Starshade High Contrast Imaging Demonstration Update

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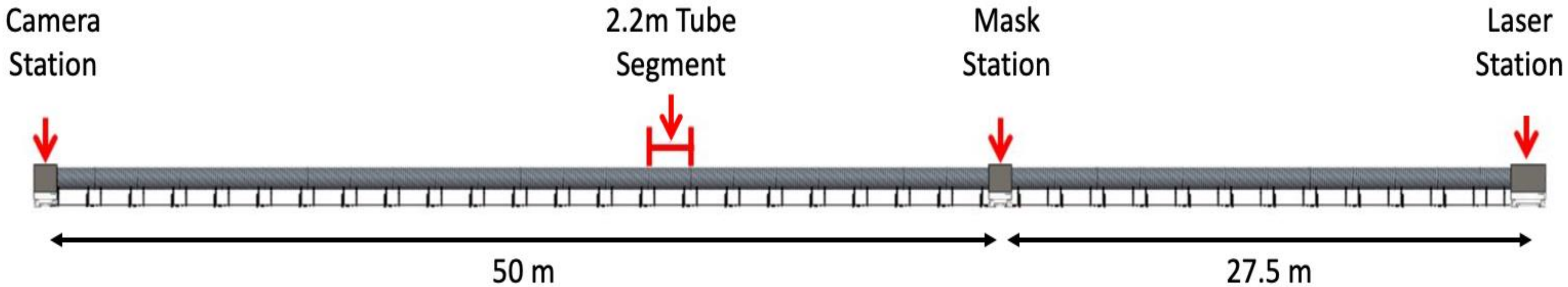
February 6, 2020

CL#20-0646

Princeton Testbed

- Located in basement of Frick Chemistry Building on Princeton Campus
- Tube is ***not*** evacuated and is filled with ambient air
- Fiber-fed laser operating at:
- 641, 660, 699, 725 nm



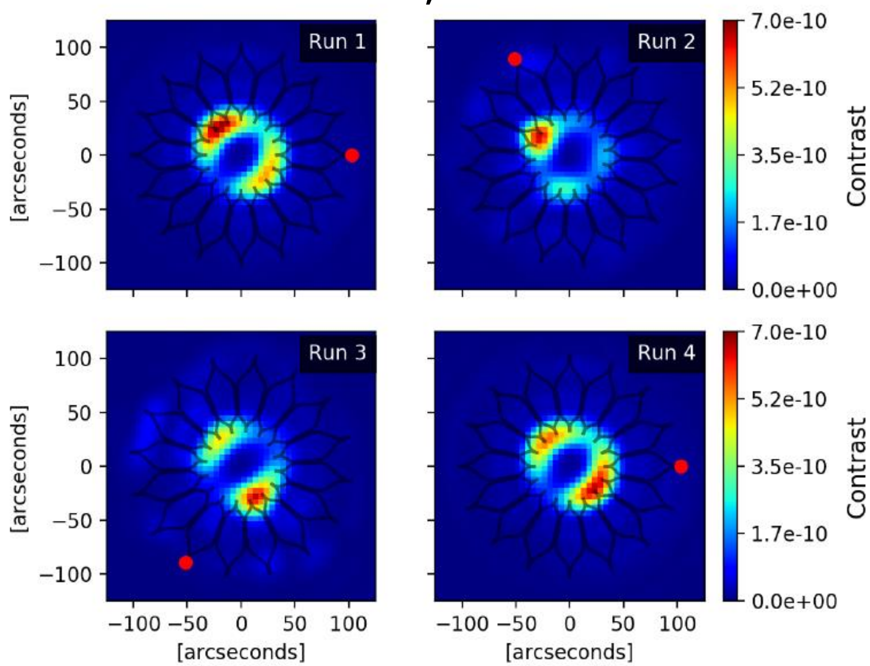
Overview

- Milestone 1A/B Open Issue: Vector Diffraction Models
- Vector Diffraction Plan and Update
- M2 Plan and Update

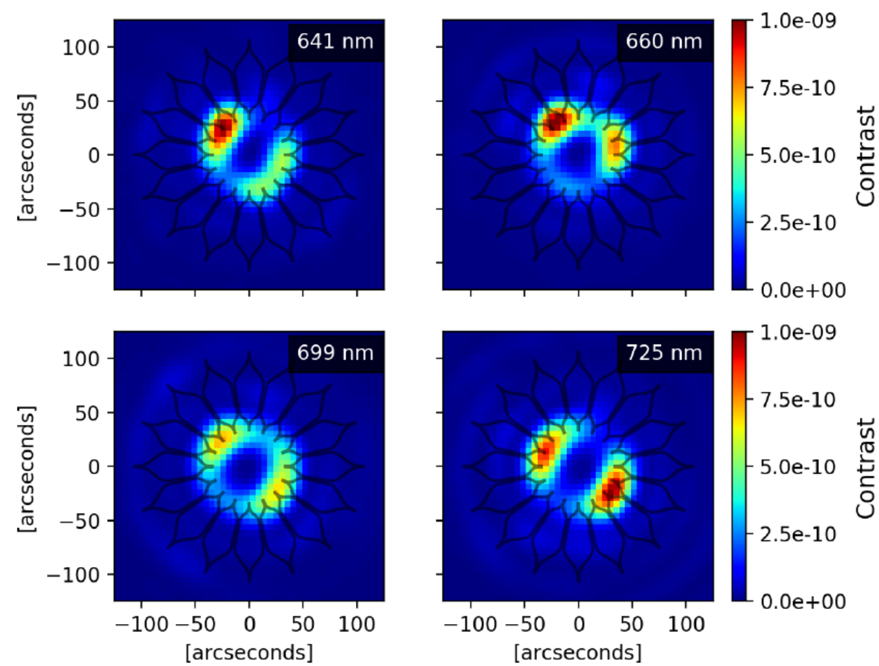
Milestone 1A/B Open Issues

- M1A (monochromatic) and M1B (4 bands 640, 660, 700, 725) achieved 10^{-10} contrast at the IWA.
  - Contrast was limited by lobes due to Polarization (Vector Diffraction)
  - Lobes showed asymmetry.

M1A: 640 nm, 4 rotations



M1B: 640, 660, 699, 725 nm

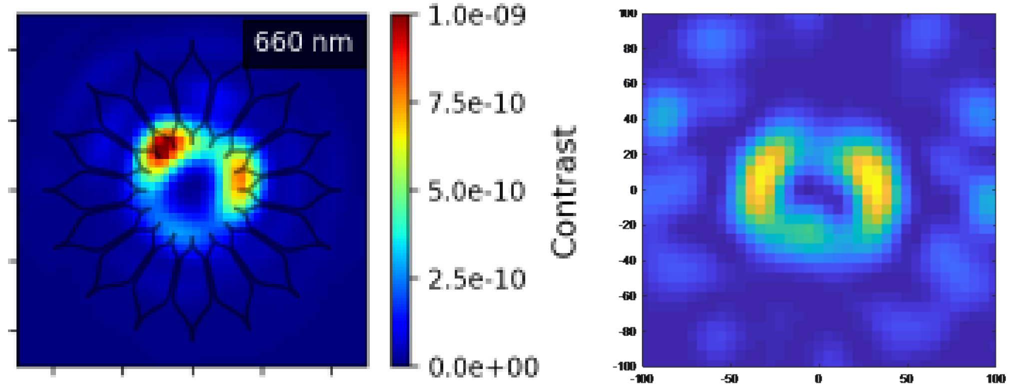


Plan to Address Vector Diffraction

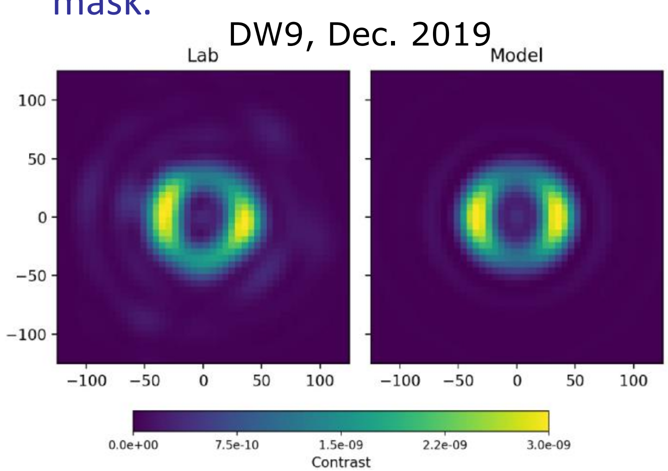
- Lobe asymmetry: determine source of vector diffraction lobe asymmetry and validate the model prediction of asymmetry in a controlled experiment.
- Characterize the dependence of vector diffraction on
  - the number of petals by comparing a 12 petal mask to the 16 petal mask.
  - mask thickness.
- Model the vector diffraction for flight-like edges and use our vector diffraction models to predict flight performance.
- Study alternative testbeds and test configurations that could allow a larger range of starshade scales to be studied.

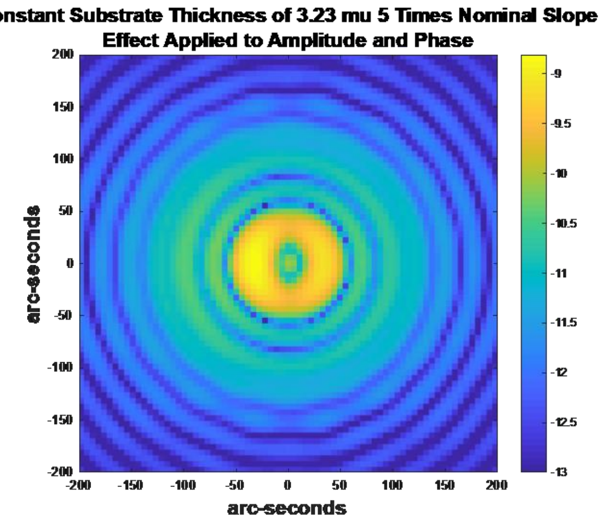
Vector Diffraction: Lobe Asymmetry Model

- Lateral pupil offset ~ 1 mm may explain the asymmetry.
- Thickness gradient across the mask may be part of the issue as well, if ~ 1 um across the mask.
- Improvement made:
  - Use blue channel (outside starshade band where contrast is poor) to align the beam at the pupil.
    - On-orbit Formation Flying technique!
  - Misalignment now well below 1 mm.
  - Good results using a 7 um thick mask.



