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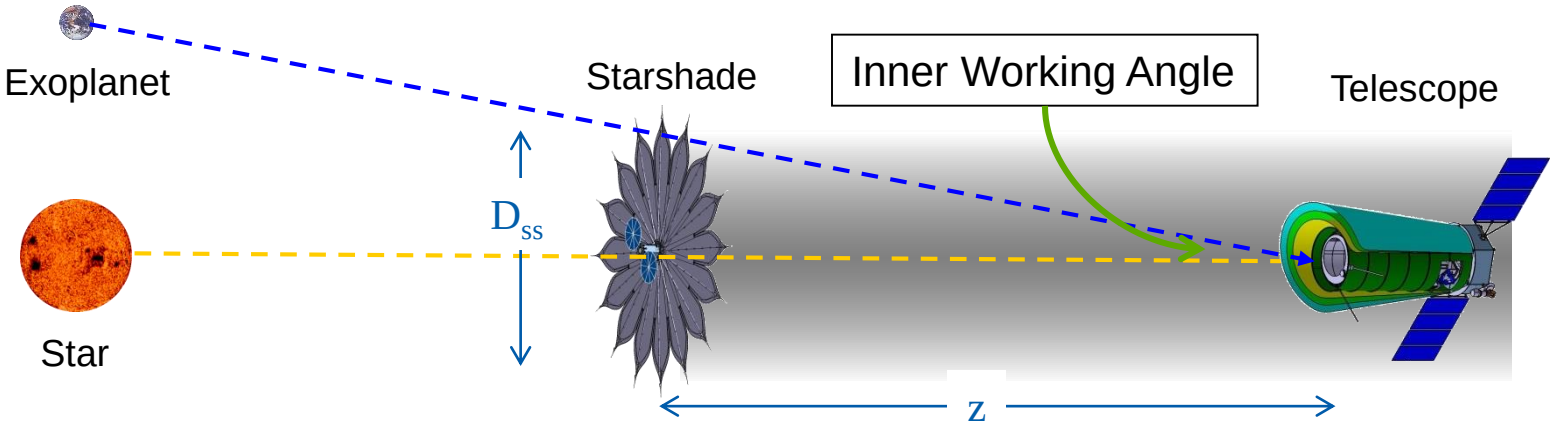
Field Testing the Starshade

11/12/2015

Steve Warwick
Starshade Program Manager

Starshade Basics – Inner Working Angle



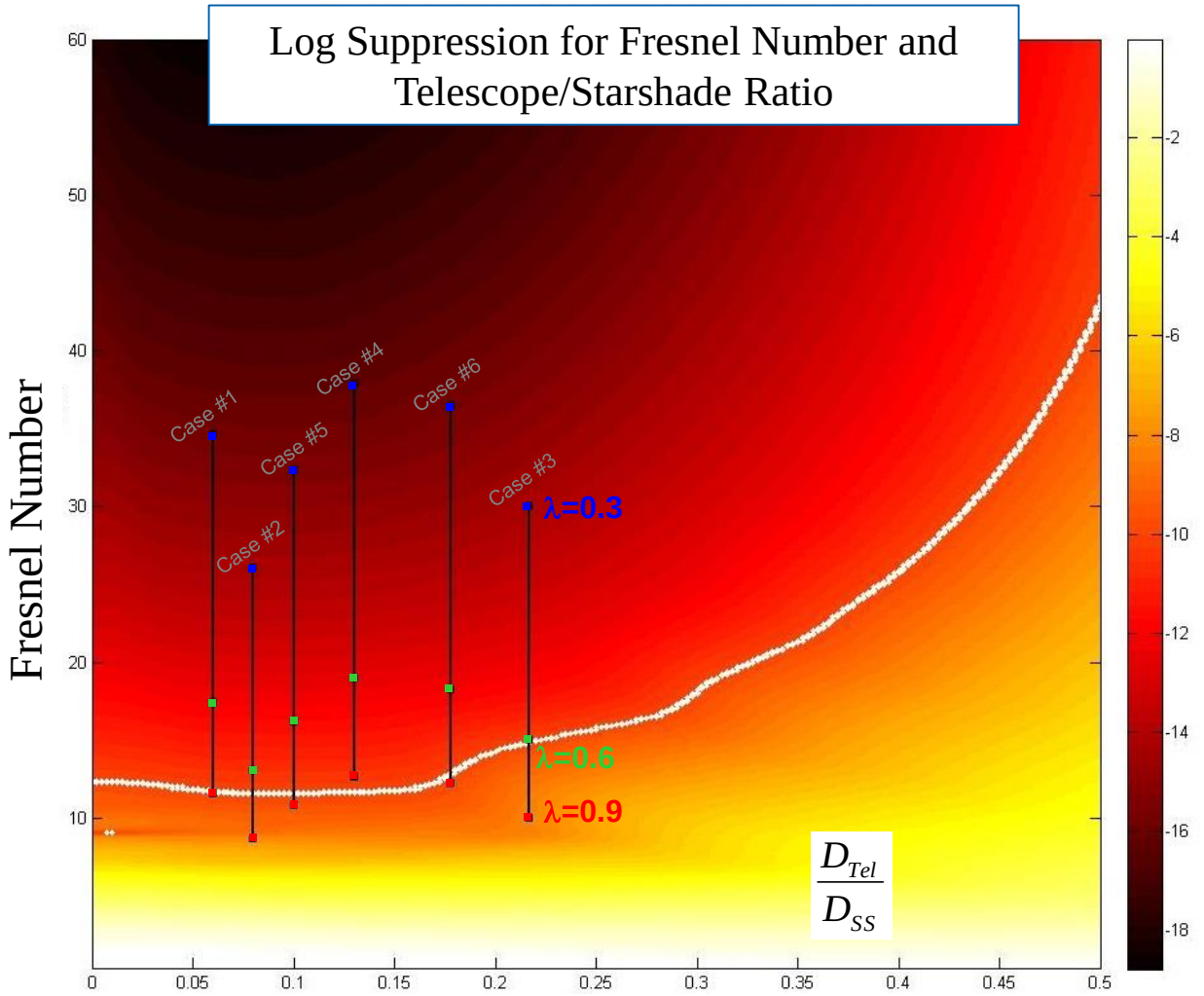
- Inner Working Angle is the closest separation of Planet and Star that we can expect to see with a given starshade
- For Hypergaussian starshade, this is approximately equivalent to:

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

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

Starshade Basics – Fresnel Number

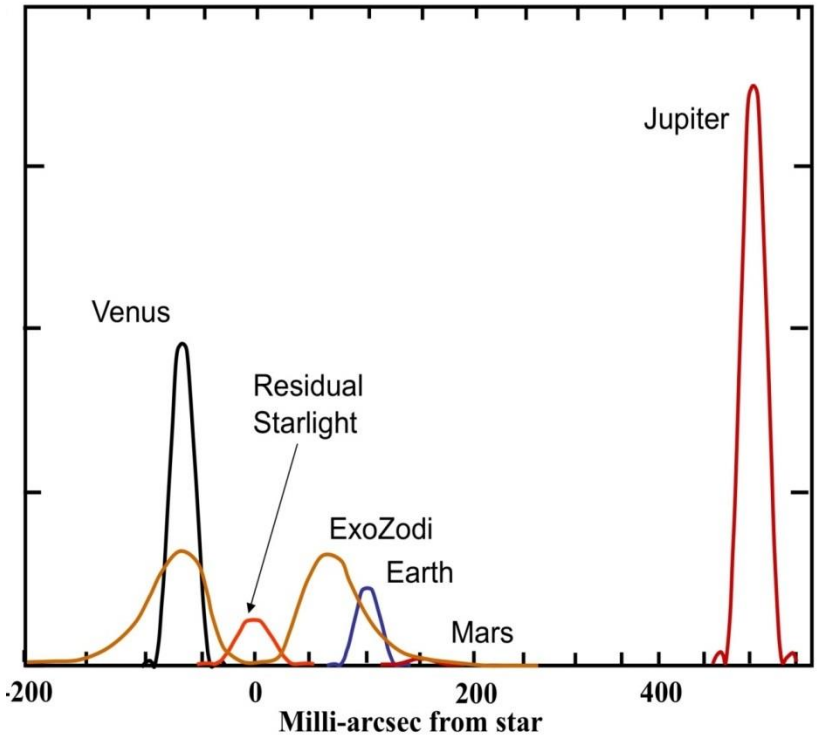
- Starlight suppression by a starshade is determined by the Fresnel Number:
  - $F\# = \frac{D_{SS}^2}{4\lambda z}$
- This factor completely specifies the shadow of a Hypergaussian starshade



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

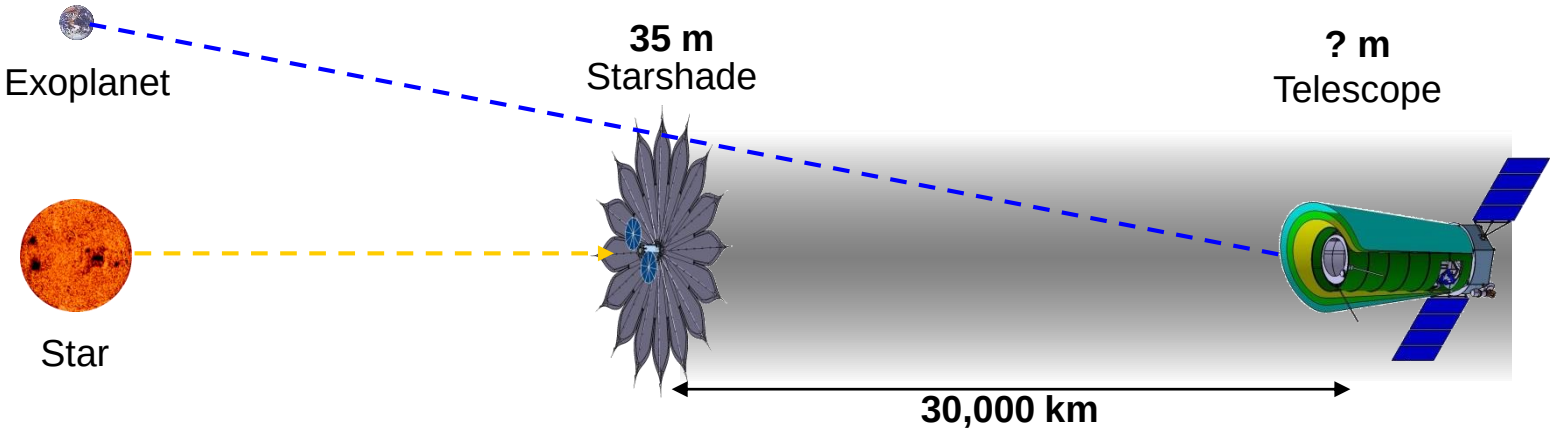
Starshade Basics – Resolution Elements

- 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 element should be equal or greater than $2\lambda/D$ to allow separation of planets and exozodi
- More resolution elements are better.



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/30,000km = **120mas**

Fresnel Number = 50m^2/(4*600nm*185,000km) = **17**

Minimum Telescope Diameter = 2*600nm/120mas = **2.4m**

A larger telescope gives better resolution and collects more photons

IWA and Suppression are independent of the telescope diameter

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Field Testing a Starshade

Field Testing 2014/15

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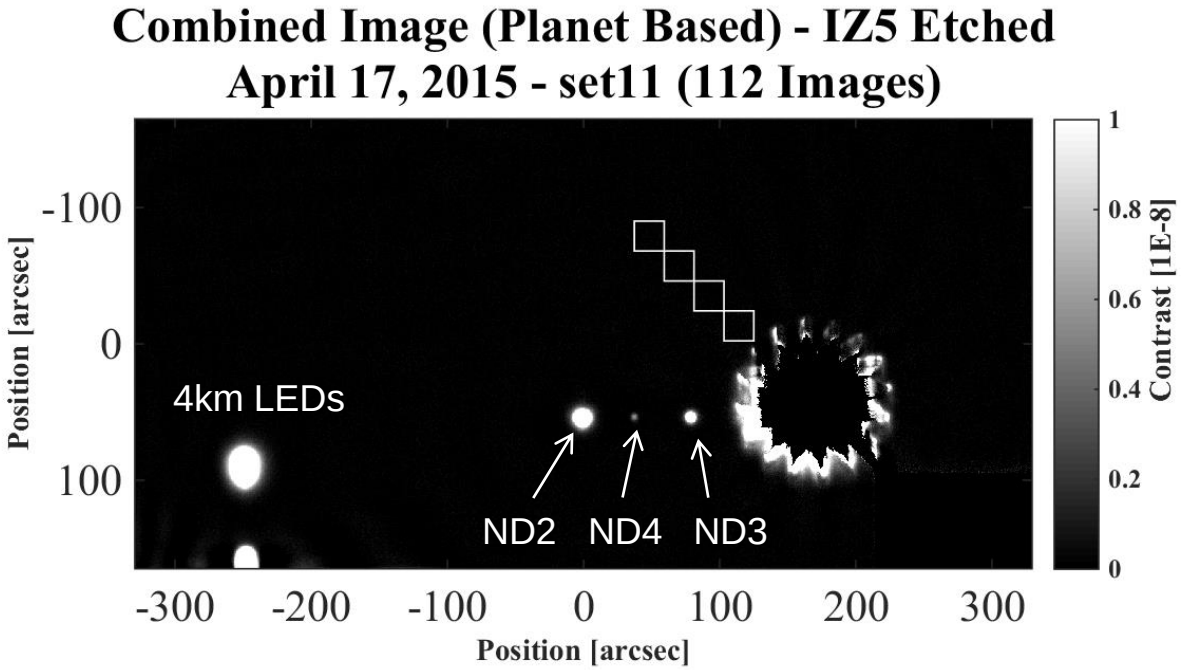
NASA JPL / Northrop Grumman 100th Scale Starshade

