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Starshade Field Testing and Optical Model Validation

6/11/2016

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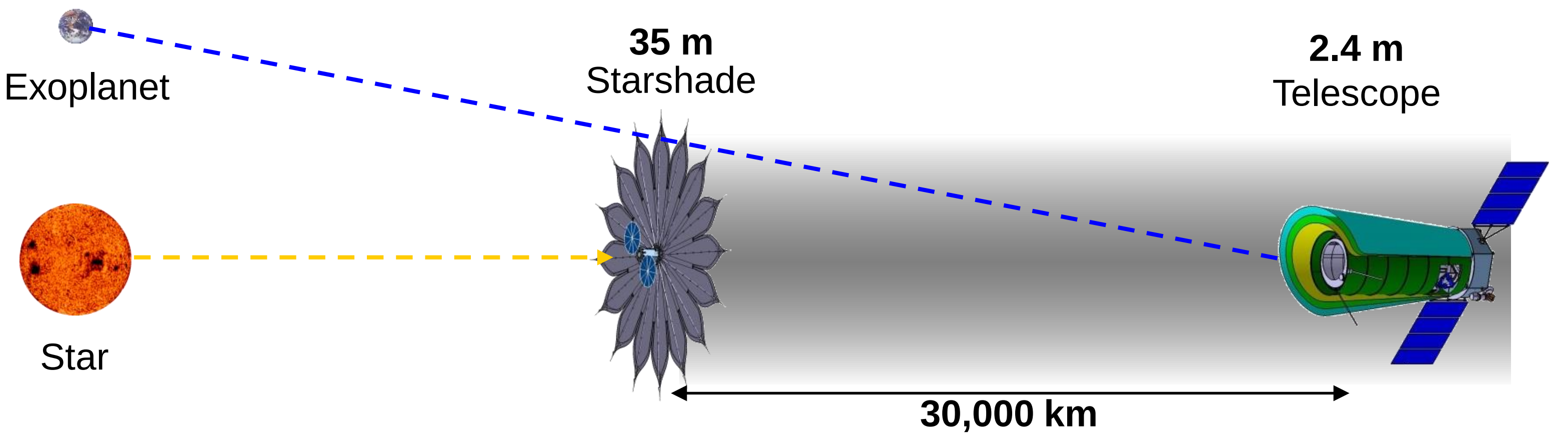
Starshade Basics



- Starshades are an external occulter used in conjunction with a space telescope
- The light from the star is blocked by the starshade, while the light from the nearby exoplanet is not
- Starshades are extremely large (35m+ in diameter) and therefore cannot be tested at the full flight-like scale
- Scaled down field testing can help validate optical models of starshade effects

Field Testing a Starshade

Field Testing 2014/15

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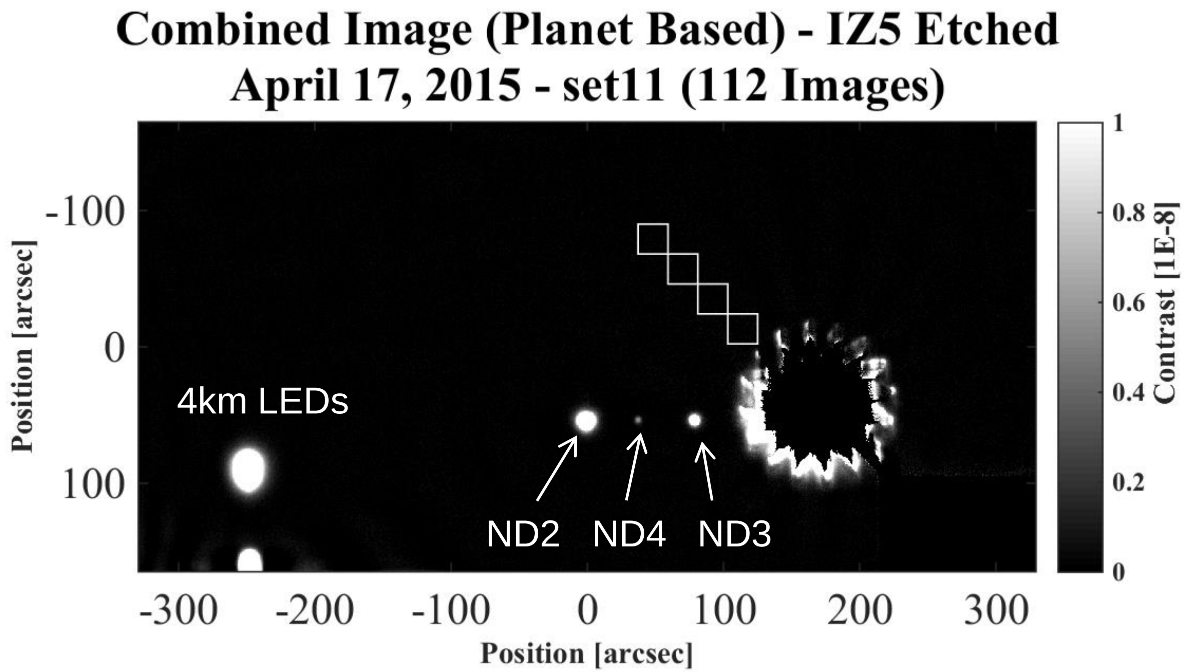
NASA JPL /
Northrop Grumman
100th Scale
Starshade

Best Contrast Ratio – Desert Field Tests

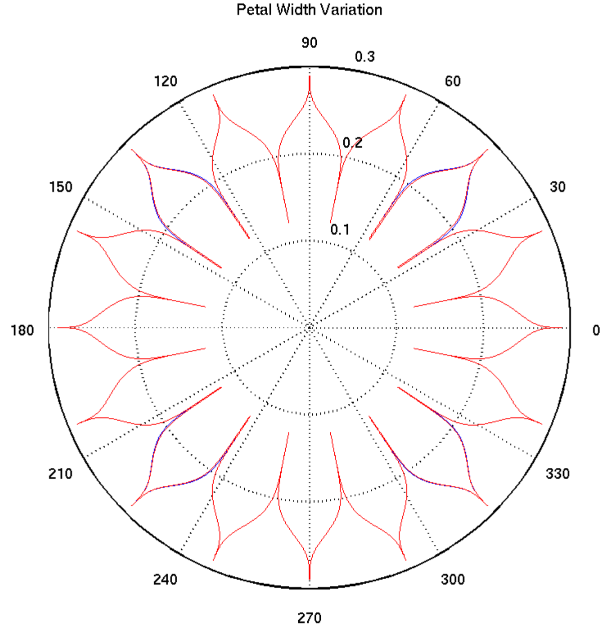
- Planet LEDs are Standard LEDs with ND filters in front.
  - ND4 planet ~8E-9 below main source
- Light Scatter from dust is modelled and subtracted from the image
- Slight vertical variation between images due to air disturbances.
  - Images collocated using Planet LEDs

