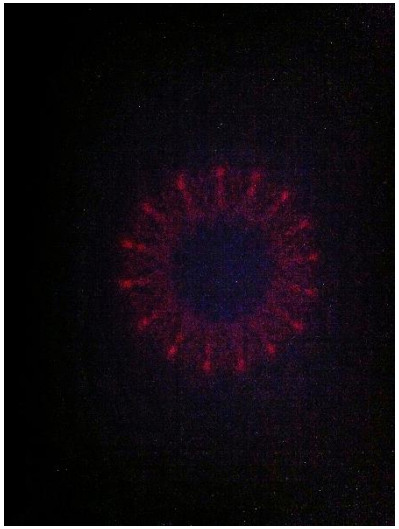

Experiment

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

# Beam Propagation – 638 nm





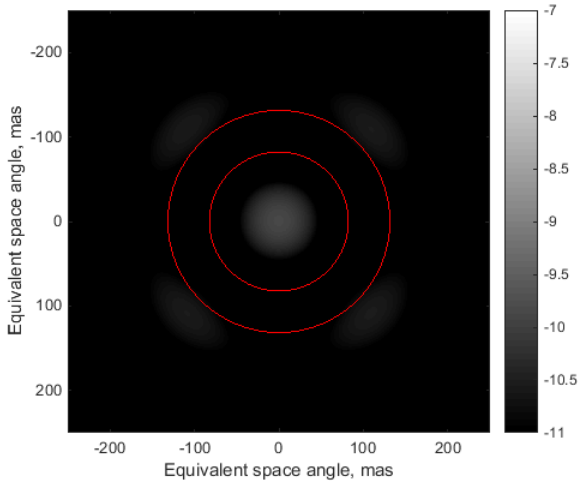


Camera Station

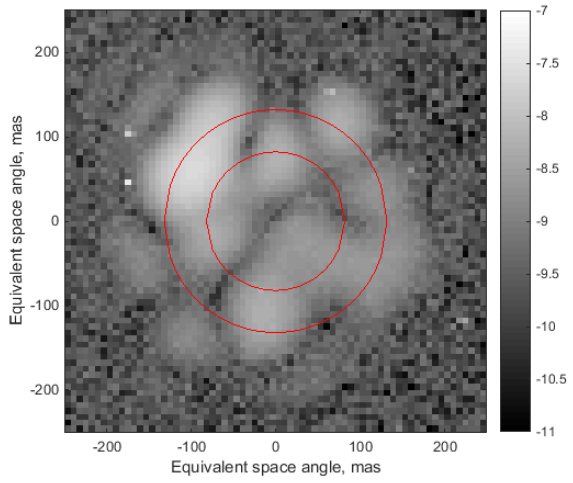
Mask Station

Laser Station

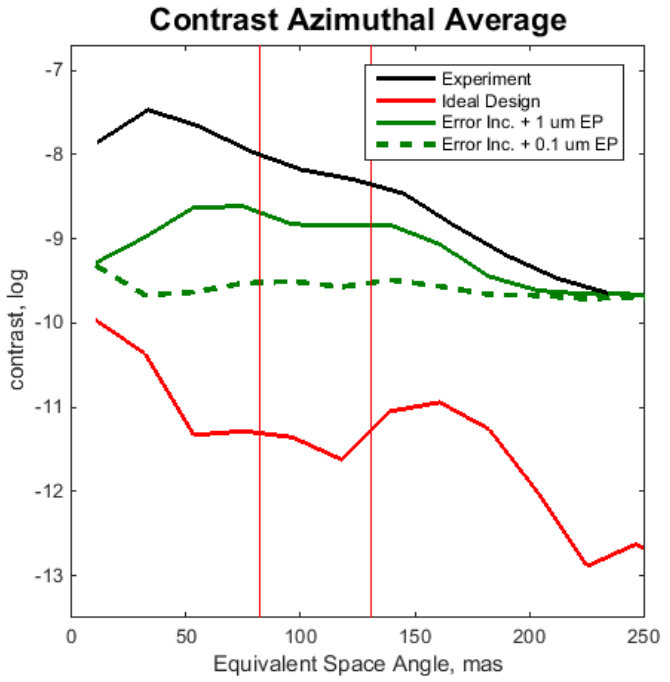
# Contrast at Designed Aperture – 638 nm

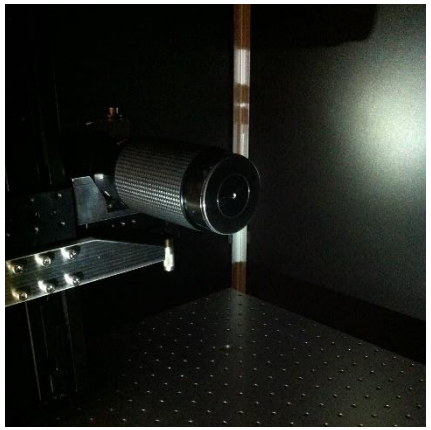



Ideal Simulation

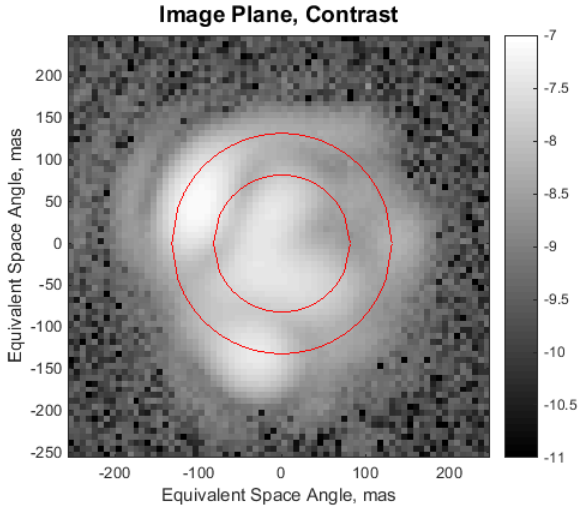



Error Included + 1um EP



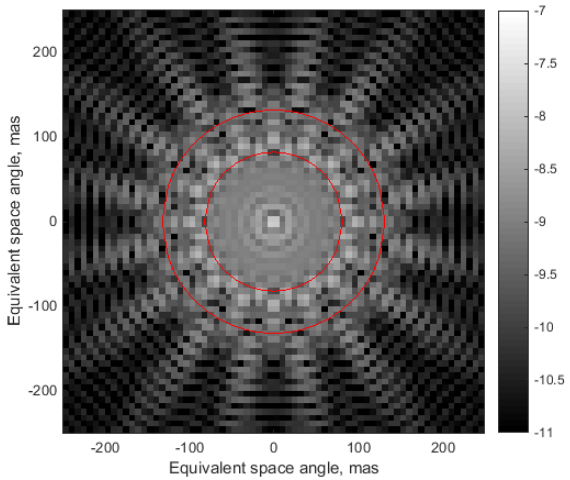
Designed Aperture
(Diameter 3.8 mm)