Light Sources

Best Contrast Ratio

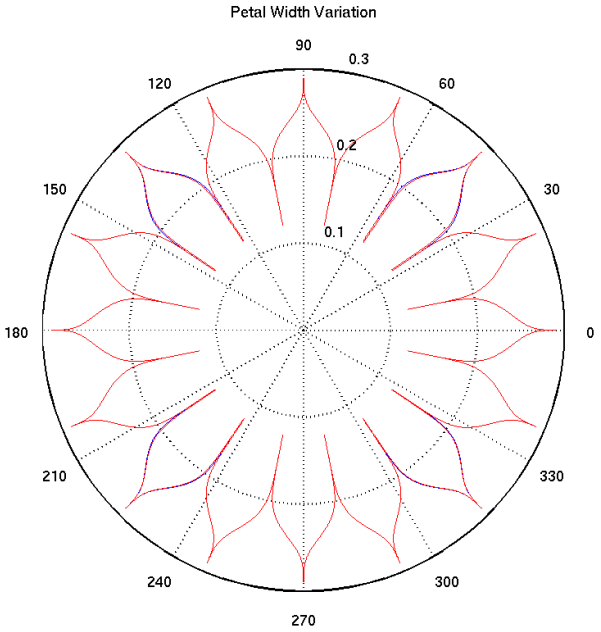
- Planet LEDs are Standard LEDs with ND filters in front.
  - ND4 planet ~8E-9 below main source
- Light Scatter from dust is modelled and subtracted from the image
- Slight vertical variation between images due to air disturbances.
  - Images collocated using Planet LEDs

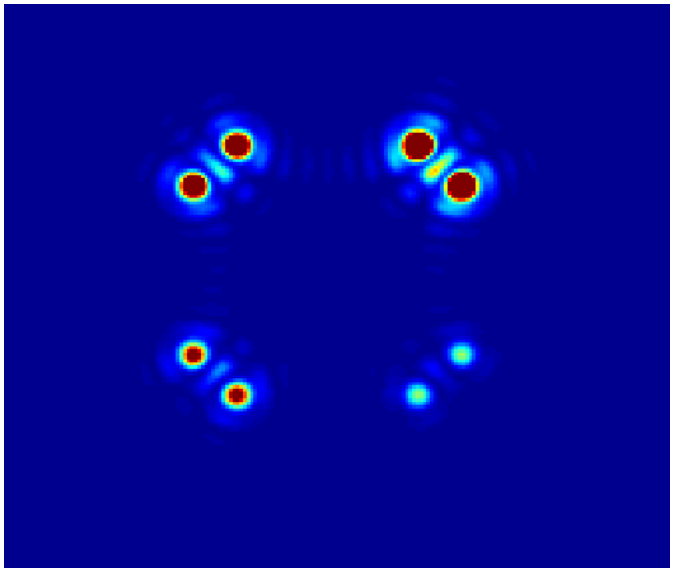


3σ Standard Deviation in box closest to the starshade = **9.09E-10**

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

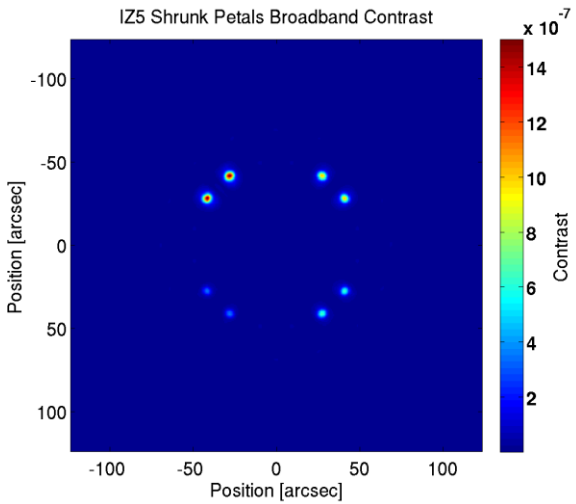
Testing Engineering Sensitivities –
Flawed Starshade Performance



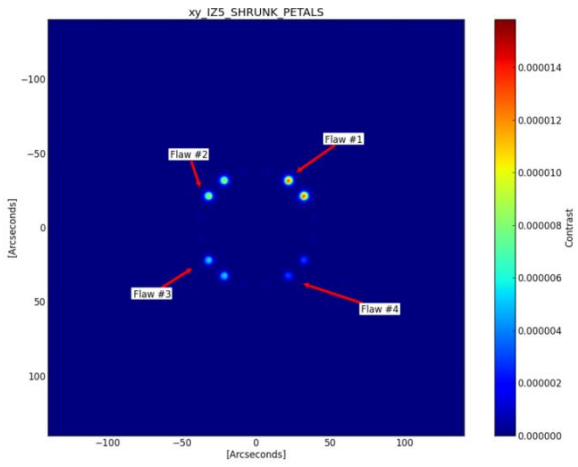


- 6 families of flaw each applied to Hypergausian and Numerically Determined Starshades
  - Simulations predict patterns field test optical lengths