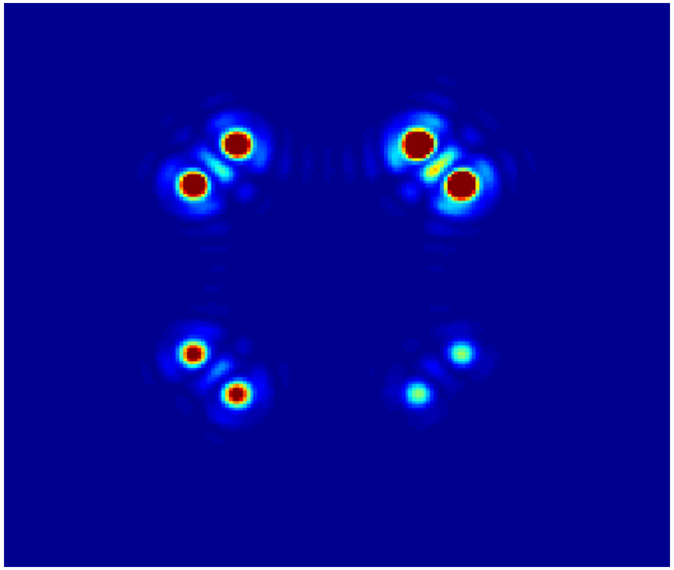


3σ Standard Deviation in box closest to the starshade = **9.09E-10**

Starshade to Telescope Separation	Starshade Diameter	Telescope Aperture	Resolution	Resolution Elements	Inner Working Angle	Fresnel Number
1km	0.5m	0.04m	3.8 arcsec	26.8	51 arcsec	210
80,000km	50m	2.4m	0.063 arcsec	2	0.065 arcsec	13

Testing Engineering Sensitivities – Flawed Starshade Performance





- 6 families of flaw each applied to Hypergausian and Numerically Determined Starshades
  - Simulations predict patterns field test optical lengths

Model Verification

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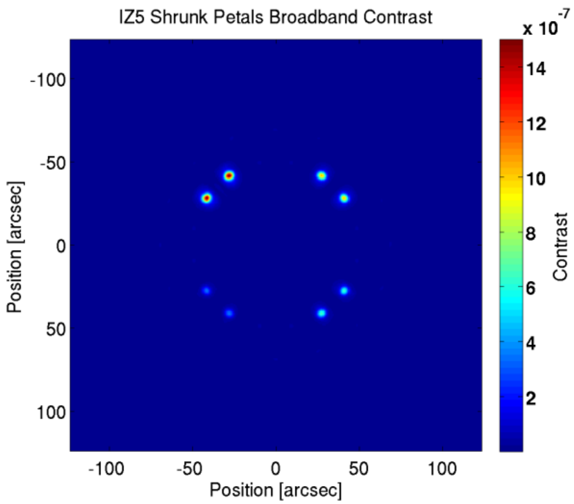
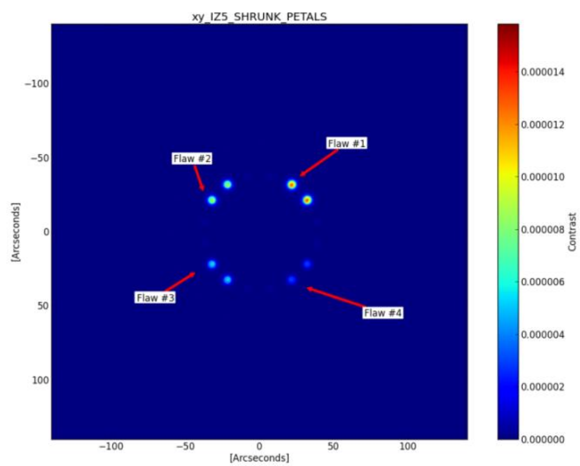
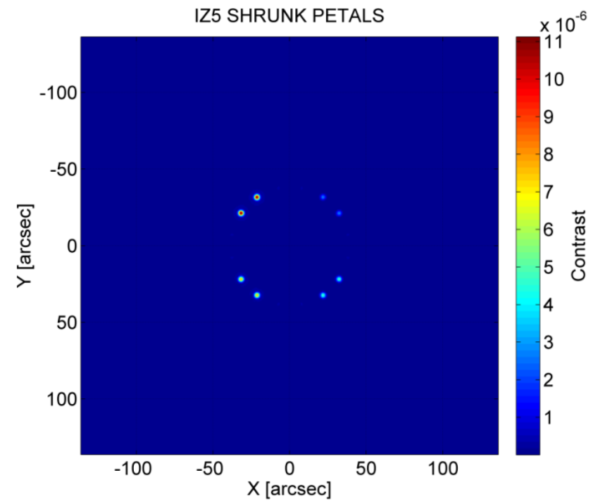