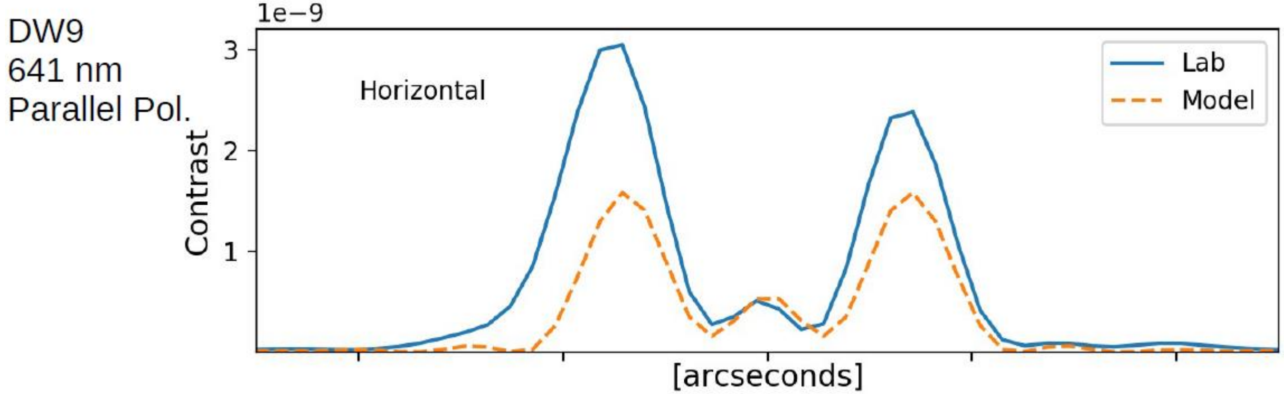
Left: data from Milestone 1b (early 2019). Right: a model (assuming a horizontal polarization) with the telescope pupil displaced vertically by 1 mm.

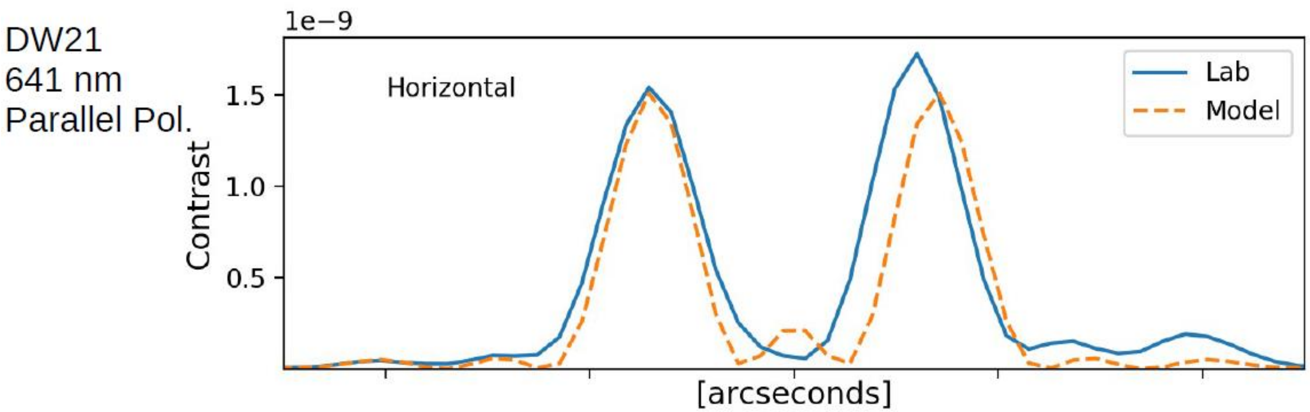




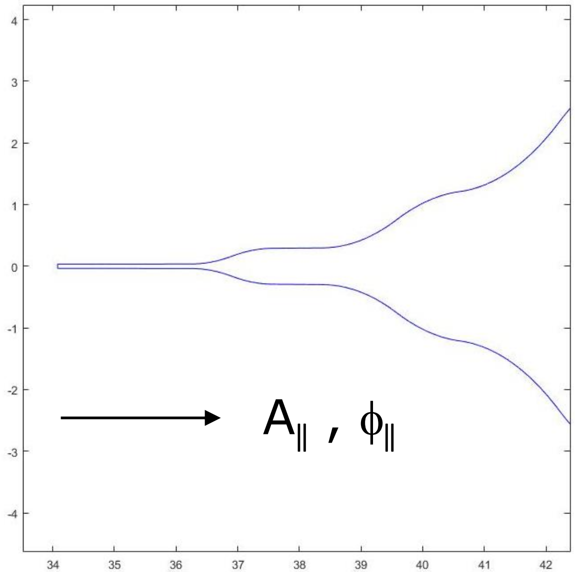
Vector Diffraction Status: Dependence on Mask Thickness

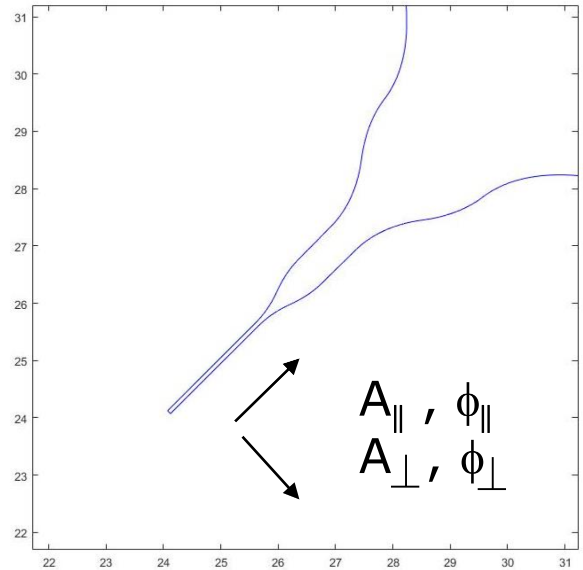
- DW9: 7 um thick, 7.5 um gaps.
- DW21: 3 um thick. 16 um gaps.
- Same model is applied to both masks.
- Works equally well at different wavelengths.
- We'd like to improve the correlation and understand why the model isn't more consistent.

