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NORTHROP GRUMMAN

Field Testing the Starshade

1/3/2016

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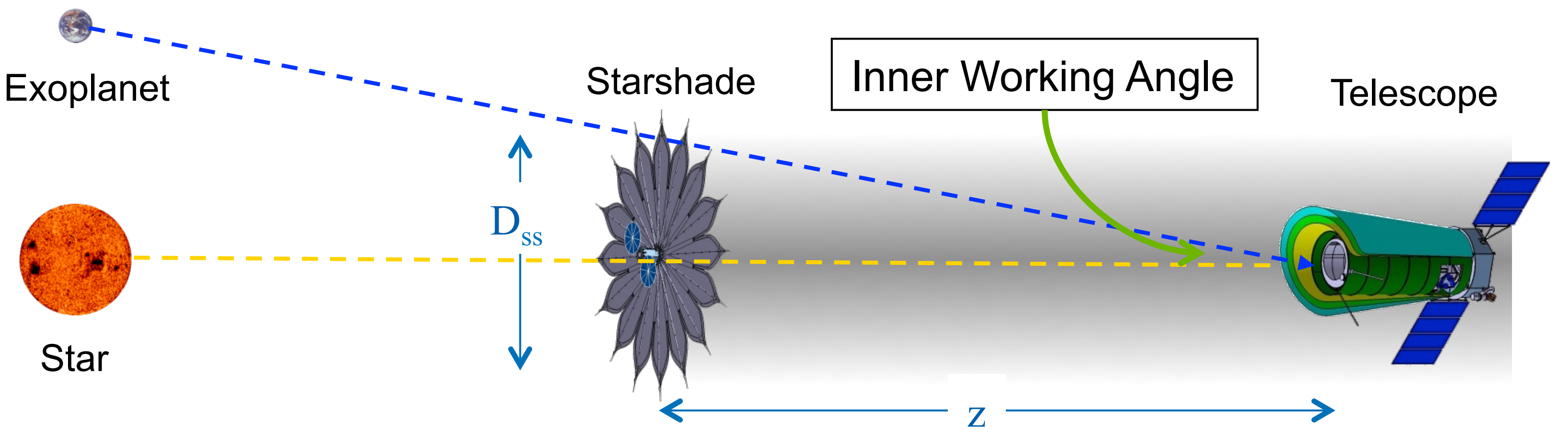
Starshade Basics – Inner Working Angle



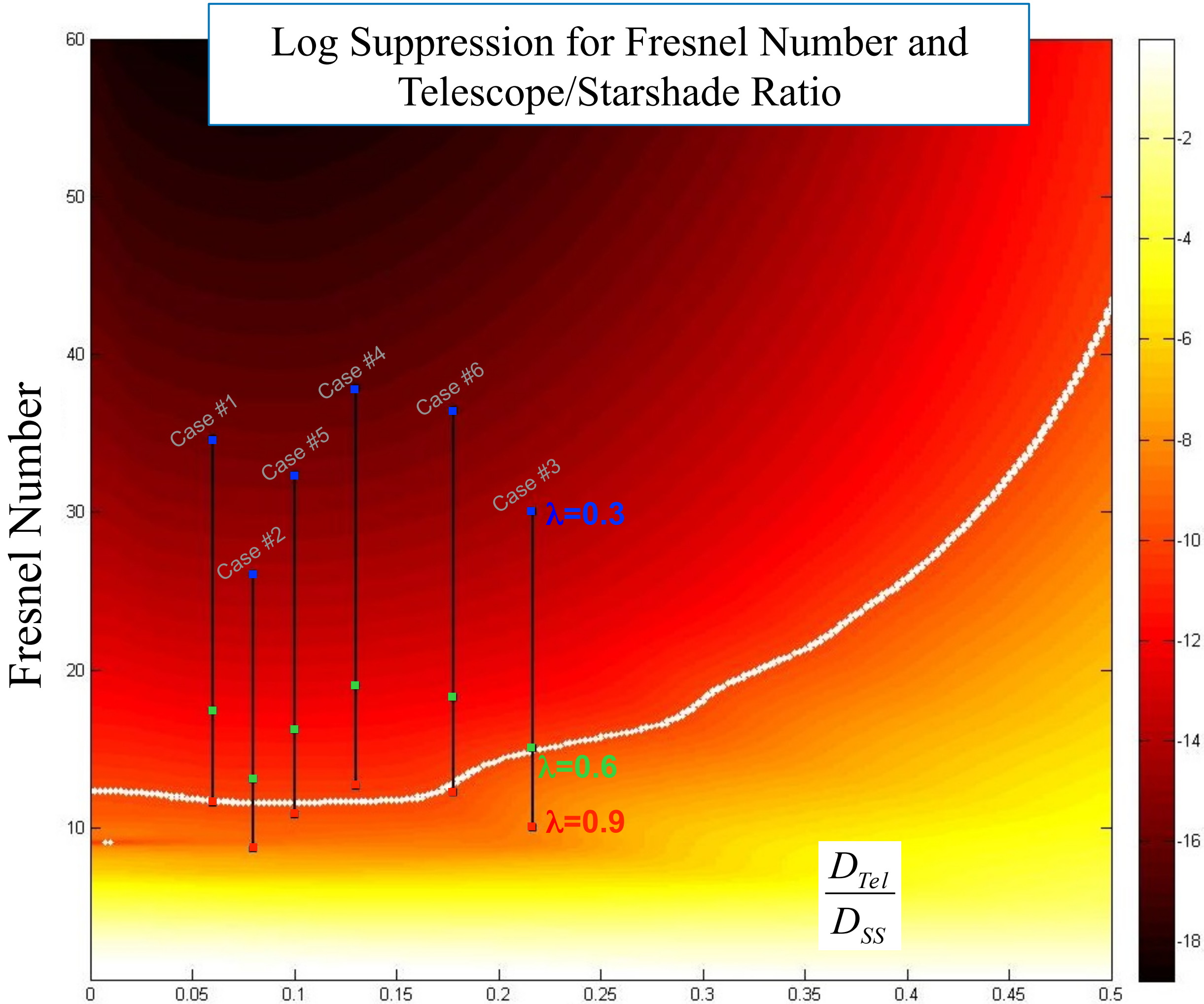
- Inner Working Angle is the closest separation of Planet and Star that we can expect to see with a given starshade
- For Hypergaussian starshade, this is approximately equivalent to:

$$IWA = \frac{D_{SS}/2}{z}$$

The smaller the IWA, the more habitable zones we can examine

Starshade Basics – Fresnel Number

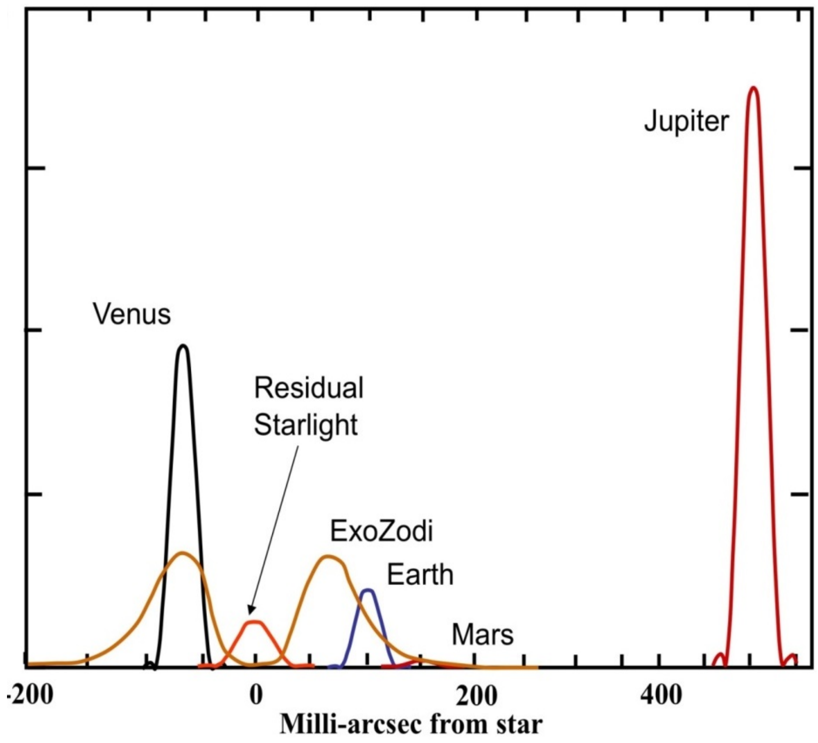
- Starlight suppression by a starshade is determined by the Fresnel Number:
  - $F\# = \dfrac{D_{SS}^2}{4\lambda z}$
- This factor completely specifies the shadow of a Hypergaussian starshade



For a fixed Suppression, a larger Starshade at a greater distance gives a smaller IWA

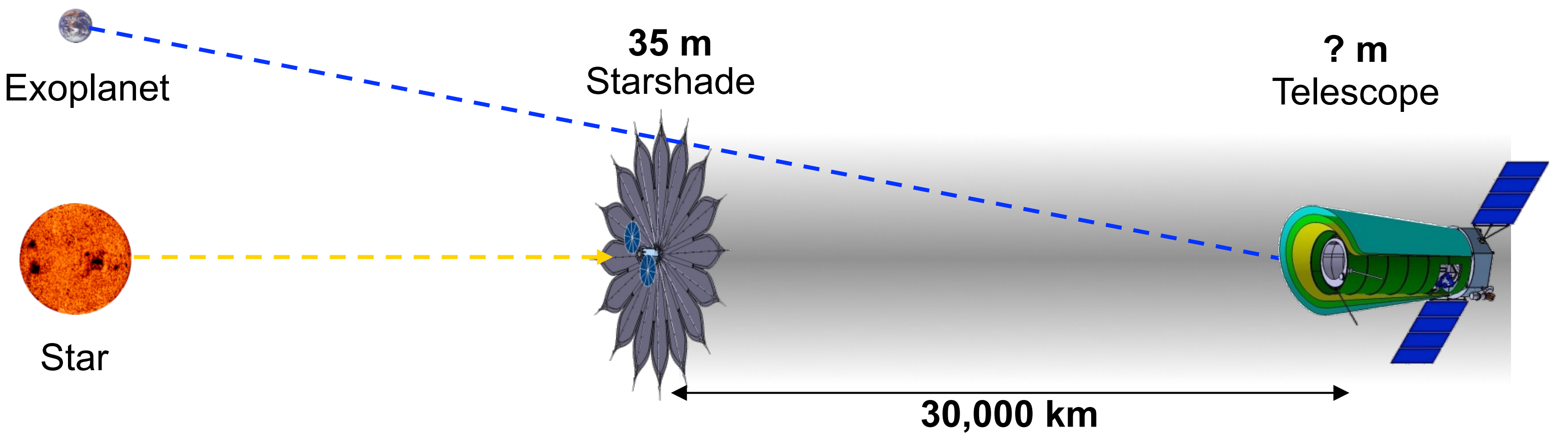
Starshade Basics – Resolution

- Resolution is the diffraction limited resolution of the **telescope**
- Resolution elements refers to the IWA of the starshade divided by the resolution of the telescope
- General agreement is that resolution should be equal or greater than $2\lambda/Dtel$ to allow separation of planets and exozodi
- Better resolution makes separation of sources easier.



For a Smaller IWA, a larger telescope is required for a fixed number of Resolution Elements

Starshade Basics – An Example



Inner Working Angle = 17.5m/40,000km = **88mas**

Fresnel Number = 50m^2/(4*600nm*40,000km) = **12**

Minimum Telescope Diameter = 2*600nm/88mas = **2.8m**

A larger telescope gives better resolution and collects more photons

IWA and Suppression are independent of the telescope diameter

Field Testing a Starshade

Field Testing 2014/15

NASA JPL / Northrop Grumman 100^{th} Scale Starshade

Best Contrast Ratio – Desert Field Tests

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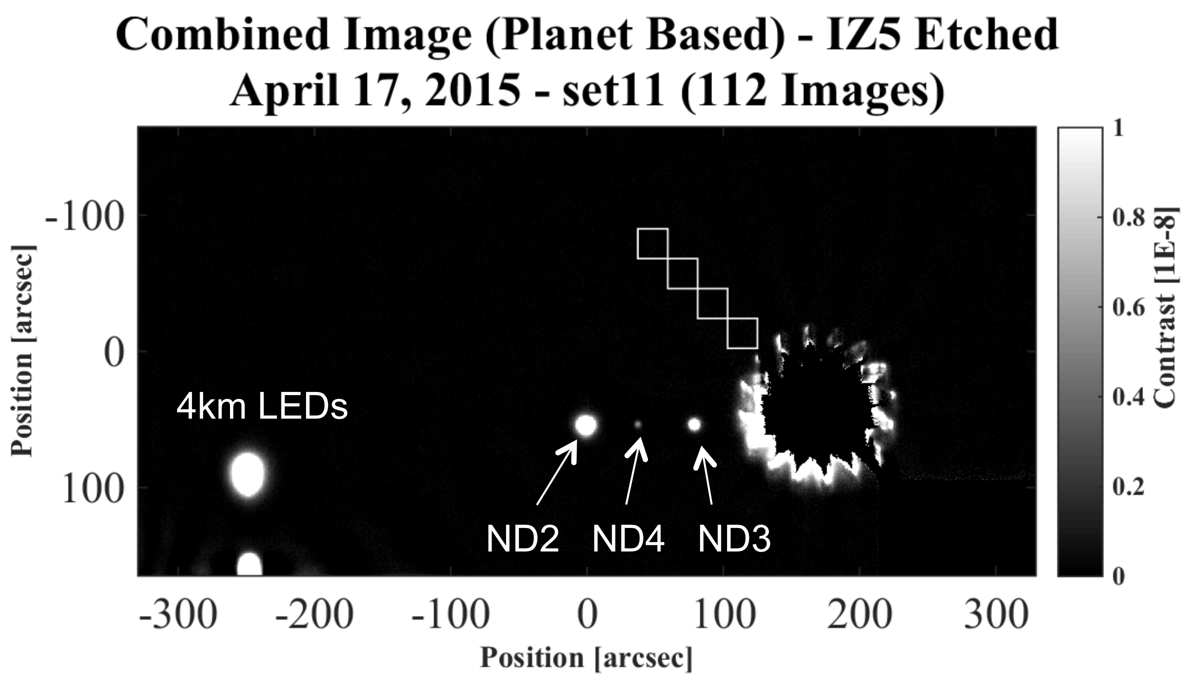
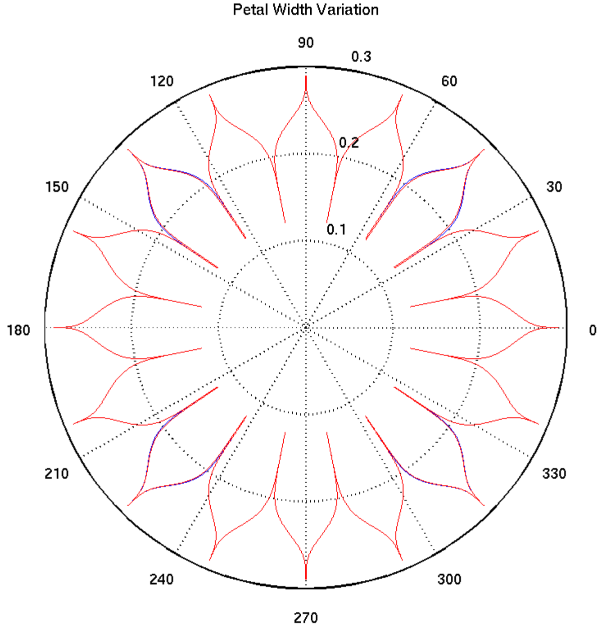
- Planet LEDs are Standard LEDs with ND filters in front.
  - ND4 planet ~8E-9 below main source
- Light Scatter from dust is modelled and subtracted from the image
- Slight vertical variation between images due to air disturbances.
  - Images collocated using Planet LEDs