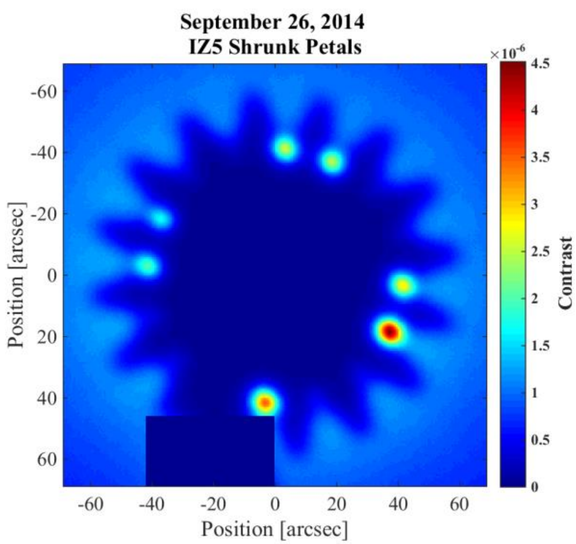
NG Model



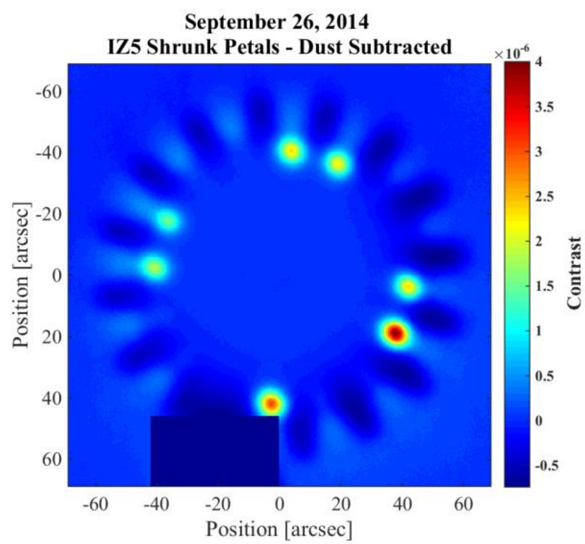
CU Model



JPL Model

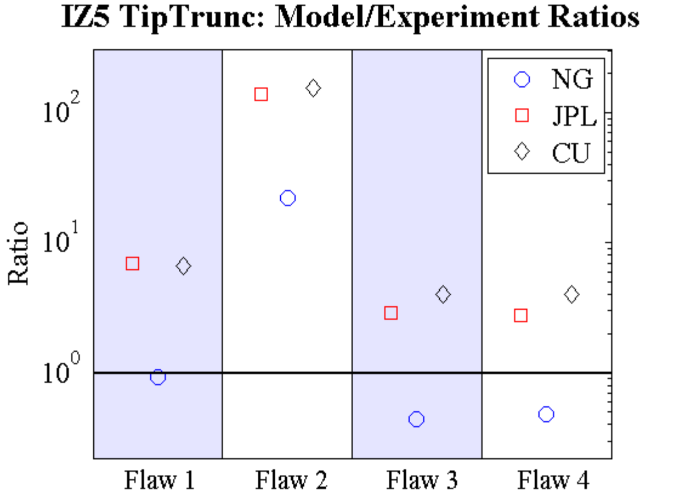


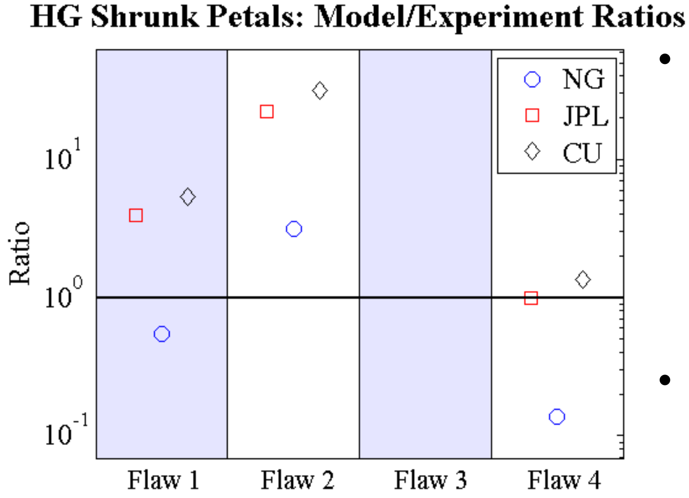
Measured

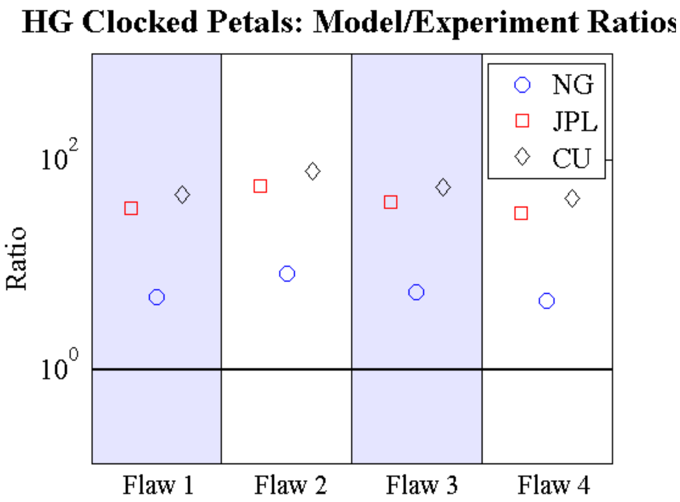


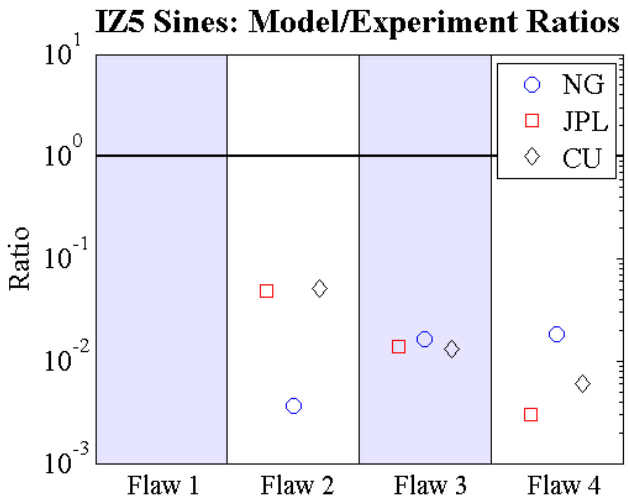
Measured & Dust Subtracted

Model Predictions vs. Measurements: January 2016









- Ratios of flaw peaks modeled independently by NG, JPL, and CU to the peaks measured in the field.
- Points above the line indicate the model predicted a brighter response than was measured
- Lots of scatter amongst model predictions and significant differences between predictions and observations

Optical Models of Starshades

Modeling Challenge

- Four groups are collaborating to investigate the differences in model predictions for field testing scenarios
  - JPL
  - CU
  - Princeton
  - Northrop Grumman

- Previous comparisons between the different models for **flight-like systems** were in agreement to within 5%

- Field testing scenarios require a **different treatment**
  - Higher Fresnel numbers
  - Expanding beam

Modeling Approach

- Each group has a model with a slightly different design based on the same optical principles.

- Each model has two separate components
  - Propagating the light from the star past the starshade and to the pupil of the telescope
  - Propagating the light through the telescope and to a detector

- Two types of starshades used: Hypergaussian (HG) and IZ5
  - HG edges defined by the equation: $A(r) = e^{\left(-\left(\frac{r-a}{b}\right)^{n}\right)}$
  - IZ5 is a numerically determined shape optimized by JPL for the Fresnel numbers and distances used in the desert tests.

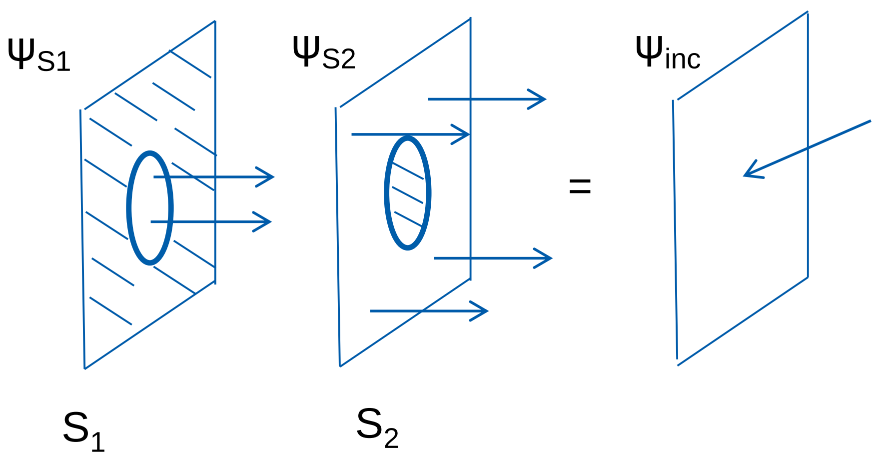
- Model comparisons done at multiple wavelengths and a large range of distances between the source and the starshade
  - Distances ranged from 1km to 10^{17} km
  - Distance between starshade and telescope kept constant at 1km