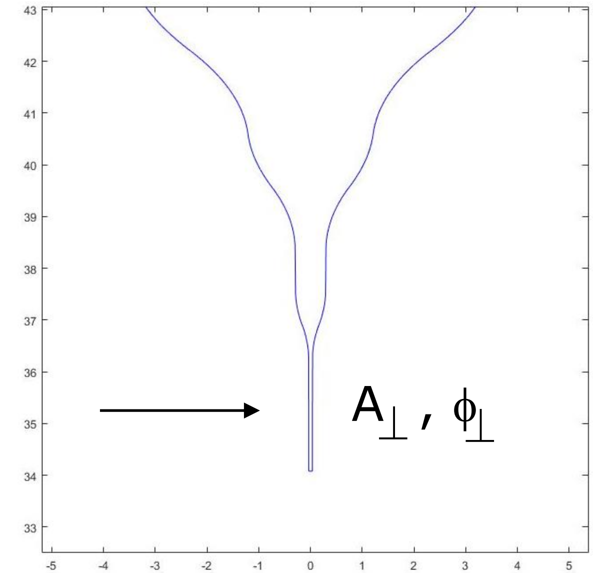




Vector Diffraction: Observe signal through crossed polarizers





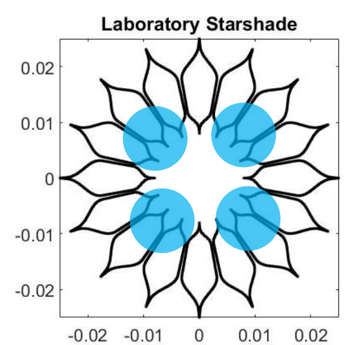


Input Horizontal Polarization

Output Polarization

Transmission Thru Vertical analyzer at Camera

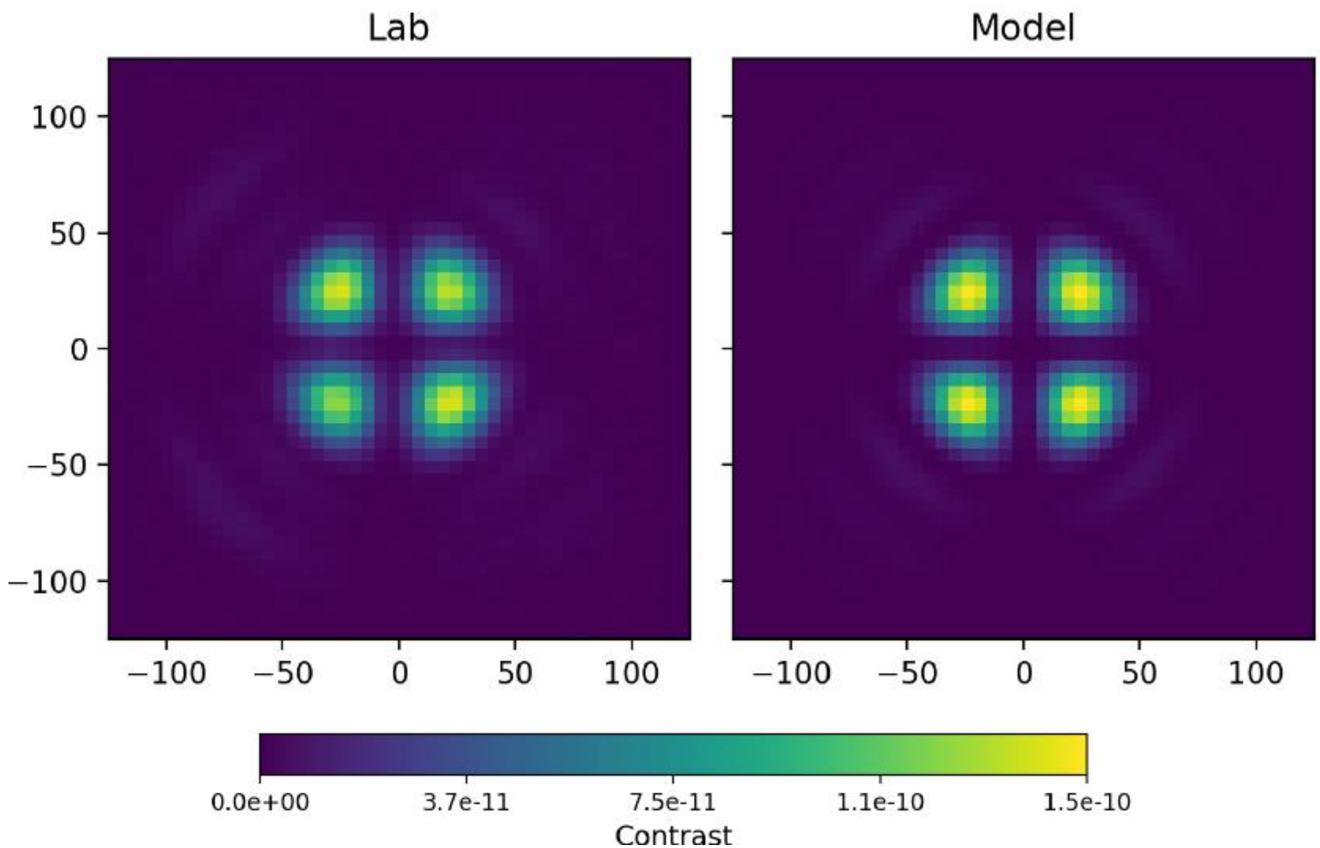
Zero



Zero

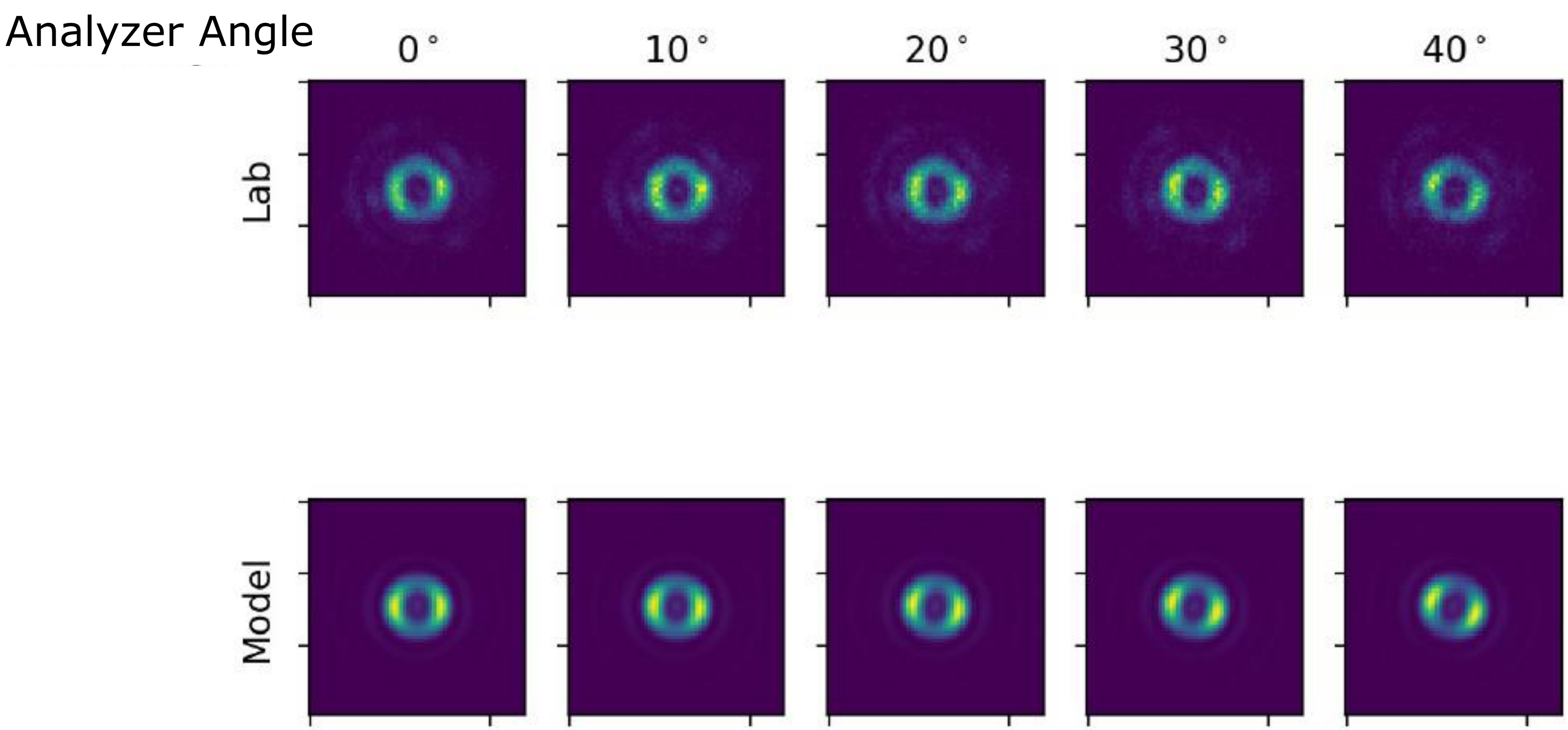
Vector Diffraction: Confirmation

- Crossed-polarizer model matches data to < 1e-10 at the IWA.

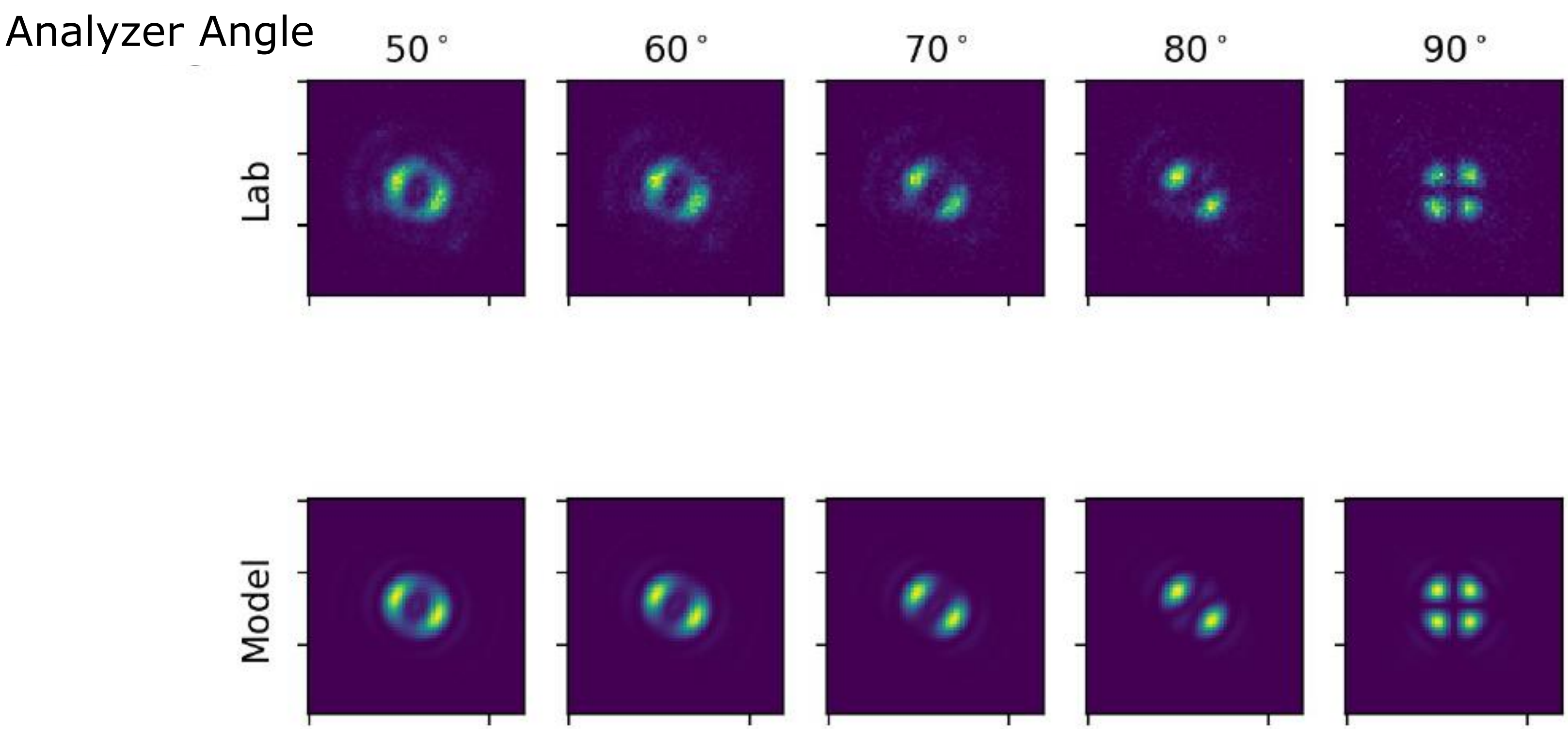


Polarization Model Confirmation

- Lobe asymmetry improved through careful alignment.
- Polarization nature of the lobes confirmed through cross-polarizer experiment.