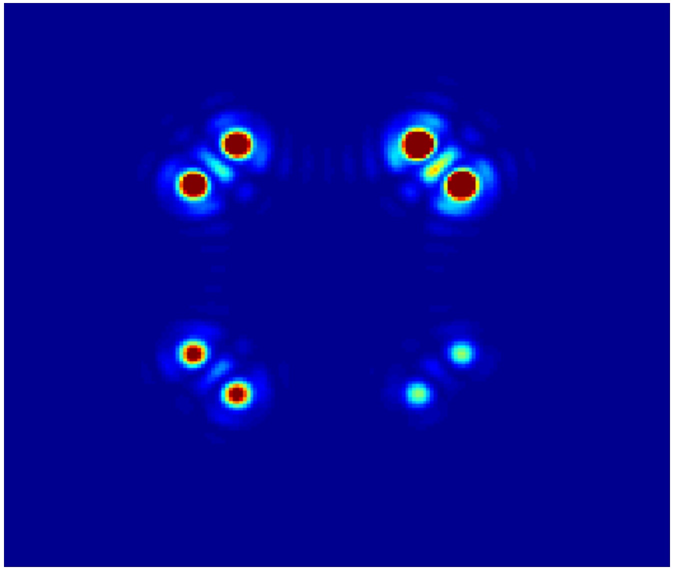


3σ Standard Deviation in box closest to the starshade = **9.09E-10**

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

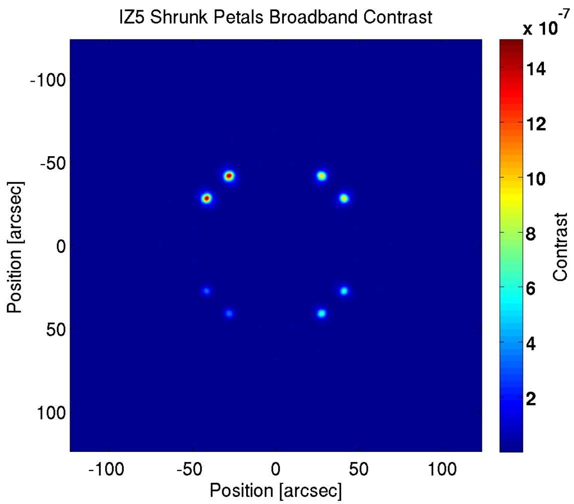
Testing Engineering Sensitivities –
Flawed Starshade Performance



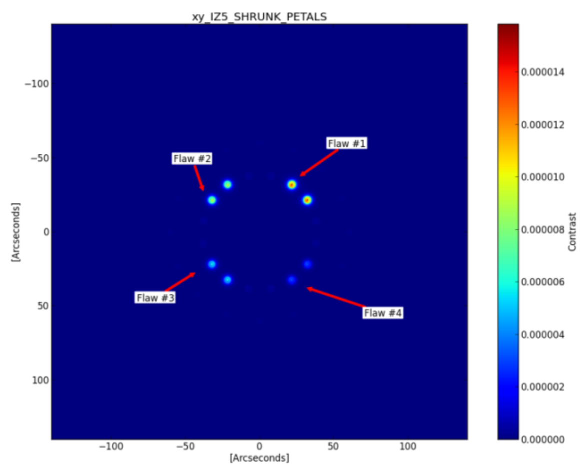


- 6 families of flaw each applied to Hypergausian and Numerically Determined Starshades
  - Simulations predict patterns field test optical lengths

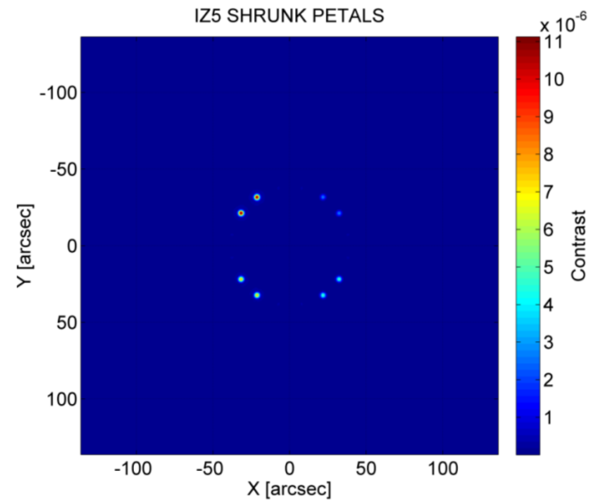
Model Verification



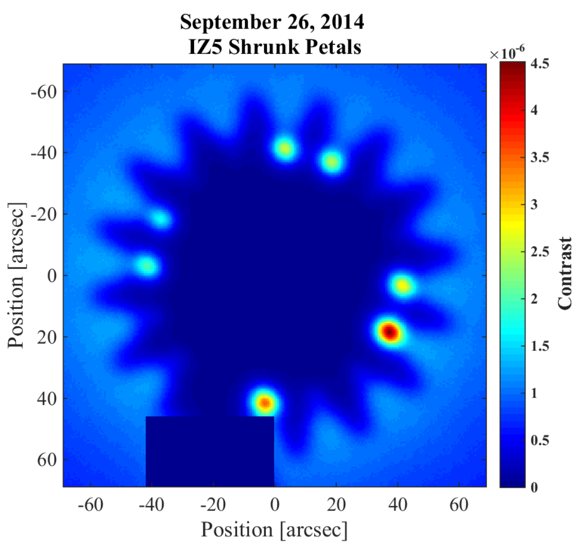
NG Model



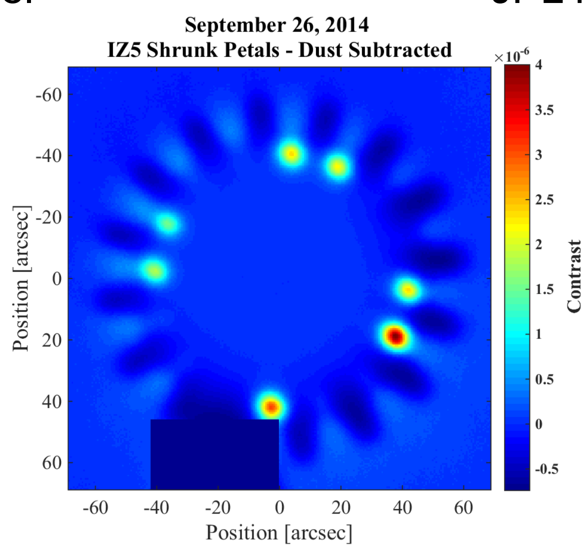
CU Model



JPL Model



Measured



Measured & Dust Subtracted

Model Predictions vs. Measurements

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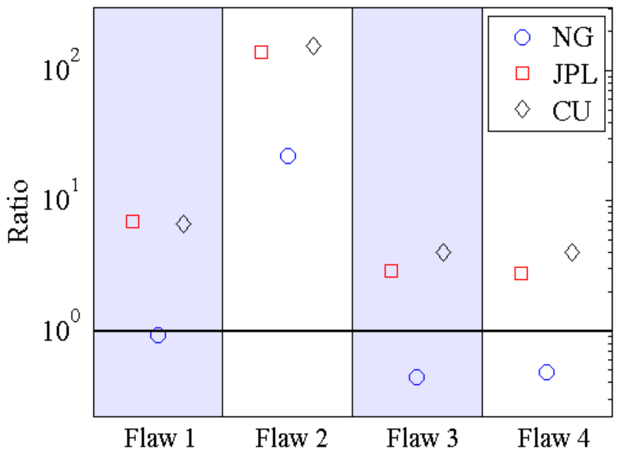
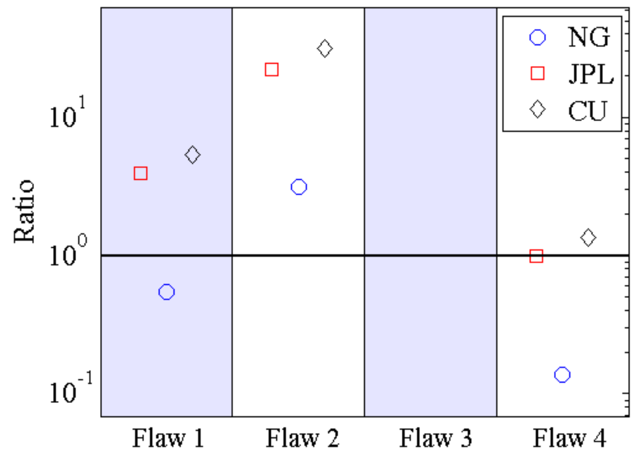
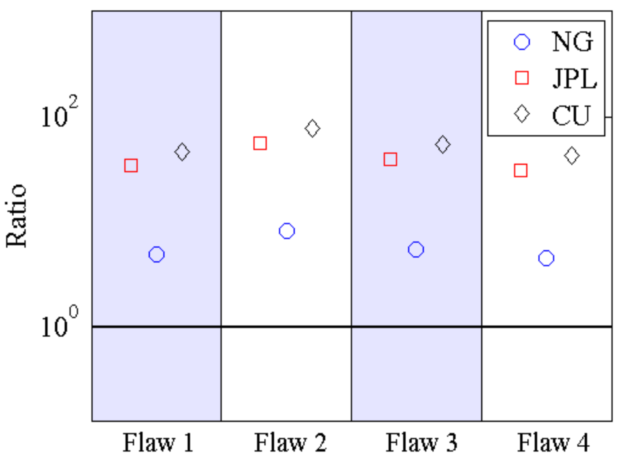
IZ5 TipTrunc: Model/Experiment Ratios



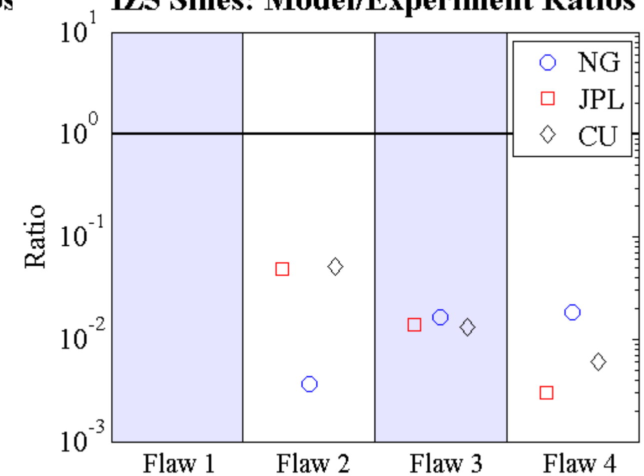
HG Shrunk Petals: Model/Experiment Ratios