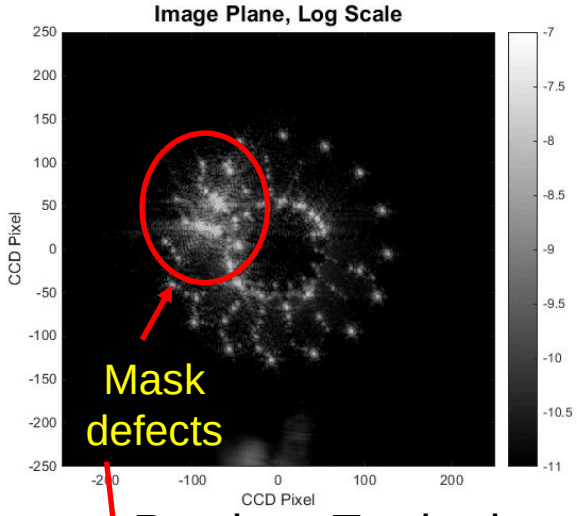

Experiment

- 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

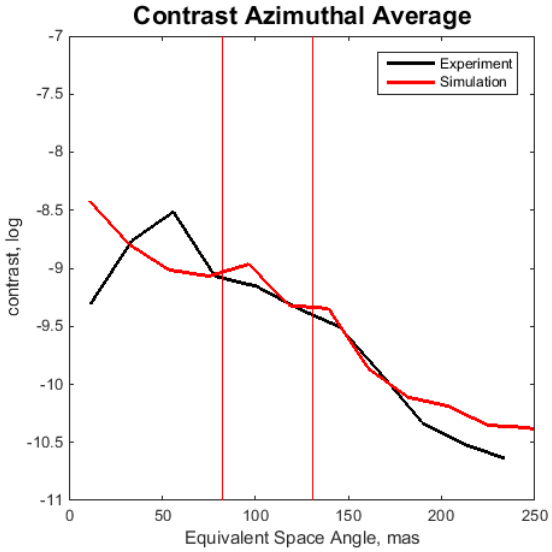
# Contrast at Large Aperture – 638 nm



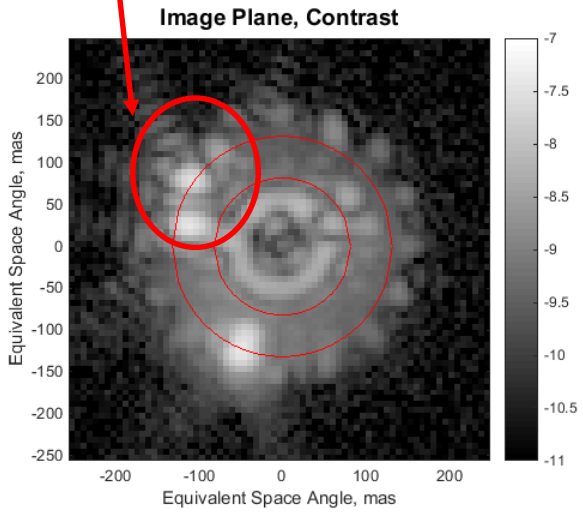

Ideal Simulation




Previous Testbed



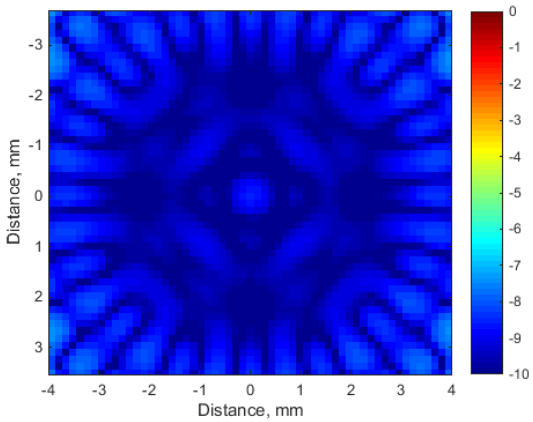

Large Aperture
(Diameter 13.6 mm)



