Measurements of High-Contrast Starshade Performance in the Field

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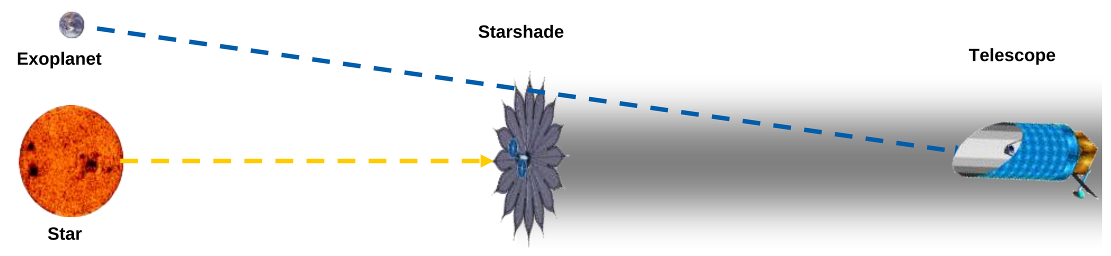
Abstract

The external Starshade is a method for the direct detection and spectral characterization of terrestrial planets around other stars, a key goal identified in ASTRO2010. In an effort to validate the starlight-suppression performance of the Starshade, we have measured contrast better than $1X10^{-9}$ using 58 cm Starshades at points just beyond the Starshade tips. These measurements were made over a 50% spectral bandpass, using an incoherent light source (a white LED), and in challenging outdoor test environments. Our experimental setup is designed to provide Starshade to telescope separation and telescope aperture size that are scaled as closely as possible to the flight system. The measurements confirm not only the overall starlight-suppression capability of the Starshade concept but also the robustness of the setup to optical disturbances such as atmospheric effects at the test site. The spectral coverage is limited only by the optics and detectors in our test setup, not by the Starshade itself. Here we describe our latest results as well as detailed comparisons of the measured results to model predictions. Plans and status of the next phase of ground testing are also discussed.

Introduction

- A key goal of the Astro2010 Decadal Survey is to find and characterize habitable planets
- System must be capable of observing a planet with an intensity of $4x10^{11}$ times less than its star and a separation of <100 milliarcseconds
- Starshades, external occulting screens that block starlight before it enters the telescope, can be used in conjunction with a space telescope to block the light of the host star but not the planets
- Development of this technology has been funded under the NASA Research Announcement, ROSES: Strategic Astrophysics Technology, under the Technology Demonstration for Exoplanet Missions (TDEM) focus area



Test Concept

- Compare measurements using a scaled-down (58 cm diameter) version of the Starshade to numerical model predictions (developed by Northrop Grumman) to prove starshade performance and verify models
- Starshade performance is measured by 'contrast ratio', which we define as the ratio of signal brightness at a location offset from the star to the peak brightness of the unblocked star
- Intentional defects added to the Starshades to mimic possible mission complications and to provide points of comparison between models and observations
- Deep integrations on 'perfect' starshade shapes to measure upper-limit contrast performance of our Starshades.

Test Details

Test Setup

- Smith Creek dry lake bed in Nevada; altitude ~6000ft
- Telescope –Starshade and Starshade-Light Source distances were 1 km each for best contrast, 1 km and 2 km respectively for model comparison data.
- Test dates: Apr. 16 – 20, Oct. 9 – 13 2015
- Starshades: Two baseline starshade shapes were tested – a Hypergaussian shape and a numerically optimized 'IZ5' shape. There was no significant performance gap between the two shapes. While data from both shapes is included here, complete data sets for both shapes are not shown. Starshade diameter: 58 cm
- Main Source: 1W LED (non-collimated beam)
- 'Planet' Sources: 4 1 W LEDs with neutral density filters in front (ND1-ND4)
- Spectral Bandwidth: ~0.4-0.8 µm (>60%) limited by detector and light sources

Test/ Observatory	Starshade Size tip to tip(m)	Starshade-Source Distance(km)	Starshade-Camera Distance(km)	Effective Distance (km)	Fresnel Number	Telescope Diameter (m)	Resolution Elements (nλ/D)
Smith Creek-2km	0.58	1	1	0.5	192	0.04	13.1
Smith Creek-3km	0.58	2	1	0.67	144	0.04	13.1
New Worlds Observer	62	N/A	80,000	80,000	13.0	4	1.7
Exo-S	30	N/A	34,000	34,000	8.2	1.1	0.6
WFIRST/AFTA	34	N/A	35,000	35,000	10.7	2.4	1.4
McMath-Pierce Solar Telescope	0.20	N/A	.420	0.420	9.9-92.2	0.02-0.08	3.3-39.7

The table above shows the relevant scale factors (Fresnel number and resolution) of our field test systems compared to flight systems. Flight system specs are highlighted in grey, and the two field tests relevant to this poster are outlined in red. The data presented here was taken with a setup that is higher in both resolution and Fresnel number by approximately an order of magnitude than flight systems.