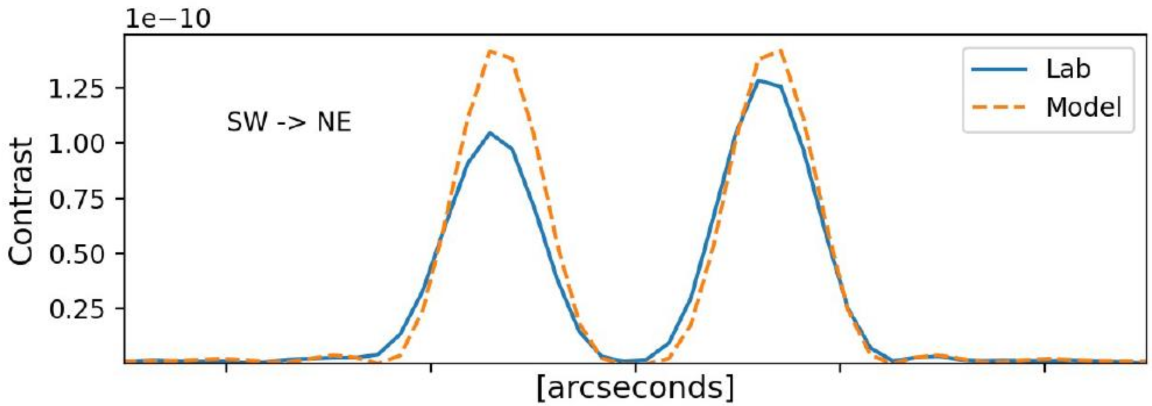
Polarization Model Confirmation



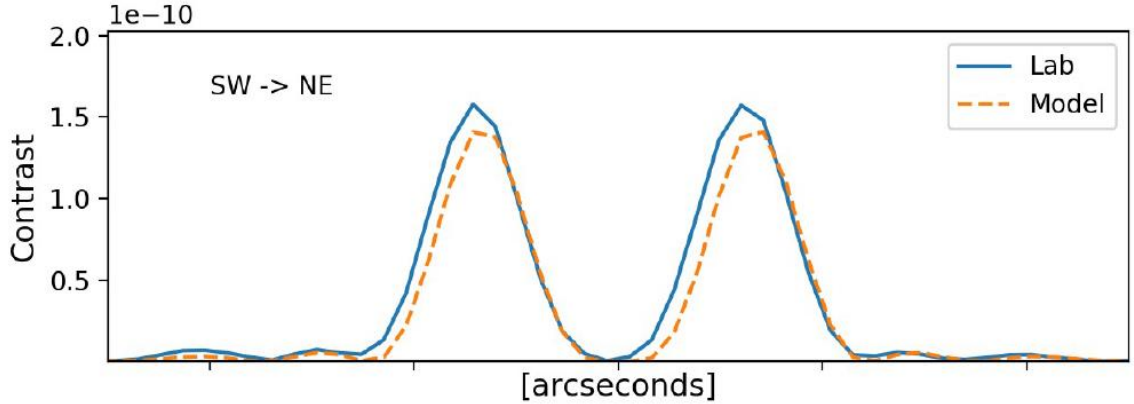
Vector Diffraction: Cross Terms in Different masks

- Model works at the 1e-10 level for two different mask, and two different wavelengths (not shown).

DW9
641 nm
Cross Pol.



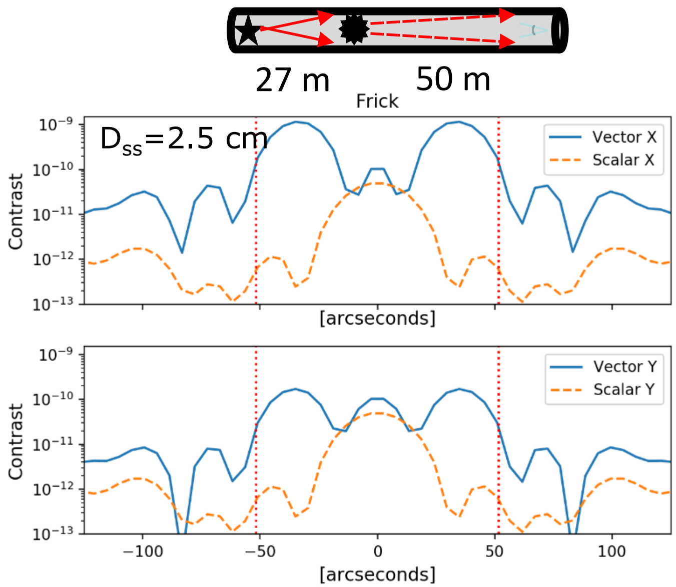
DW21
641 nm
Cross Pol.

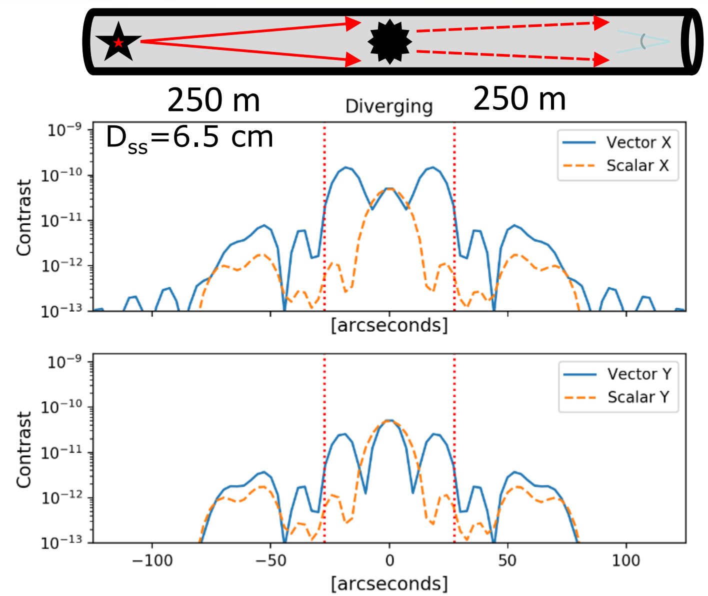


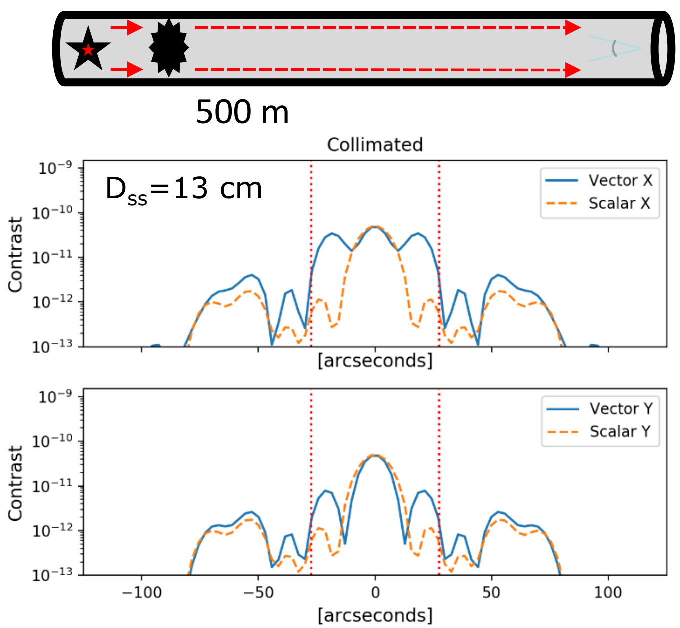
Vector Diffraction Status: Alternative Testbeds

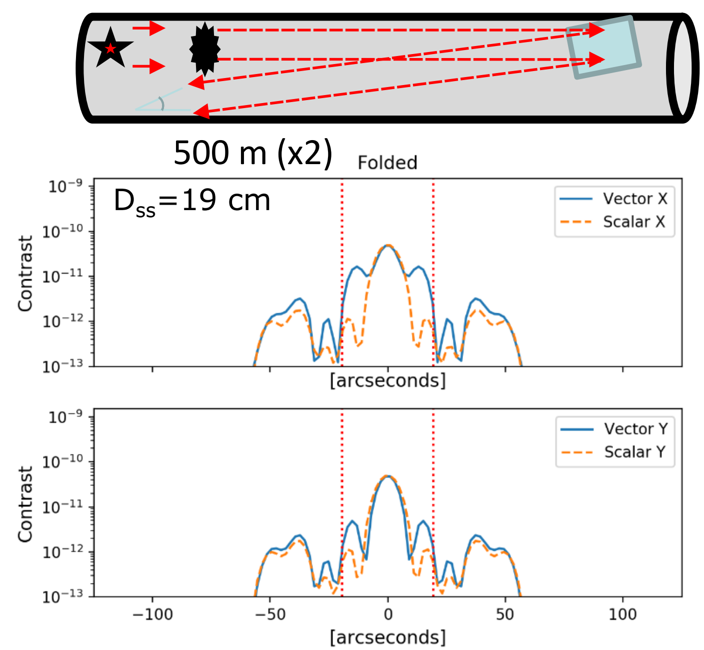
- If in the end we are not satisfied with the range/quality of results from the Frick Testbed, we need to consider larger testbeds or shorter (e.g. UV, suggested by J. Grunsfeld) wavelengths.
  - Longer testbeds: contrast should improve as 1/Length
  - UV: contrast should improve as wavelength (pending detailed study)
    - Mask fabrication is more challenging because the mask is smaller.
- Consider
  - XRCF
  - Large buildings at ARC
  - Alternative mask fabrication (thin films)
- Does not require vacuum unless there are stability issues.

Longer Testbeds: How Long?