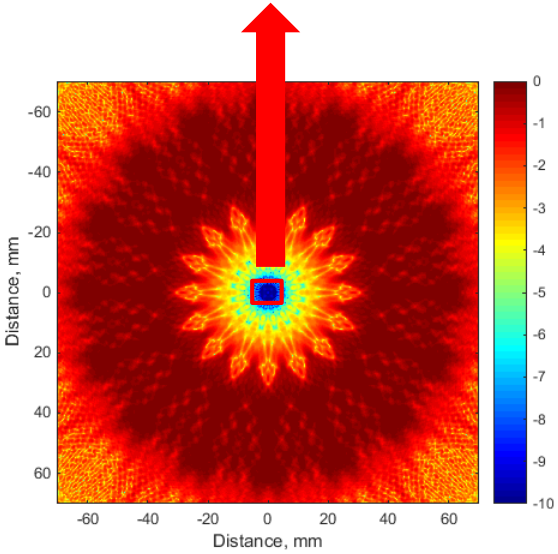

New Testbed

- 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

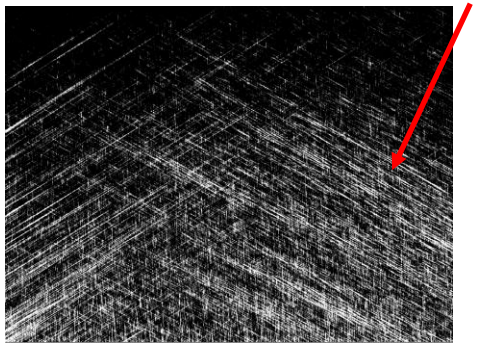
# Suppression – 638 nm




Zoom-In Center region

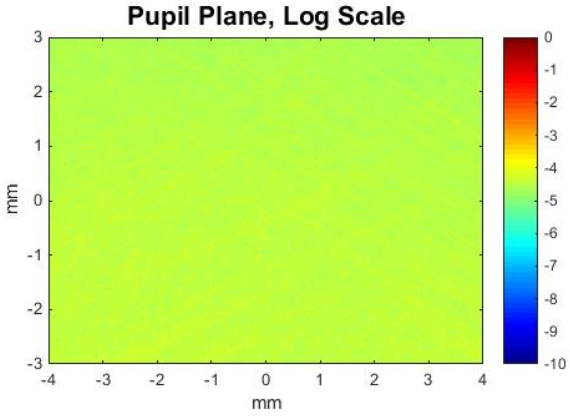



Ideal Simulation

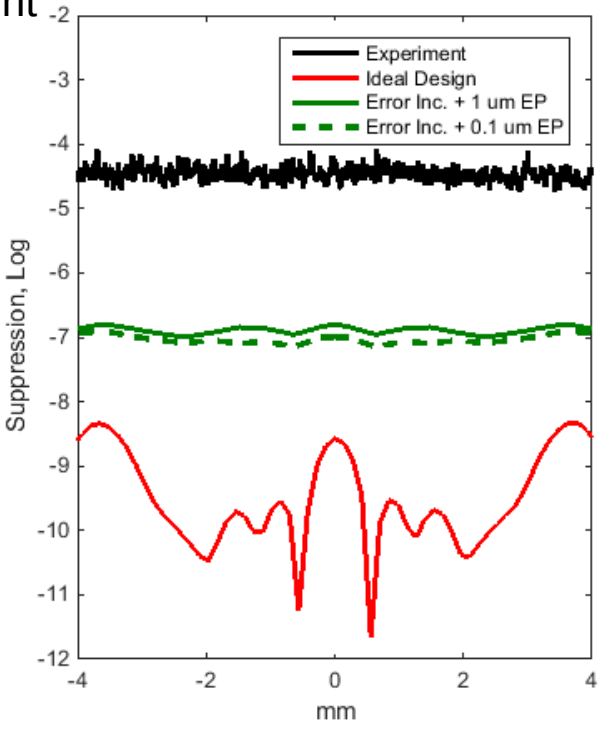


Stray light

Raw data

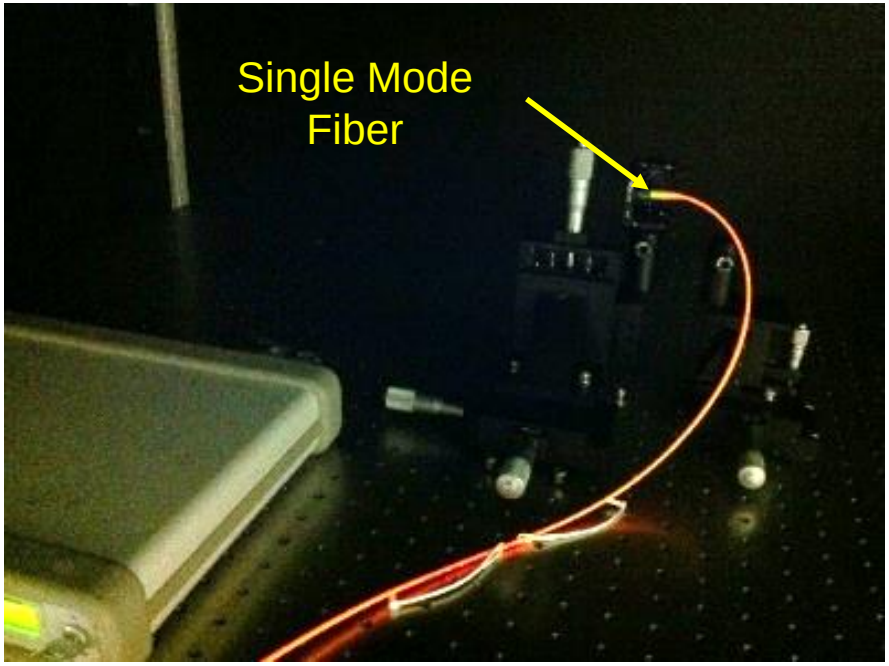



Experiment

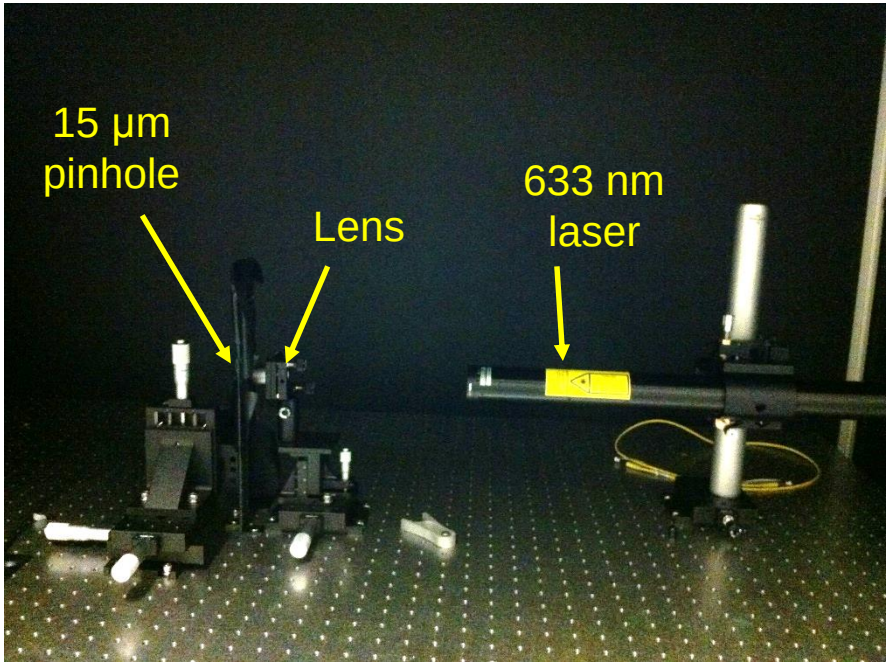



- Suppression reached a limit due to stray light
- Exposure time: 3000 sec

# Source Change




638 nm
Single mode fiber
w/o pinhole




633 nm
Diverging lens +
15 µm pinhole

# Contrast Improvement

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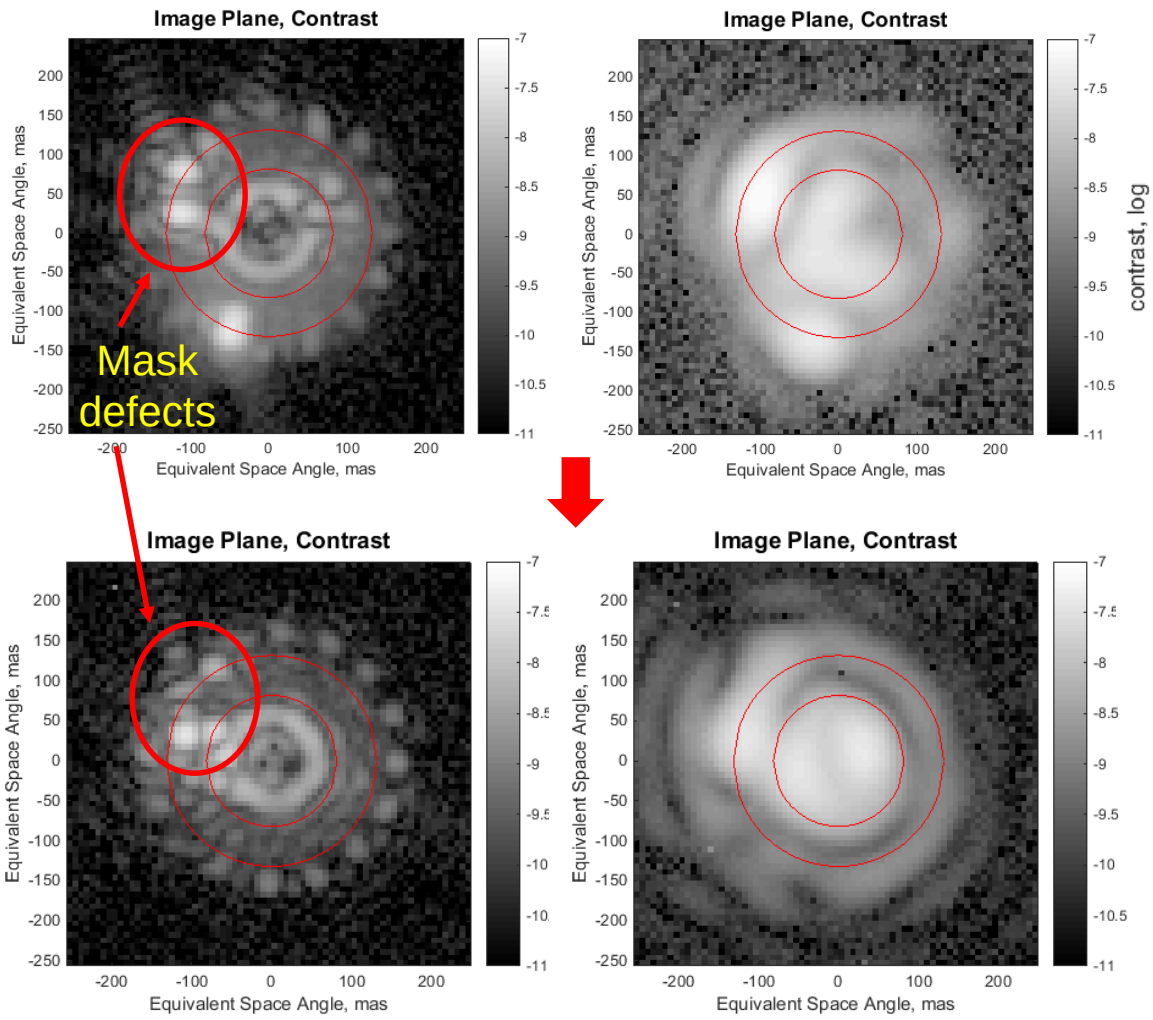
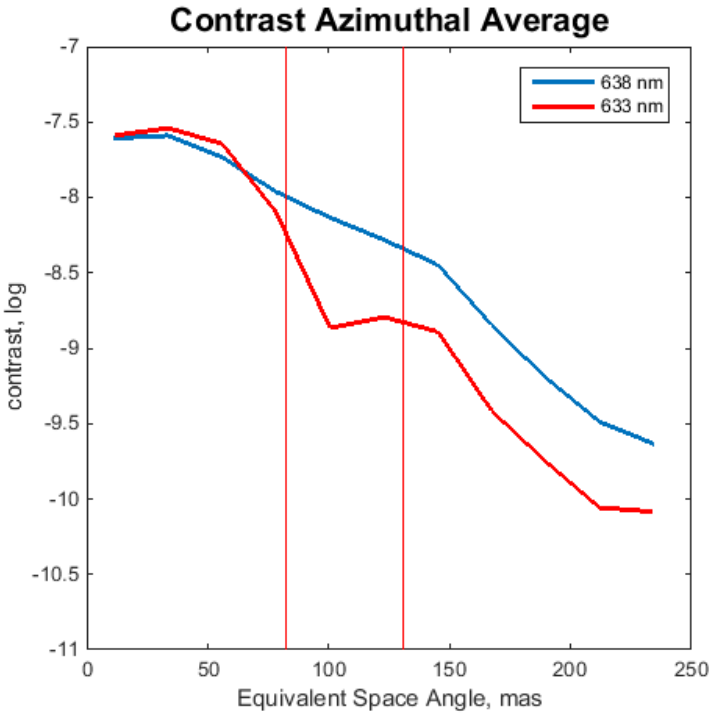
Large Aperture
(Diameter 13.6 mm)

Designed Aperture
(Diameter 3.8 mm)

638 nm

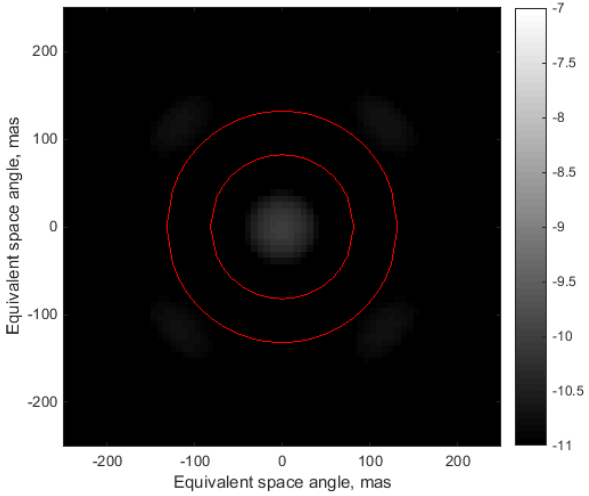
633 nm



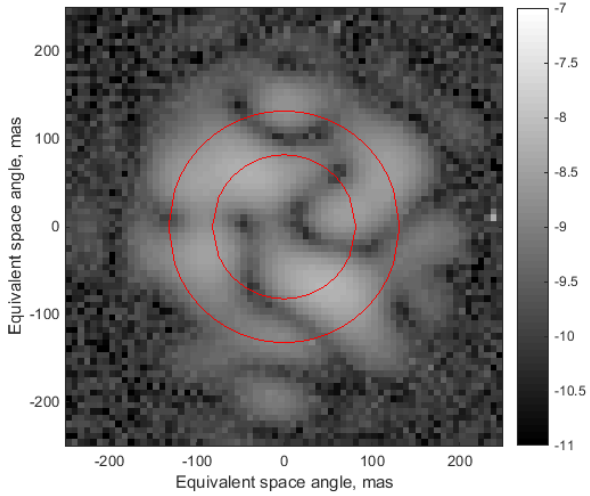




- Difference
  - Alignment Status
  - Beam Quality
  - Laser Power
  - Stray Light

