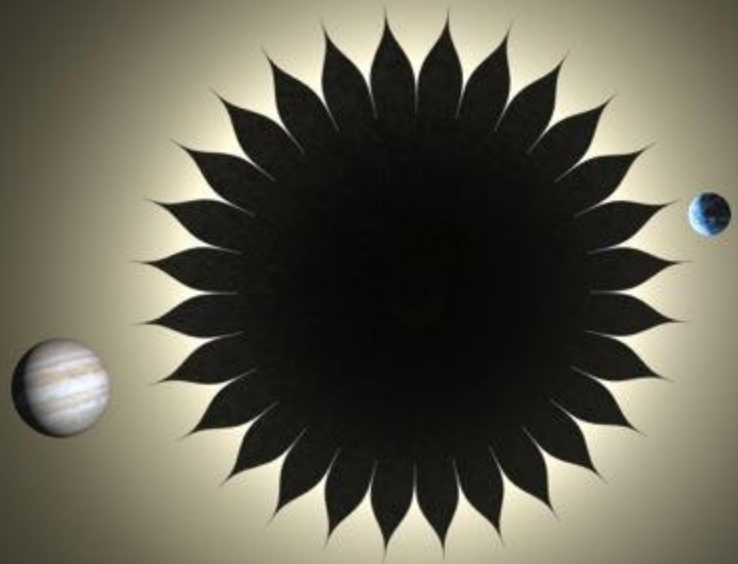
Jet Propulsion Laboratory
California Institute of Technology



Starshade Technology Status

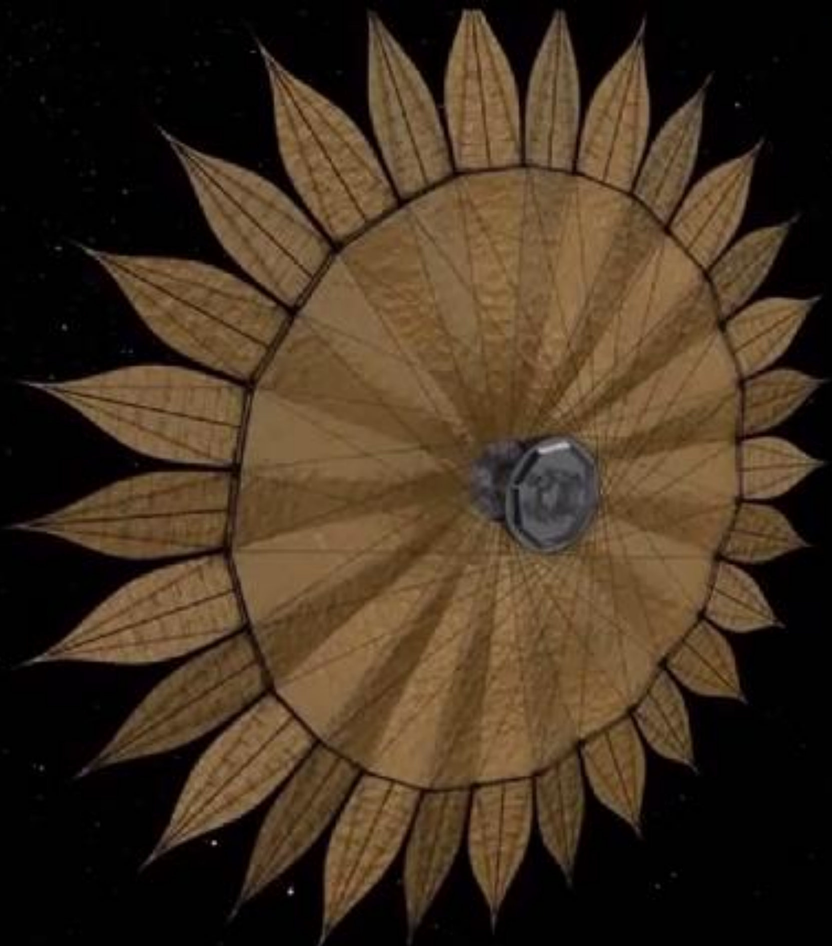
Stuart Shaklan and Nick Siegler
NASA Exoplanet Exploration Program

November 3, 2016

Acknowledgements
Inputs to this presentation came from:

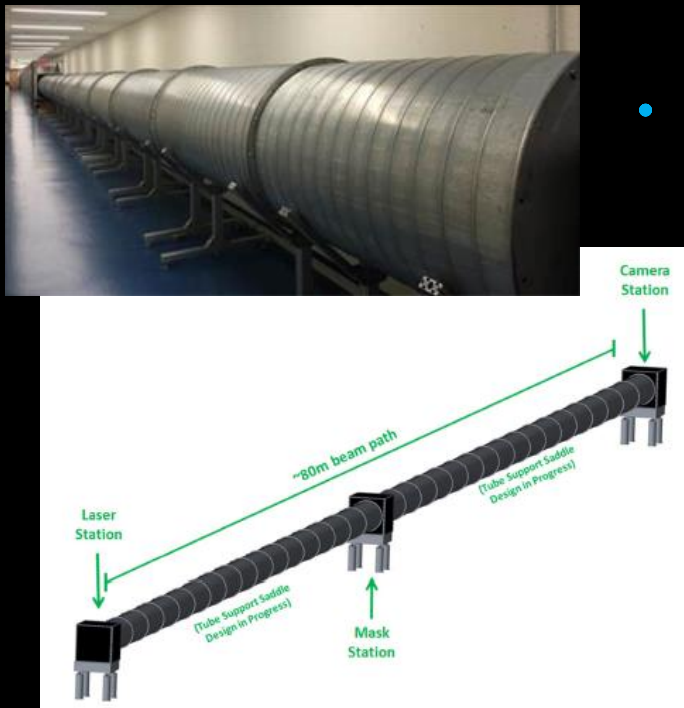
- David Webb– mechanical structures
- Stefan Martin, Will Ames, Dylan McKeithen – optical edges
- Shannon Zareh – formation flying experiment
- Anthony Harness – McMath testing, laboratory modeling
- K. Balasubramanian, J. Metzman – starshade masks and characterization
- Megan Novicki, Steve Warwick – starshade modeling

Starshade Technology Development Areas



1. Contrast performance demonstrations and optical model validation
2. Controlling edge-scattered sunlight
3. Lateral formation-flying sensing accuracy
4. Flight-like petal fabrication
5. Inner disk deployment
6. Petal latching and unfurling