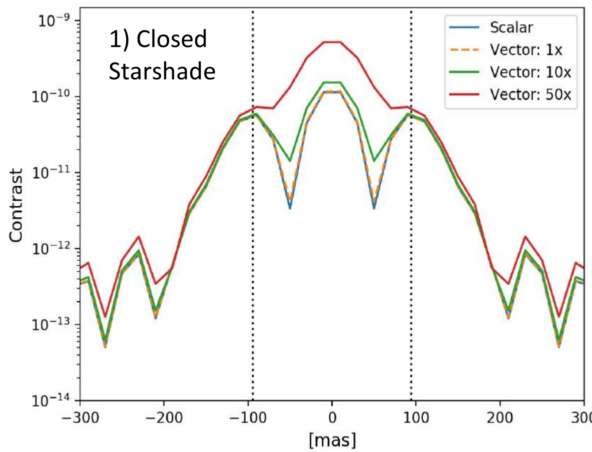


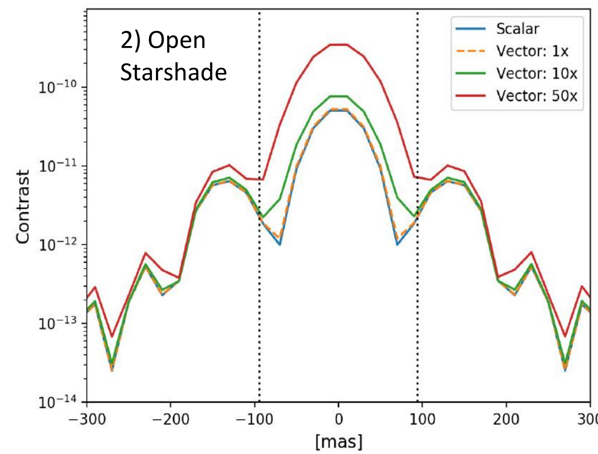


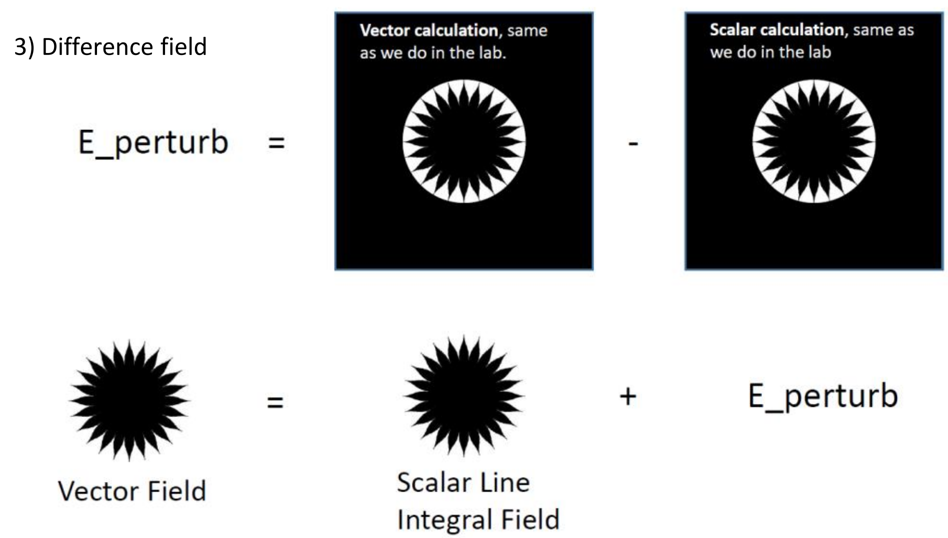


Vector Diffraction: Modeling the Flight Starshade

- Three approaches
  1) Add an outer starshade, model as if in the lab.
  2) Model as scalar, add difference phase and amplitude along the inner gaps.
  3) Compute vector over a closed starshade out to its tips, compute scalar for same region, and add difference to scalar for an open starshade.
- All rely on calculations of polarization effects at the petal edges.
  - Flight edges are metallic or coated, ~ 200 nm radius.
  - Lab edges are 2 um thick silicon with 100 nm metallic coating







Milestone 2 Progress

- Milestone statement: *Small-scale starshade masks in Princeton Testbed validate contrast vs. shape model to within 25% accuracy for induced contrast between 10^{-9} and 10^{-8}.*
- "25%" means the model predicts the observed contrast to within a factor of 1.25.

Deformations	Description	Note
Single Petal Displacement 1	Move single petal radially to induce 10^{-8} contrast	TBD Displacement
Single Petal Displacement 2	Move single petal radially to induce 2×10^{-8} contrast	TBD Displacement
Global Petal Displacement	Move all petals to induce 10^{-8} contrast	TBD Displacement
Petal Edge Segment Displacement	Move edge segment near IWA. On opposite petal, displace edge segment on outer petal. Inner contrast 10^{-8}, outer contrast 3×10^{-9}.	Segment length is ~ 1/15 of petal length. Amplitude ~ 2 microns.
Petal edge sine error	Add sine wave over 75% of inner petal edge and ~ 50% of outer petal edge. Inner contrast 10^{-8}, outer contrast 3×10^{-9}.	Sine wave has 4 periods on inner starshade, 5 periods on outer starshade. Amplitude ~ 1.5 microns.
Combined Errors	Combine sine wave and edge segment displacements	TBD Amplitudes

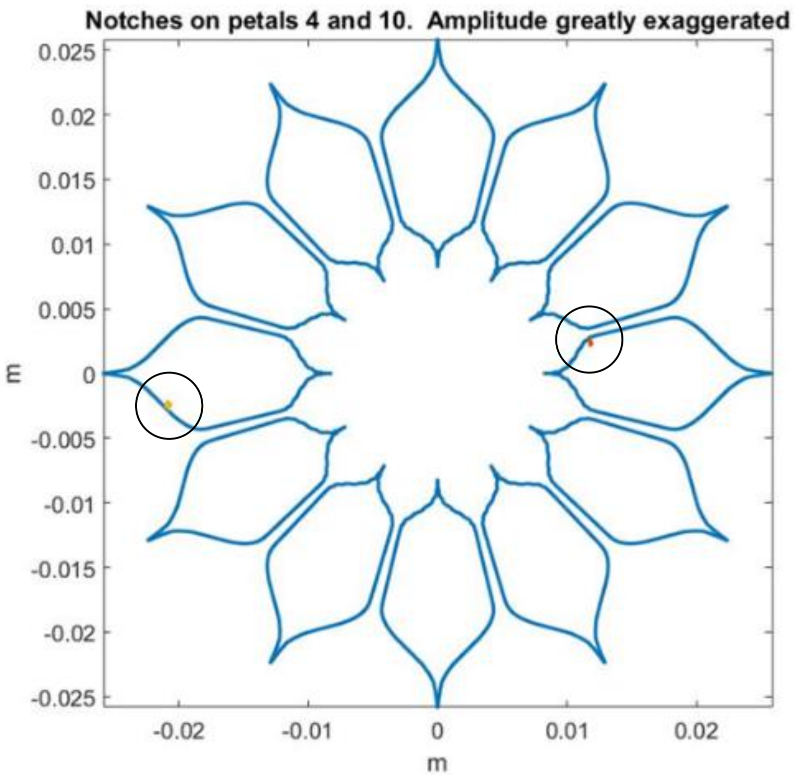
Combine in one mask

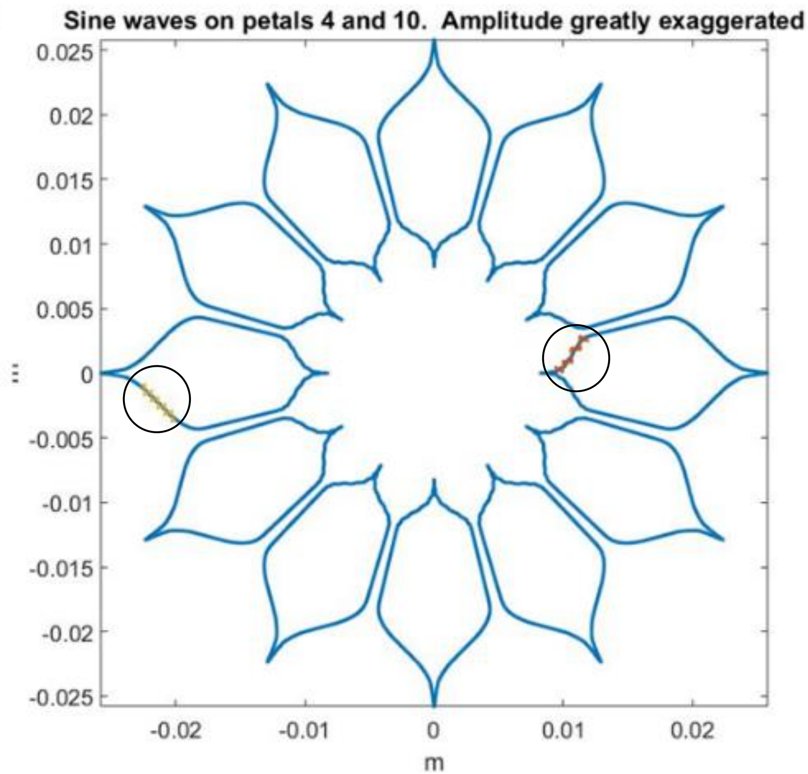
What We Learn from M2 Testing

- The experiment has many unknowns:
  - Model inaccuracy: including the Fresnel approximation, choice of boundary conditions, vector diffraction approximations.
  - Manufacturing errors: overetch, edge roughness, variable thickness
  - Other: uniformity of illumination, turbulence, stray reflections.
- Noise floor is 10^{-10} at IWA, 2×10^{-11} at OWA:
  - *This is the upper limit to the model inaccuracy.*
- M2 demonstrates the model's ability to predict contrast changes when the shape is changed in a *known* way.
  - The error budget is based on these sensitivities.
  - Goal is to validate this within a factor of 1.25.
- To achieve this goal, we have to test above the noise floor.
  - Cross-terms between unknowns require perturbations to be > 6×10^{-9} for a contrast floor of 10^{-10}, and > 10^{-9} for a contrast floor of 2×10^{-11}.
  - This is why we test for perturbations in the range 10^{-9} to 10^{-8}.

Petal Edge Segment and Petal Sine Wave Masks Designs

- These two masks have been tested in the Frick Testbed

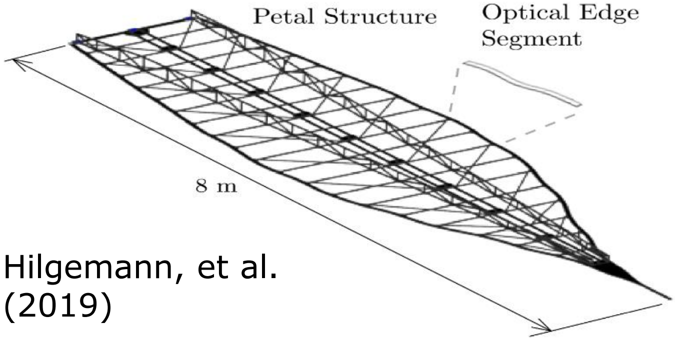




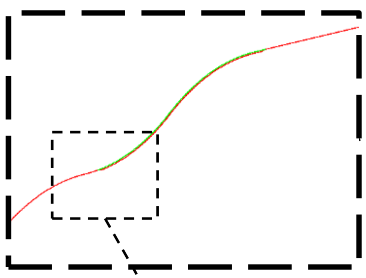
Petal edge segment displacements are modeled as 'notches' where the edge is displaced by ~ 2 microns.