Wave Propagation Model

- The total field at the aperture of the telescope in the presence of a starshade is given by the Fresnel-Kirchhoff diffraction integral:

$$\psi_{S1} = \frac{1}{2i\lambda} \iint_{S1} \frac{e^{ikd}}{d} \frac{e^{ikr}}{r} \left(\vec{n}_s \cdot \frac{\vec{r}}{r} + \vec{n}_s \cdot \frac{\vec{d}}{d} \right) d\sigma_{\xi\eta\zeta}$$

- Babinet's Principle



The entire plane is transparent. The field ψ is from a source propagating through the plane without diffraction

What we really want to calculate is ψ_{S2}, that is equal to

$$\psi_{S_2} = \psi_{inc} - \psi_{S_1}$$

so we can calculate ψ_{S1} instead

Evaluating the Diffraction Integral

- Each group takes a different approach to evaluating the diffraction integral:
  - Princeton integrates over two dimensions using a gray pixel approximation
  - JPL applies Stokes' theorem to solve the double integral as a single integral over the boundary of the starshade
  - CU uses the Dubra-Ferrari method to reduce the double integral to a single integral
  - NG uses a Taylor expansion to calculate the integral over the radius analytically and then numerically over θ using Chebychev integration

- **Convergence of all the models using different approaches to evaluating the diffraction integral increases the robustness of the solution**

Telescope Model

- Telescope aperture: 2cm in radius
- Focal length: 2.032m
- Pixel size of 0.25 arcsec
- Diffraction limit: 3.77 arcsec
- Actual pixel size for observations: 0.5487 arcsec

Model Challenges and Bug Fixes

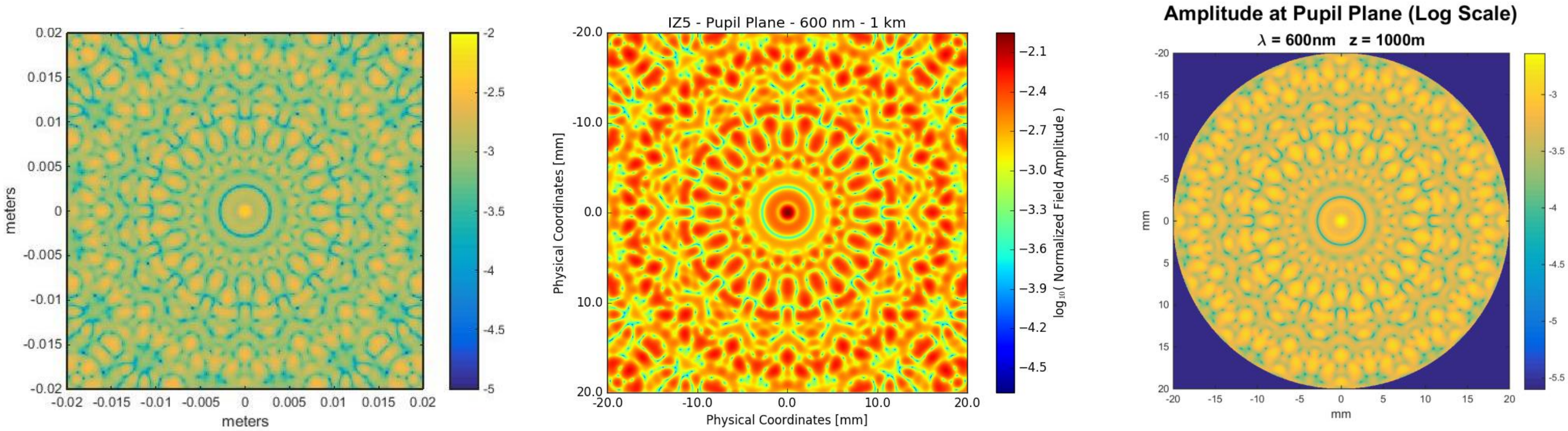
- All groups had bugs that needed to be resolved over the course of our work since January
  - Focus location
  - Pixel resolution
  - Capability of the model to handle a large range of distances
  - Consistent valley depths

- Use of the exact same petal edge for the flaws
  - Different model inputs makes this challenging

- Number of points along the edge required:
  - Perfect starshade
  - Capture the impact of the flaws

- Comparing peak values vs. integrated energy from individual flaws

Pupil Plane Comparison Example: IZ5 at 1km



- Wavelength 600nm
- From left to right: JPL pupil plane, CU pupil plane, and NG pupil plane
- Qualitative comparisons over the entire pupil look good
  - Same morphology
  - Similar values

Pupil Plane Comparison Example – HG at 2km

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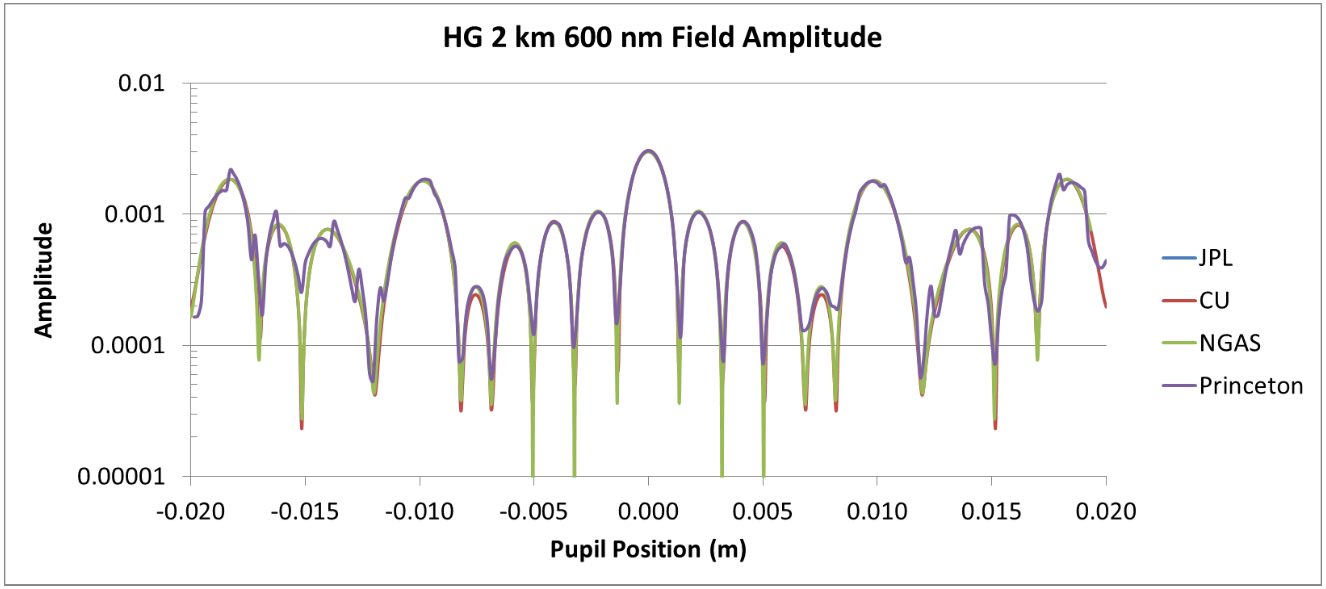