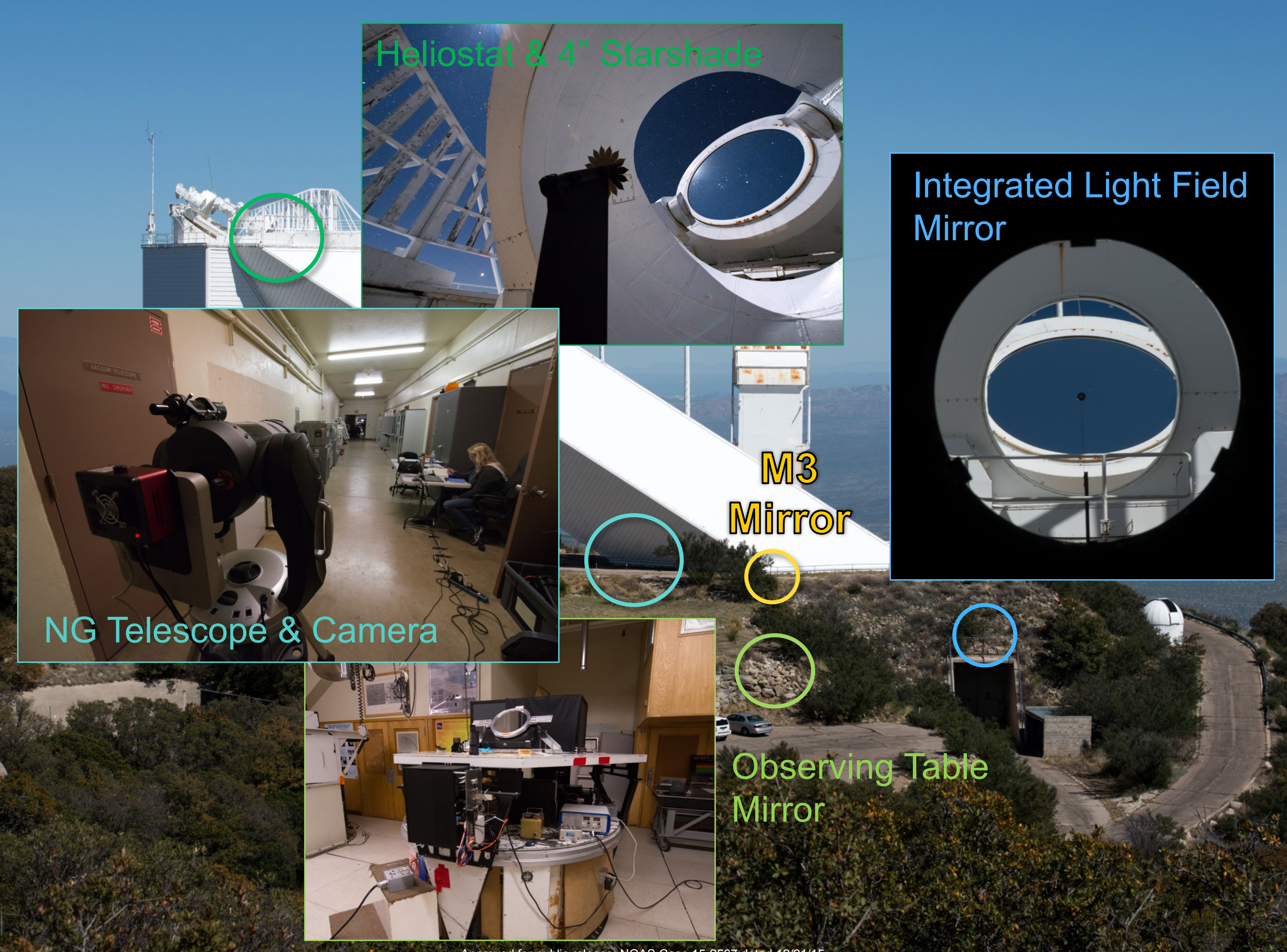
HG Clocked Petals: Model/Experiment Ratios



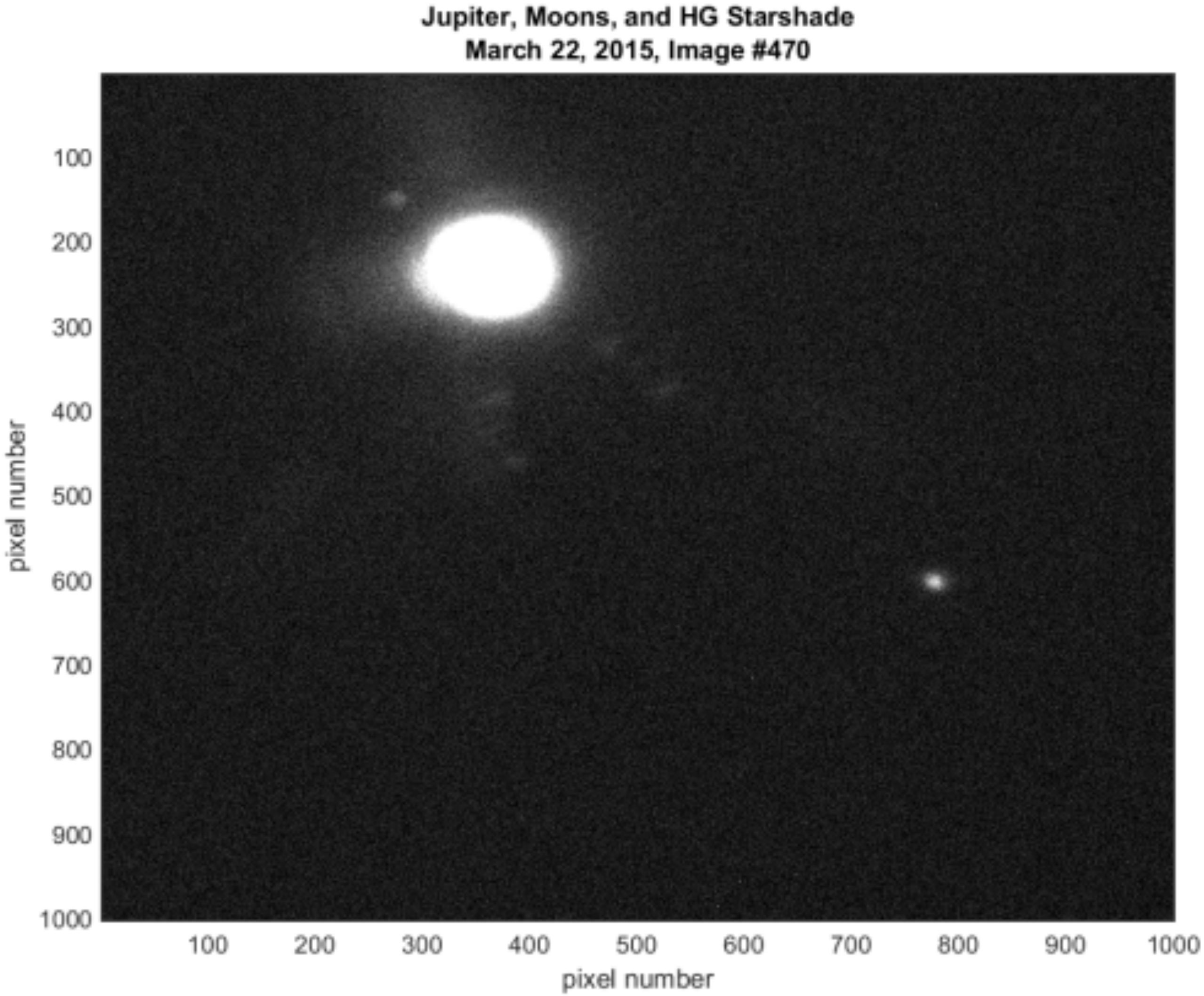
IZ5 Sines: Model/Experiment Ratios



- 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

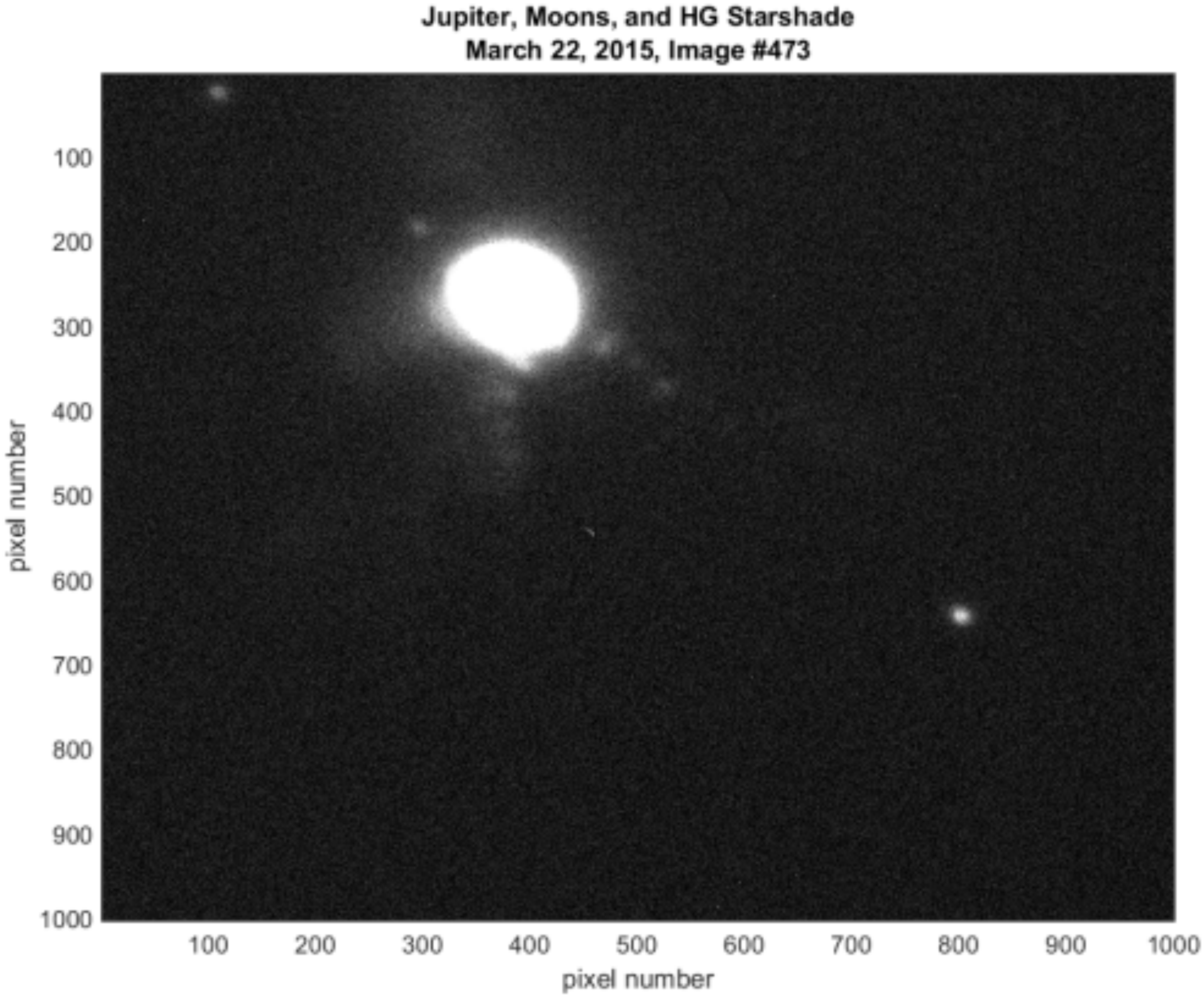

Heliostat & 4" Starshade
Integrated Light Field
Mirror
M3
Mirror
NG Telescope & Camera
Observing Table
Mirror

Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (1 of 11)



Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (2 of 11)



Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (3 of 11)

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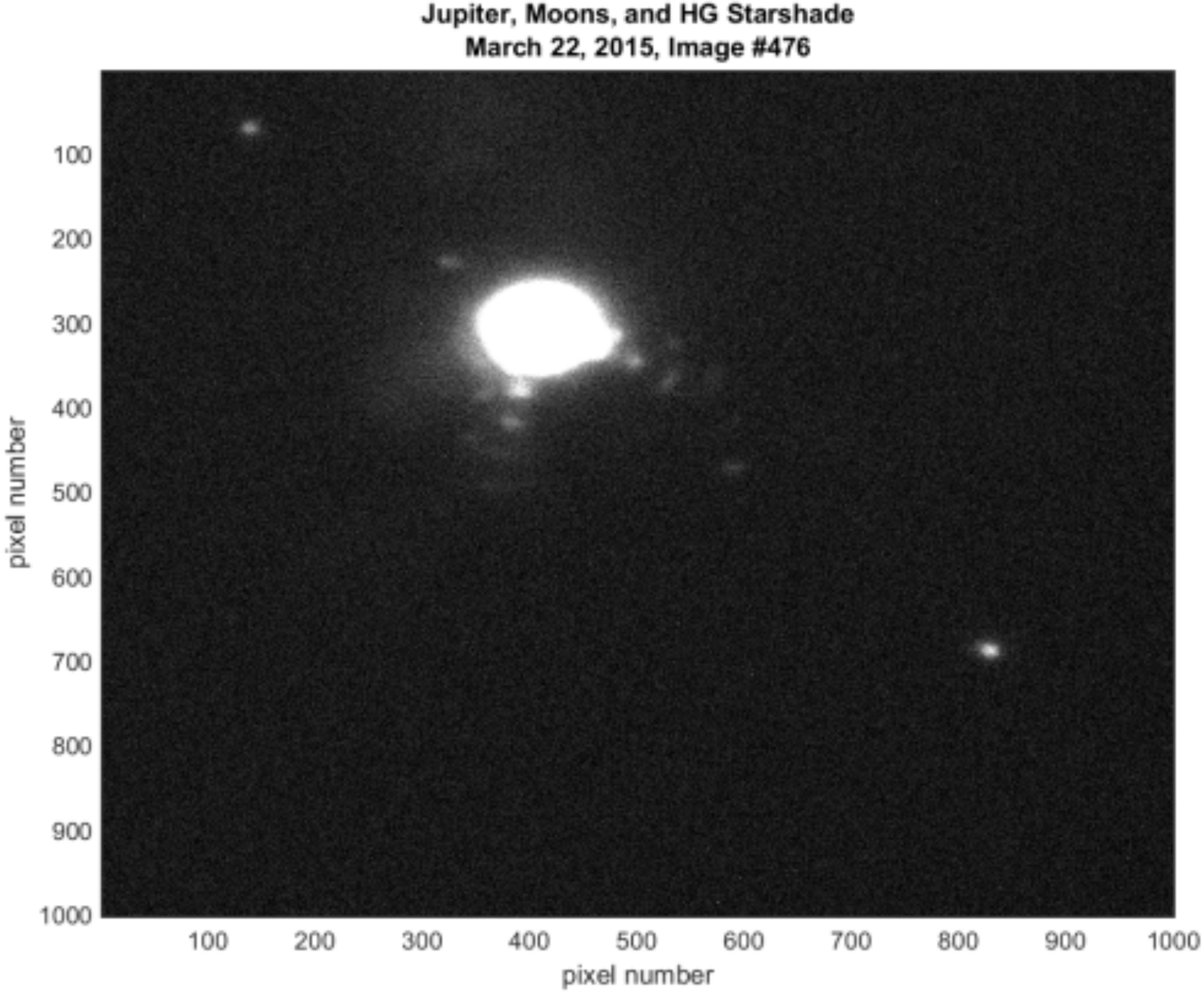
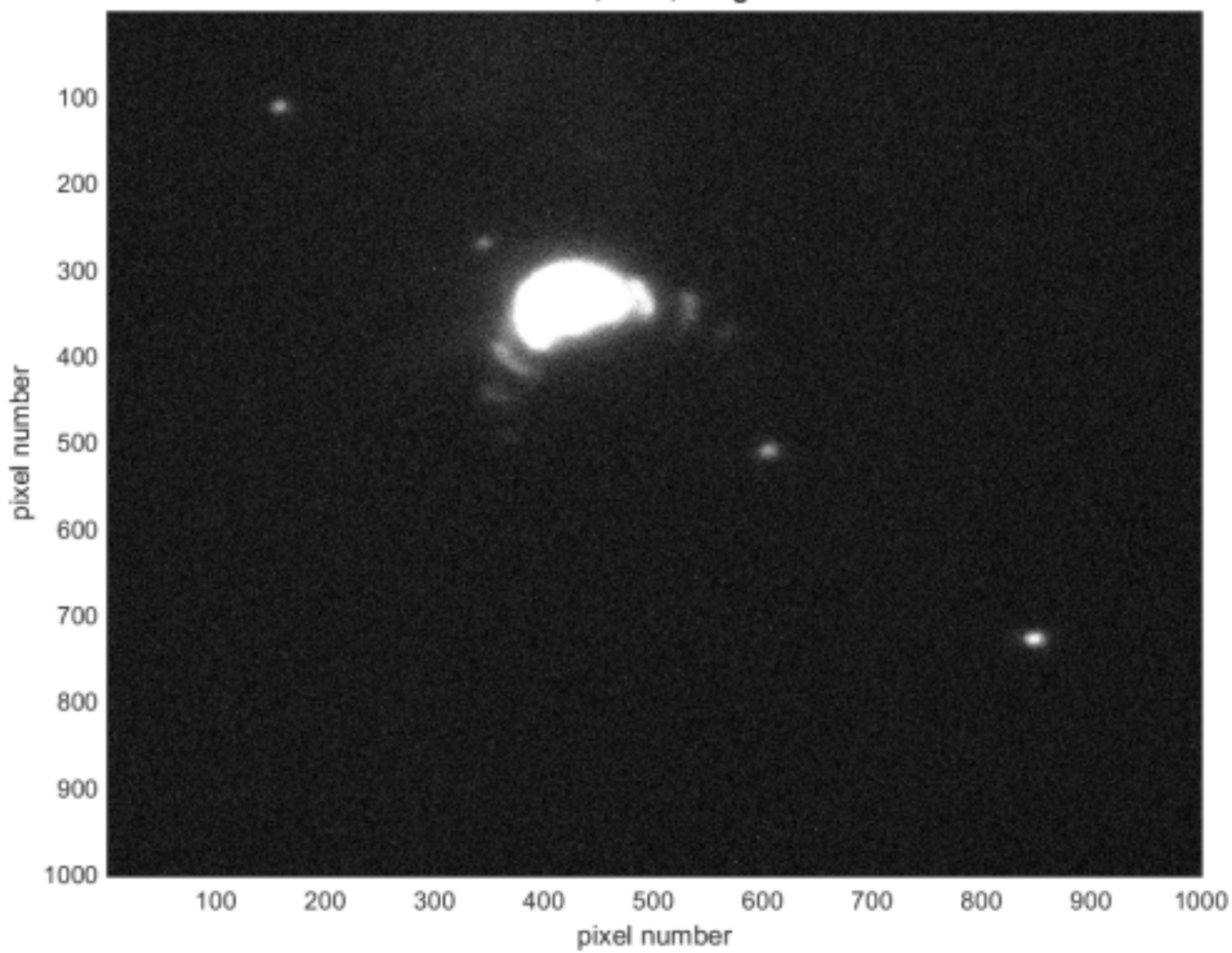