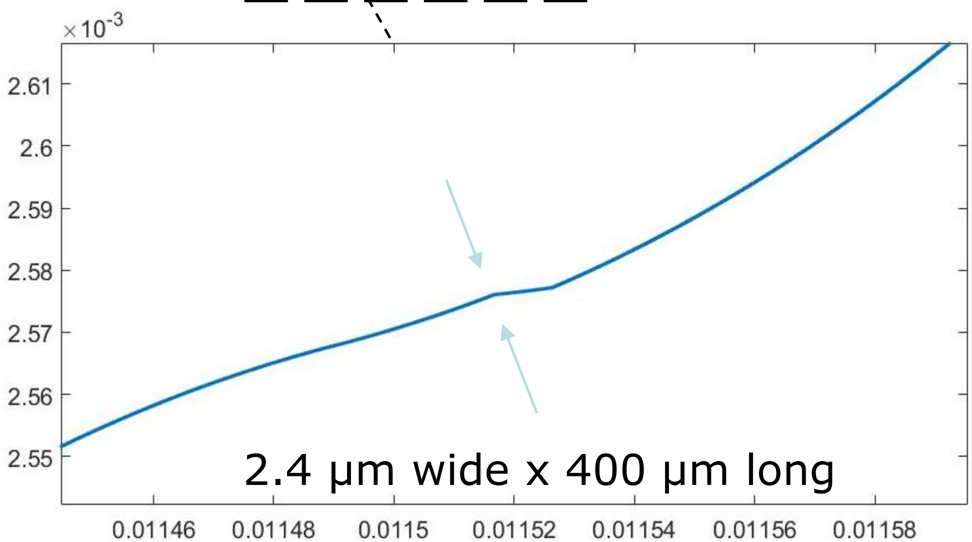
Long period sine waves with an amplitude of 1.5 microns along the petal edge. Displacement and sine amplitudes are greatly exaggerated in these plots.

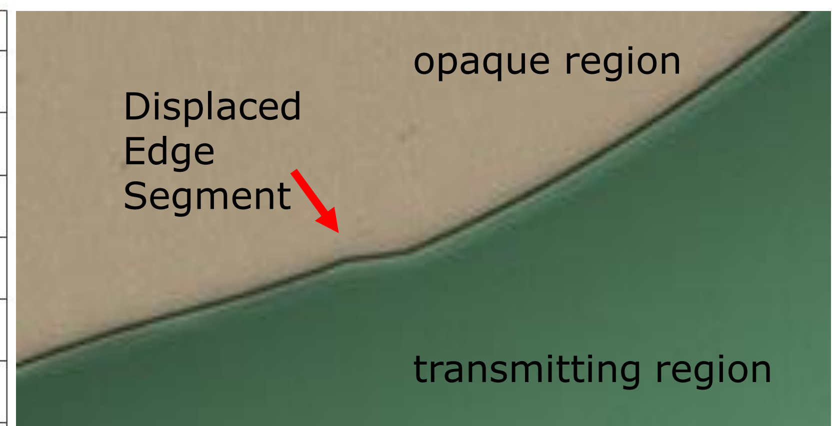
Displaced Petal Edge Segment Mask



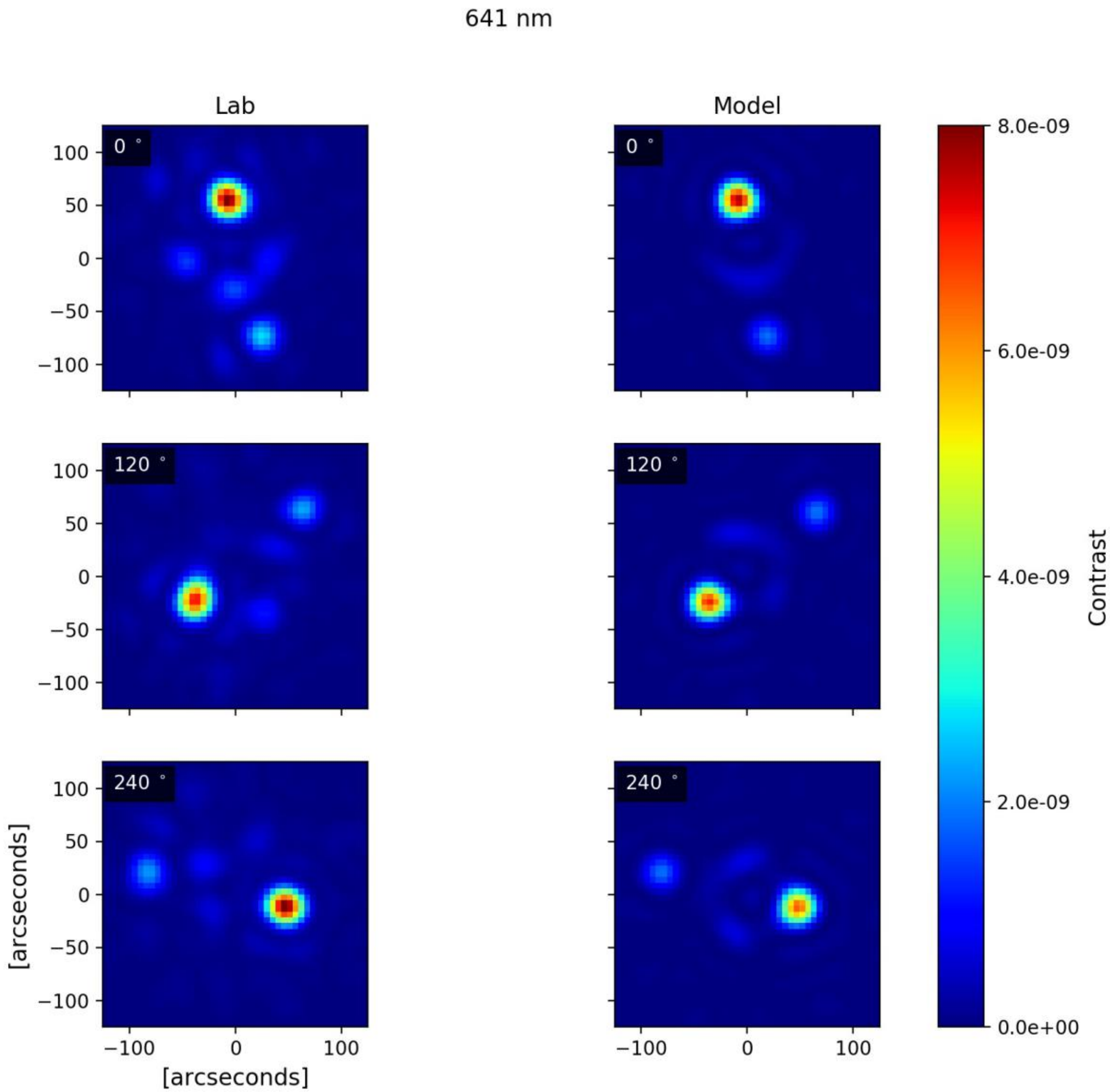
Hilgemann, et al. (2019)