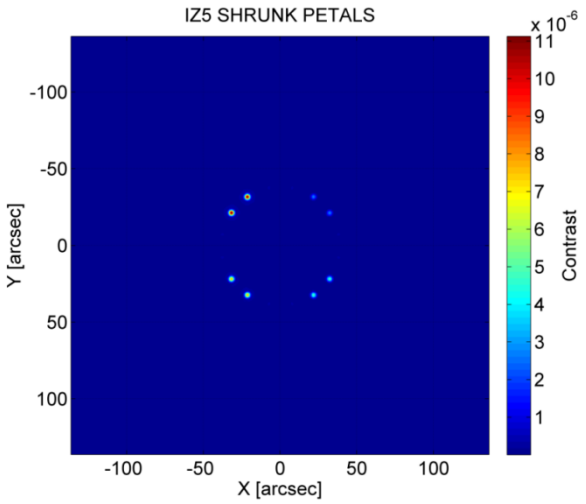
Model Verification



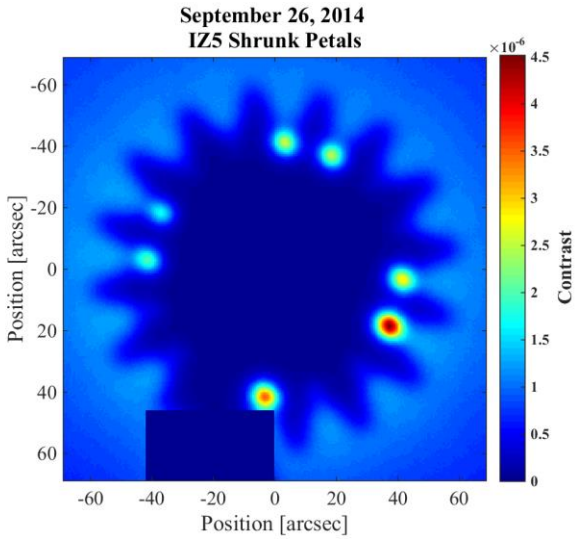
NG Model



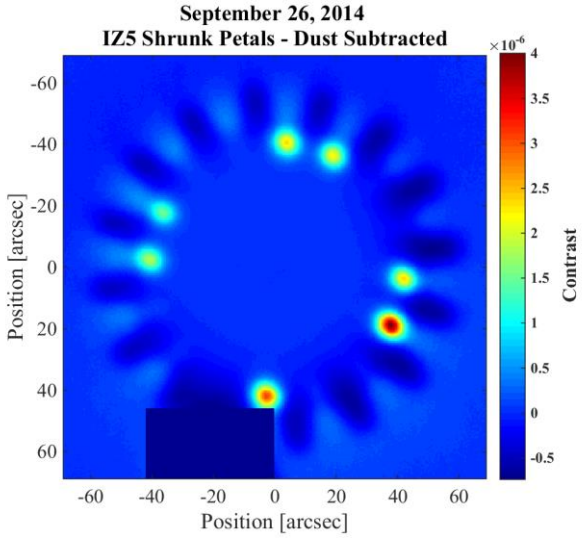
CU Model



JPL Model

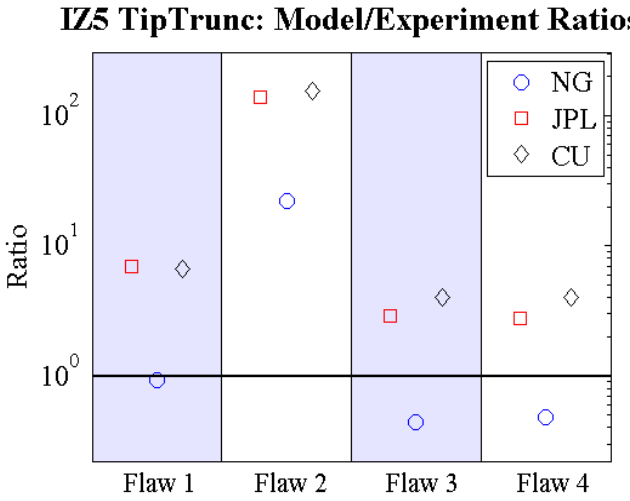


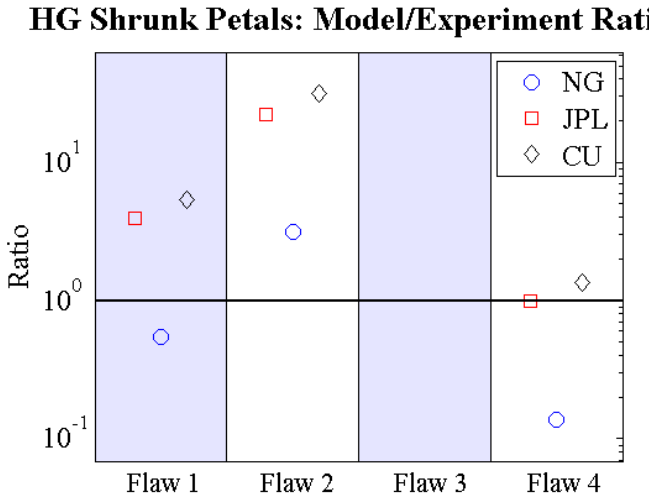
Measured

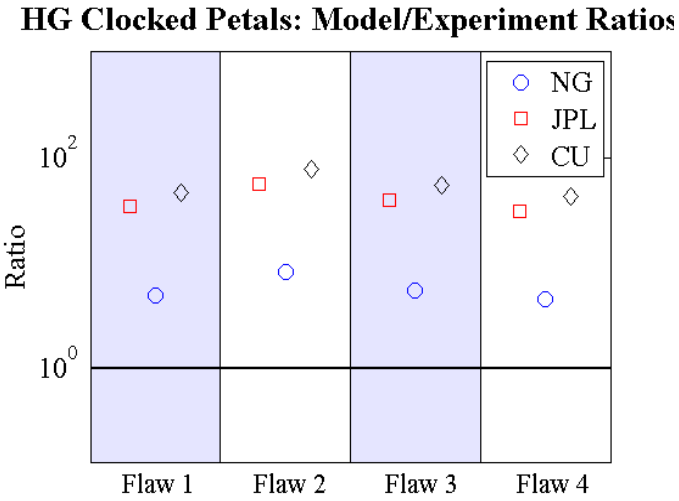


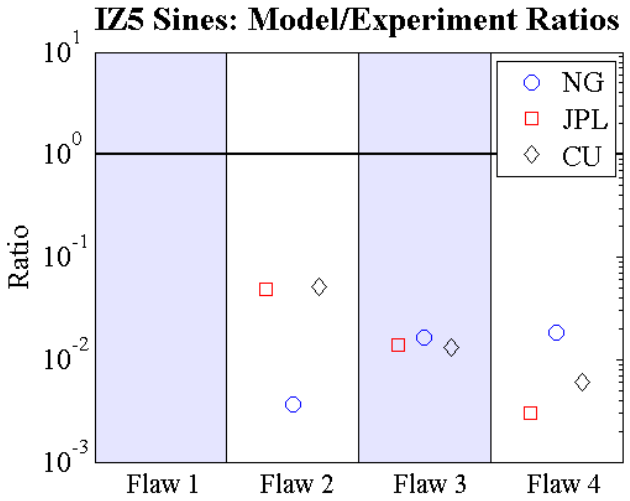
Measured & Dust Subtracted

Model Predictions vs. Measurements

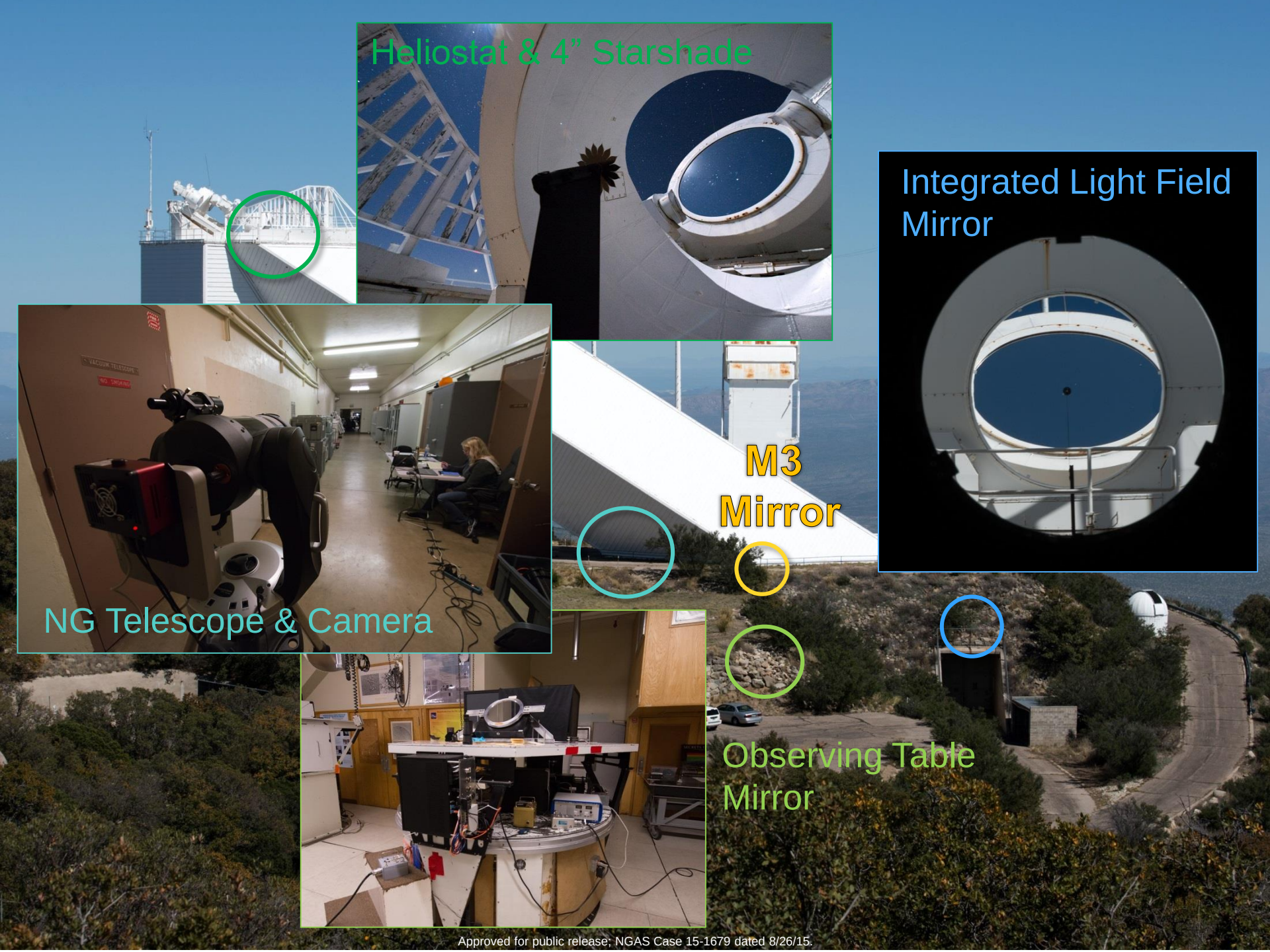




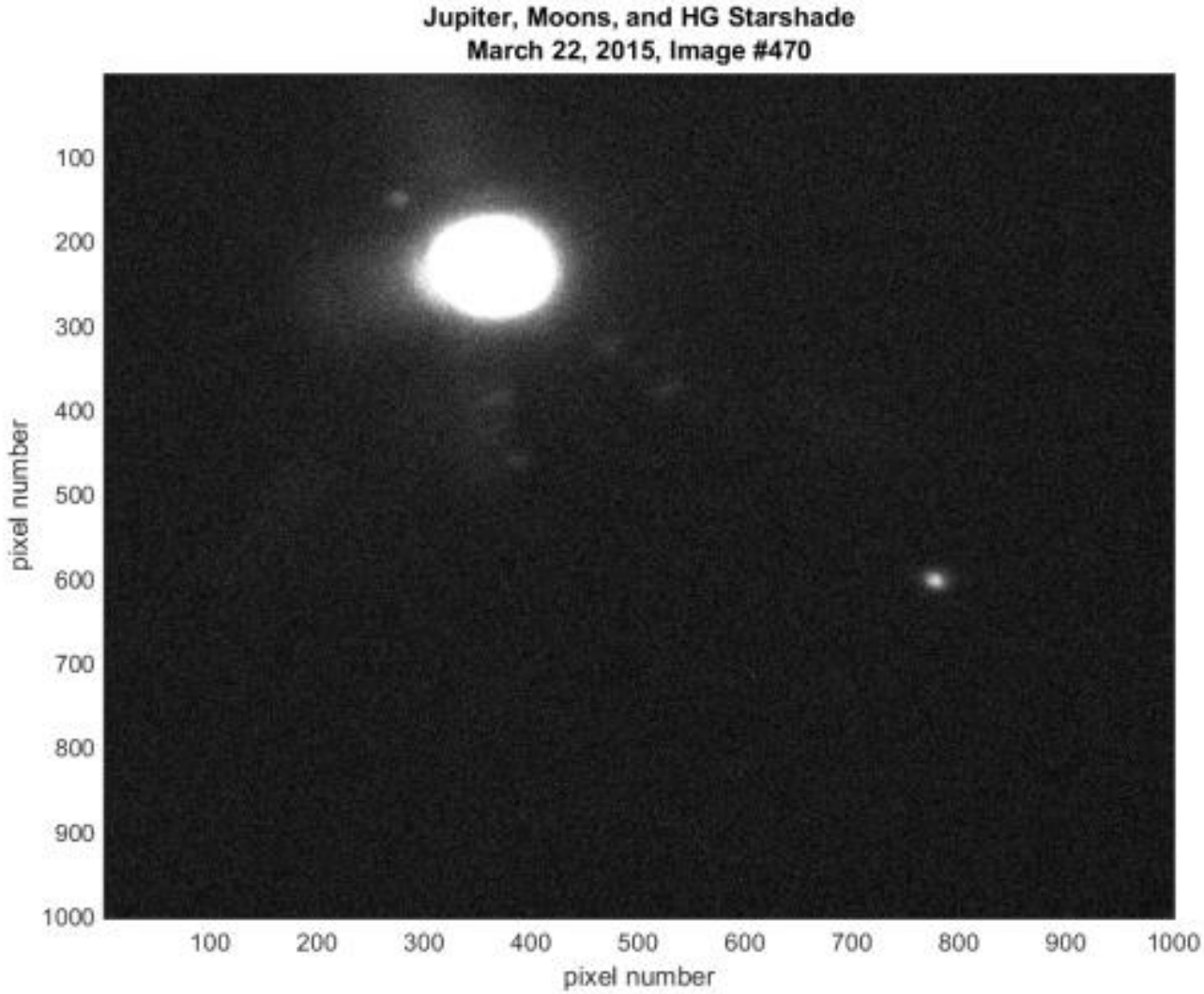




- Ratios of flaw peaks modeled independently by NG, JPL, and CU to the peaks measured in the field.
- Points above the line indicate the model predicted a brighter response than was measured

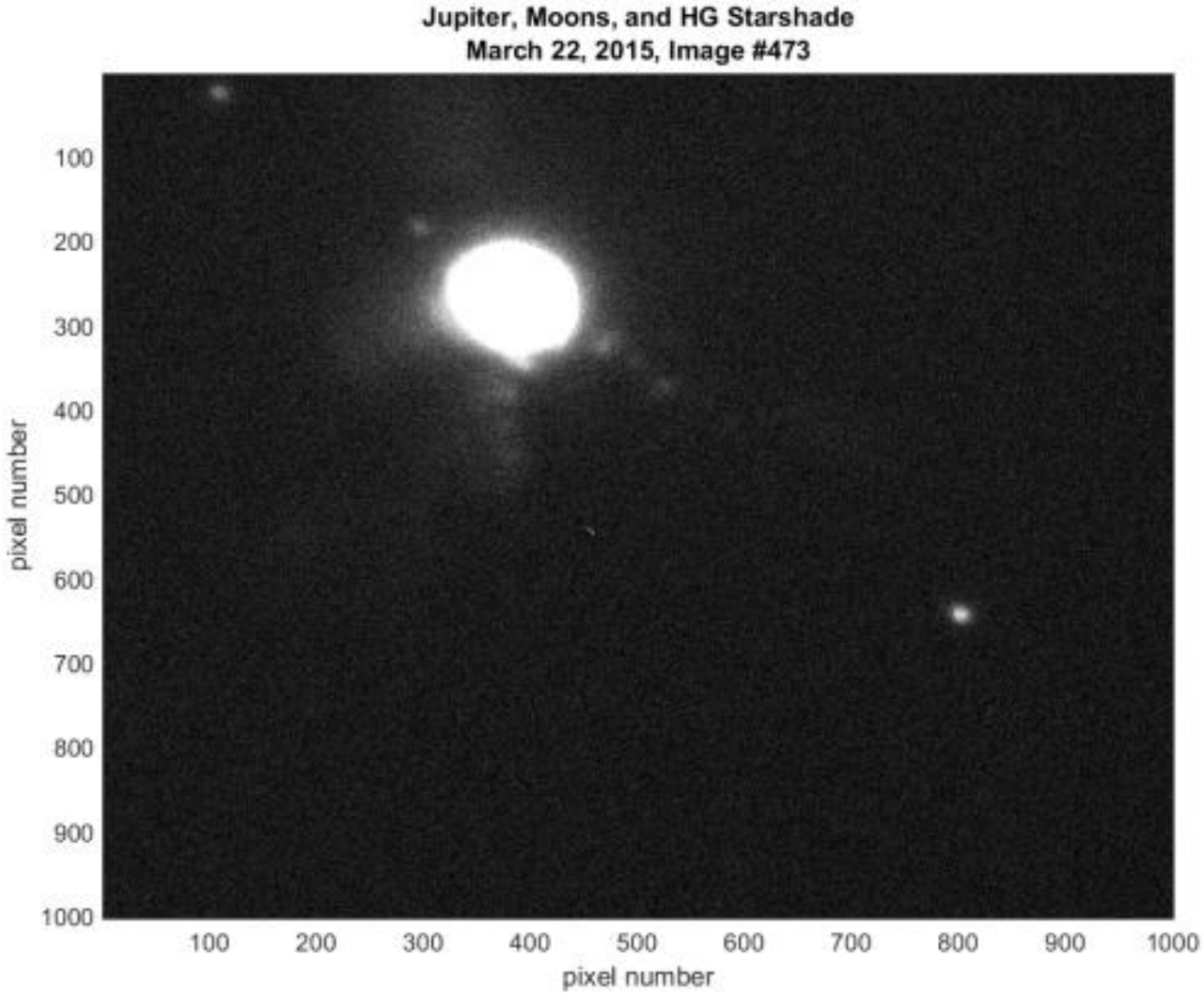


Jupiter Transit of Hypergaussian Starshade (1 of 11)