Apparent Jupiter motion controlled by Heliostat Slew Rate

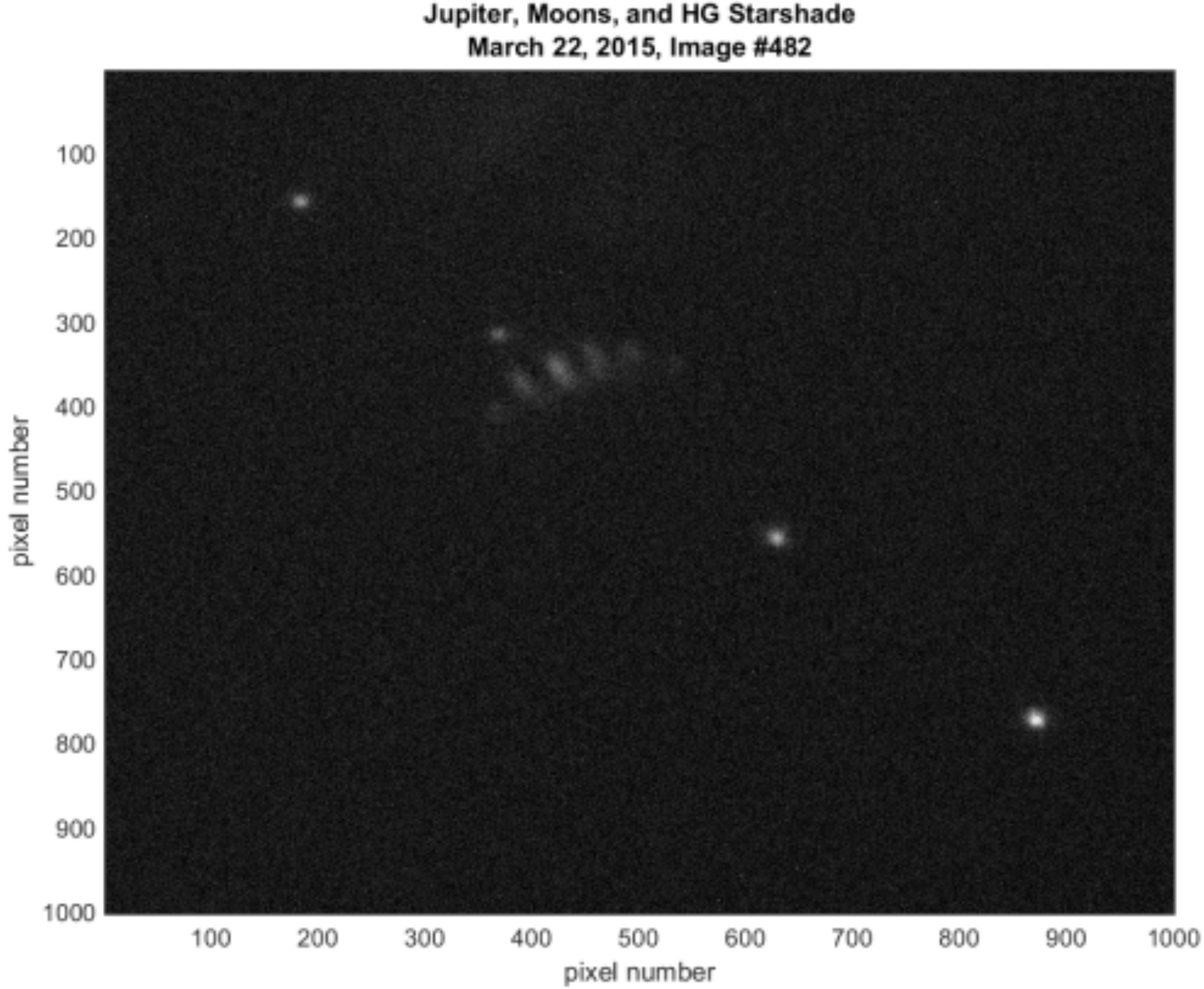
Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (4 of 11)

Jupiter, Moons, and HG Starshade
March 22, 2015, Image #479



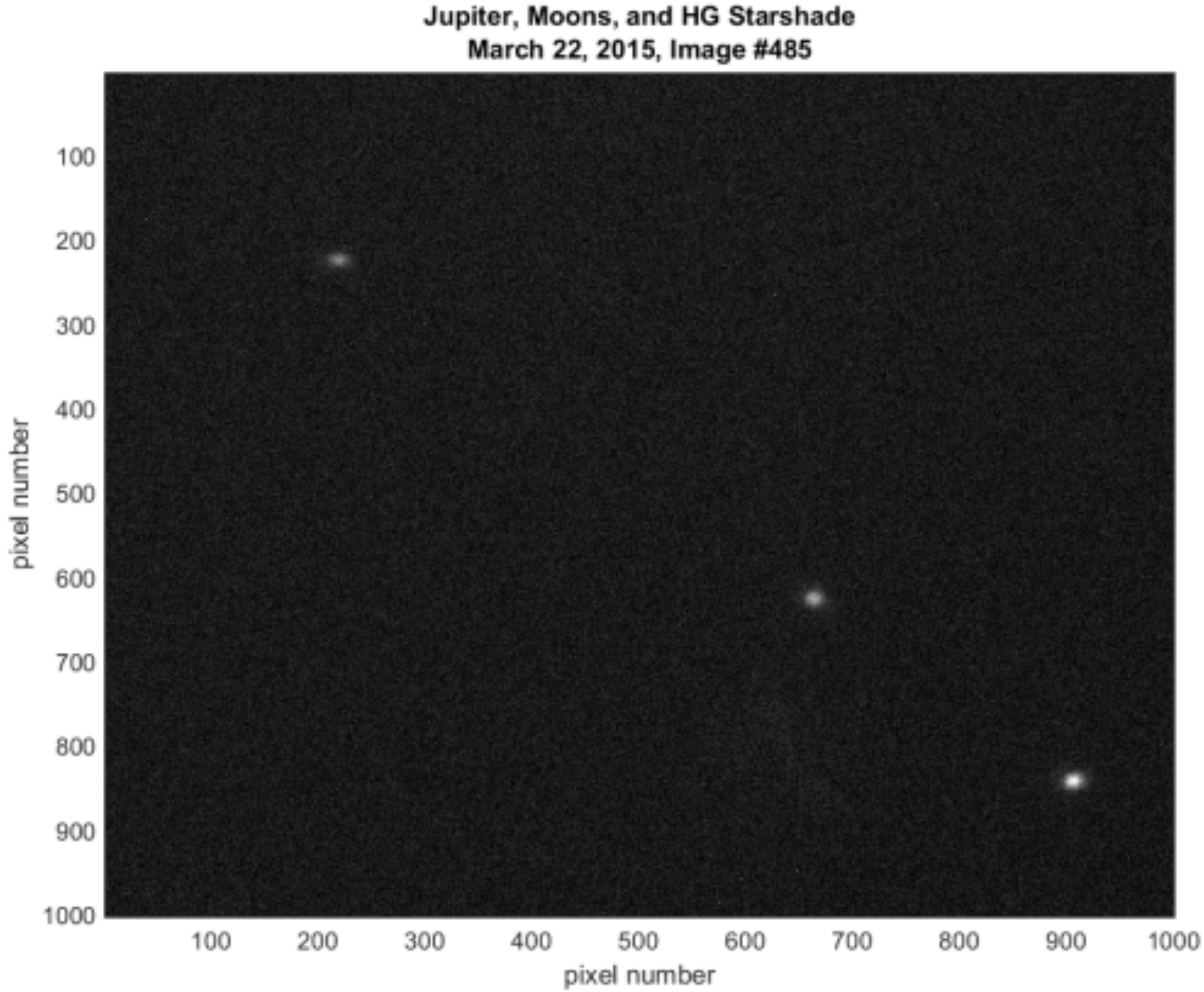
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (5 of 11)



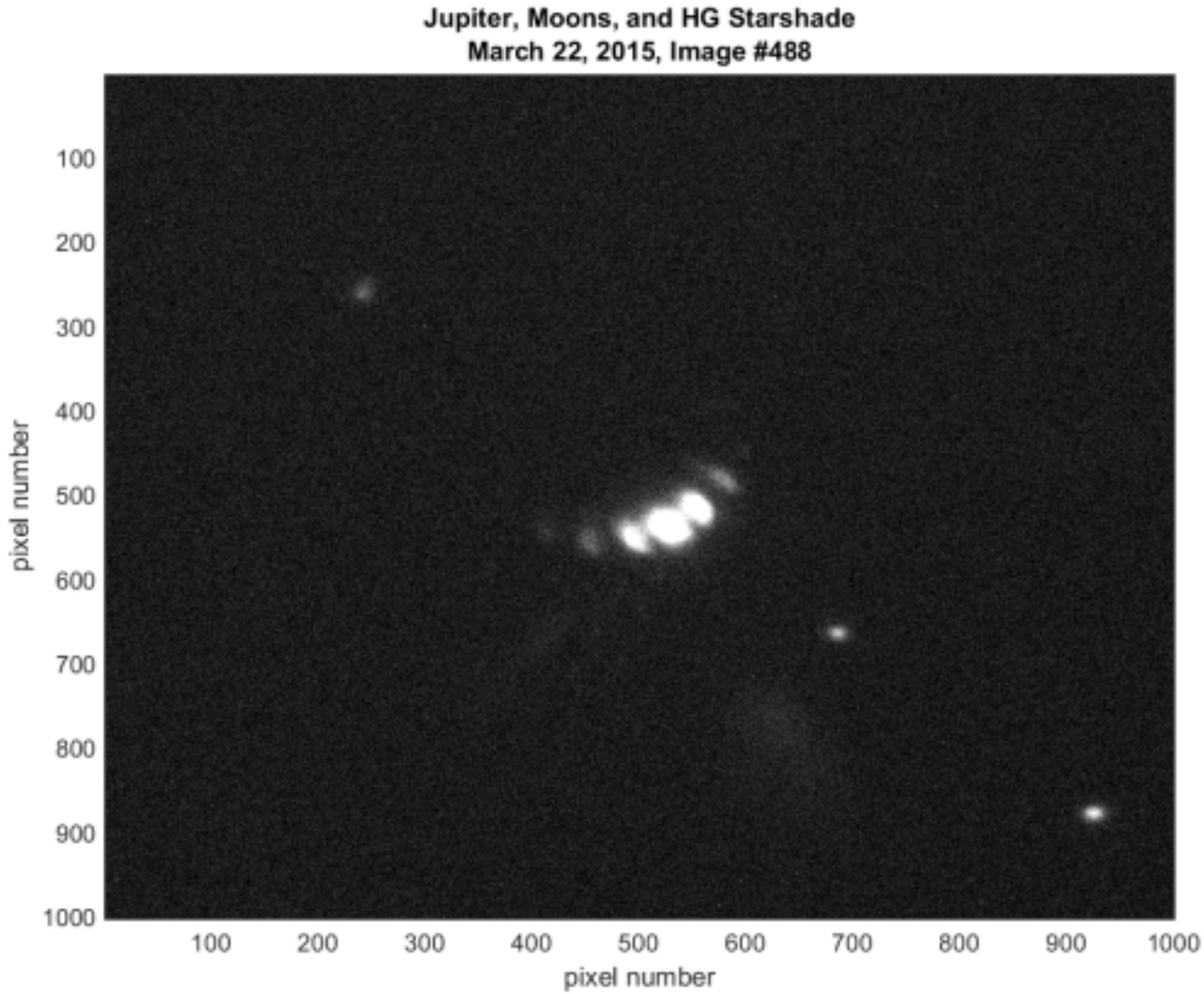
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (6 of 11)



Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (7 of 11)



Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (8 of 11)

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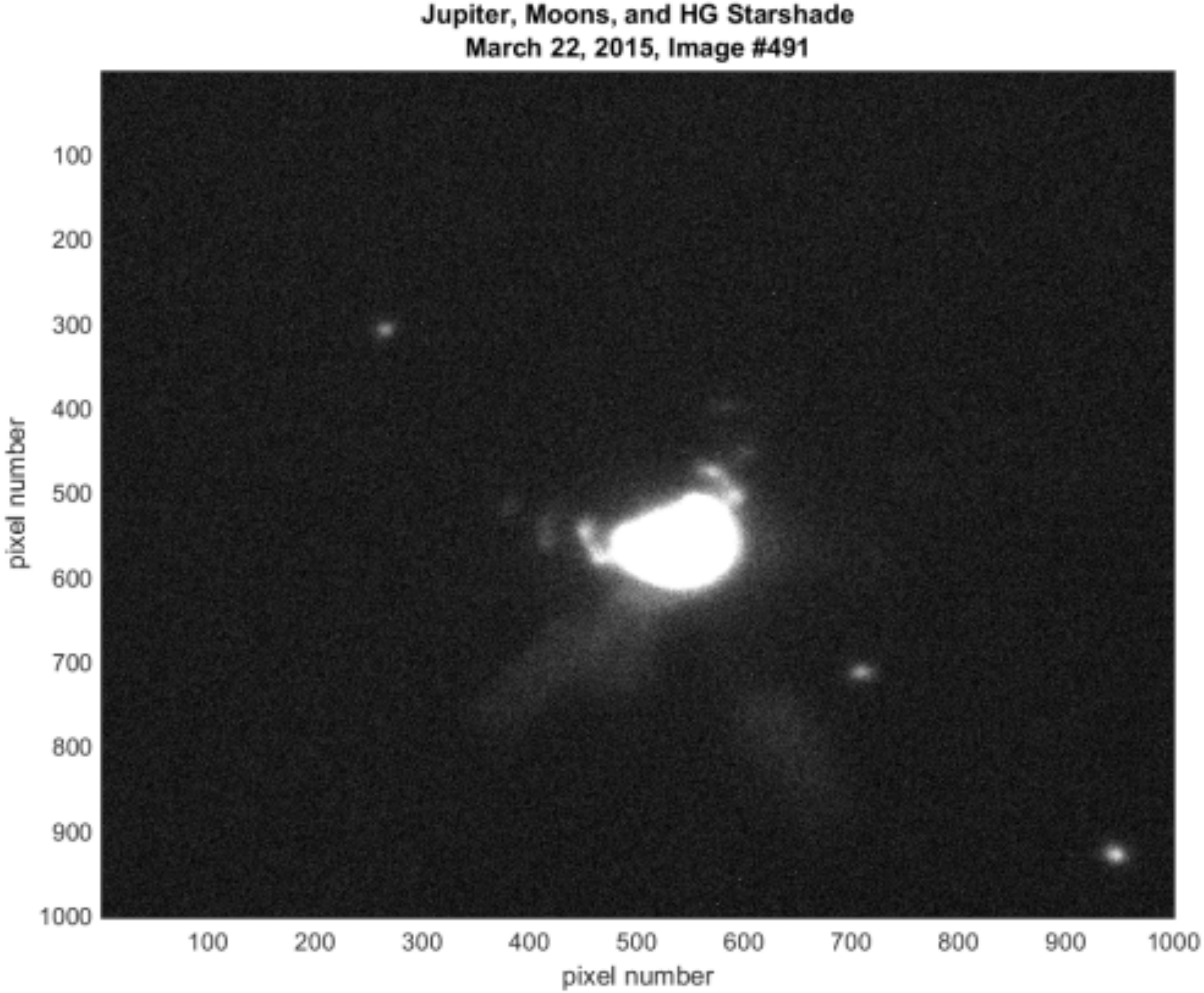
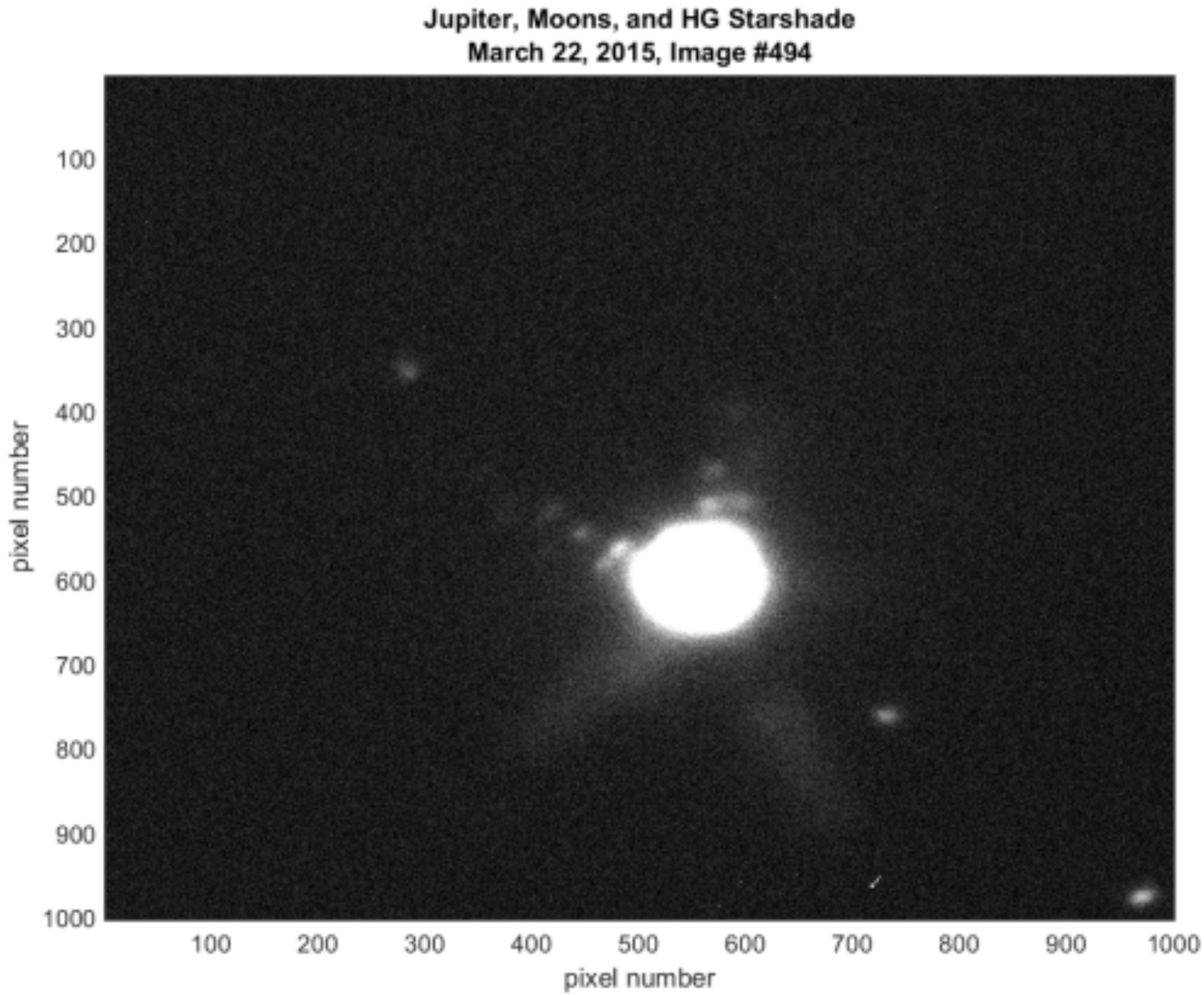
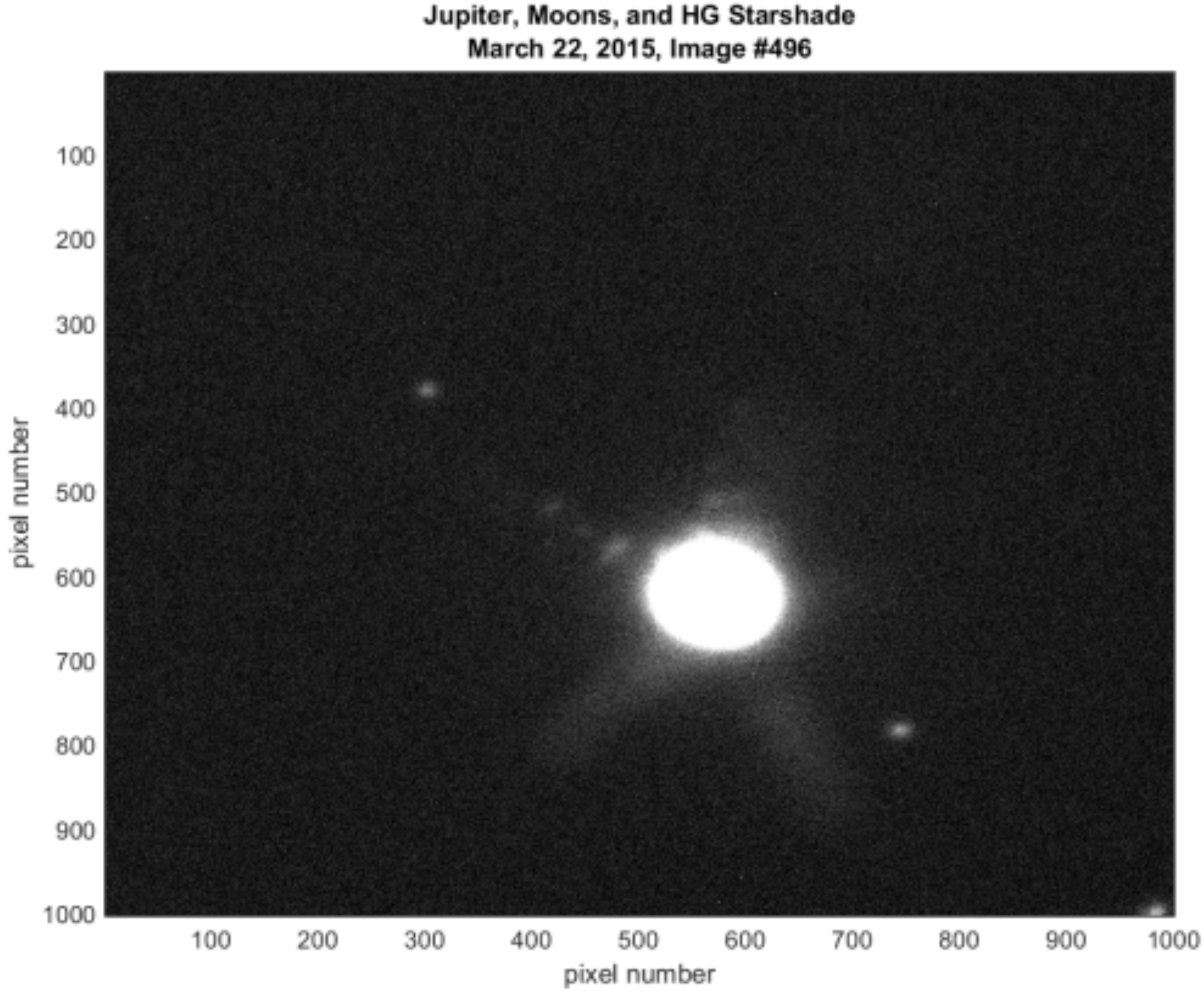


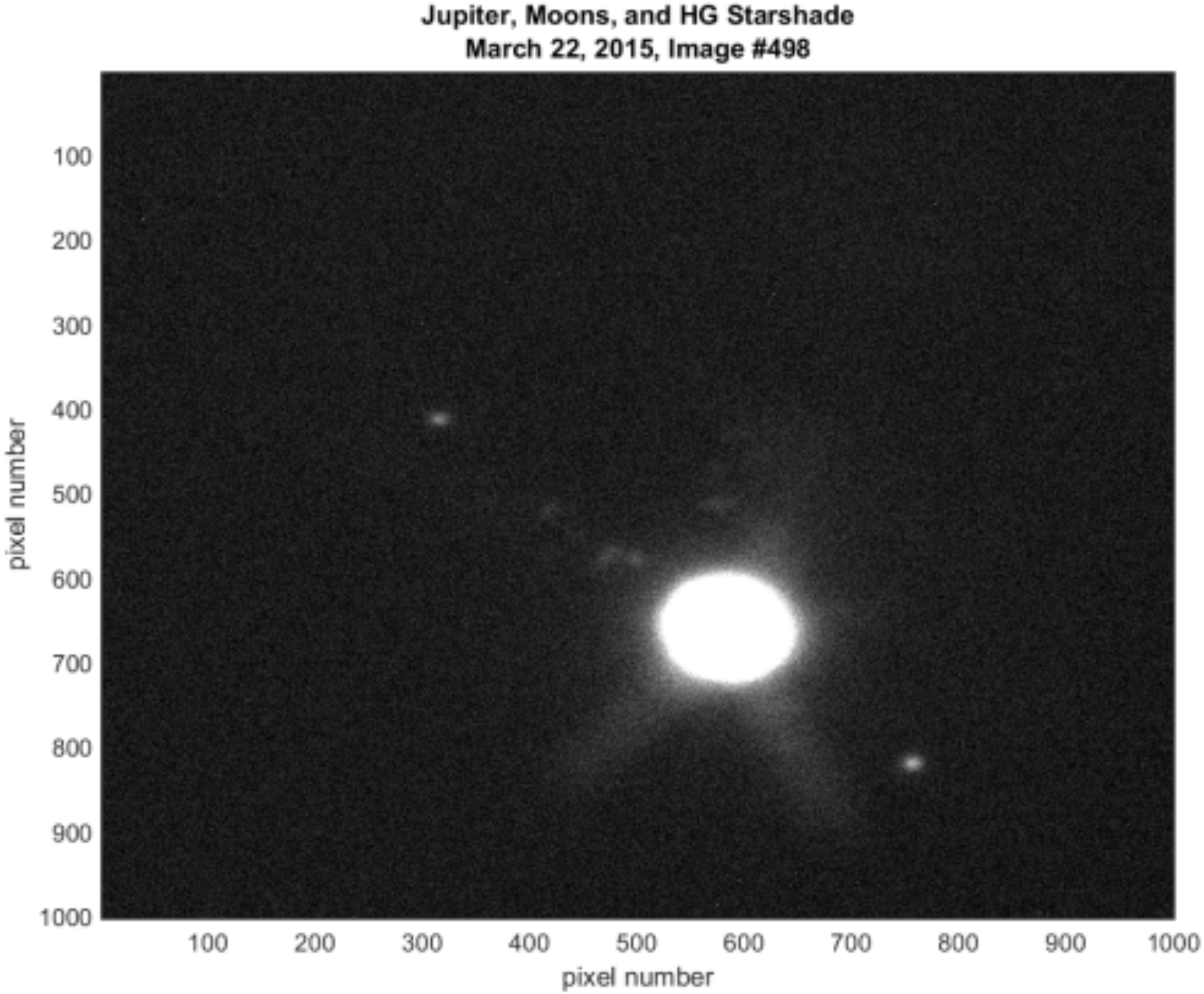
Jupiter Transit of Hypergaussian Starshade (9 of 11)



Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (10 of 11)



Jupiter Transit of Hypergaussian Starshade McMath 140m Setup (11 of 11)



Physics of Starshade Shape Demonstrated on Jupiter using McMath 140m Setup

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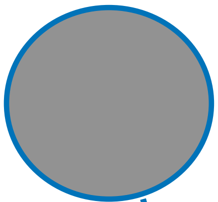
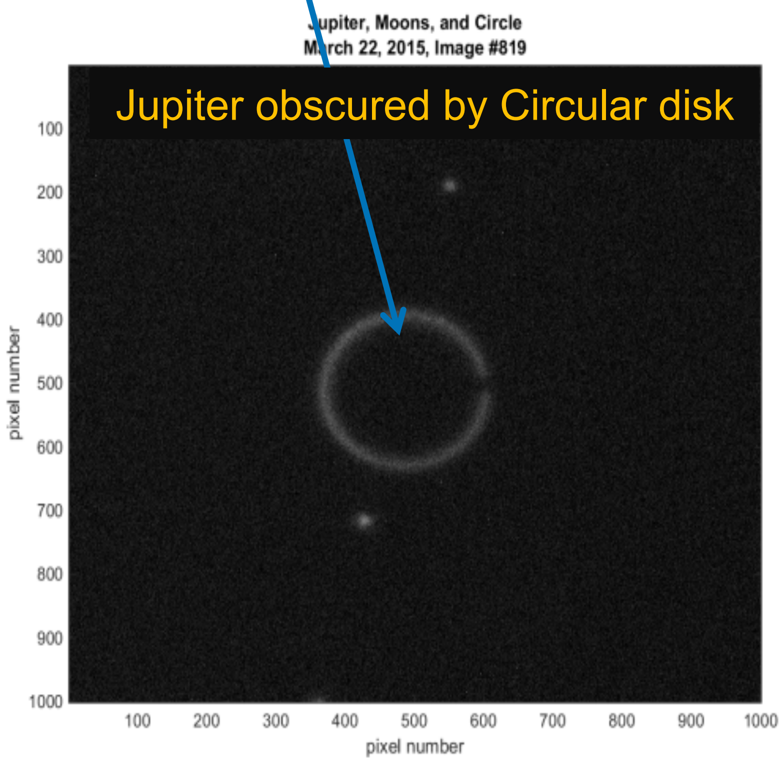
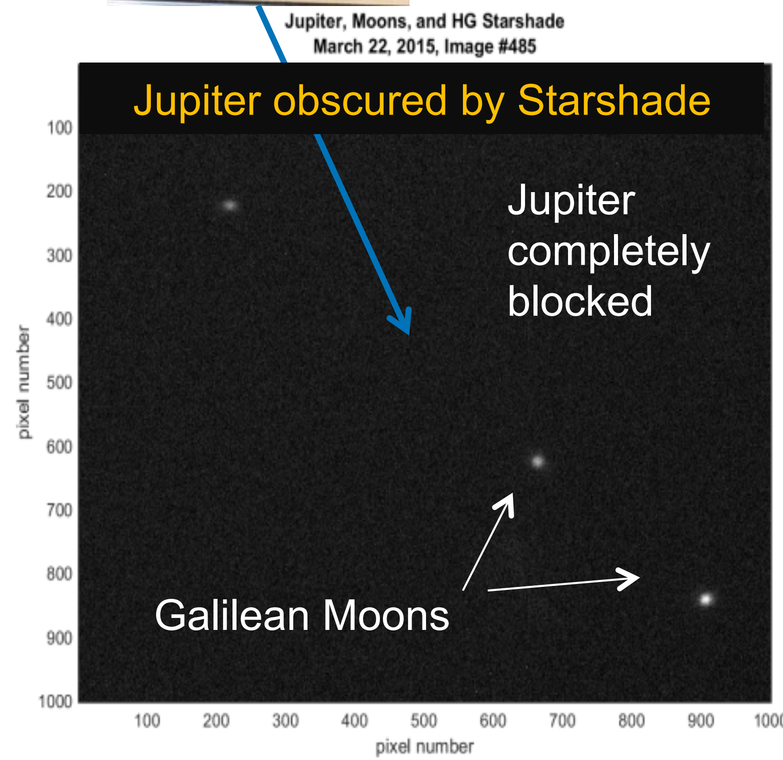


Circular Disk creates classic ring diffraction pattern of an obscured light source

Starshade Shape cancels bright diffraction ring





Physics-Defined proper shape cancels source light of object

M3 Blocked vs Unblocked - McMath 140m Setup

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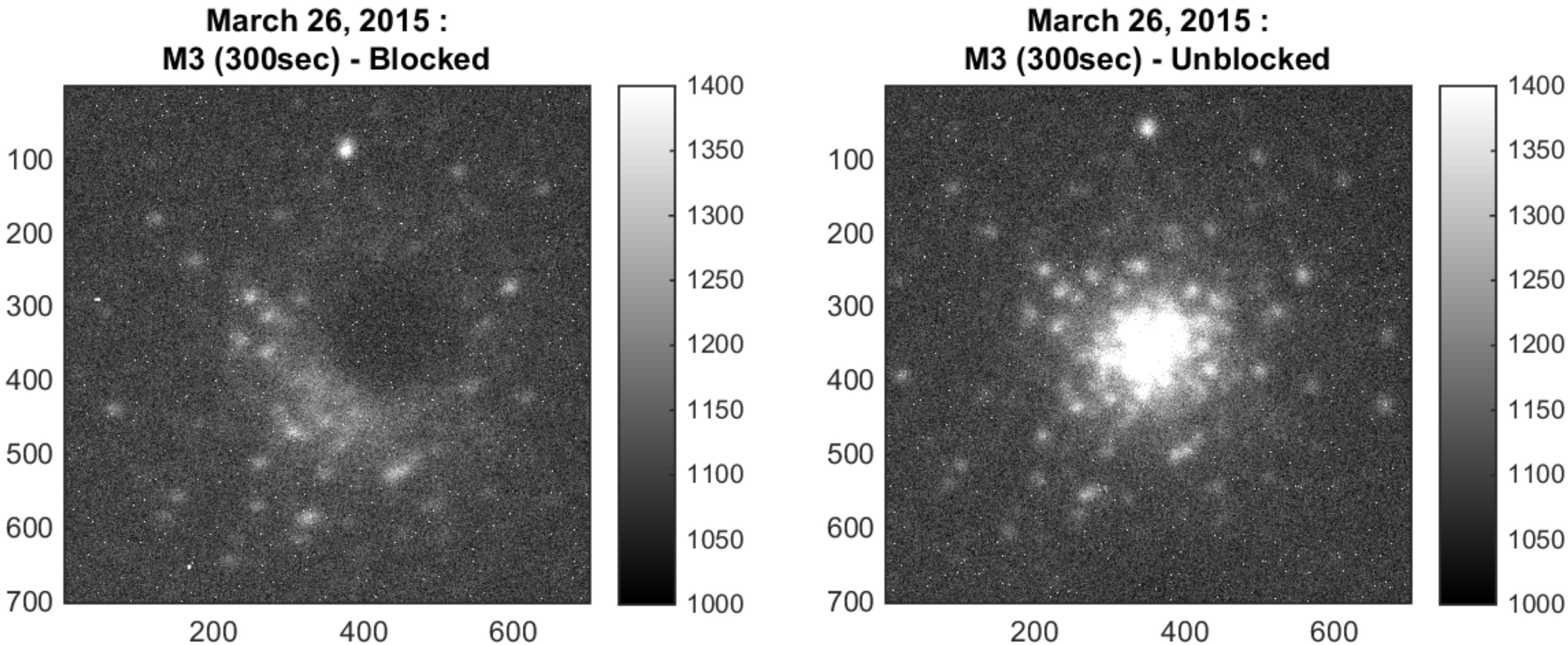
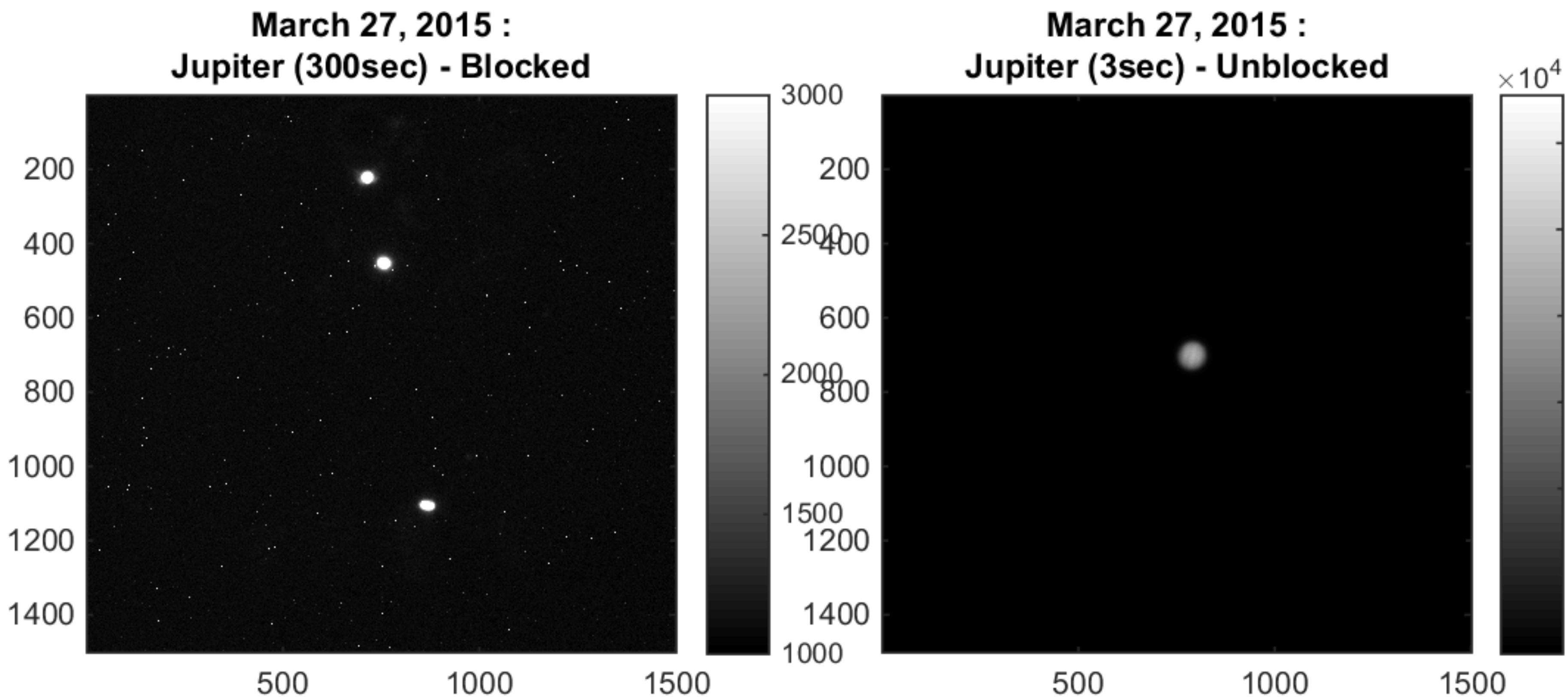