Model Contrast Compared with Observations

- Prior to field observations, we created Starshades with five different 'error' types and used our model to predict contrast performance for each.
- Flaws were chosen to be similar to flaws which might arise during manufacture, deployment, & operation of an on-orbit Starshade.
- Each Starshade had one type of flaw with four different magnitudes that were exaggerated to be visible in the test.
- After observing these starshades, the measured and predicted flaw brightnesses were compared in detail to validate the models.

New to 2015 Model Comparisons

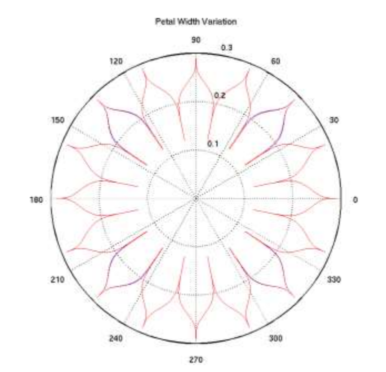
Detailed model/observation comparisons were completed using an experimental data set taken in 2014, and revealed that our three independent numerical models (developed by Northrop Grumman, University of Colorado, and Jet Propulsion Laboratory) disagree with both each other and the experimental data

The three models have been found to agree to within 5% when considering the parallel light case, so it is thought that discrepancies between the models lie within modifications made to account for the spherical wavefronts of our test setup

In the 2015 data set presented below, we address this hypothesis by moving the light source further from the Starshade (from 1 km to 2 km), effectively flattening the wavefronts.

Example: Hypergaussian Starshade with Shrunk Petals

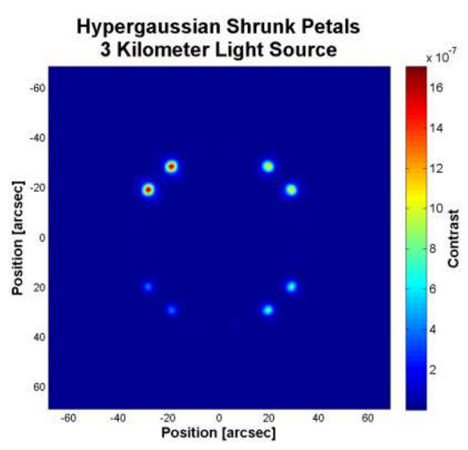
Starshade Parameterization



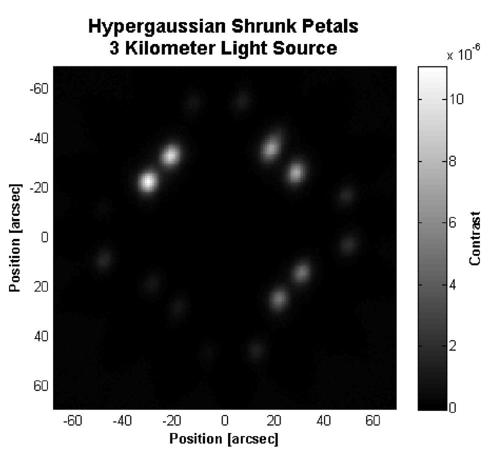
Baseline Starshade(blue)
Error Starshade overlaid (red)

Actual Starshade

Contrast map (model)



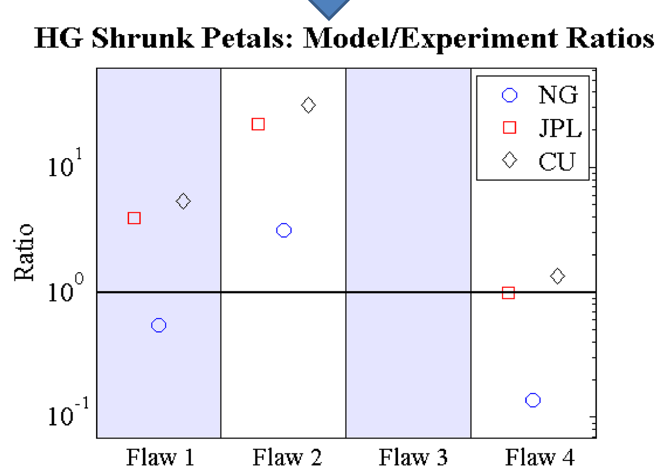
Contrast map (experiment)