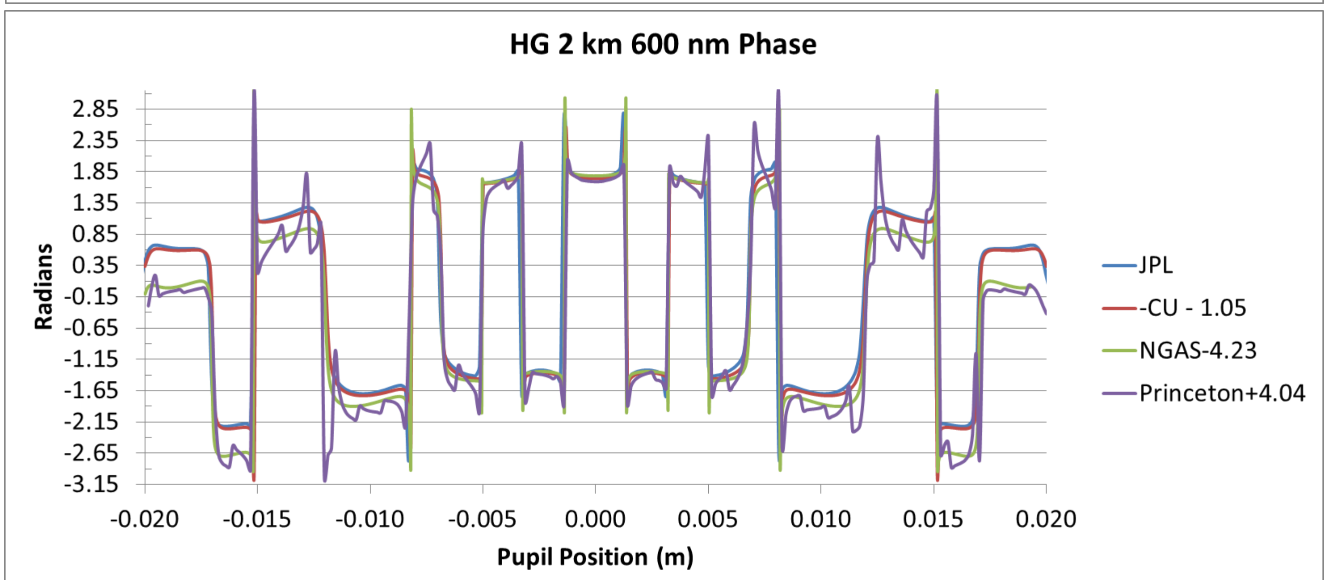

- Wavelength 600nm
- Horizontal slice through the center of the aperture
- Top panel is the amplitude component of the field
- Bottom panel is the phase component of the field
- Phase overall morphology matches well, but values are offset between the different groups

Image Plane Comparison

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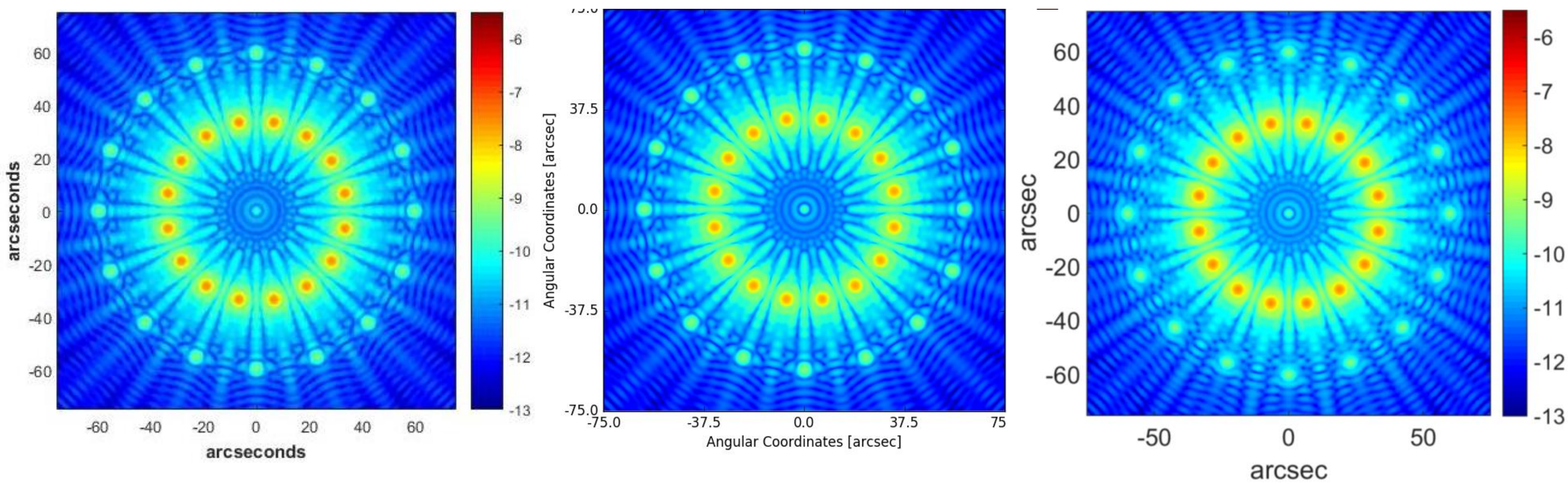
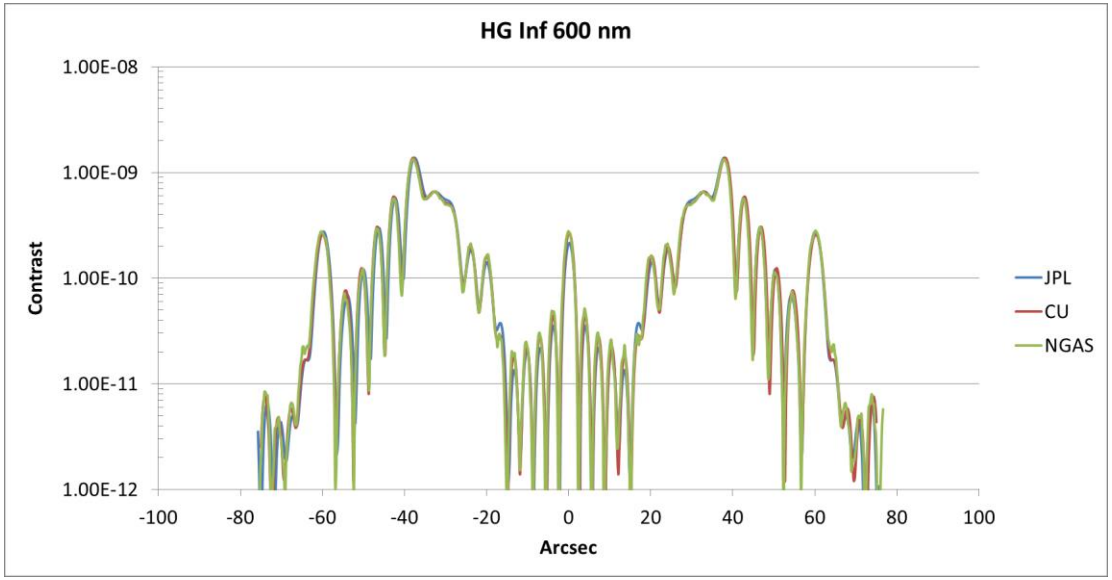
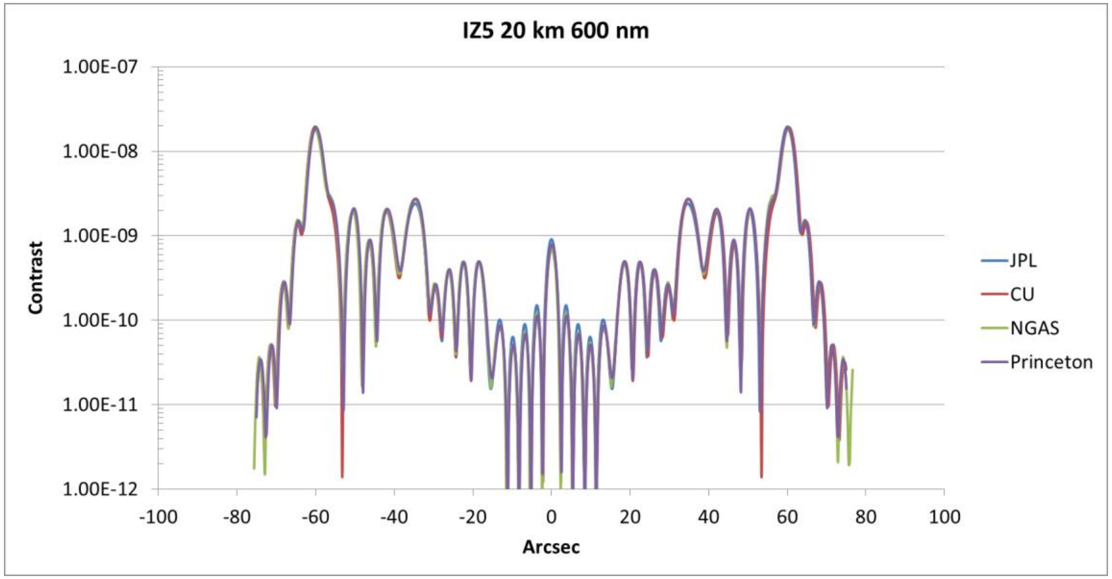