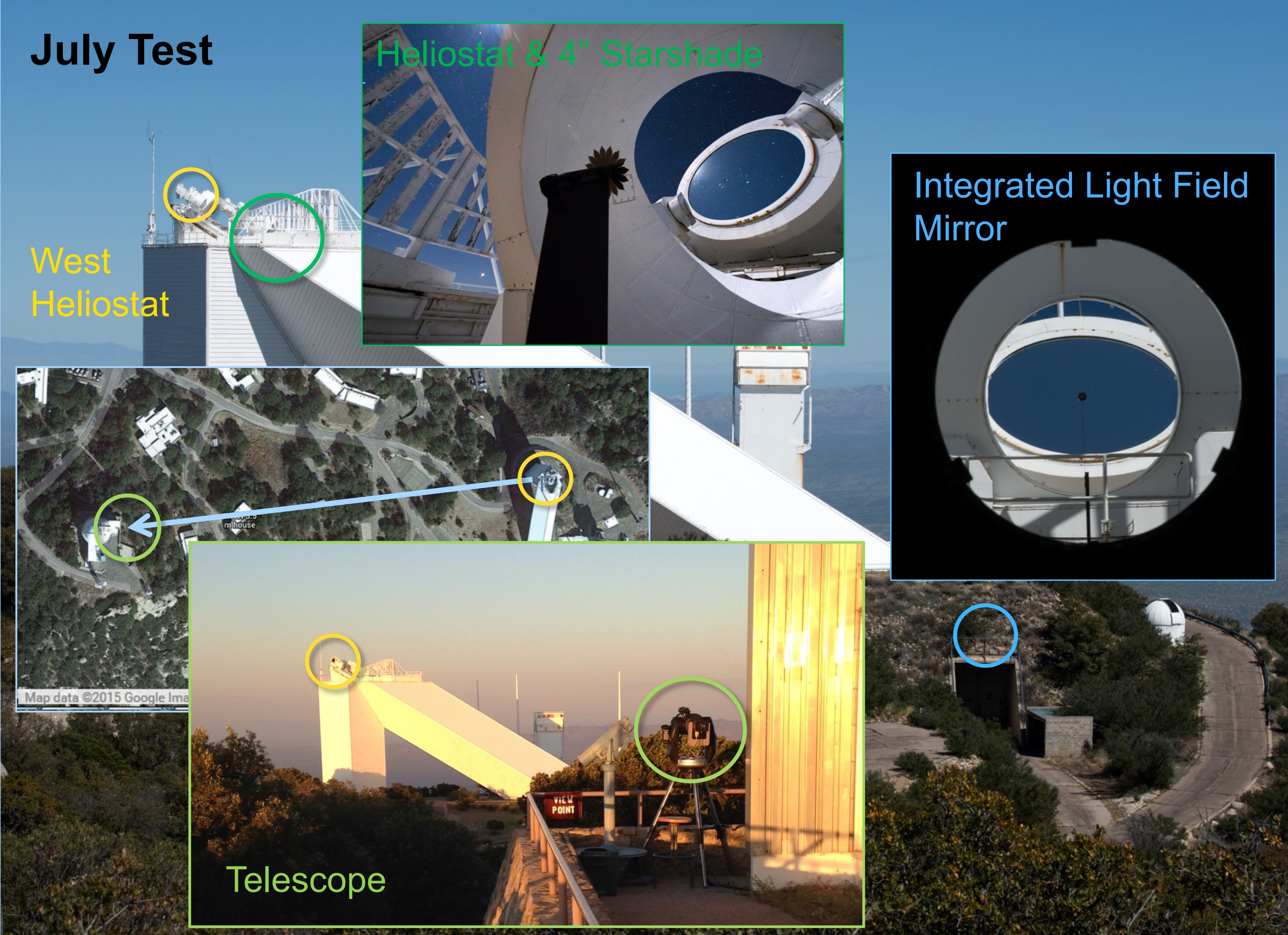
- M3 globular cluster – Blocked and unblocked, 2cm Aperture
- Allows measurement of the effective Inner Working Angle of the starshade
  - We know that the starshade is effectively 180arcseconds tip to tip this image lets us see how far between the tips we can see.
- May indicate ripple or beating effects beyond the edge of the starshade

Jupiter Blocked vs Unblocked - McMath 140m Setup

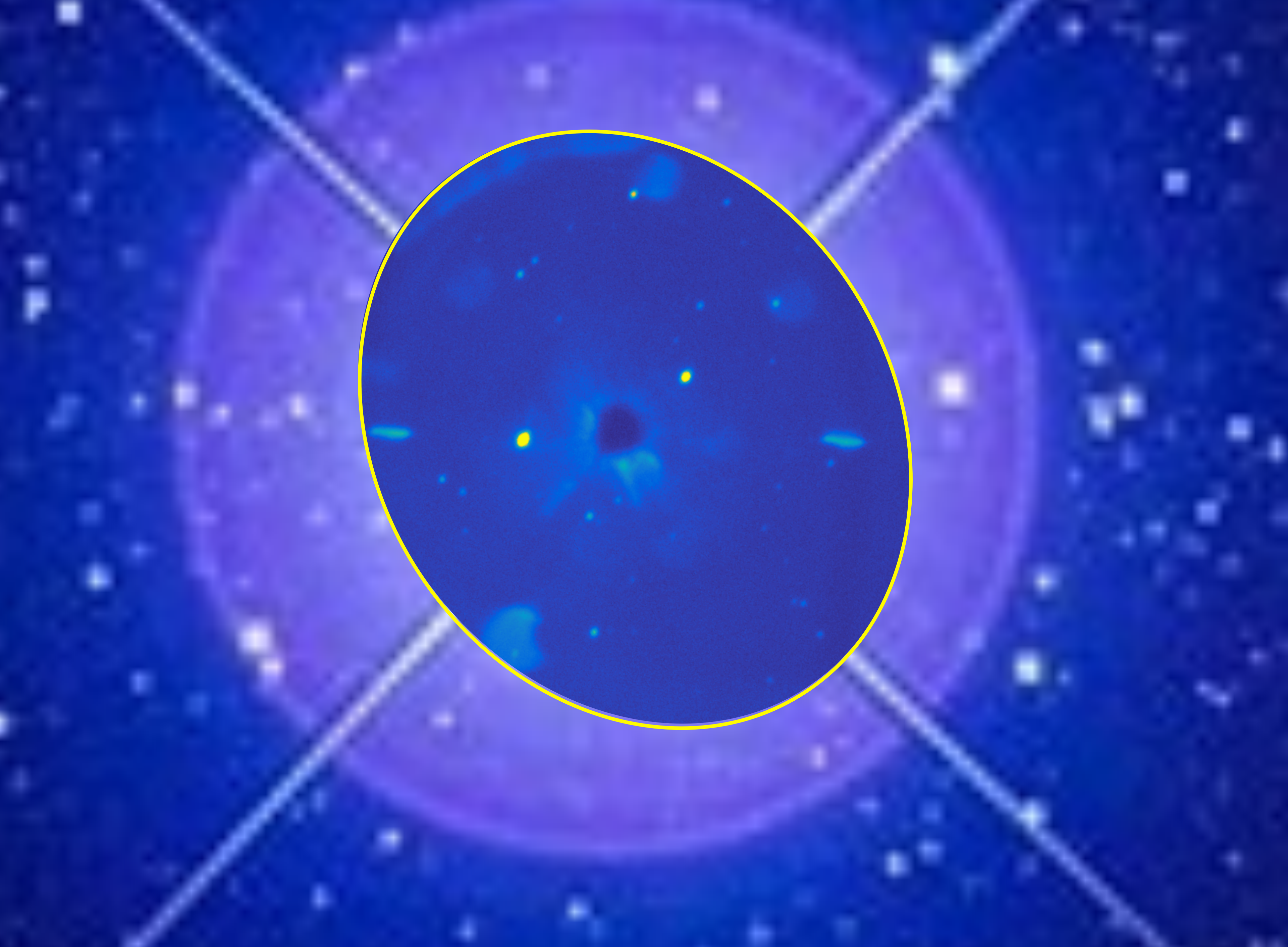


- Both images use 2cm aperture without filtering
- Blocked image has 100x integration time
- Residual light from blocked Jupiter is below noise floor

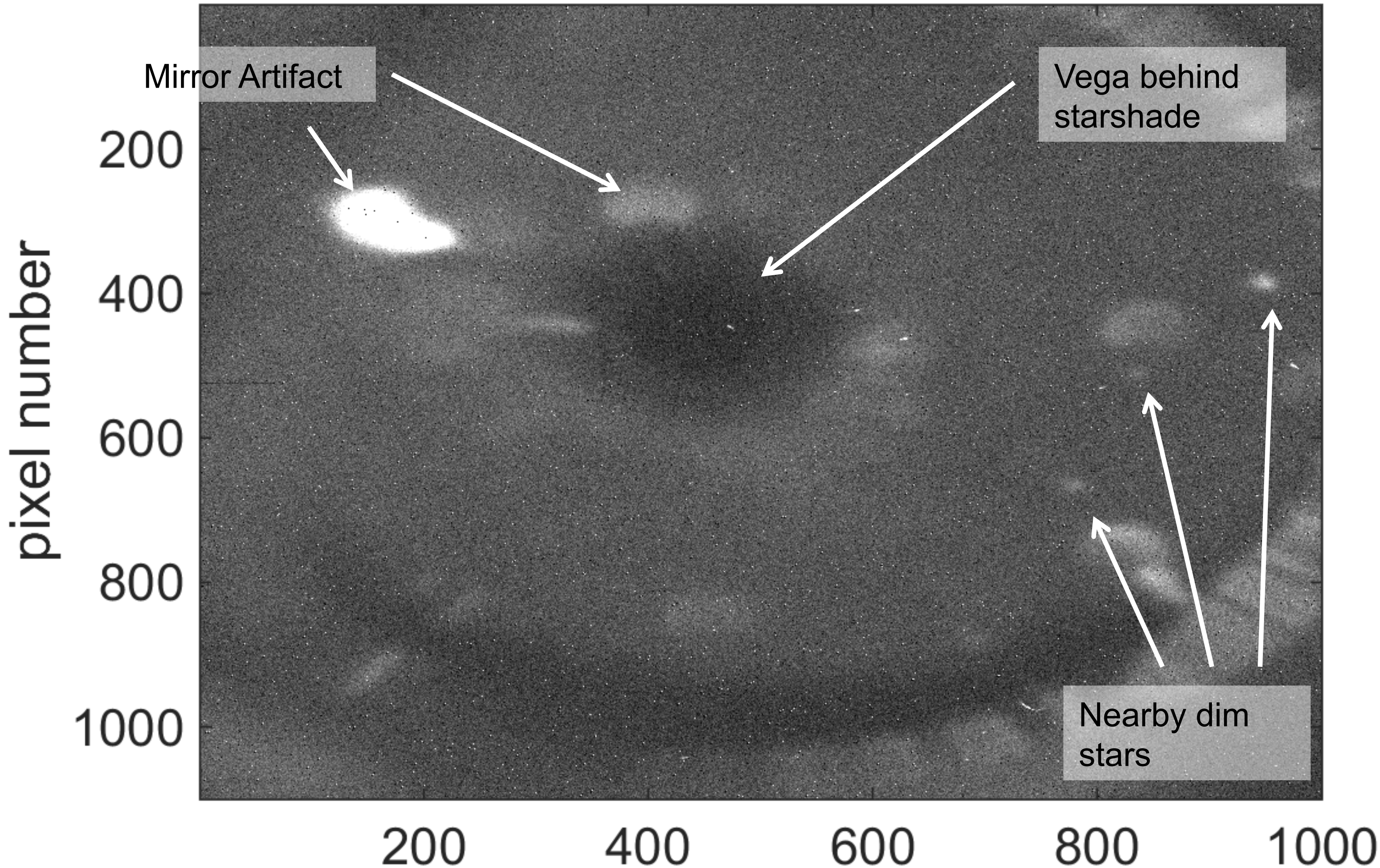
July Test



Heliostat & 4" Starshade
Integrated Light Field Mirror
West Heliostat
Map data ©2015 Google Ima
Telescope
VIEW POINT

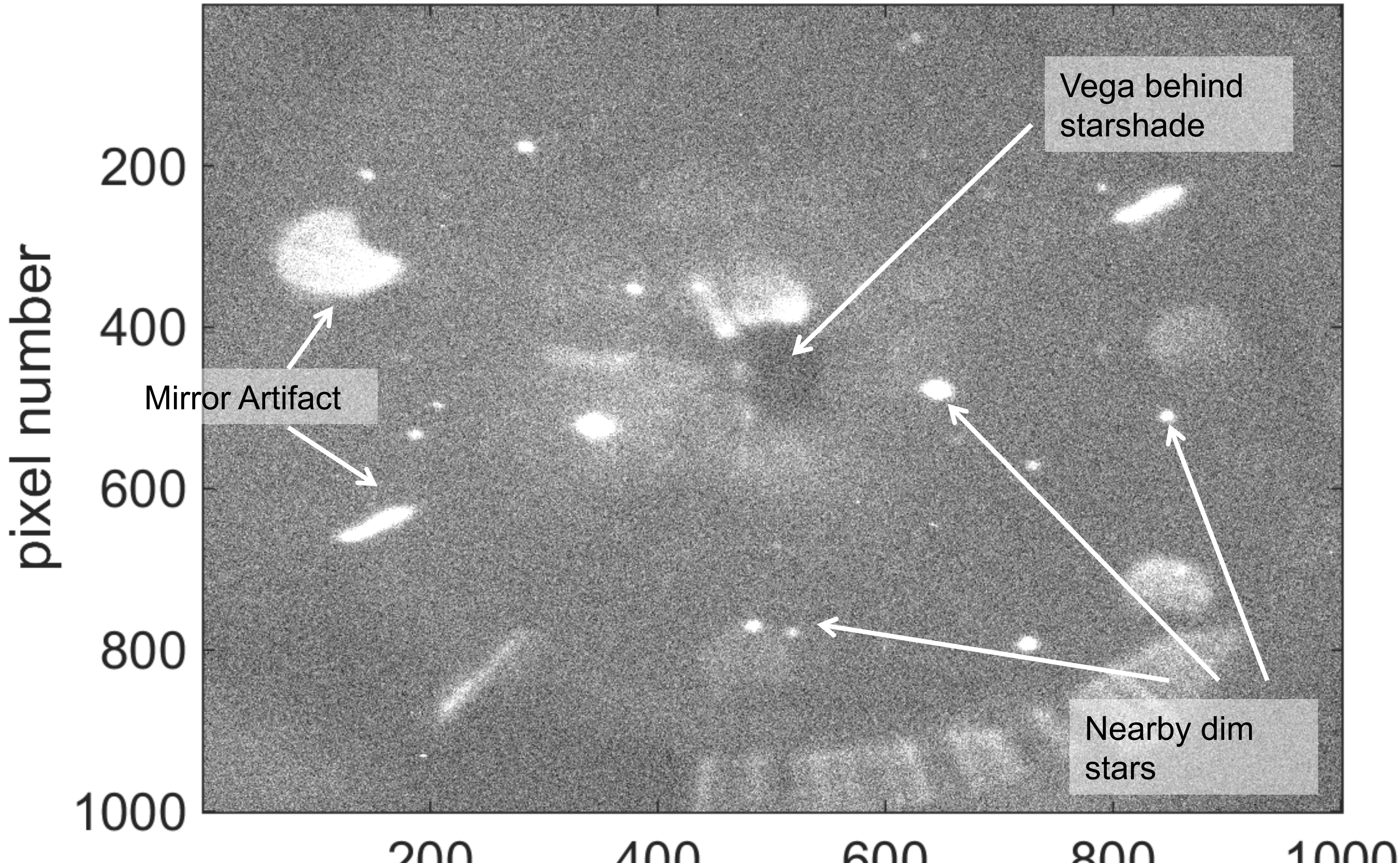


Vega with 12" HG Starshade: June 16, 2015
Image #165 (300 Seconds)