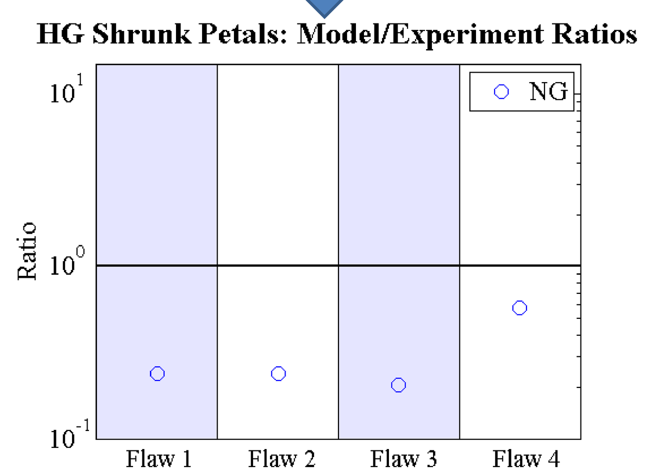


2014 data set: 3 models disagree with each other and with experiment

Light source moved further away to give a flatter wavefront

2015 data set: Preliminary comparisons of experimental data with Northrop Grumman model shows more precision





Ratio Plots: Above are plots that show the ratios of contrast flaw peak predictions generated by the numerical models (developed independently by Northrop Grumman, University of Colorado, and Jet Propulsion Laboratory) to the flaw peaks measured in the field. The black line represents the value measured in the field, and each point represents the ratio of the model prediction to that value. For the 2015 data set, JPL and CU models have not yet been run.

Results

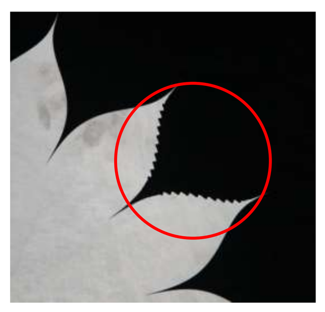
These tables show the model comparison results from our latest data set (2015 data set, main light source 2 km from the starshade). A picture and description of each intentional flaw that we modeled/observed is included, with the flaws circled in red. The 'Model' value reported is the peak contrast value created by each flaw, as predicted by the Northrop Grumman numerical model. The 'Experiment' value reported is the peak contrast value created by each flaw, determined by Gaussian fits to the experimental data (non-dust-subtracted images). The 'Ratio' value reported is the ratio of 'Model' to 'Experiment'. **Our model generally under-predicts our measurements by about an order of magnitude.**

Truncated Tips

Tips truncated at 0.283 to 0.268m from the center of the Starshade. (Nominal length of 0.29m)

Flaw	Model	Experiment	Ratio
1	$1.1x10^{-6}$	$1.3x10^{-5}$	0.1
2	$2.2x10^{-7}$	$2.9x10^{-6}$	0.1
3	$3.1x10^{-8}$	$4.4x10^{-7}$	0.1
4	$4.0x10^{-9}$	$3.2x10^{-8}$	0.1

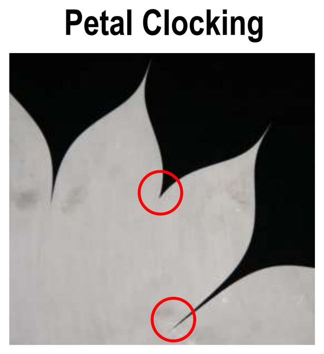
Sines



Sine wave introduced on top of the nominal petal shape. Frequencies: 25 and 50 cycles/ petal length. Amplitudes: 0.1 and 0.15cm.

Flaw	Model	Experiment	Ratio
1	$1.3x10^{-8}$	$7.2x10^{-7}$	0.02
2	$2.6x10^{-8}$	$1.6x10^{-7}$	0.2
3	$8.2x10^{-8}$	$1.1x10^{-7}$	0.7
4	$1.8x10^{-7}$	$8.4x10^{-8}$	2.2

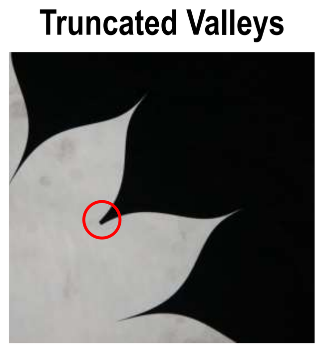
Petal Clocking



Entire petal rotated relative to the center of the Starshade. Rotation amplitudes: 0.02 to 0.08 radians.