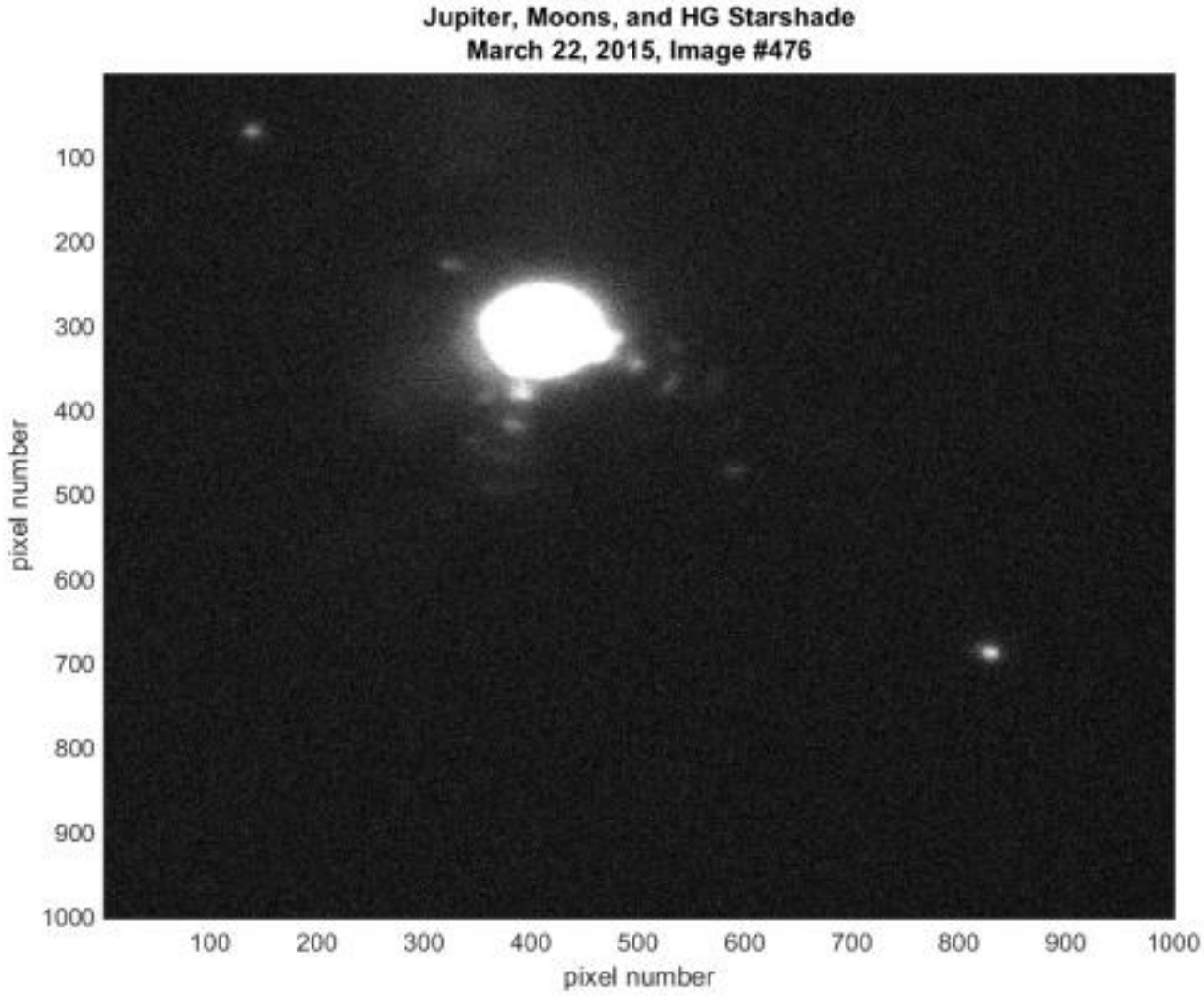
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade (2 of 11)



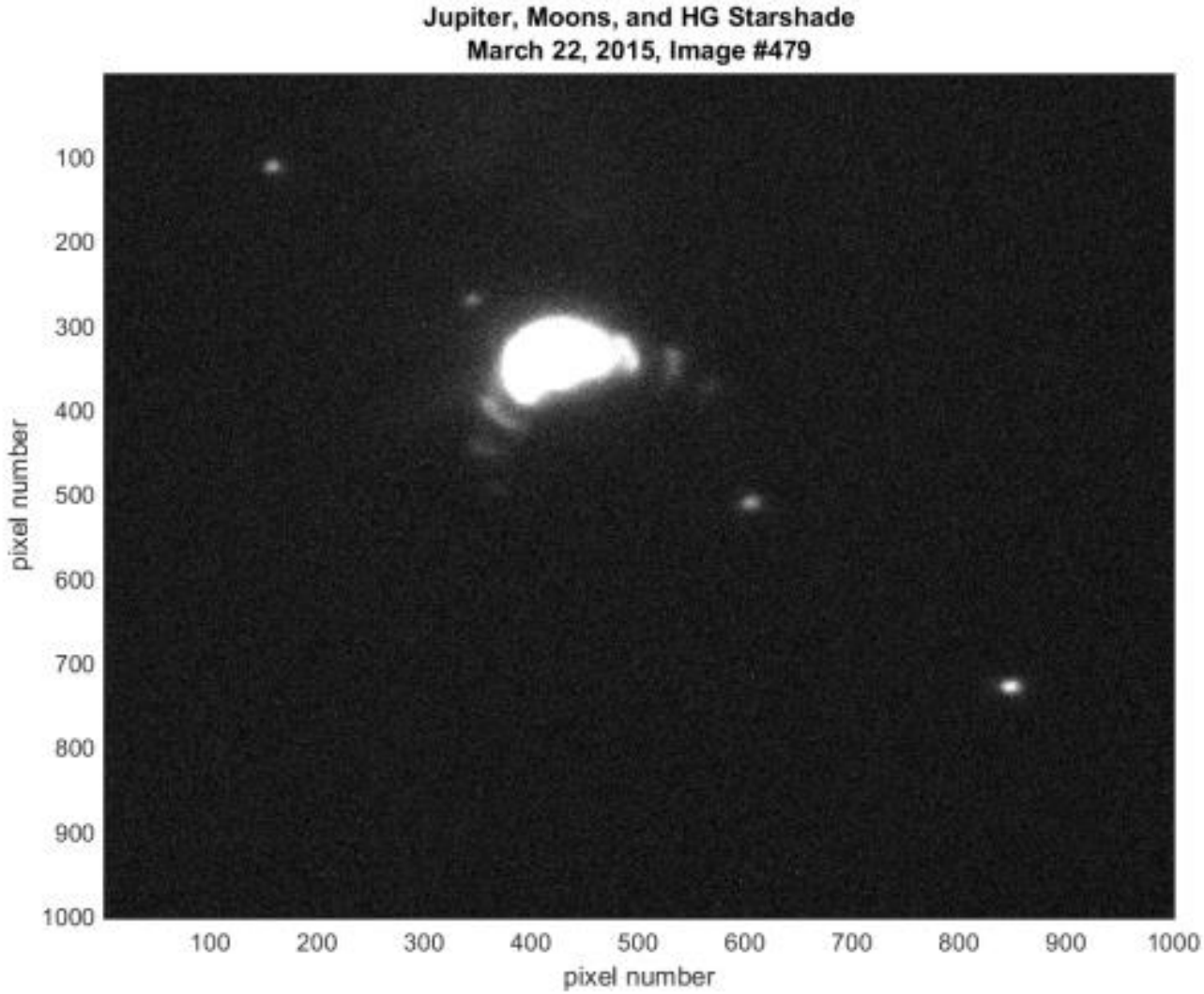
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade (3 of 11)



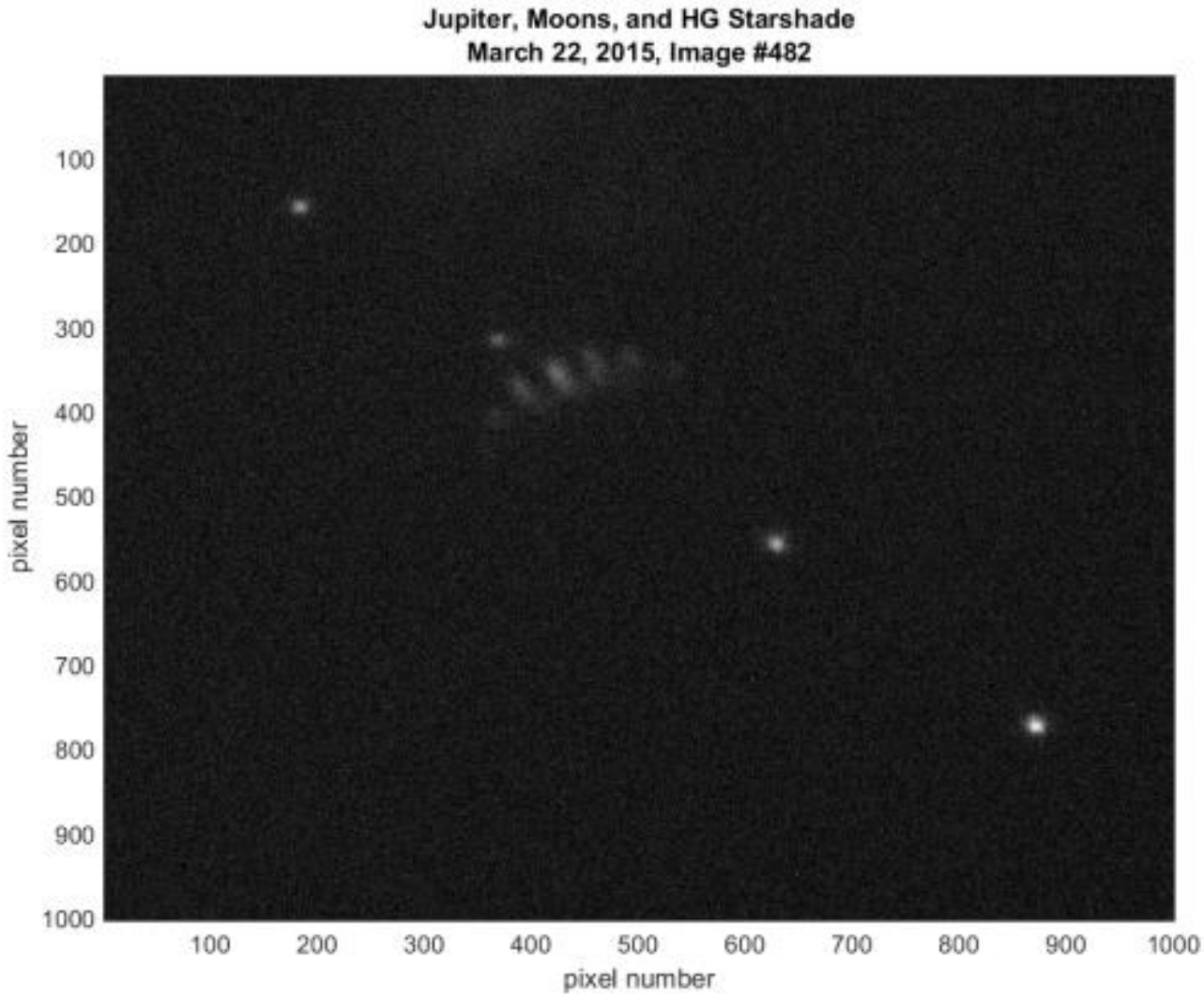
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade (4 of 11)



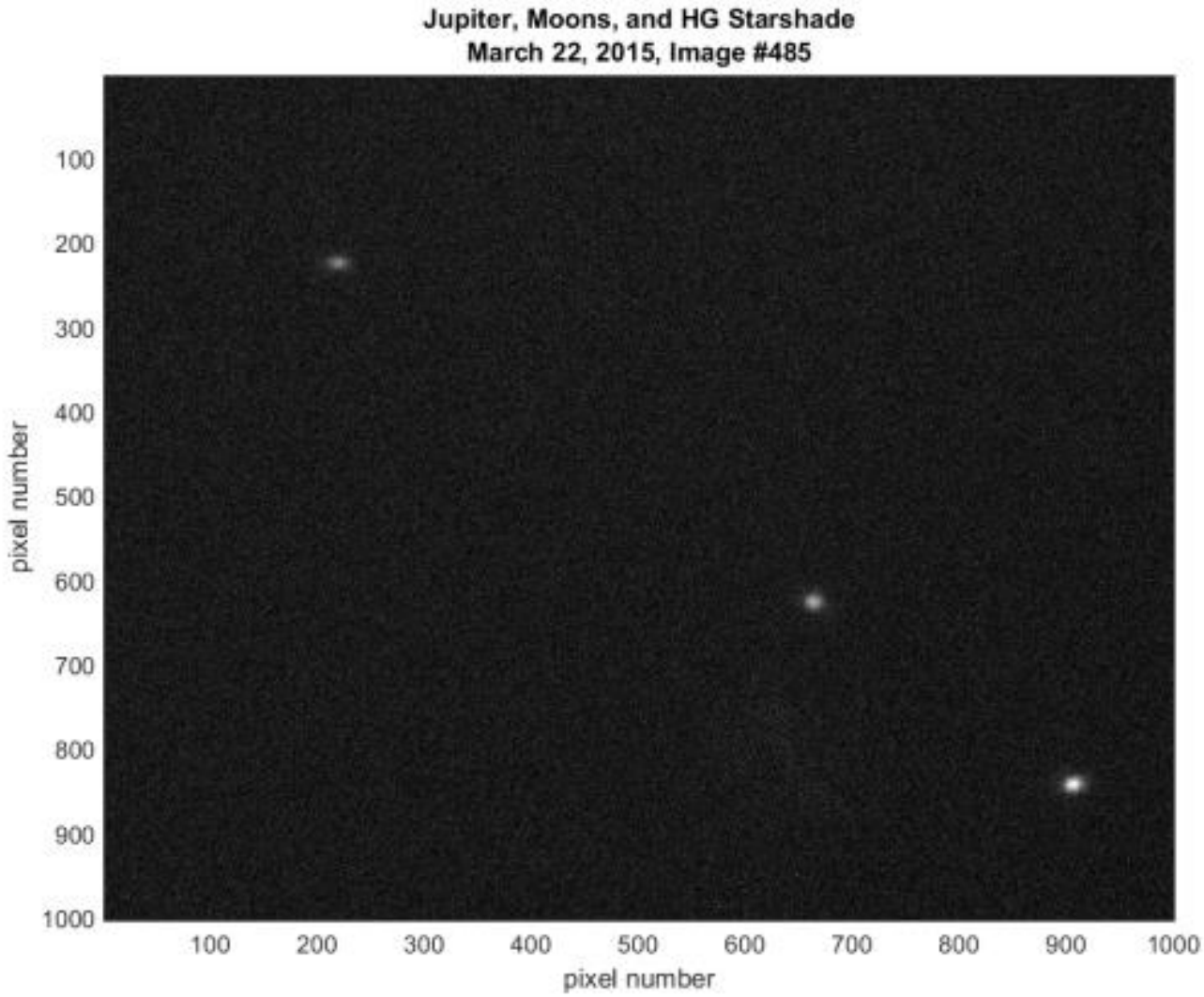
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade (5 of 11)