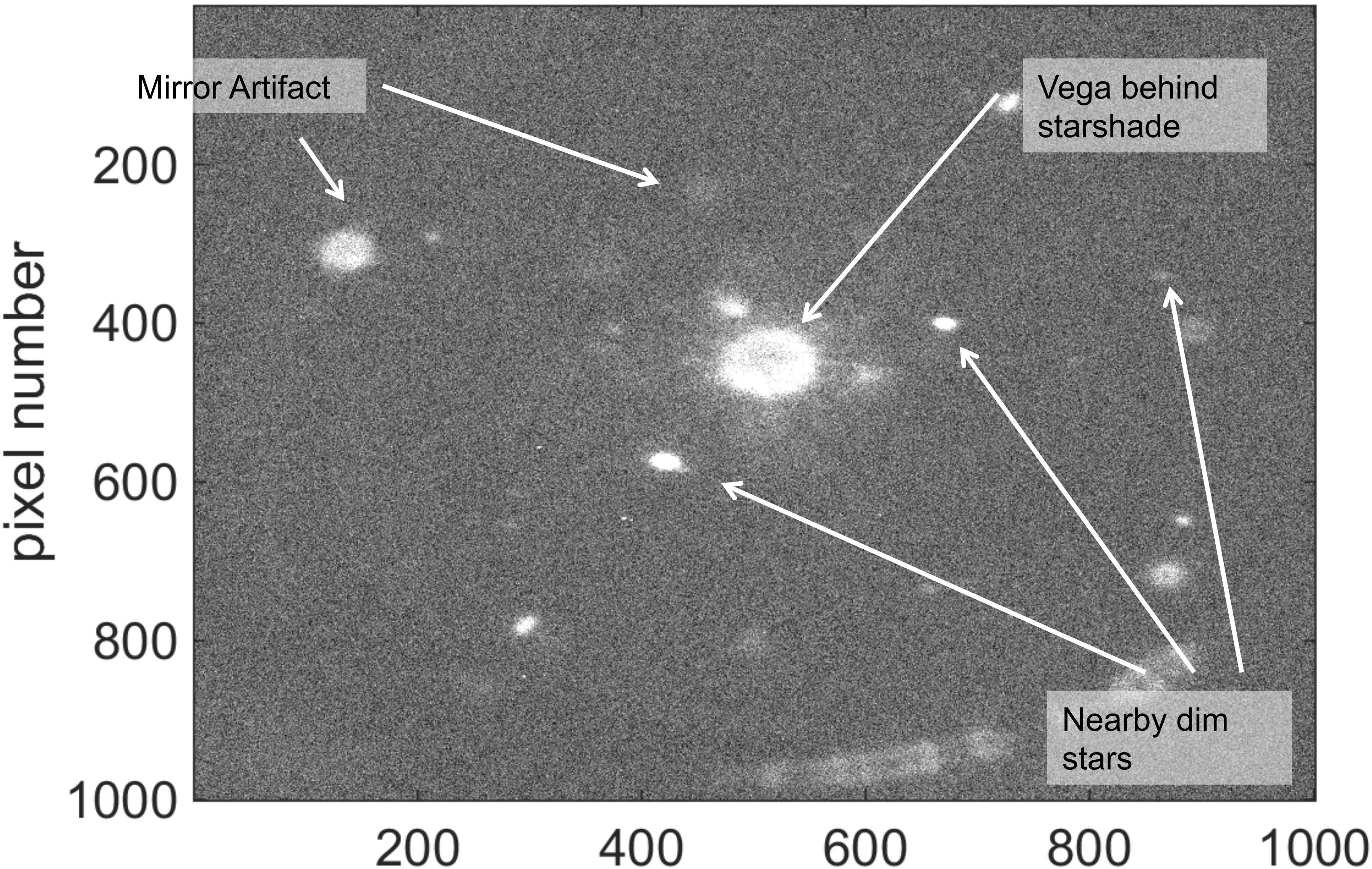
McMath 400m Setup

Vega with 8" HG Starshade: June 18, 2015
Image #173 (120 Seconds)



McMath 400m Setup

Vega with 4" HG Starshade: June 18, 2015
Image #246 (120 Seconds)



McMath 400m Setup

Comparison of tests

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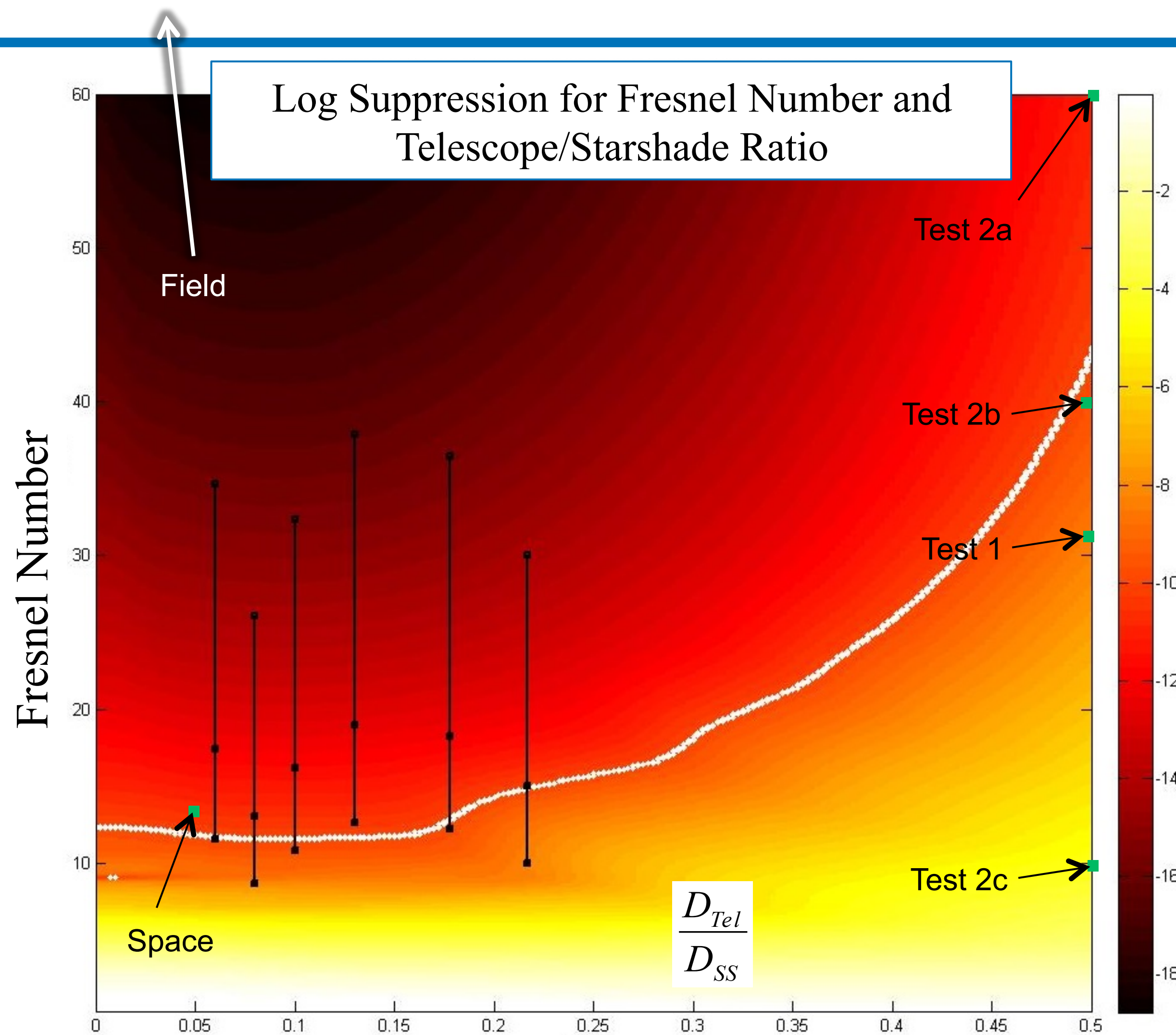
Test	Starshade to Telescope Separation	Starshade Diameter	Telescope Aperture	Resolution	Resolution Elements	Inner Working Angle	Fresnel Number
1	0.14km	0.10m	0.04m	3.8arcsec	31.1	59arcsec	32
2a	0.4km	0.29m	0.12m	1.5arcsec	82.7	62arcsec	87
2b	0.4km	0.20m	0.08m	1.9arcsec	43.2	41arcsec	42
2c	0.4km	0.10m	0.04m	3.8arcsec	11.1	21arcsec	10
3	2.4km	0.29m	0.04m	3.8arcsec	4.0	12arcsec	14
Field	1km	0.5m	0.04m	3.8arcsec	26.8	51arcsec	210
Space	80,000km	50m	2.4m	0.063arcsec	2	0.065arcsec	13

- McMath Tests allow flight like Fresnel number and close to flight like Resolution elements
- McMath Inner working angle remains ~400 times larger than flight like.

Starshade Basics – Fresnel Number

- Starlight suppression by a starshade is determined by the Fresnel Number:
  - $F\# = \frac{D_{SS}^2}{4\lambda z}$
- This factor completely specifies the shadow of a Hypergaussian starshade



For a fixed Suppression, a larger Starshade at a greater distance gives a smaller IWA

Final Thoughts

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- Field and McMath testing are complementary
  - Desert test results use controlled known radiance bright sources
  - McMath collects on astronomical targets and using flat wavefront light and flight like optical numbers
  - Both use systematic collection methods
- November McMath test at longer baseline ***may*** be able to image astronomical bodies with IWA of 12 arcsecond
  - Data collected, processing underway
- Next steps
  - Desert testing at Flight similar Fresnel number using smaller starshades and a 4km baseline
  - Improving the robustness of McMath testing for long baselines

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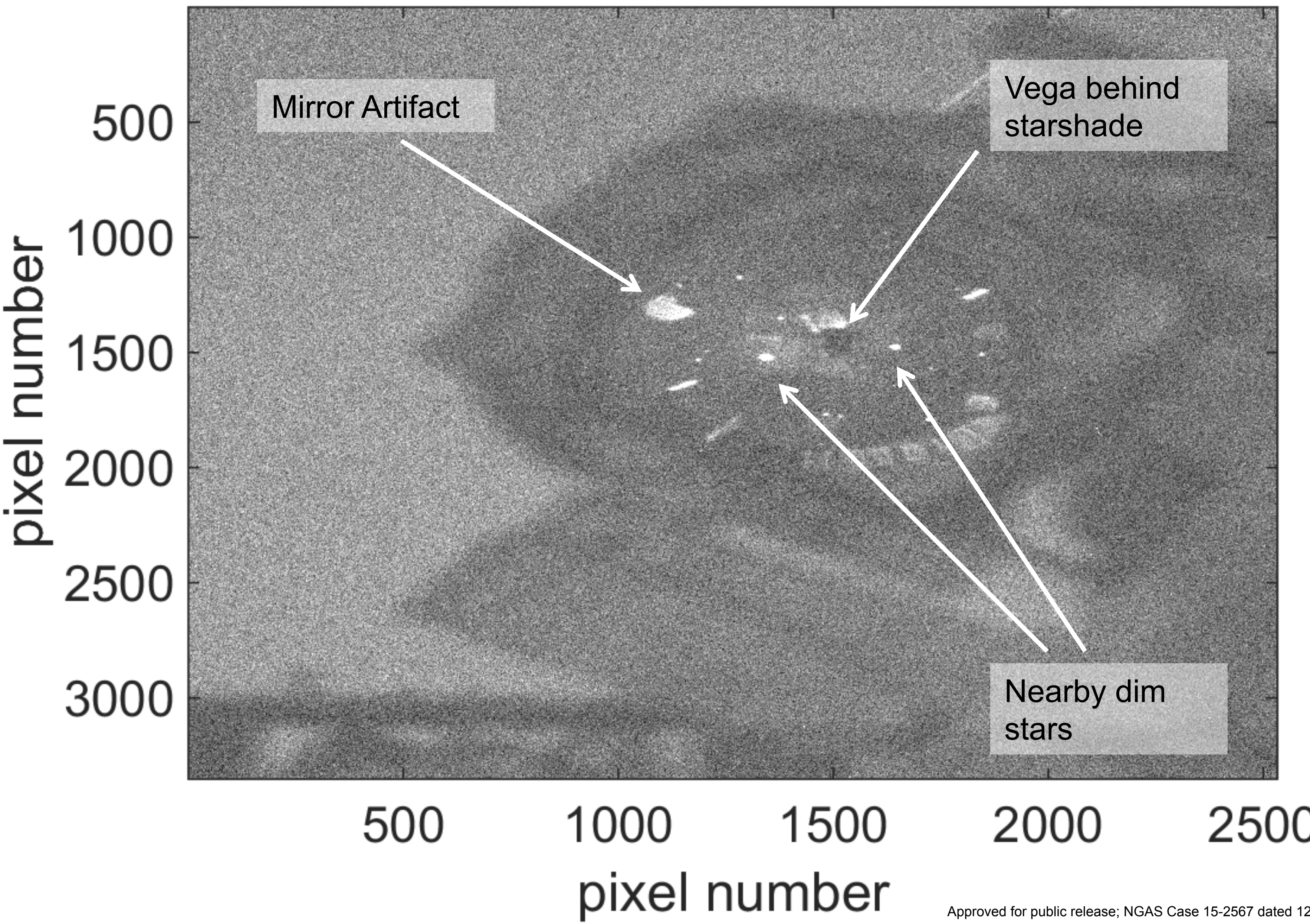
Vega with 8" HG Starshade: June 18, 2015
Image #173 (120 Seconds)



Vega with 4" HG Starshade: June 18, 2015
Image #246 (120 Seconds)