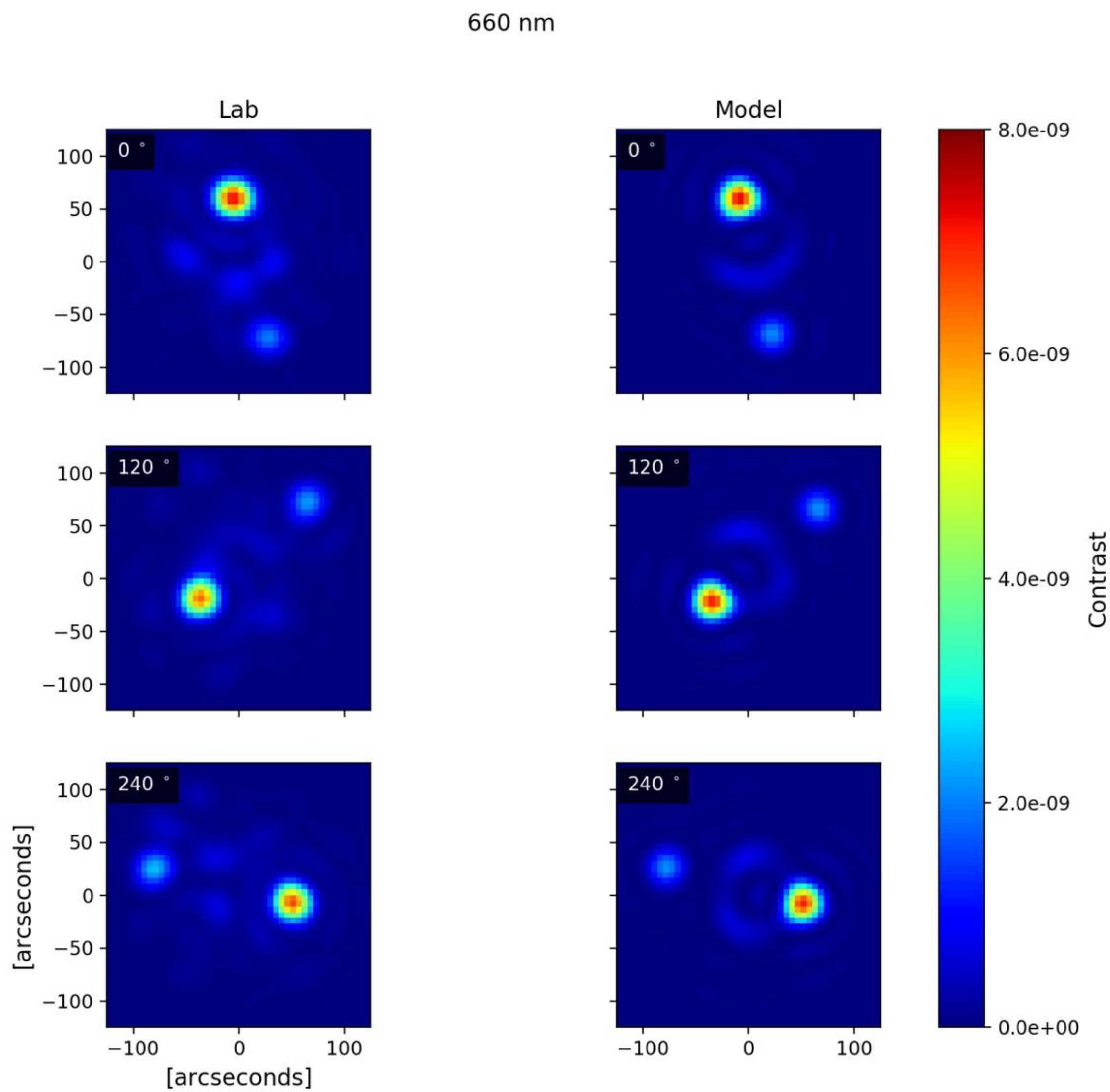




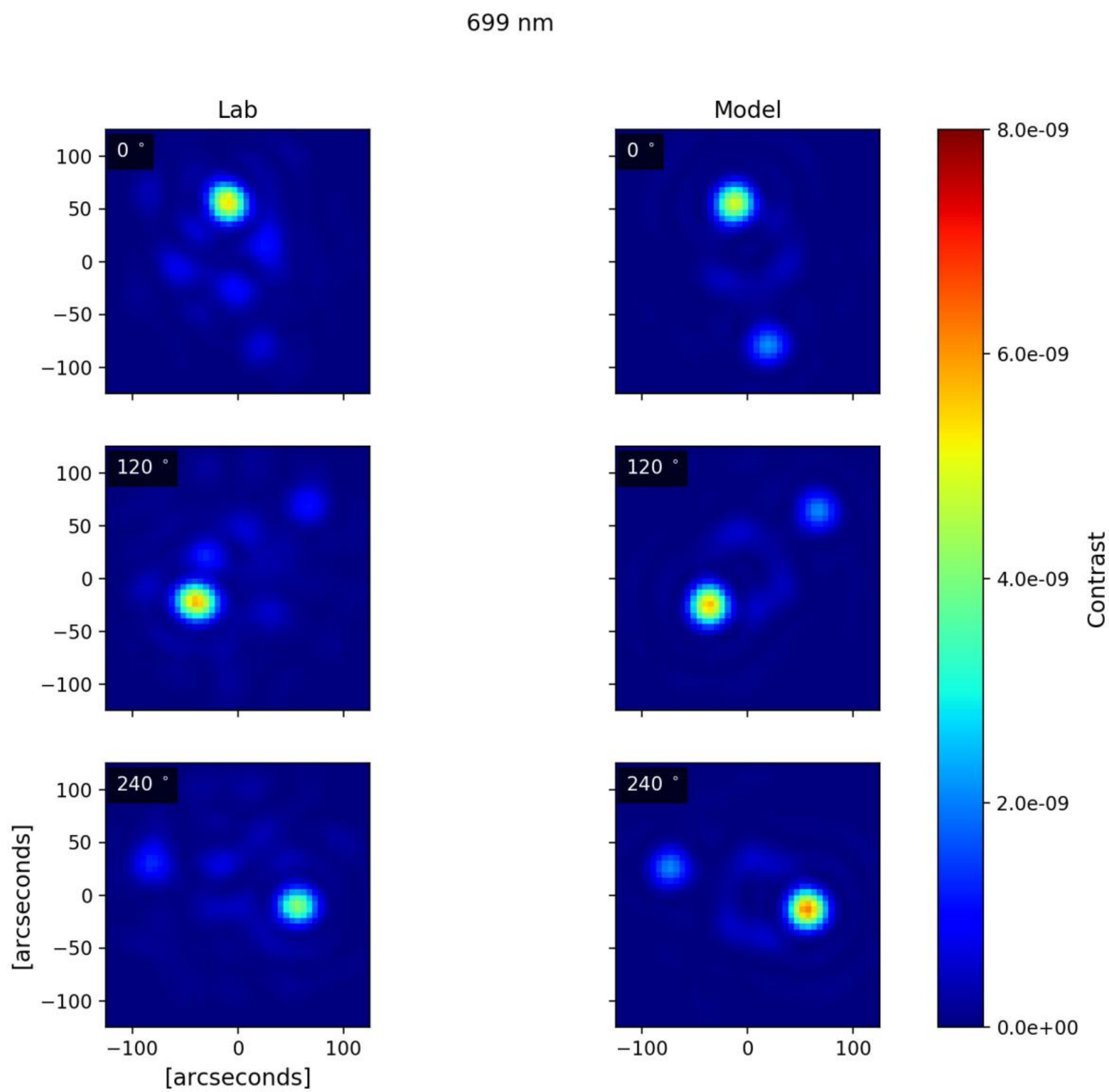
Displaced Edge Segment Mask: 641 nm



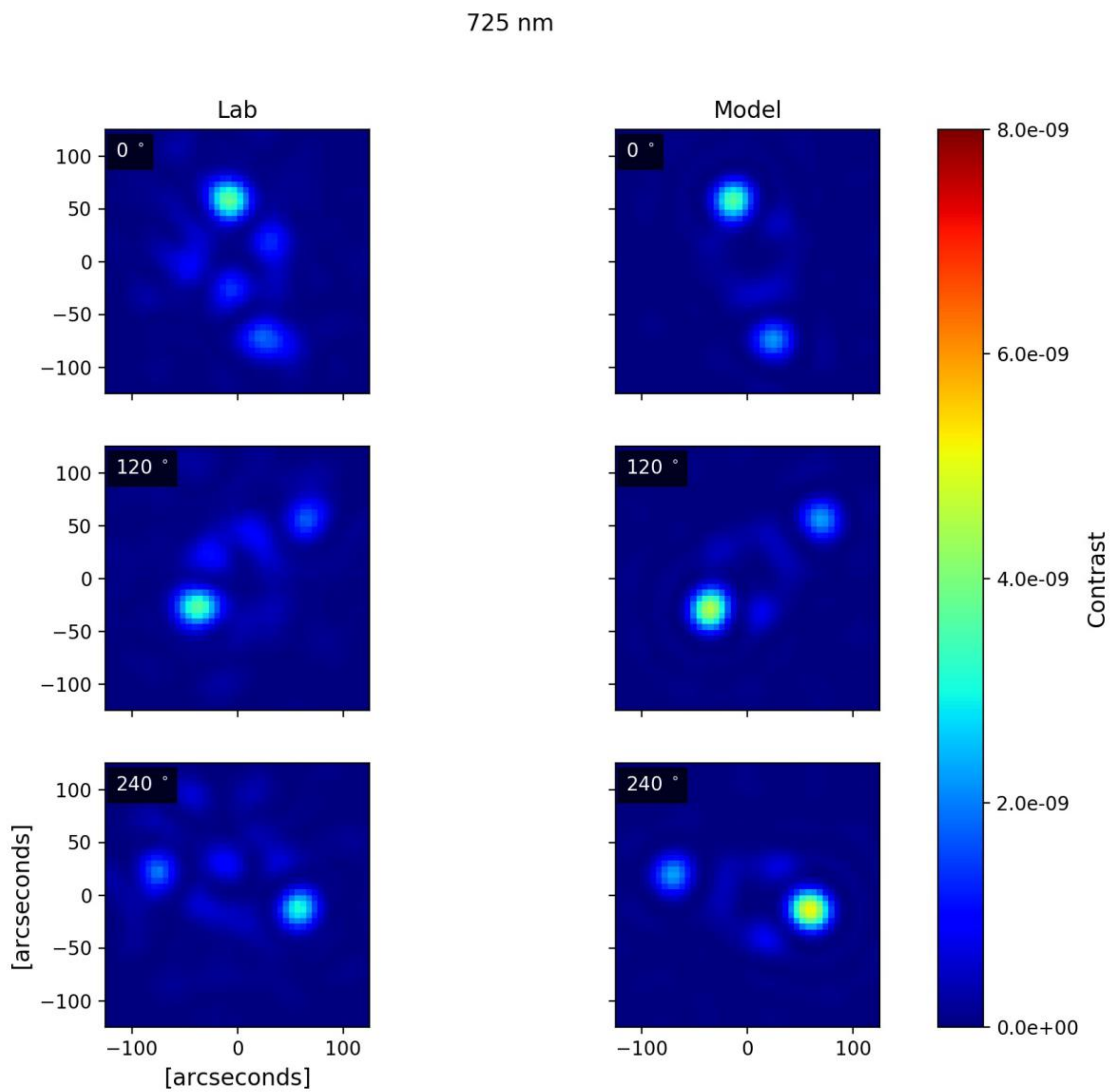
Displaced Edge Segment Mask: 660 nm



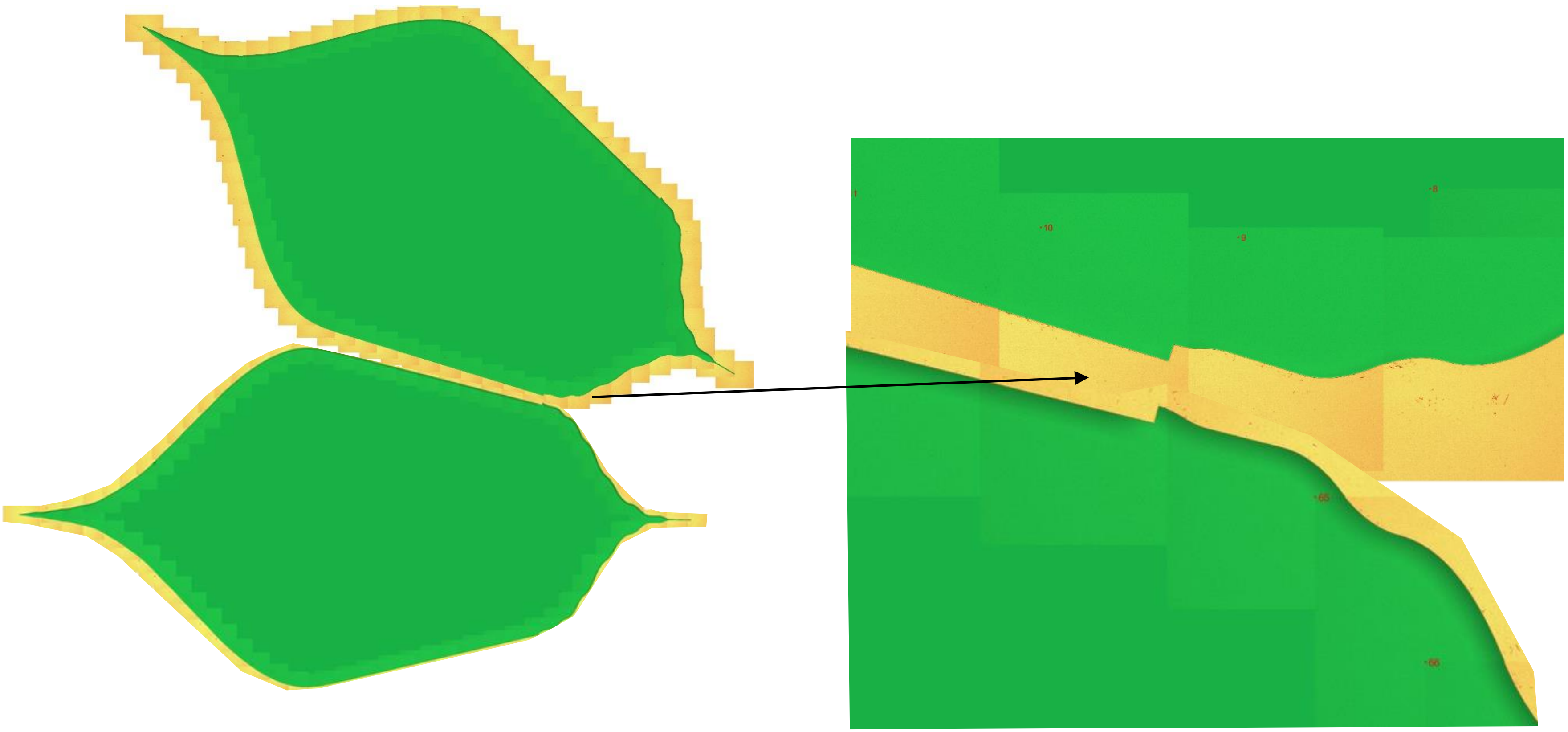
Displaced Edge Segment Mask: 699 nm



Displaced Edge Segment Mask: 725 nm



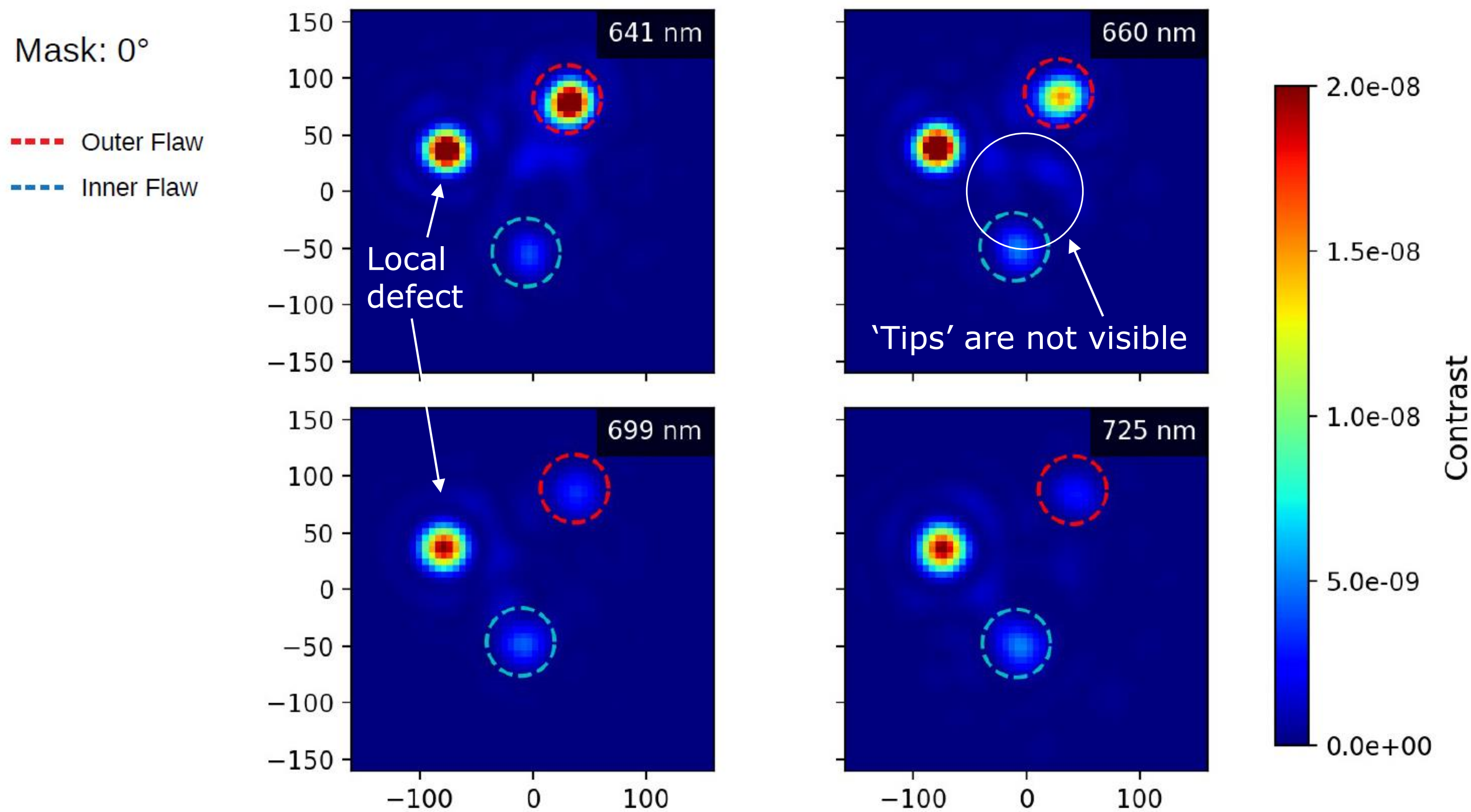
Petal Sine Wave Mask Includes ‘Tips’ at Edge of Inner Starshade



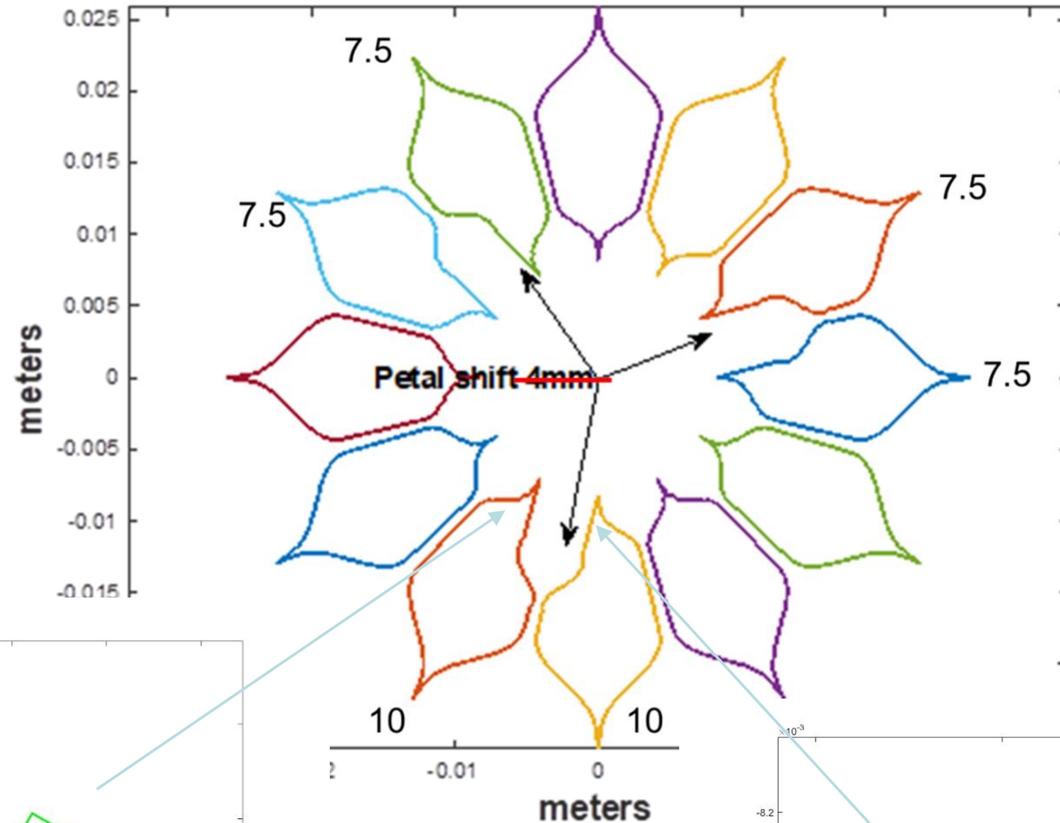
Tips are formed by rotating the outer starshade concentrically around the inner starshade to form 50 um wide tips.

According to the model, these should not diffract significant light.

Edge Sine Wave Mask: 0 deg



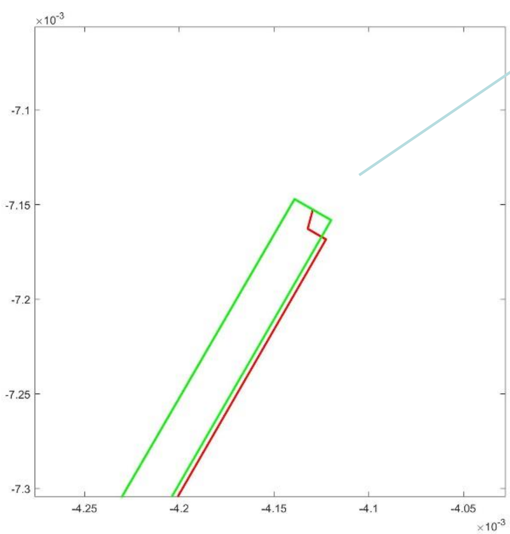
Shifted Petal Mask: In Production



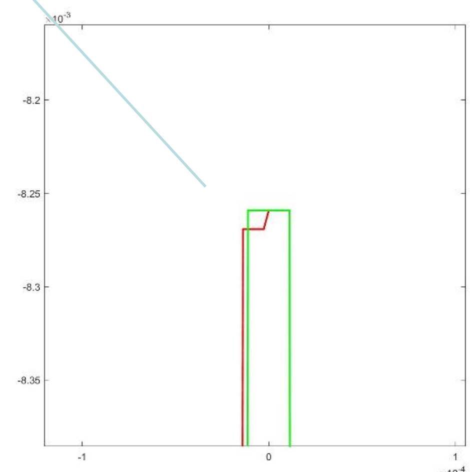
Two regions are shifted by 7.5 um.

One region is shifted by 10 um.

Shifts are greatly exaggerated in the figure.



The red lines show the shape of the inner tips in the shifted regions. There are tips like this (3 pairs).



Final Thoughts

- Laboratory tests are demonstrating 10^{-10} contrast at flight Fresnel numbers.
- The miniature scale of the lab tests brings into play small scale features that require vector diffraction mathematics.
- The vector diffraction model explains the lobes and the observation of the pattern through crossed polarizers confirms that the lobes we are seeing is entirely due to polarization effects.
- The first two M2 tests have been successfully completed.
  - The model accuracy is generally better than a factor of 1.25.
  - There are some anomalies at the factor of 2 level that we have yet to understand.
- So far the Frick Testbed has proved to be highly successful and adequate for milestone testing.
  - We are on track to complete the Milestone by the beginning of June.
  - Need testbed > 500 m long to get polarization lobes below 10^{-10}.