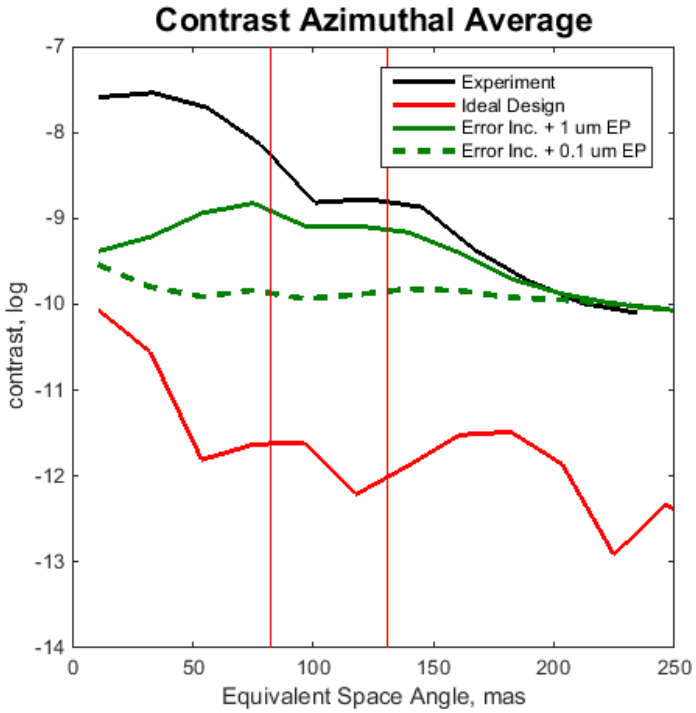
# Contrast – 633 nm

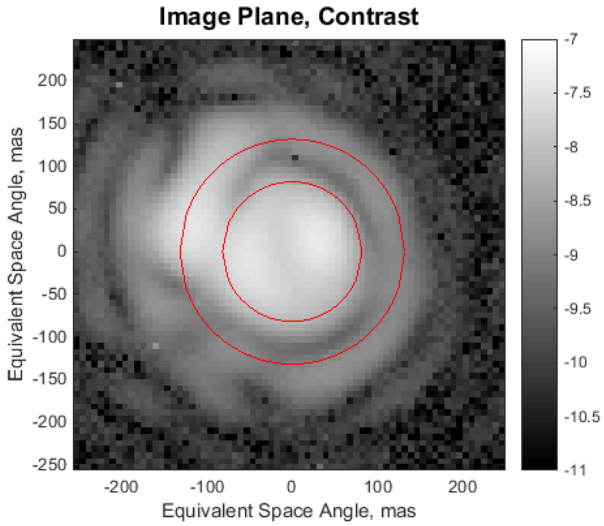



Ideal Simulation




Error Included +
1um Edge Pert.



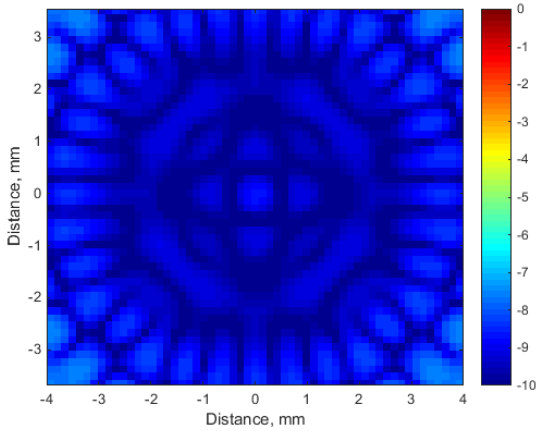




Experiment

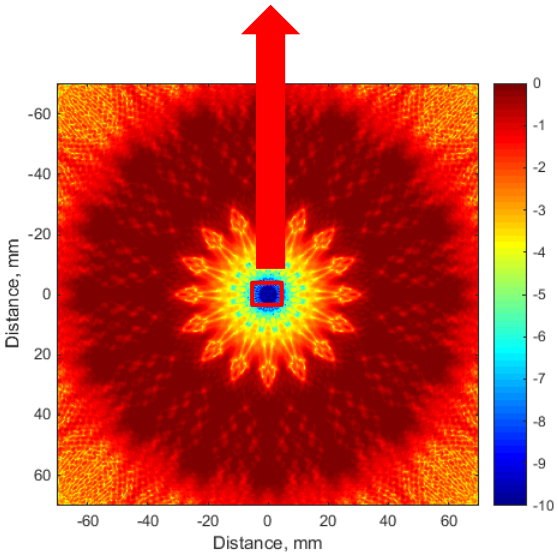
- Inner petal region is brighter than as we expected
- Exposure time: 3000 sec
- Contrast $10^{-9}$ is a limit of current mask quality

| Feature Size | Edge Pert. | Beam Disp. | Pinhole Abr. | Mask Tilt | Cam Abr. |
|---|---|---|---|---|---|
| 0.5 um | 0.1 um<br>1.0 um | 0.1 mm | 60 nm | 1 deg | 60 nm |

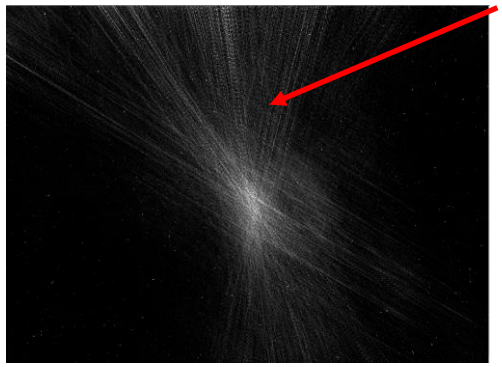
# Suppression – 633 nm




Zoom-In Center region

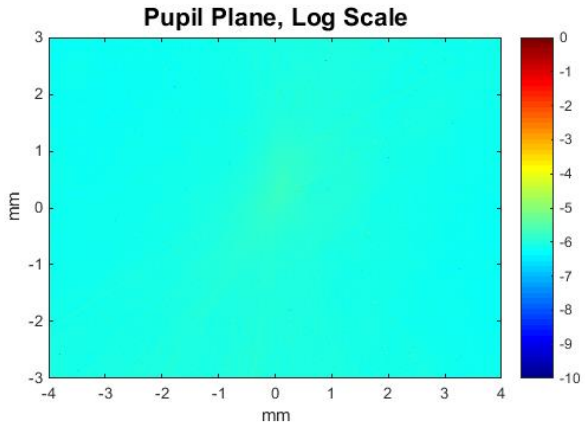



Ideal Simulation

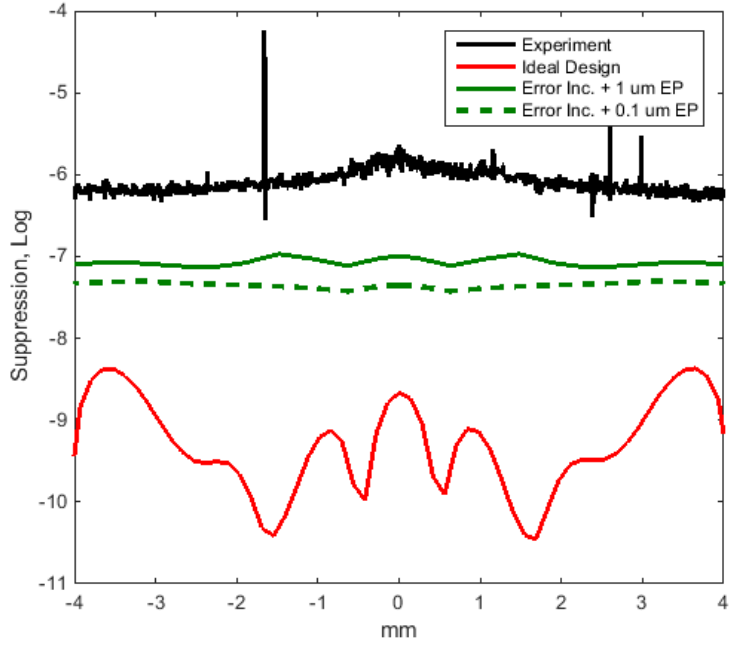


Stray light

Raw data




Experiment




- Suppression reached a limit due to mask defect
- Removed major stray source
- Another error source appeared
- Exposure time: 3000 sec