JPL CU NGAS

- Broadband images of the perfect HG starshade at a distance of 2km from the source
- All images shown on the same scale

Image Plane Comparison Examples



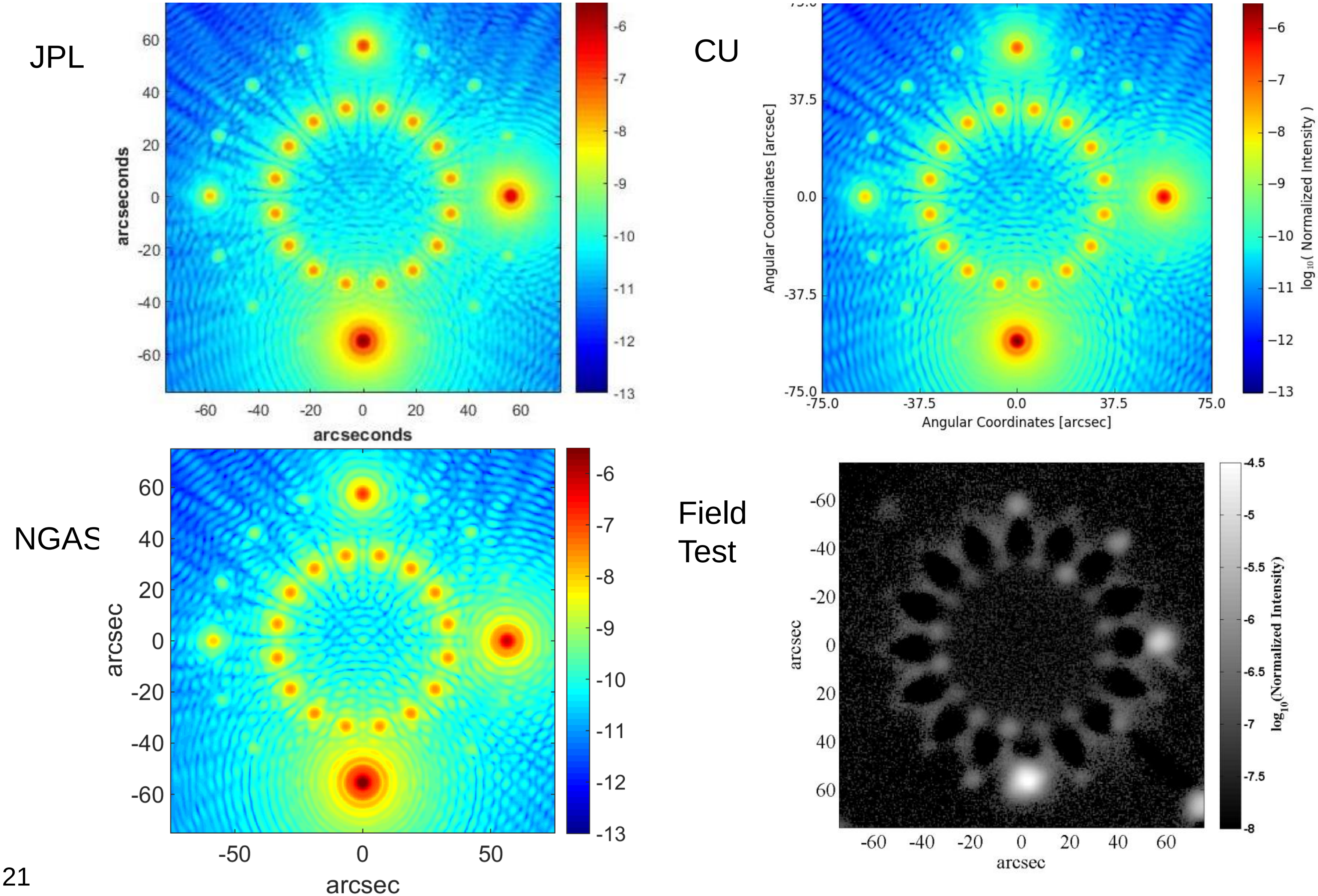


- Above left is a comparison of a horizontal cut through the image plane for a source placed at infinity and using a HG starshade
- Below left is a comparison of a horizontal cut through the image plane for a source placed at 20km and using an IZ5 starshade
- Models agree well amongst all the groups