Flaw	Model	Experiment	Ratio
1	$7.3x10^{-6}$	$2.6x10^{-7}$	27.6
2	$4.4x10^{-6}$	$2.2x10^{-7}$	20.2
3	$2.1x10^{-6}$	$1.4x10^{-7}$	15.2
4	$7.0x10^{-7}$	$3.0x10^{-7}$	2.3

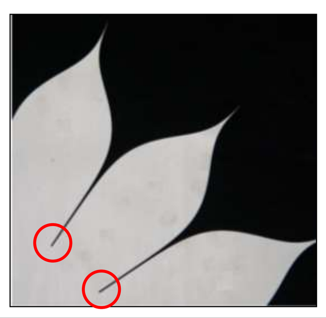
Truncated Valleys



Valleys truncated at 0.175 to 0.19m (HG, nominal = 0.16), and 0.189 to 0.195m (IZ5, nominal = 0.188m)

Flaw	Model	Experiment	Ratio
1	$3.1x10^{-6}$	$2.3x10^{-5}$	0.1
2	$1.2x10^{-6}$	$1.1x10^{-5}$	0.1
3	$4.6x10^{-7}$	$4.4x10^{-6}$	0.1
4	$1.6x10^{-7}$	$1.9x10^{-6}$	0.1

Shrunk Petals



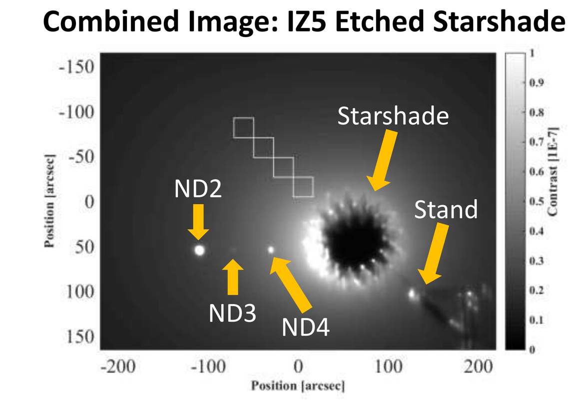
Entire petal shrunk by a constant percentage. Shrinkage magnitudes: -2 to -5%.

Flaw	Model	Experiment	Ratio
1	$1.7x10^{-6}$	$1.2x10^{-5}$	0.1
2	$1.2x10^{-6}$	$7.6x10^{-6}$	0.2
3	$7.5x10^{-7}$	$4.8x10^{-6}$	0.2
4	$4.1x10^{-7}$	$8.8x10^{-7}$	0.5

Best Contrast

A long series of exposures was taken with both the HG and IZ5 baseline Starshades to make an estimate of best observable contrast for this test. Contrast was calculated by comparing images with the Starshade in and out of alignment. Here we present data for the IZ5 Starshade with and without dust subtraction.
The performance is limited by background noise originating from dust in the air.
Numbers are likely to improve with additional exposure time .

Combined Image: IZ5 Etched Starshade



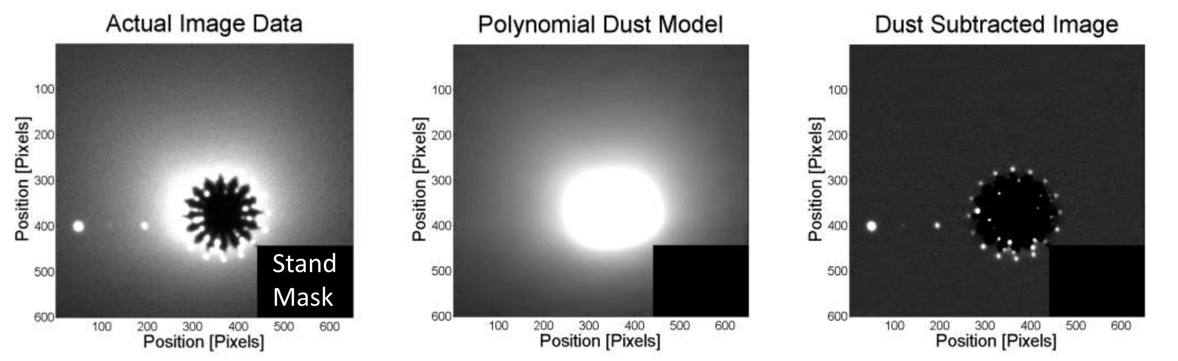
Original Best Contrast (no dust subtraction)