# Summary

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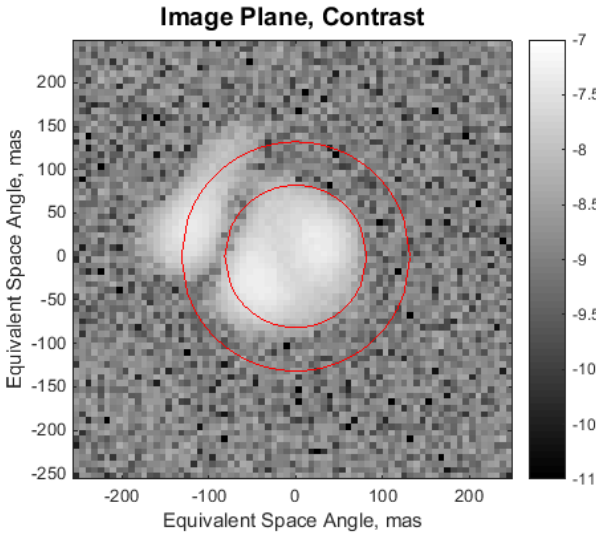
- We achieved a first light result for a starshade at flight Fresnel number 14.5 with $10^{-9}$ contrast and $10^{-6}$ suppression at 633 nm
- From the analysis the inner petal region is brighter than design
- Limiting factor of current setup is mask defects, accuracy and stray light
- Images extremely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

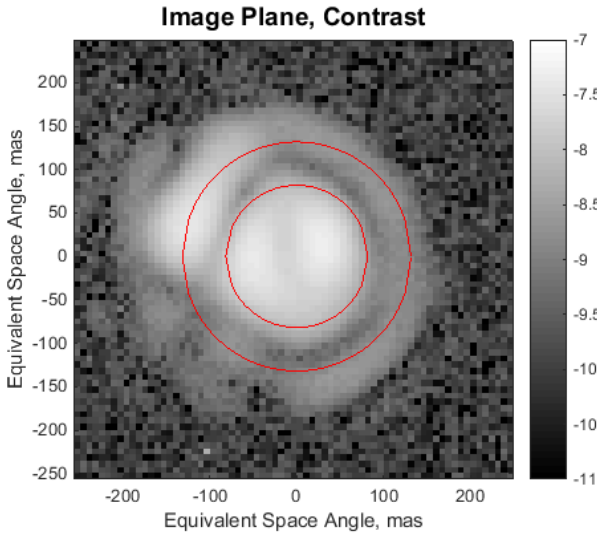
# Thank you for your attention!