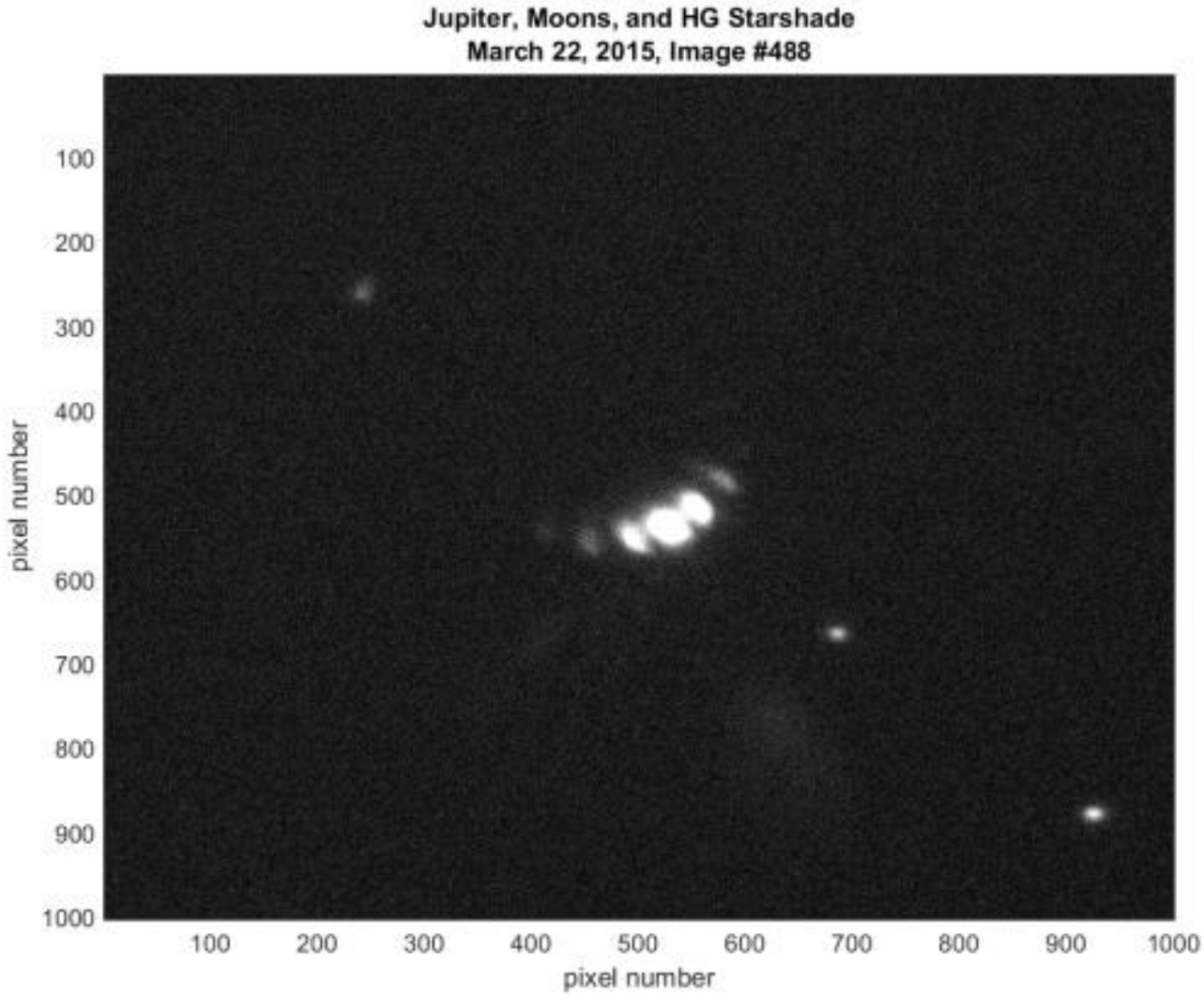
Apparent Jupiter motion controlled by Heliostat Slew Rate

Jupiter Transit of Hypergaussian Starshade (6 of 11)

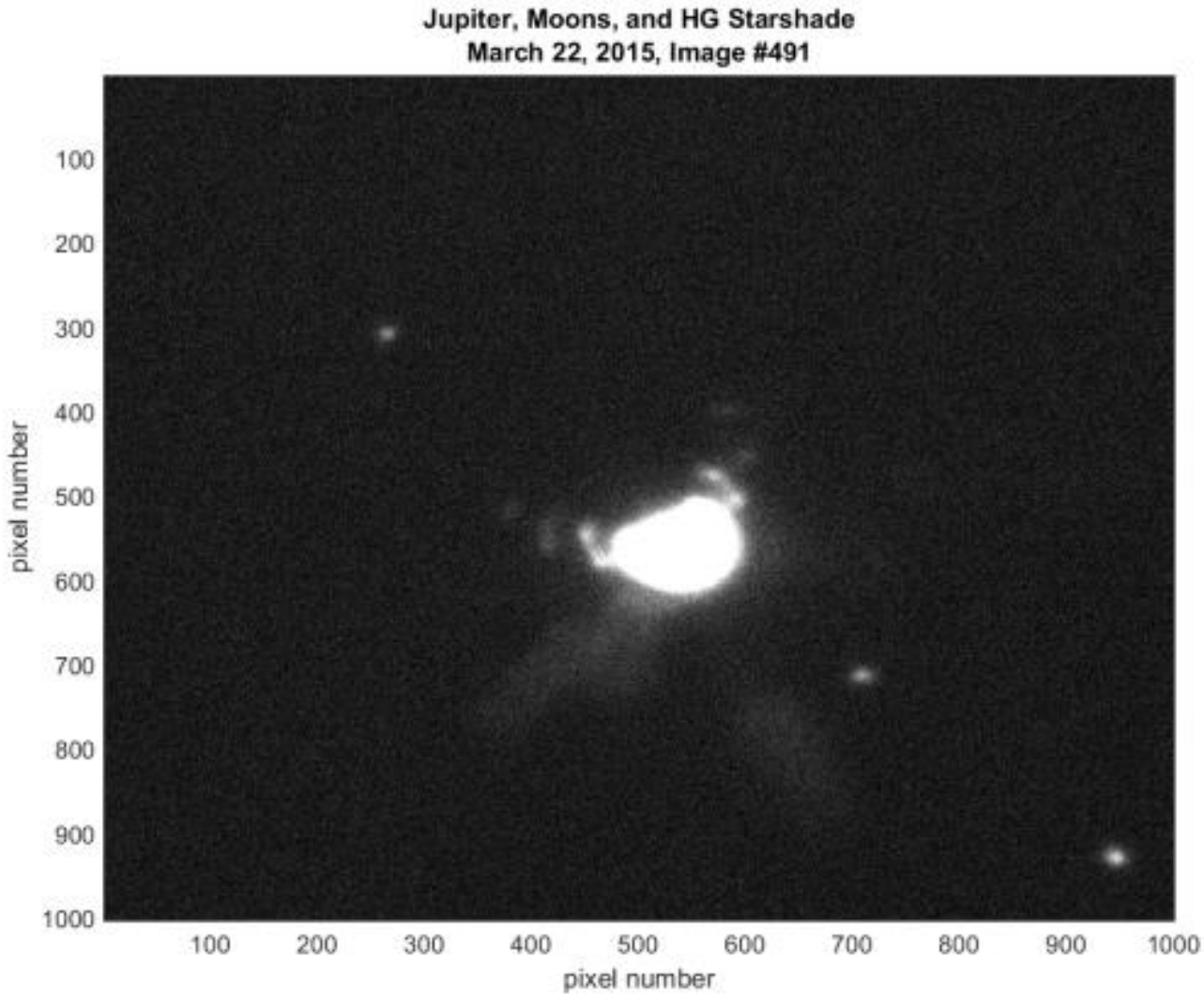


Apparent Jupiter motion controlled by Heliostat Slew Rate

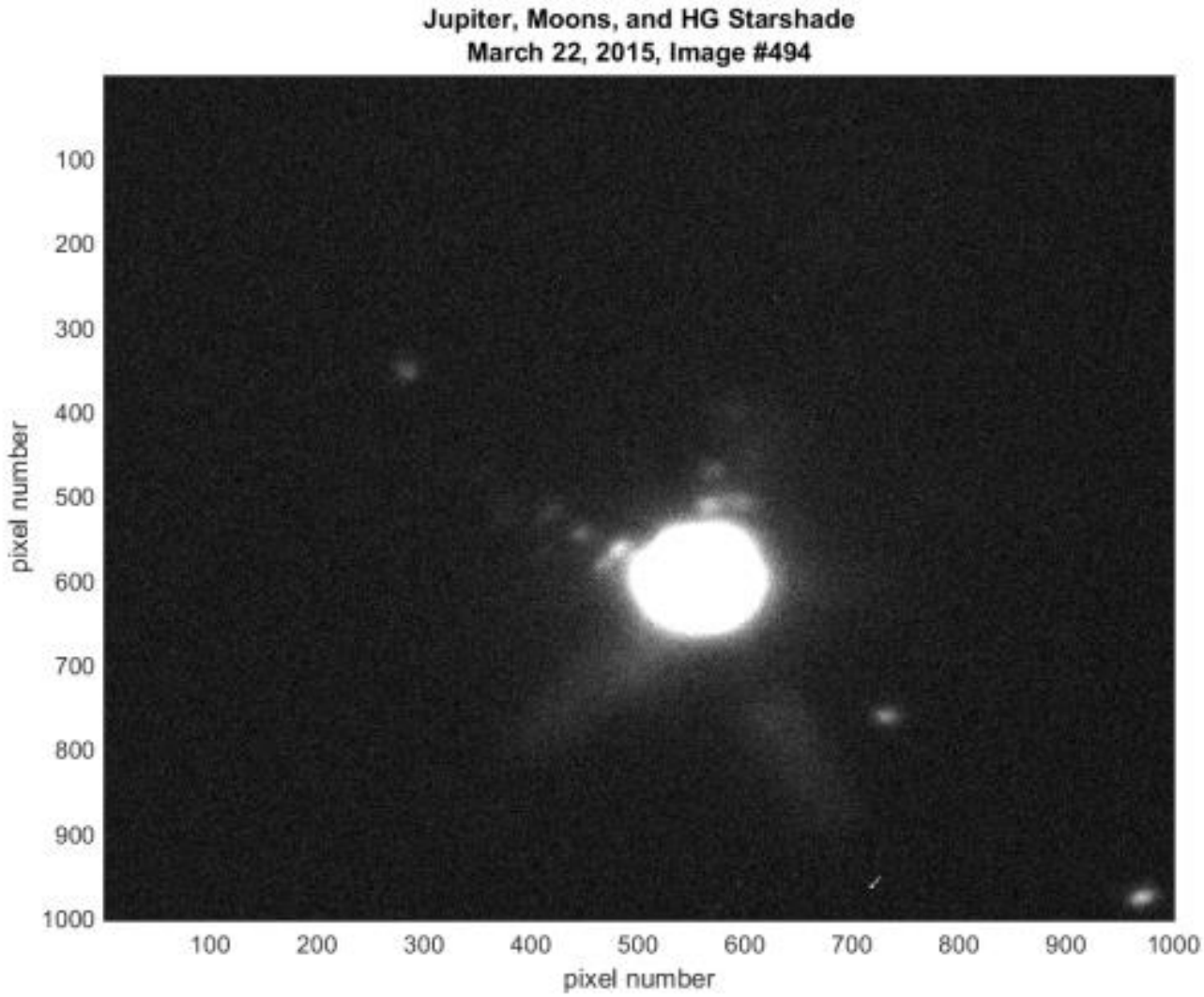
Jupiter Transit of Hypergaussian Starshade (7 of 11)