Flawed Starshades

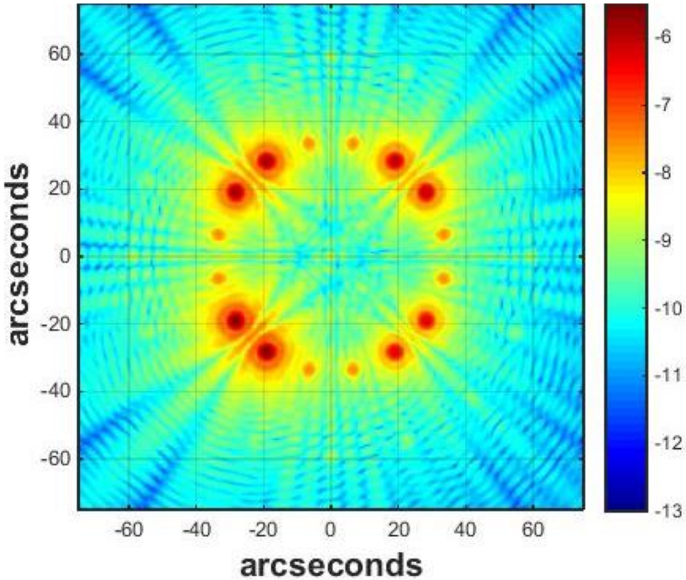
- 6 types of flaws were defined for use in desert testing:
  - Truncated valleys
  - Truncated tips
  - Lateral in plane rotation of the petals (petal clocking)
  - Shrunk petals – petals narrower than expected
  - Sines on edges – sine wave added on top of the nominal edge shape
  - Displaced edges – a section of the petal displaced outward from the nominal edge
- More complete description of the flaws (size, placement, etc.) is available in our 2012 TDEM Final Report
- Modeling of all flaws in progress
- We present our findings here for truncated tips, shrunk petals, and sines