# Appendix

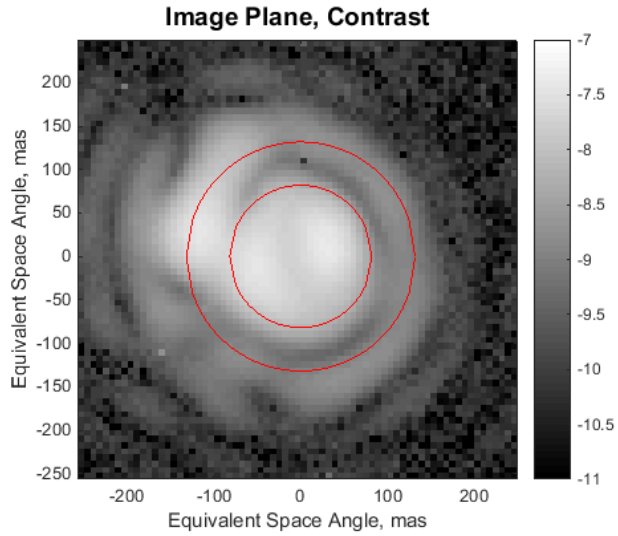
# Contrast – 633 nm



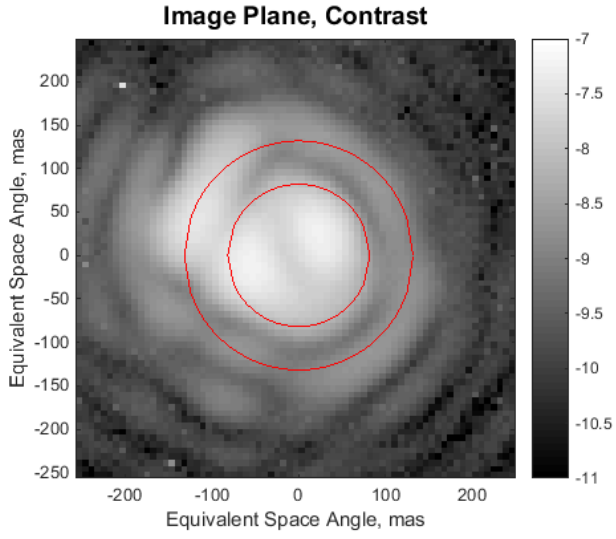

50s



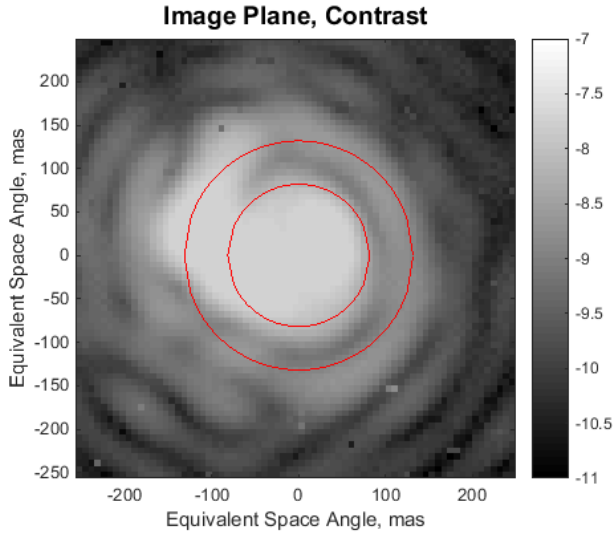

500s



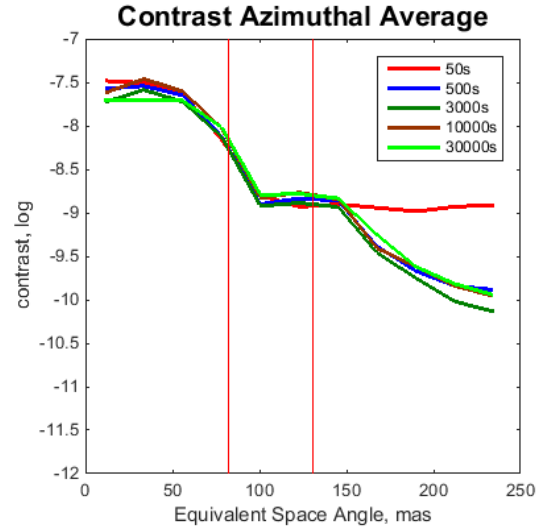

3000s




10000s




30000s



# Camera Mount Replacement

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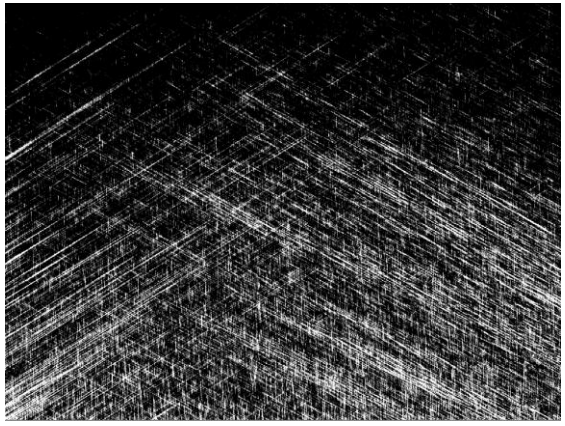
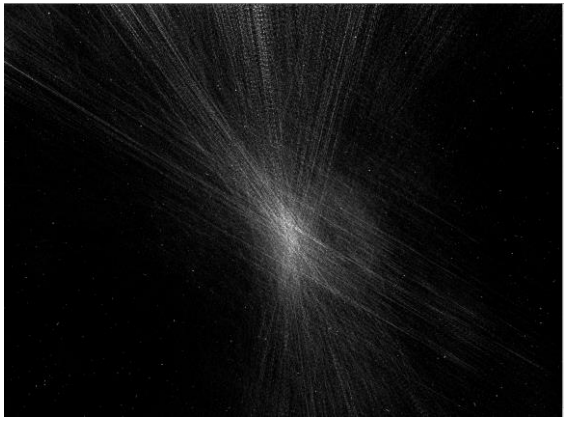
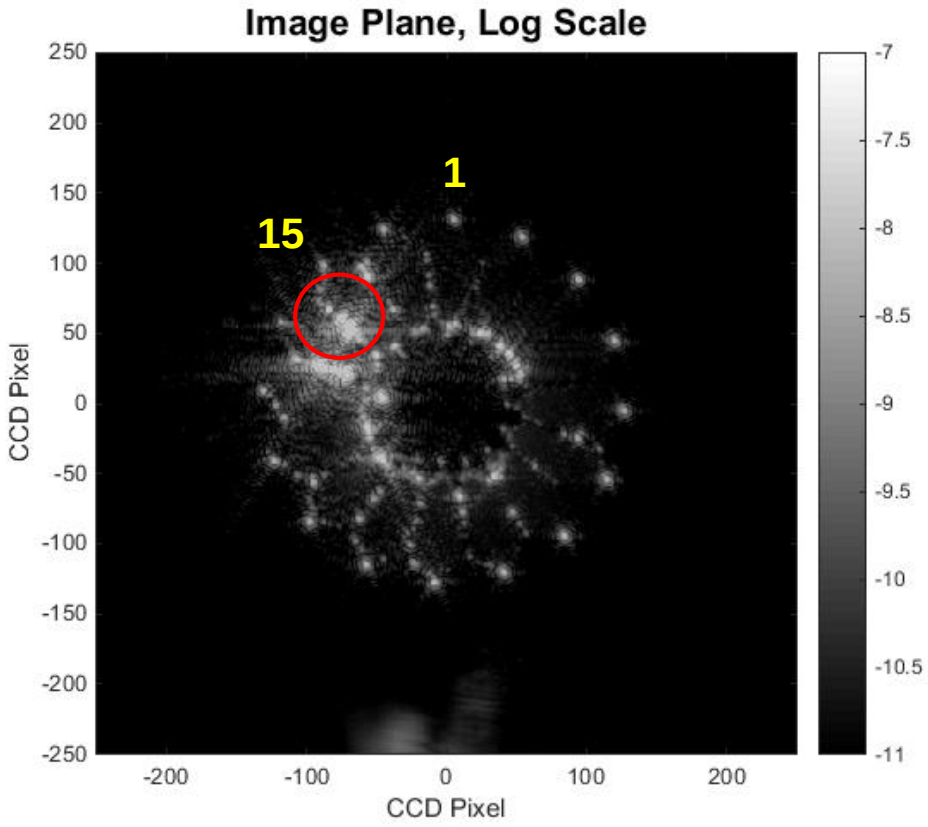
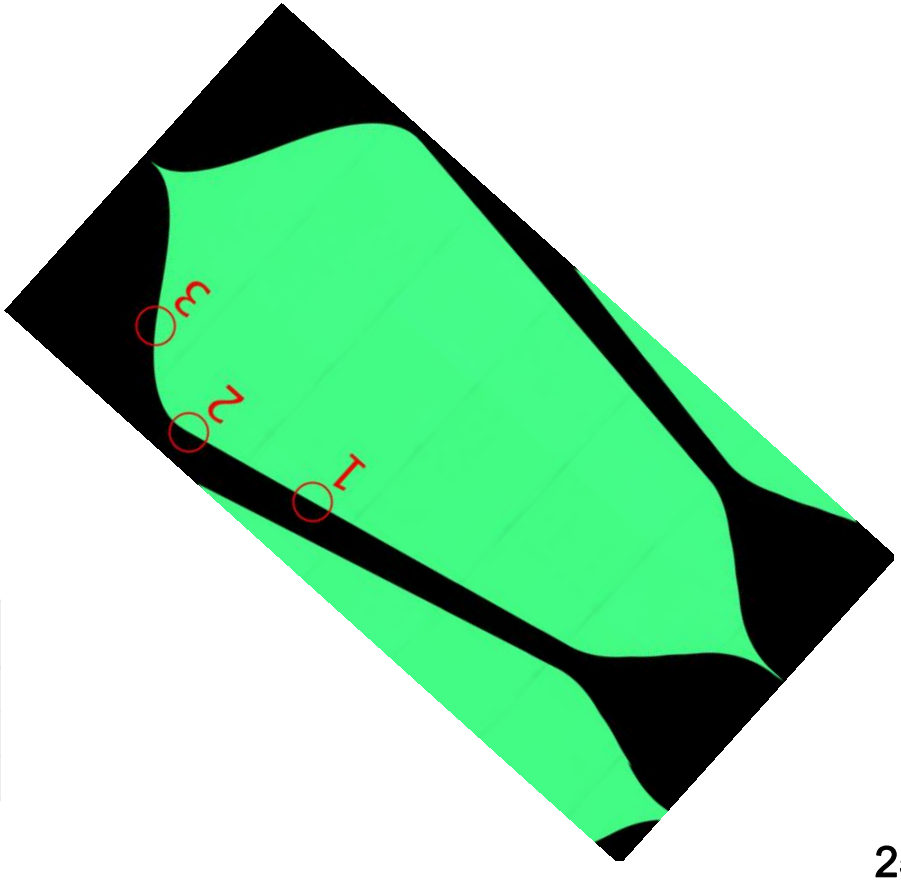




# Microscope Image

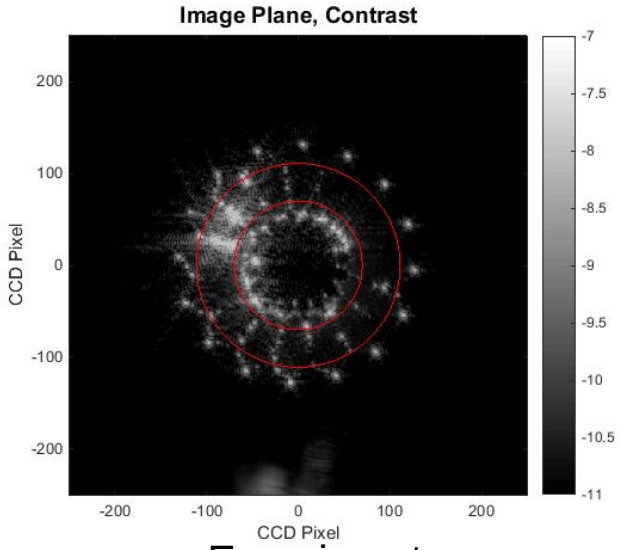



Bright point on petal 15 in experiment image is matched to the microscope Image of 15-1 and 15-2.

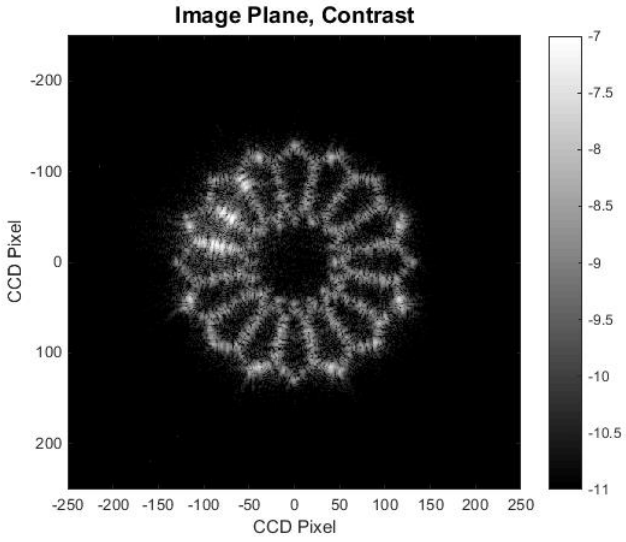



| Petal Number | Defect | Position from Inner Tip of Petal (Microns) | Distance from line (perpendicular) (Microns) | Size (Height) (Microns) | Size (Width) (Microns) |
|---|---|---|---|---|---|
| 15 | 1 | 9254.1 | 3875.1 | 5.84 | 7.08 |
| 15 | 2 | 11995 | 4480.8 | 13.99 | 9.69 |
| 15 | 3 | 13232 | 6299.4 | 6.23 | 6.27 |