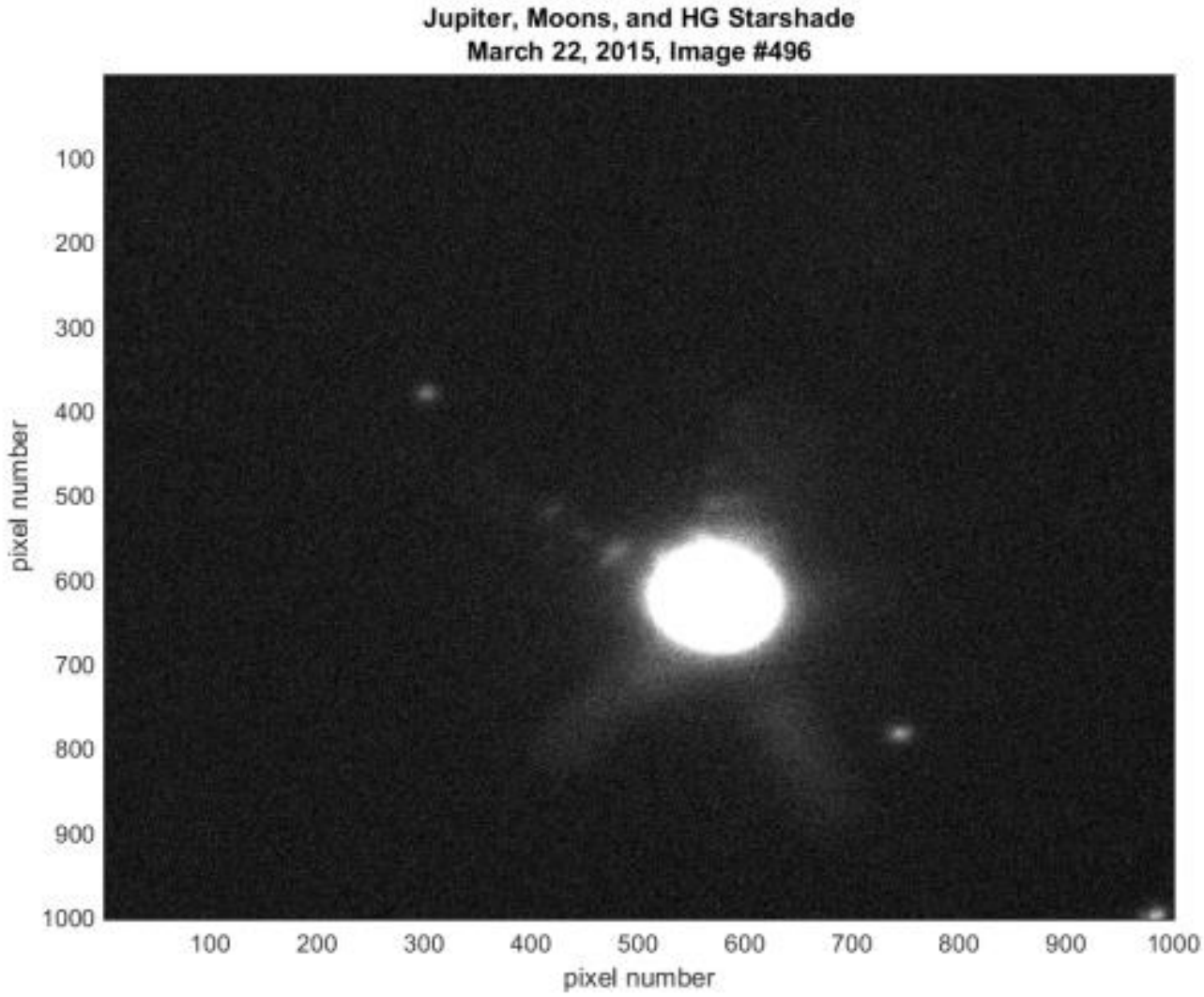
Jupiter Transit of Hypergaussian Starshade (8 of 11)



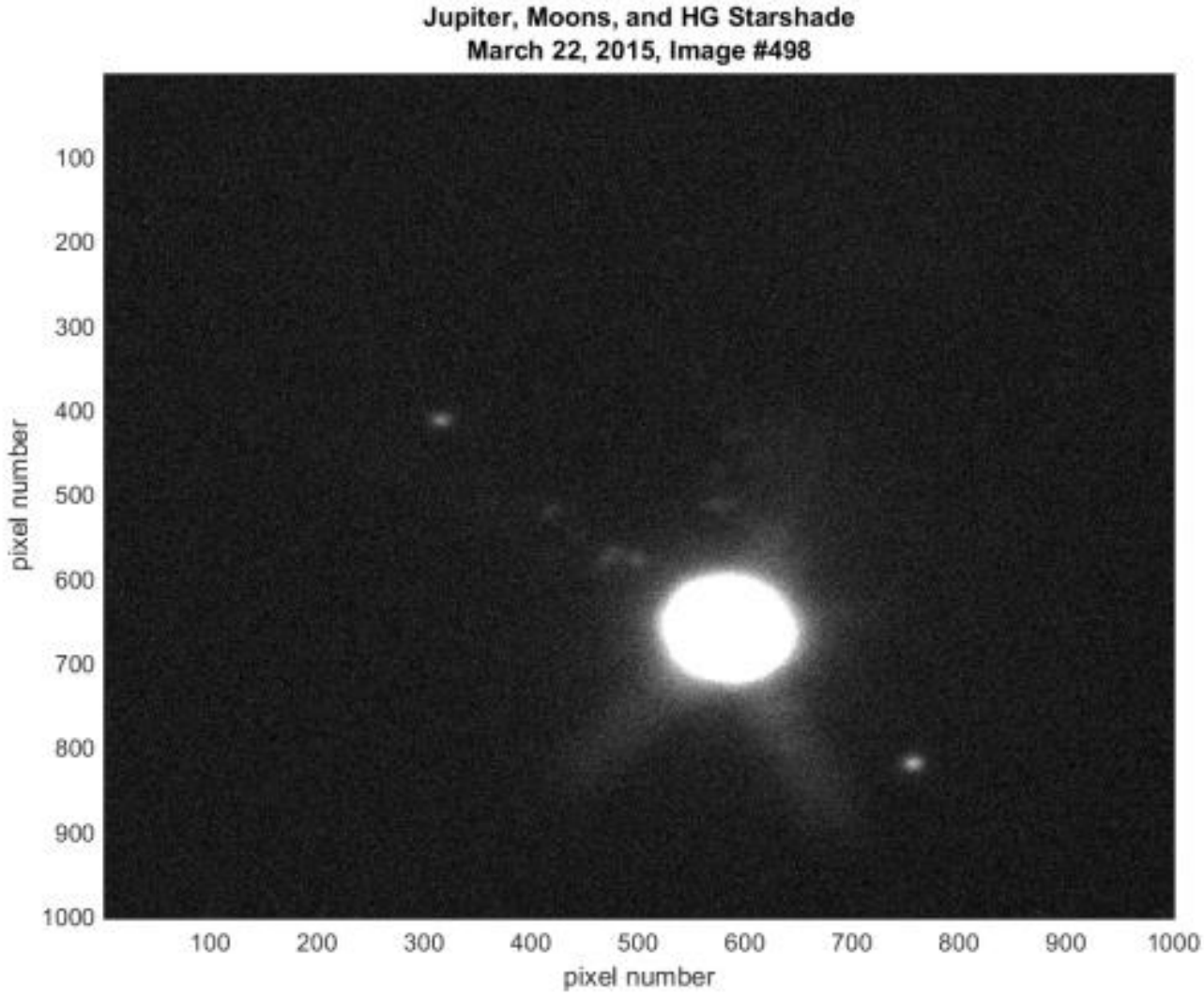
Jupiter Transit of Hypergaussian Starshade (9 of 11)



Jupiter Transit of Hypergaussian Starshade (10 of 11)



Jupiter Transit of Hypergaussian Starshade (11 of 11)



Physics of Starshade Shape Demonstrated on Jupiter using McMath Telescope

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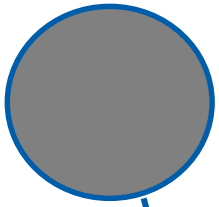
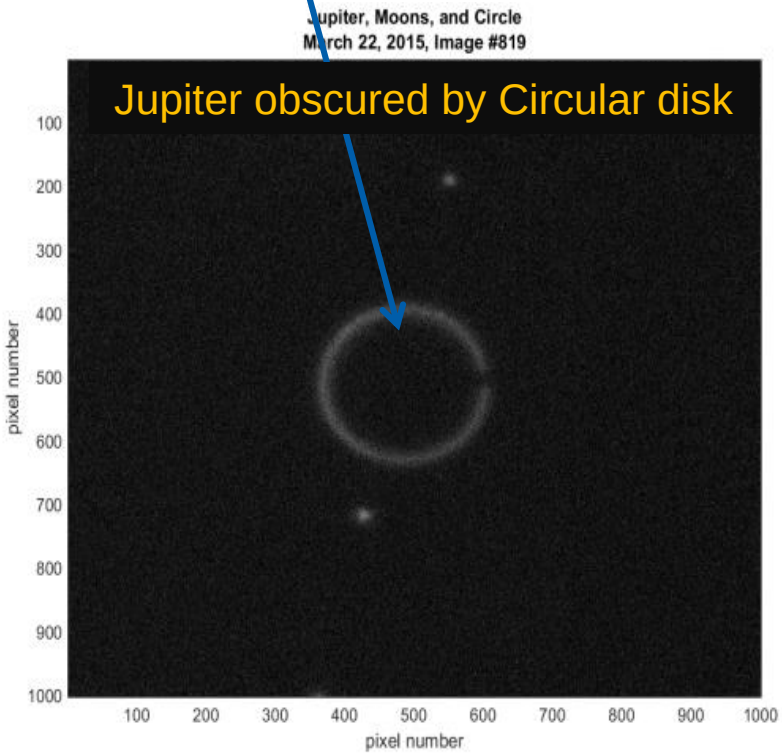
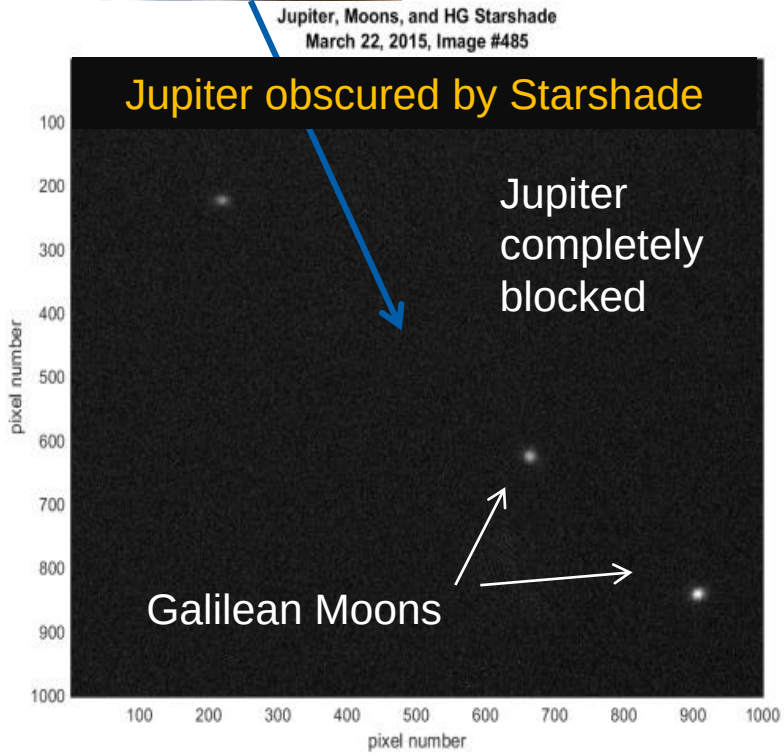


Circular Disk creates classic ring diffraction pattern of an obscured light source

Starshade Shape cancels bright diffraction ring





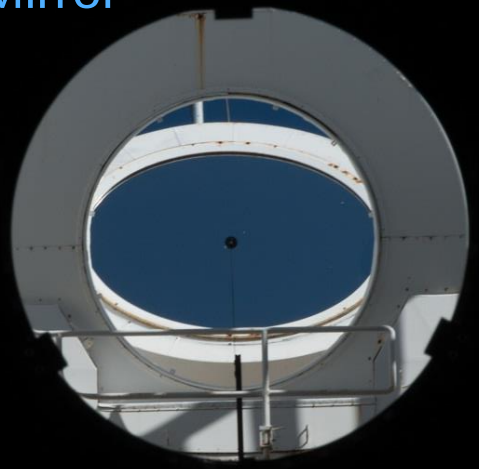
Physics-Defined proper shape cancels source light of object