Total exposure time of 2850 seconds

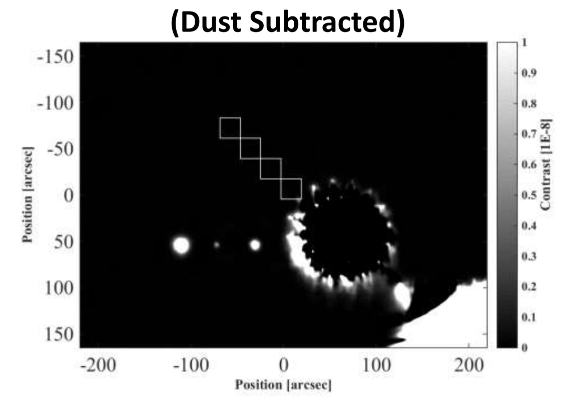
Box #	Mean Background	3σ Contrast Upper Limit
1	$4.6×10^{-8}$	**$1.1×10^{-8}$**
3	$2.7×10^{-8}$	**$4.0×10^{-9}$**

Dust Subtraction

Scattering due to dust in the atmosphere was a heavily present consequence of the environment where the data were being taken. This scattering produced a halo of light surrounding the Starshade in each image. The size and shape of this dust halo varied significantly by individual image, so it was necessary to remove its influence from each image in order to combine images over large periods of time. This was accomplished by modeling the dust halo in each individual image and subtracting it from the image before combination. In order to account for the flexibility of the shape of the dust halo, the dust halo was modeled by a large (25-40) degree polynomial. Since any physical model of dust scattering would be able to be approximated with a polynomial, the use of such a model allowed for the computational speed necessary for fitting every individual image. An example of the dust subtraction process is shown below. As the range of concern for best contrast is limited to outside of the tips of the Starshade, the Starshade itself was not modeled. This results in over subtraction of the Starshade itself, producing the visual deterioration seen below. (The separate dust modeling done for Starshade flaws includes modeling the Starshade itself to prevent this over subtraction.)



Combined Image: IZ5 Etched Starshade (Dust Subtracted)

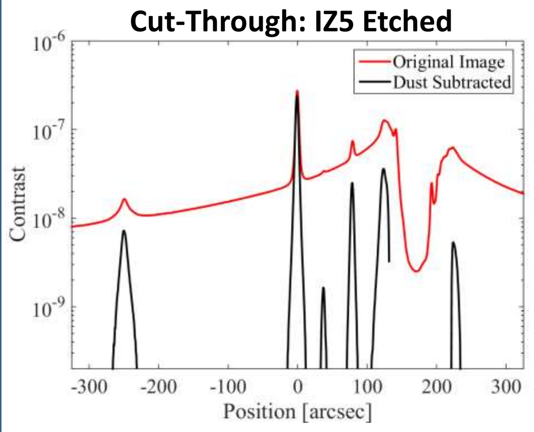


Dust Subtracted Best Contrast

Total exposure time of 2850 seconds

Box #	Mean Background	3σ Contrast Upper Limit
1	$-2.9×10^{-11}$	**$7.3×10^{-10}$**
3	$-2.1×10^{-11}$	**$7.4×10^{-10}$**

Cut-Through: IZ5 Etched



Cut-Through of Best Contrast

The mean of a 50 pixel slice through our best contrast image on a log scale with and without dust. For the dust subtracted case the background is approximately zero. The slice contains the edge of the 4km source, which is visible on the left

Conclusions

- With the light source located 2 km from the Starshade (2014 data set), Northrop Grumman's numerical model generally under-predicts the experimental flaw brightnesses by factors of 2 – 10. With the light source 3 km from the Starshade (2015 data set) **the model generally under-predicts the experimental flaw brightnesses by a factor of 10.**
- Just beyond the Starshade tips, we have demonstrated the ability of our Starshades to **detect sources fainter than $8x10^{-10}$ the brightness of the main light source** in the field with 3σ confidence
  - This measurement is likely limited by background noise originating from dust in the air rather than the performance of the Starshade
  - Numbers are likely to improve with additional exposure time

Potential Future Work

- Further Analysis of Existing Data
  - Collaborative modeling effort with University of Colorado and Jet Propulsion Laboratory to resolve the discrepancies in the models
  - Compute contrast using photometry rather than source peak values
- Follow-on testing
  - Longer observations of the baseline starshades to achieve better contrast performance despite background-limited conditions
  - Contrast and starshade flaw performance at Fresnel numbers closer to flight like optics