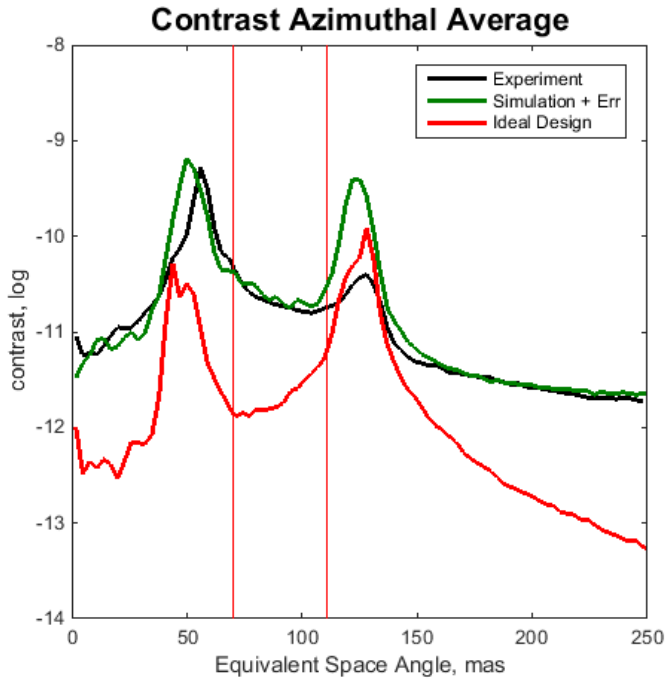
# New Mask at Previous Testbed




Experiment



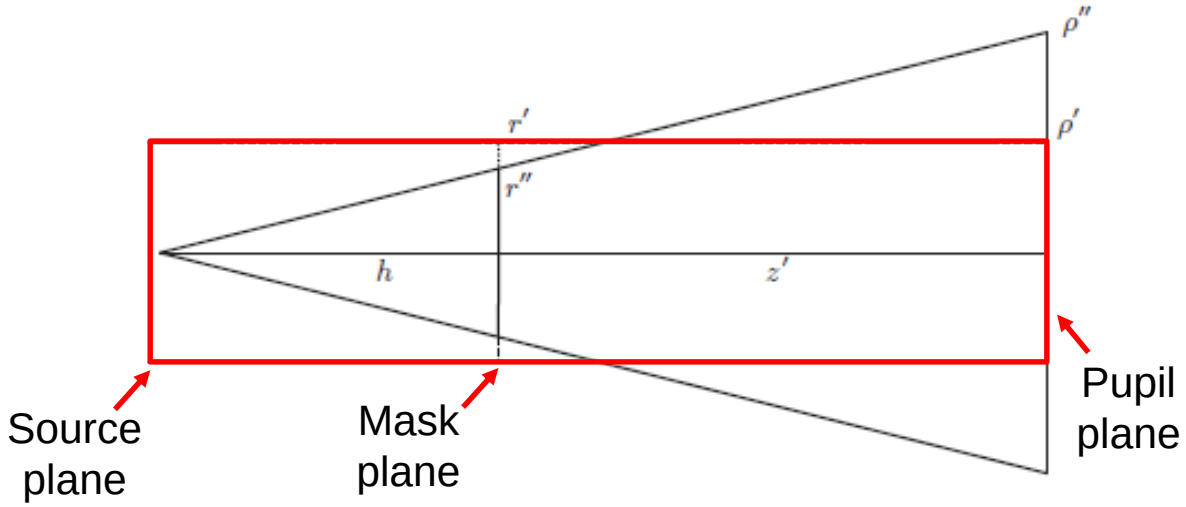

Simulation




| Measured Supp. | Simulated Supp. | Ideal Supp. |
|---|---|---|
| -5.2 | -5.4 | -6.1 |

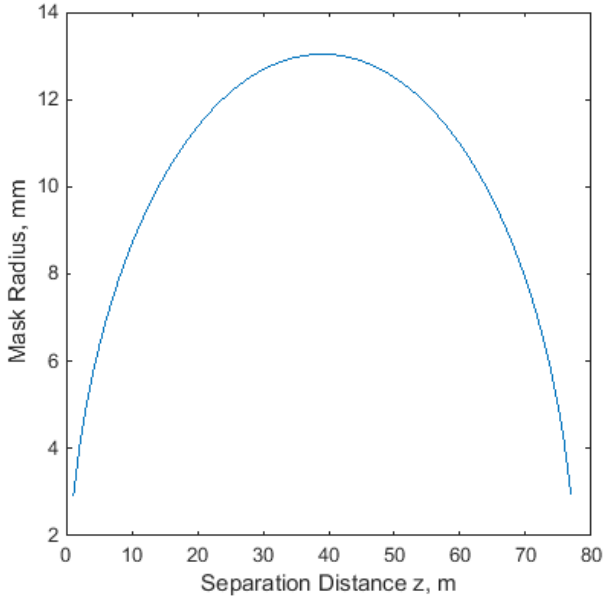
| Feature Size | Edge Pert. | Beam Disp. | Pinhole Abr. | Mask Tilt | Cam Abr. |
|---|---|---|---|---|---|
| 0.5 um | 0.5 um<br>5.0 um | 0.1 mm | 60 nm | 1 deg | 60 nm |

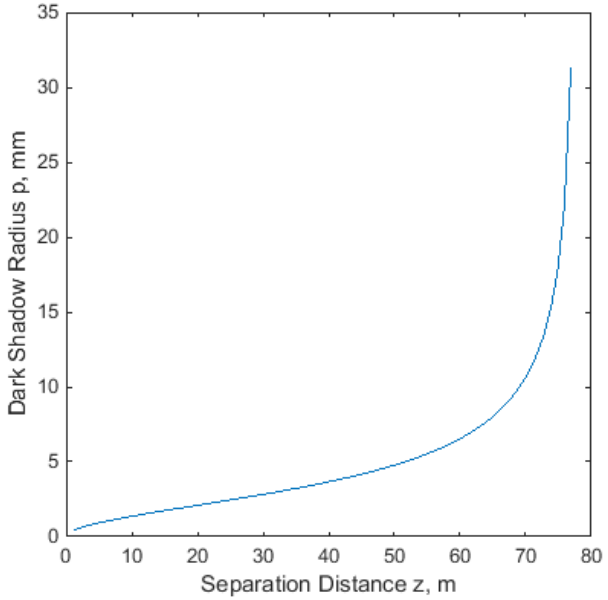
# Divergent Beam Scaling



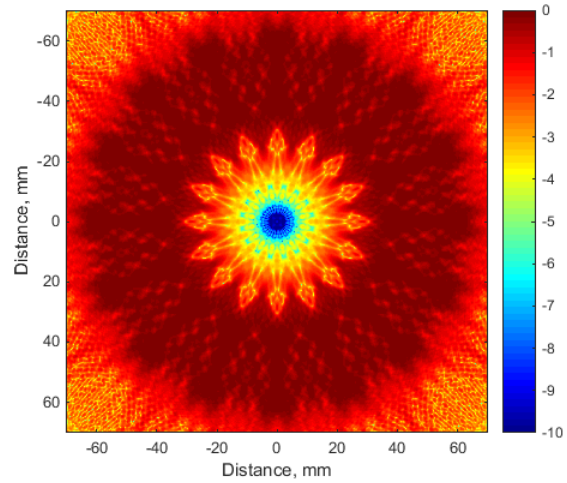

| labZ (z′, m) | Mask Radius (r″, mm) | Dark Radius (ρ″, mm) | Margin (mm) |
|---|---|---|---|
| 38.6 | 13.0 | 3.6 | ± 1.7 |
| 50 | 12.4 | 4.8 | ± 2.9 |
| 60 | 10.8 | 6.6 | ± 4.7 |
| 65 | 9.5 | 8.2 | ± 6.3 |
| 70 | 7.6 | 11.1 | ± 9.2 |