Flawed Starshade – Tip Truncation

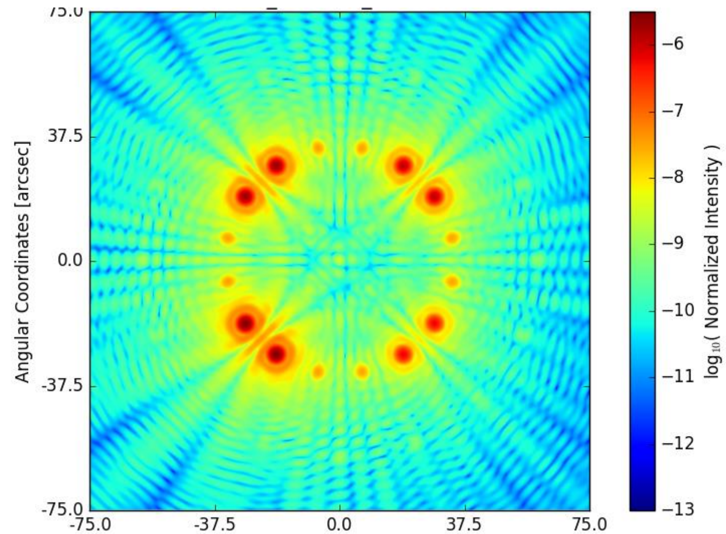


Flawed Starshade – Shrunk Petals

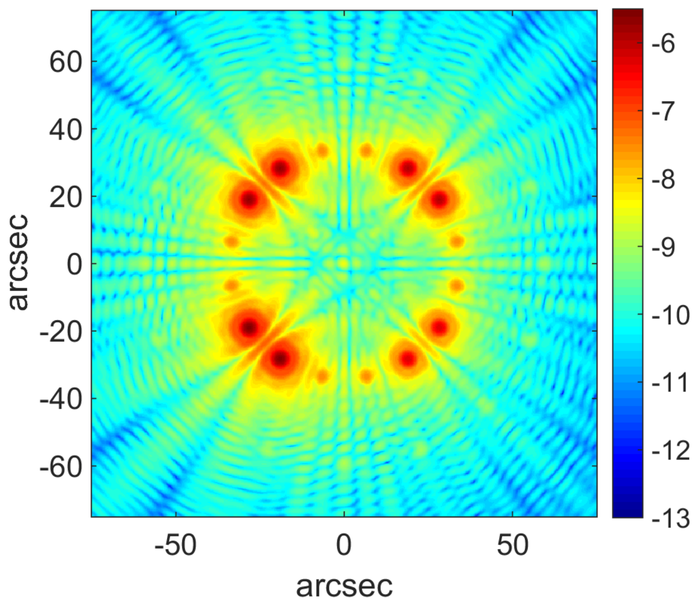
JPL



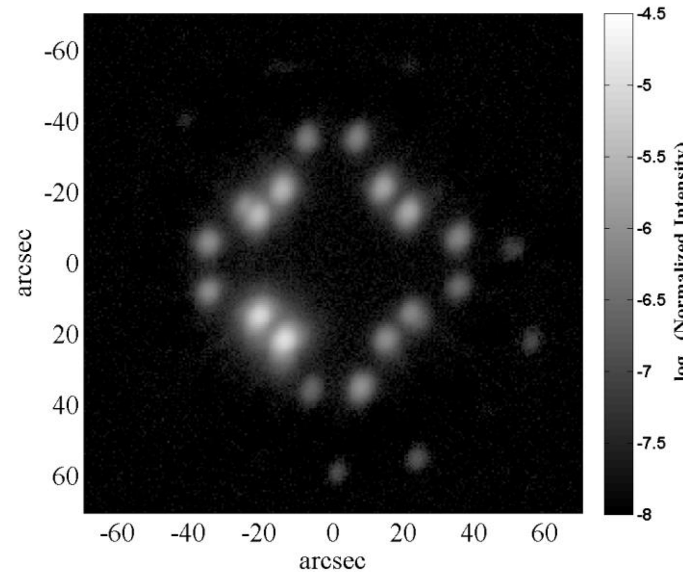
CU



NGAS

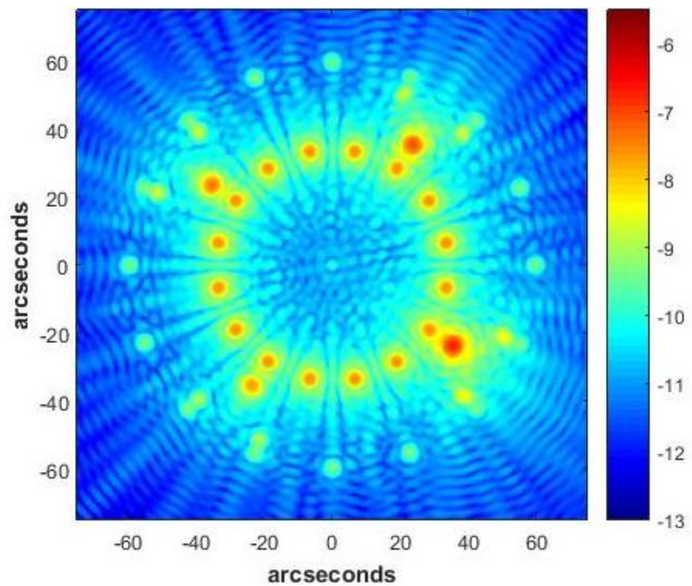


Field Test

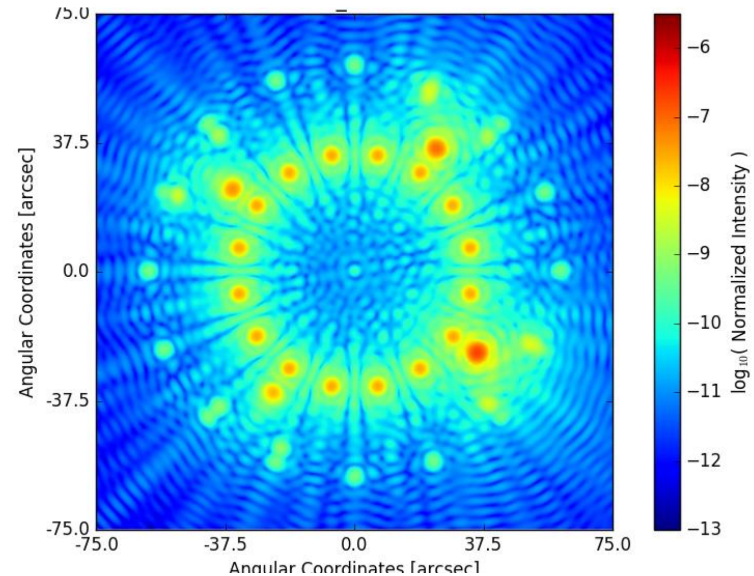


Flawed Starshade – Sines on Edges

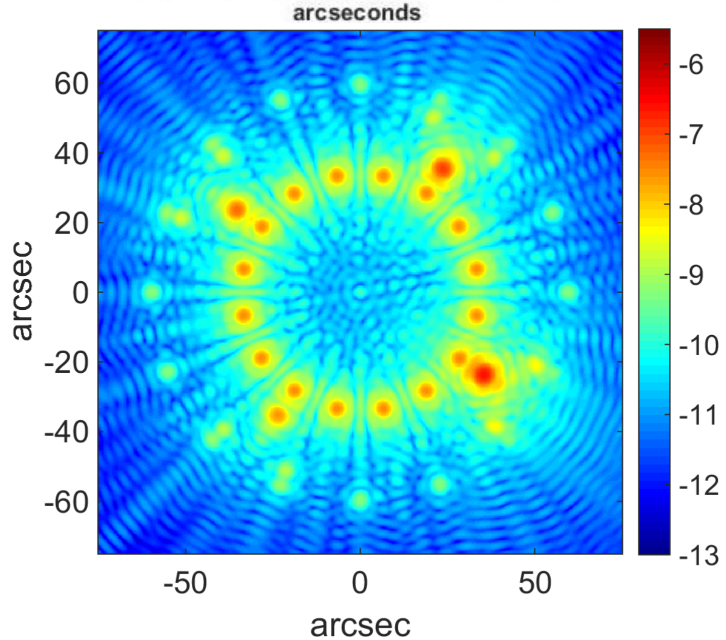
JPL



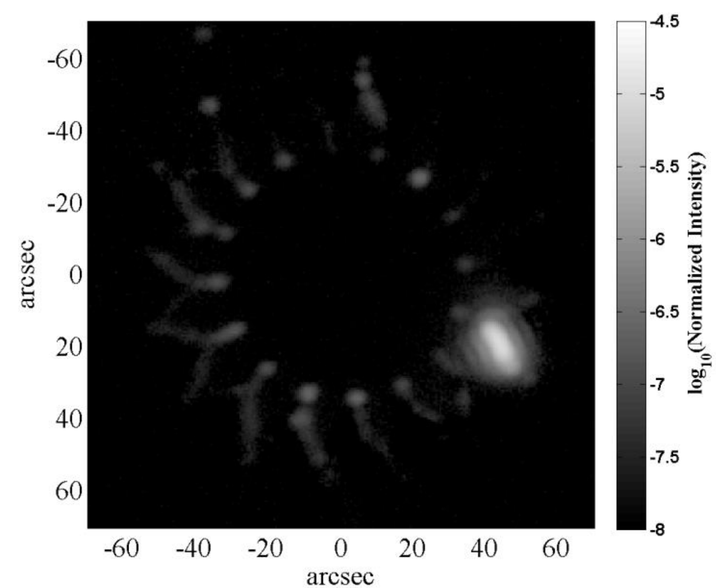
CU



NGAS



Field Test



Flaw Peak Comparison

TIP TRUNCATION		JPL	CU	NGAS	JPL/CU	JPL/NGAS	CU/NGAS
		1.28E-07	1.31E-07	1.40E-07	0.98	0.91	0.94
		7.56E-07	7.72E-07	8.73E-07	0.98	0.87	0.88
		3.42E-06	3.49E-06	4.11E-06	0.98	0.83	0.85
		1.36E-08	1.36E-08	1.09E-08	1.00	1.25	1.25
SINES on EDGES							
		8.48E-08	1.06E-07	1.12E-07	0.80	0.76	0.95
		1.91E-07	2.40E-07	2.52E-07	0.80	0.76	0.95
		2.29E-08	2.47E-08	2.59E-08	0.93	0.88	0.95
		4.66E-08	5.18E-08	5.23E-08	0.90	0.89	0.99
SHRUNK PETAL							
		1.18E-06	1.17E-06	1.16E-06	1.01	1.02	1.01
		6.14E-07	6.07E-07	5.93E-07	1.01	1.04	1.02
		2.87E-06	2.84E-06	2.86E-06	1.01	1.00	0.99
		1.94E-06	1.92E-06	1.92E-06	1.01	1.01	1.00

- Different flaws show different levels of agreement between the groups
- Work is ongoing investigating the cause of these differences

Future Work

- Resolve differences in phase
  - We need to have a clear understanding of the differences
- Point to point comparison of the entire image plane
- Run all the flaws at higher wavelength resolution and combine to compare with results from October 2015 campaign.
  - Current results are at 50nm resolution, 25nm resolution desired
  - Add blurring effects to match PSF of observations
  - Detailed comparison for each flaw
  - Make measurements of as-built starshades to input into models
- Study the effects of misalignment between the source and the starshade
- Simulation of Princeton tube test mask
- Simulation of McMath observations
- Modelling of flaws same relative scale as flight flaws to inform flight error budget

Summary

- Optical models have been tested using a variety of scenarios
  - Different distances
  - Single wavelengths and broadband
  - Two starshade designs
  - 6 different flaw types
- The last 6 months has brought the differences between the different optical models from an order of magnitude down to less than 20%
- Goal is to get the models to agree with each other to within 5%
- Still have additional work to do comparing model predictions with field testing observations

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