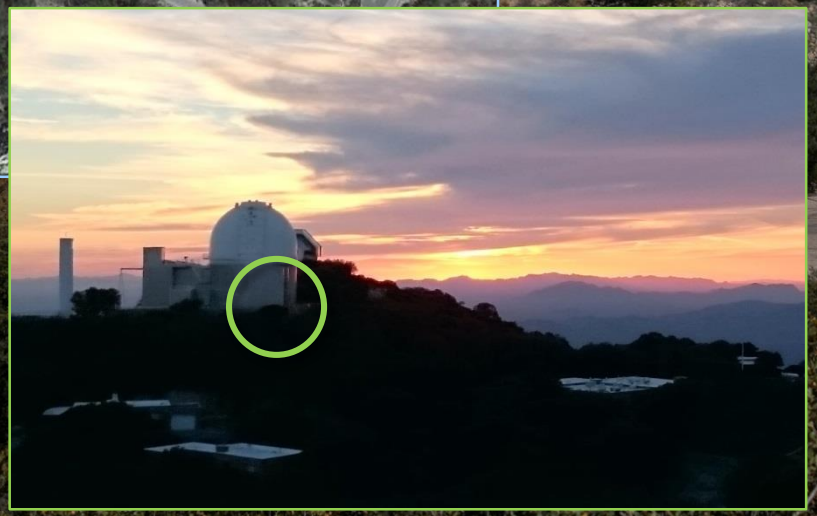
July Test

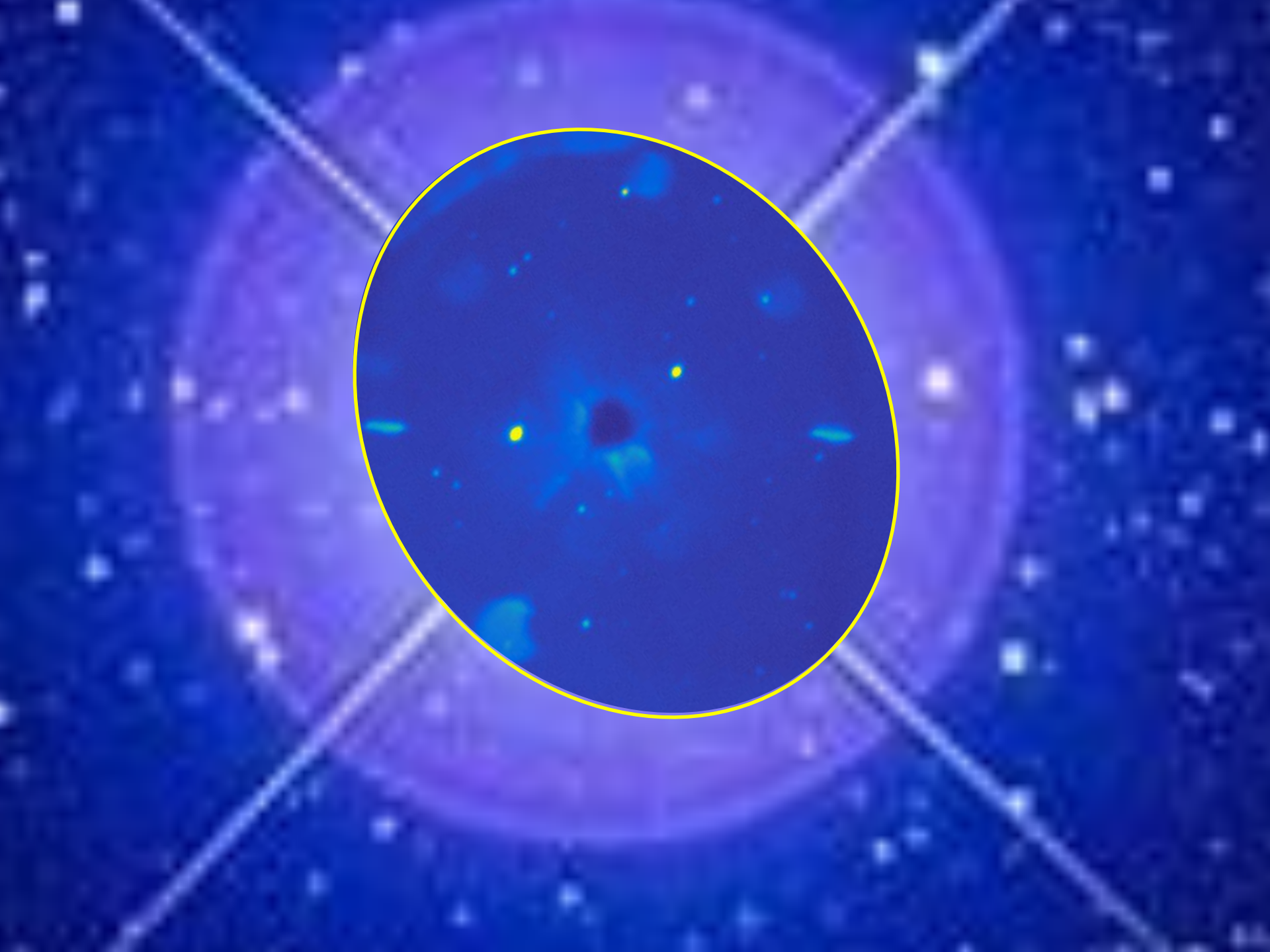
West Heliostat

Heliostat & 4” Starshade

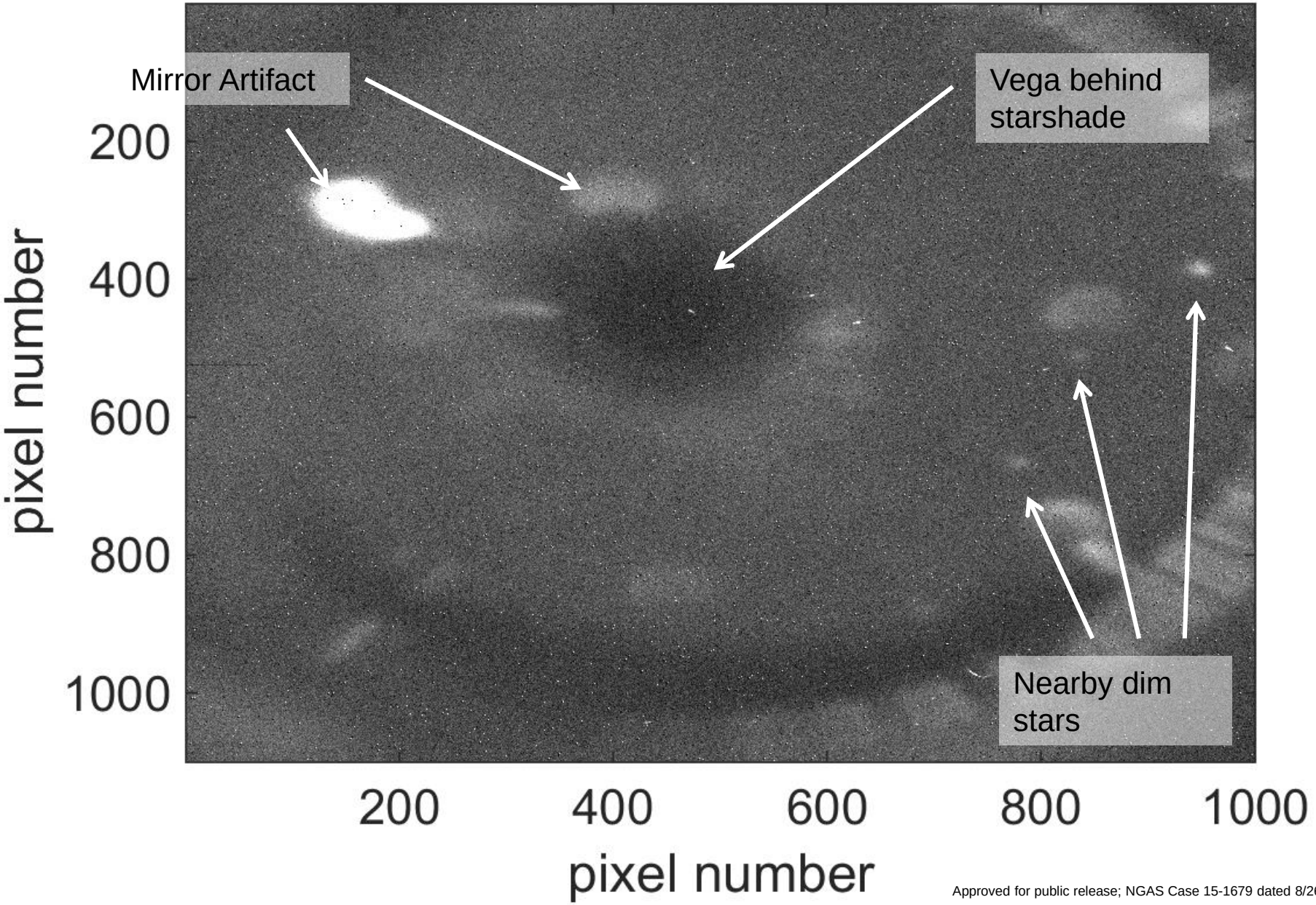
Integrated Light Field Mirror



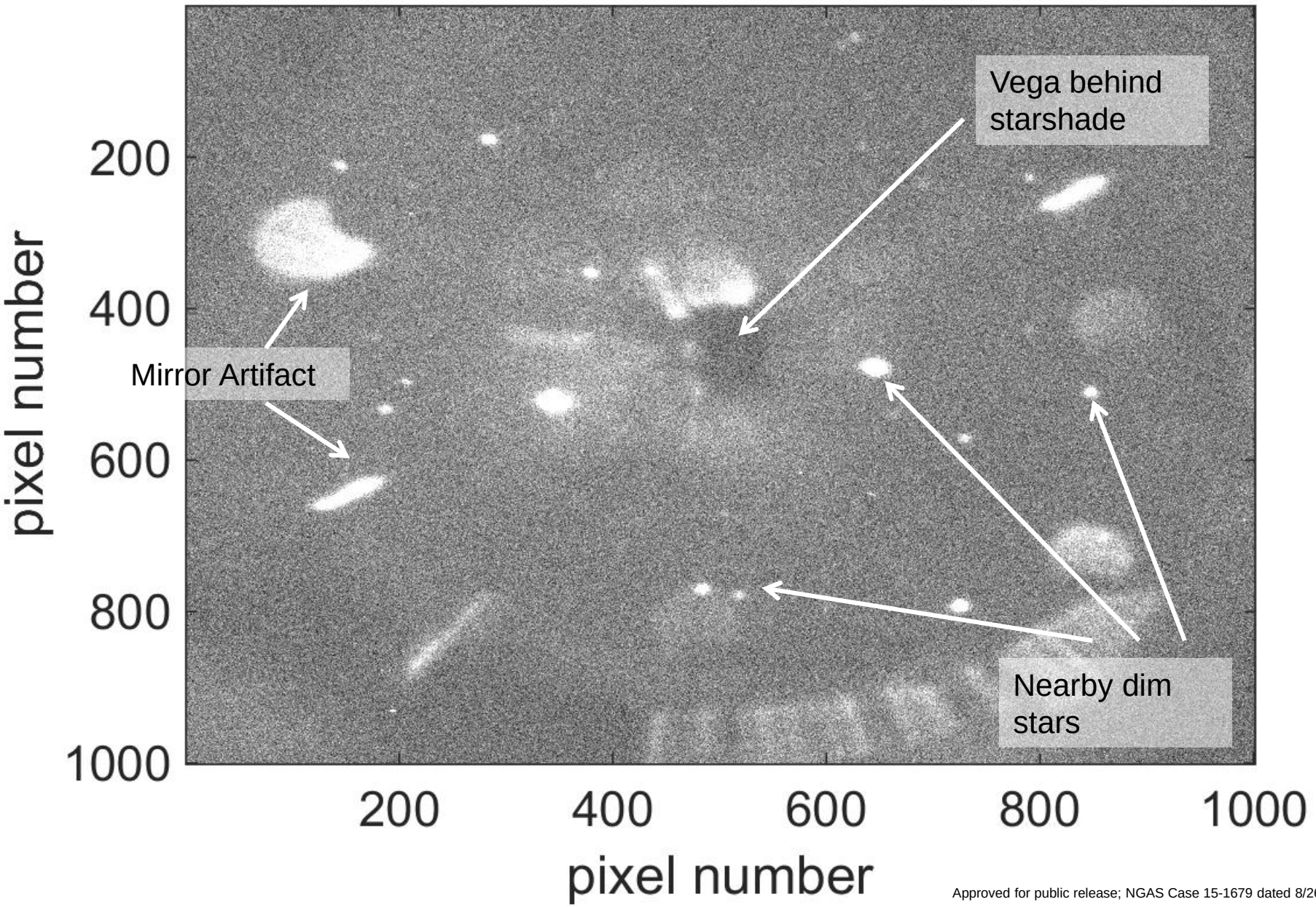




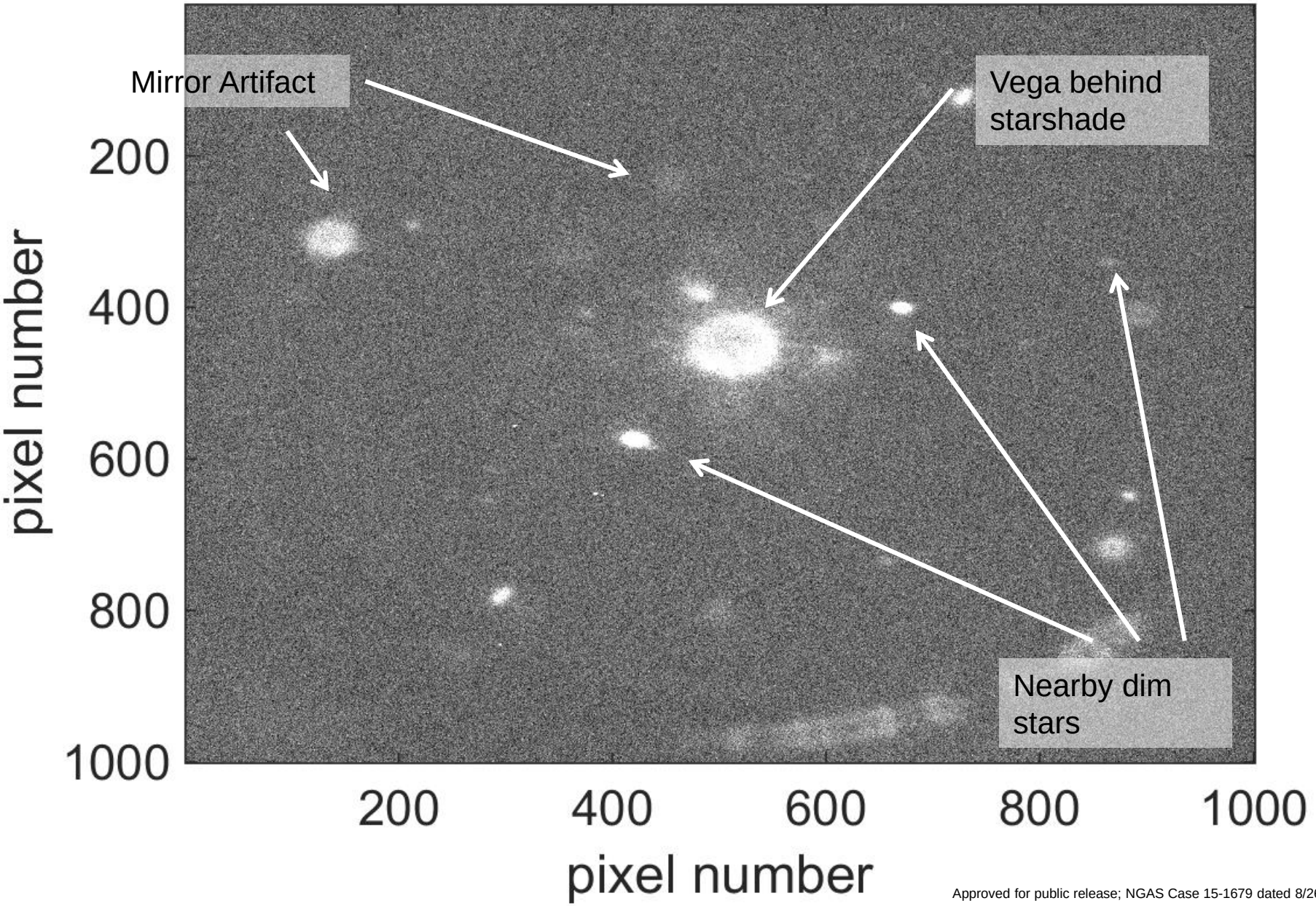
Vega with 12" HG Starshade: June 16, 2015
Image #165 (300 Seconds)



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



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



Comparison of tests

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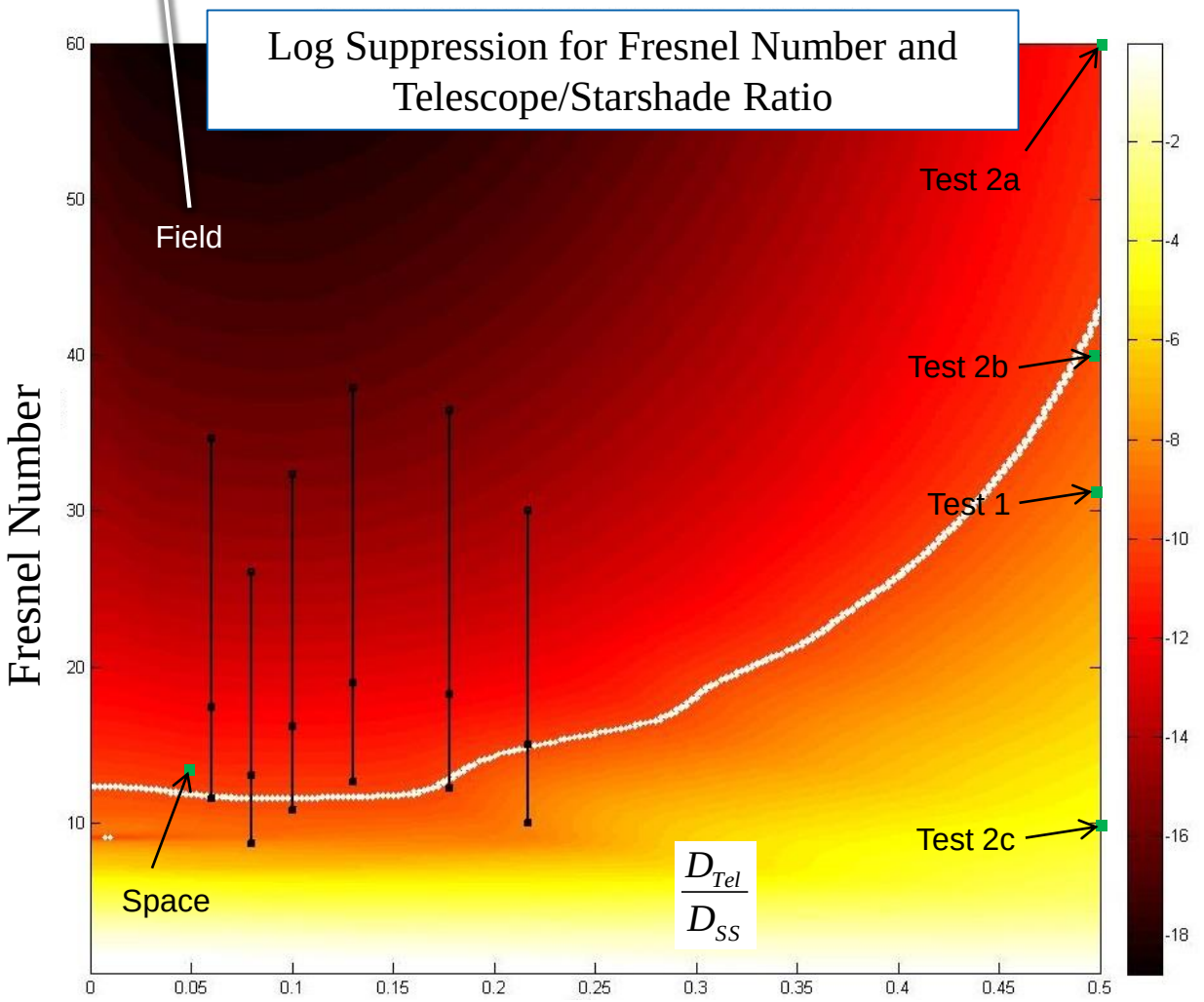
Test	Starshade to Telescope Separation	Starshade Diameter	Telescope Aperture	Resolution	Resolution Elements	Inner Working Angle	Fresnel Number
1	0.14km	0.10m	0.04m	3.8arcsec	31.1	59arcsec	32
2a	0.4km	0.29m	0.12m	1.5arcsec	82.7	62arcsec	87