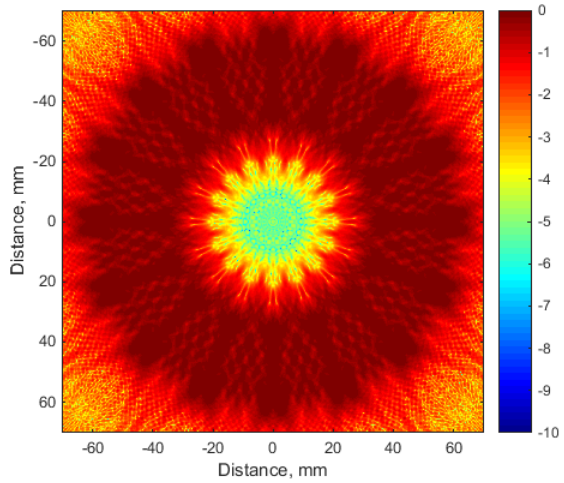
Camera Radius: 1.9 mm

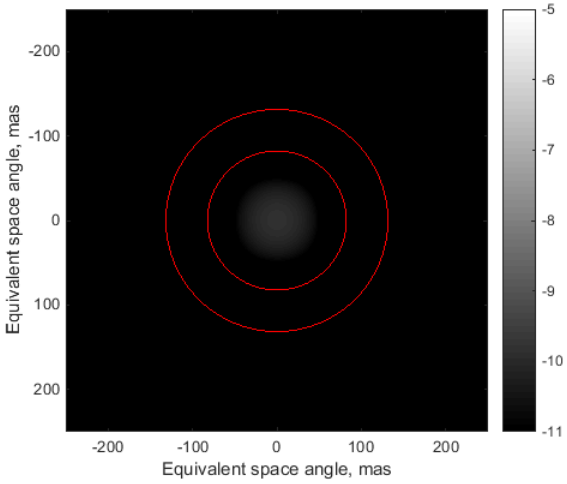


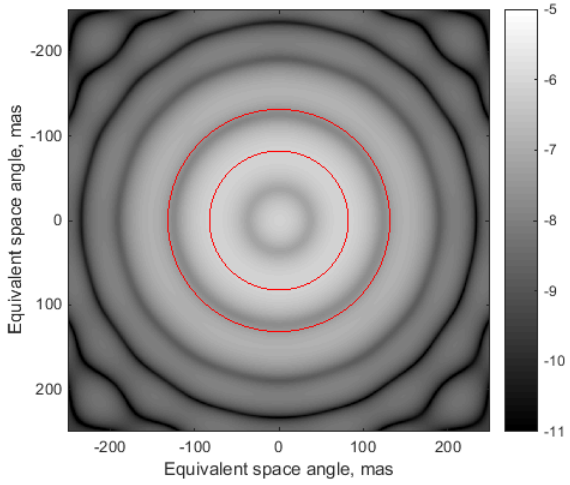
# Ideal Simulation



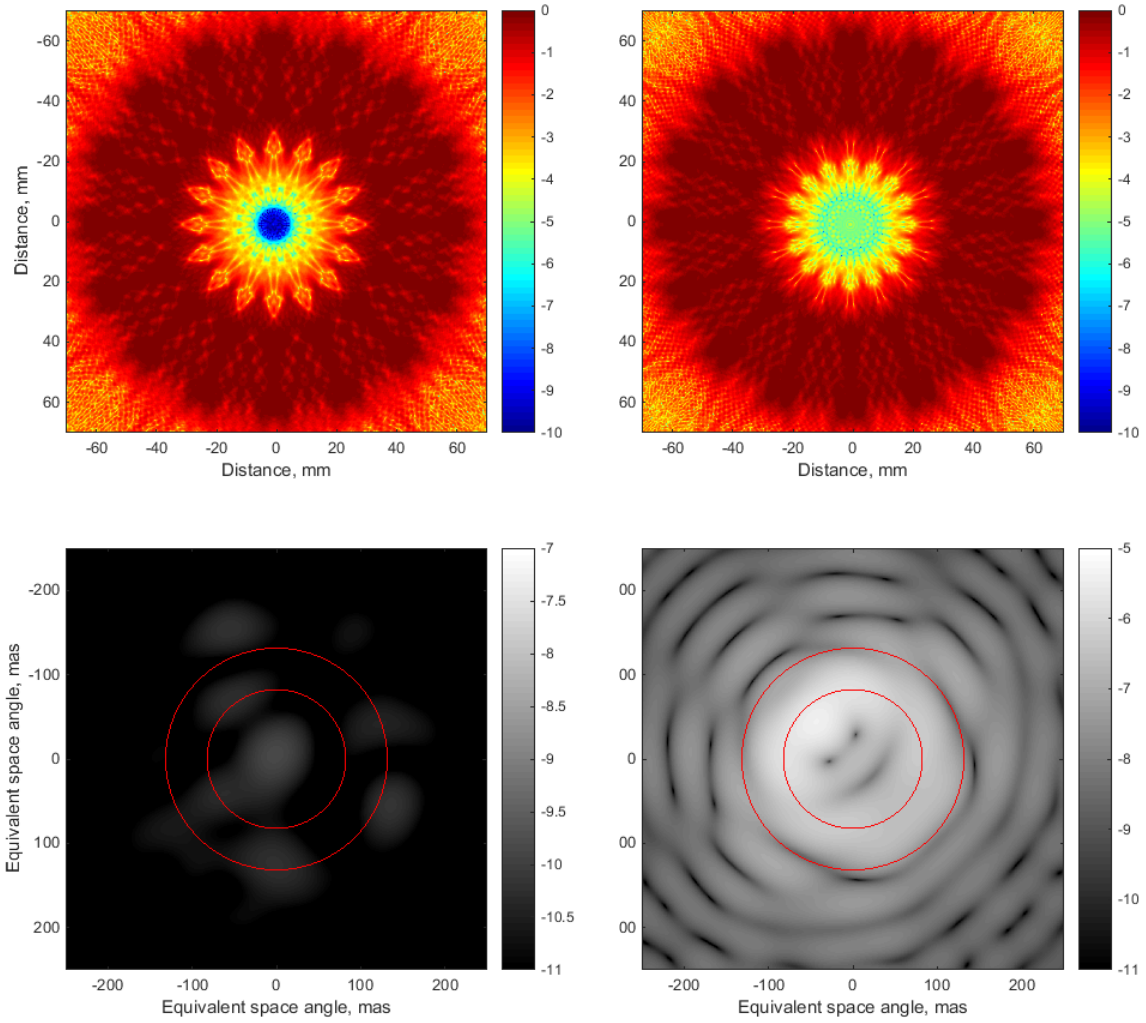

638 nm




520 nm

# All Error Combined Simulation

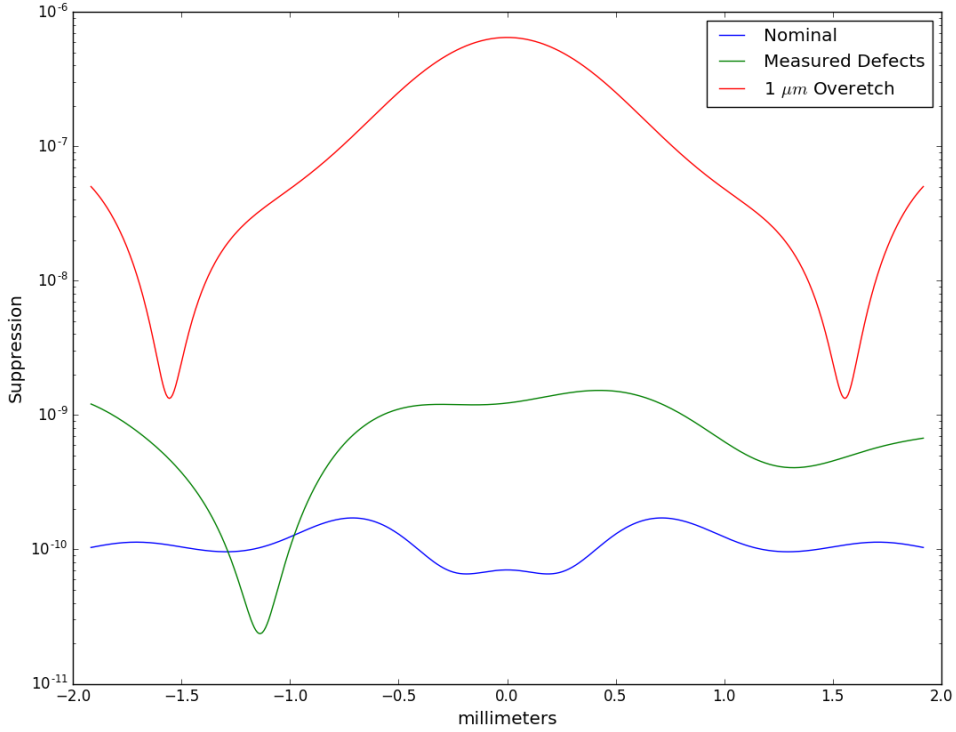
| Error Parameter | Budget |
|---|---|
| Feature Accuracy | 0.5 μm |
| Edge Perturbation | 0.1 μm |
| Optics Aberrations | λ/10 ≈ 60 nm |
| Diagonal Beam Misalignment | 1 mm |
| Mask Tilt | 1° |
| Camera Aberrations | 60 nm |



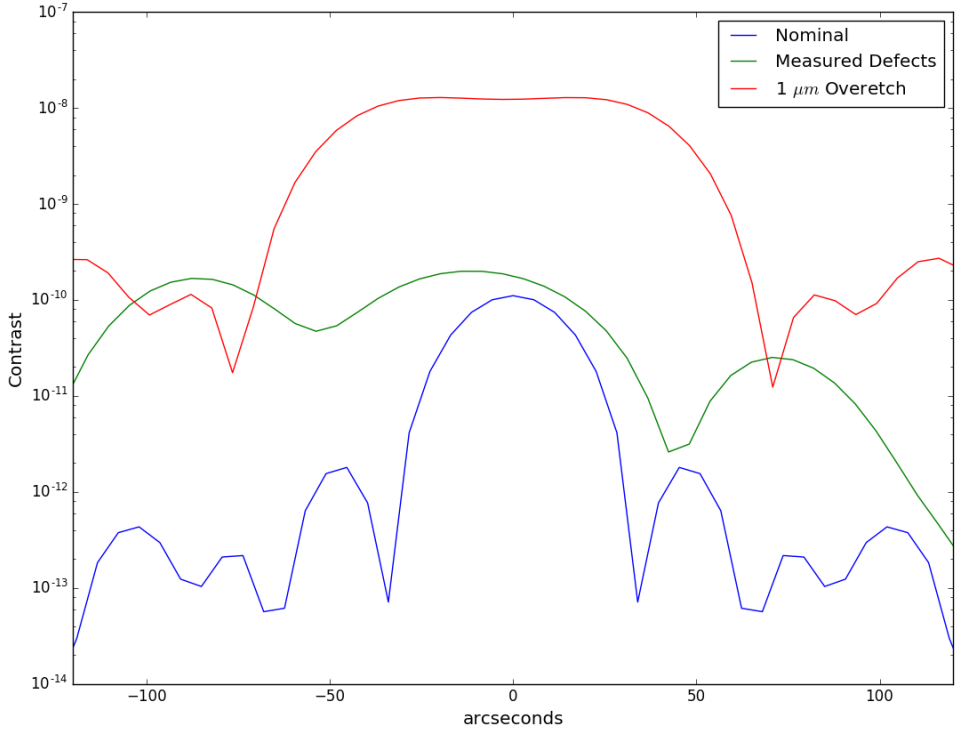

638 nm

520 nm

# Simulation Result of JPL




Suppression




Contrast