2b	0.4km	0.20m	0.08m	1.9arcsec	43.2	41arcsec	42
2c	0.4km	0.10m	0.04m	3.8arcsec	11.1	21arcsec	10
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 ~50 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

NORTHROP GRUMMAN

- Field and McMath testing are complementary
  - Flat and diverging beam
  - Very bright and not so bright
- Currently ongoing McMath test at longer baseline ***may*** be able to image astronomical bodies with IWA of 12 arcsecond
  - ***Our first target is the Fomalhaut disk***

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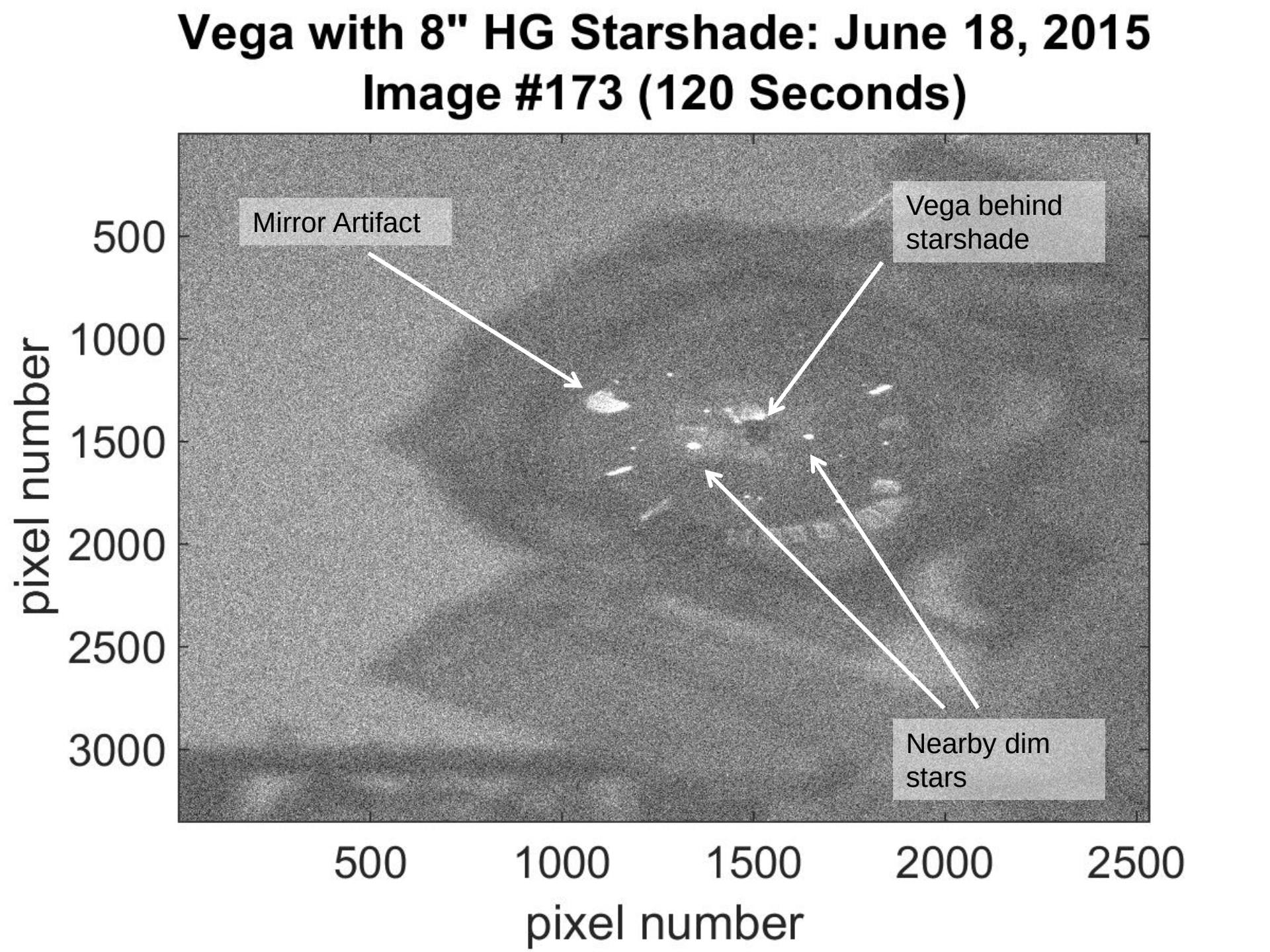
Vega with 8" HG Starshade: June 18, 2015
Image #173 (120 Seconds)
Mirror Artifact
Vega behind starshade
Nearby dim stars
pixel number
500
1000
1500
2000
2500
3000
pixel number
500
1000
1500
2000
2500

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