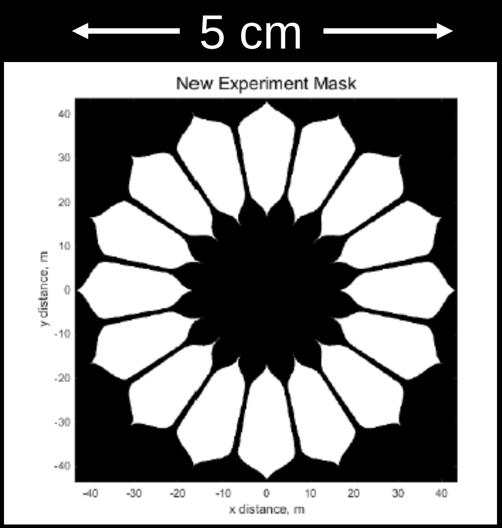
Current Optical Performance Activities

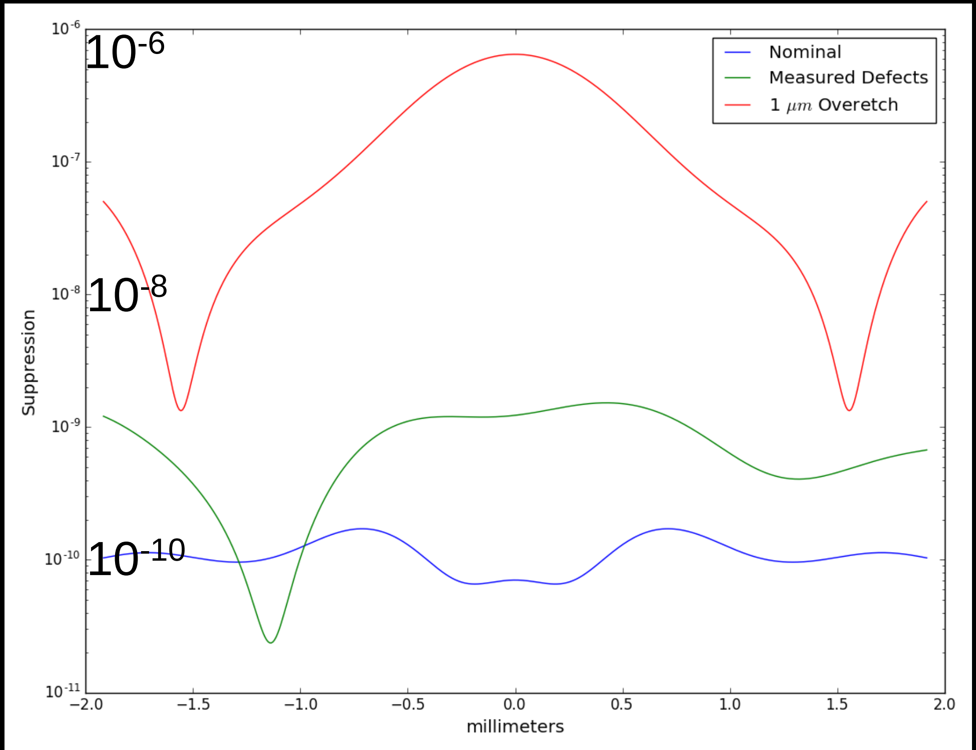


- Status
  - *~77m baseline with 44 mm mask (Princeton and JPL TDEM)*
    - *Testbed completed*
    - *Starshade mask, 50 mm, fabricated*
    - *Testing underway*
    - *Modeling*
  - *Testing over 3-4 km on a dry lakebed (NGAS)*
  - *Testing at Kitt Peak McMath Telescope (Harness and NGAS)*

Diffraction Laboratory Testing at Princeton

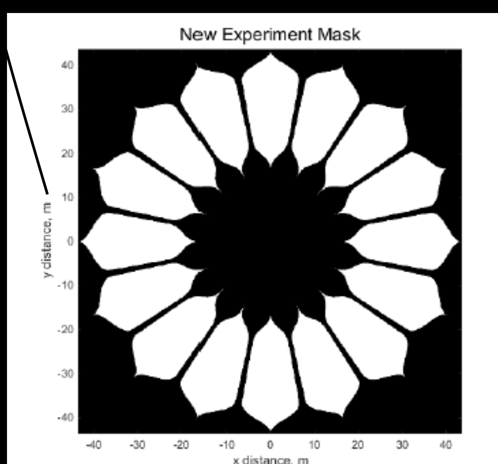
- Flight-like geometry: Fresnel # ~ 14
  - Diffraction equations as in flight
  - But 'outer' starshade needed to control diffraction and reflection interaction with the tube.
- Small scale challenge:
  - Sensitive to microscopic defects that are not important in the flight model
  - Model of 1 um overetch around the petals shows suppression approaches 5e-7 over pupil.
- First high-contrast results this year.

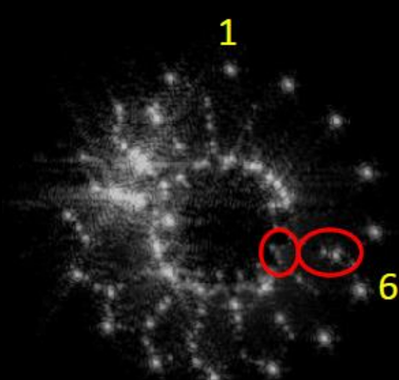


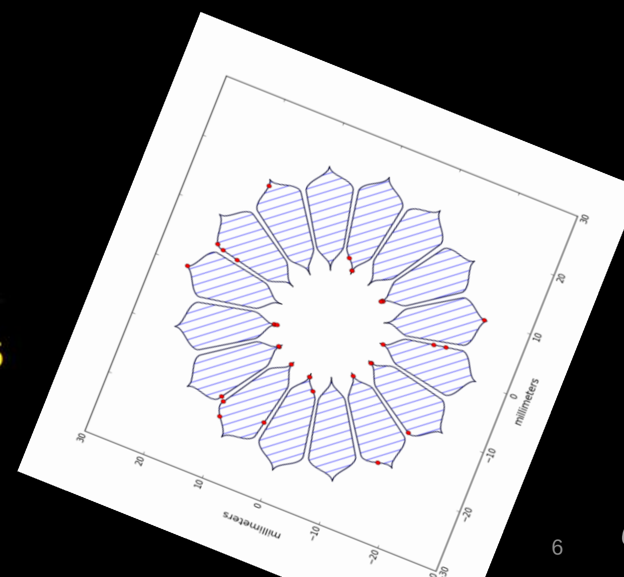


Princeton Starshade Tests

- Goal is to observe 1e-9 suppression – consistent with flight requirements and about 3 orders of magnitude deeper than previous tests.







6

NGAS Field Testing 2014/15

THE VALUE OF PERFORMANCE.
NORTHROP GRUMMAN

NASA JPL /
Northrop Grumman
100th Scale
Starshade

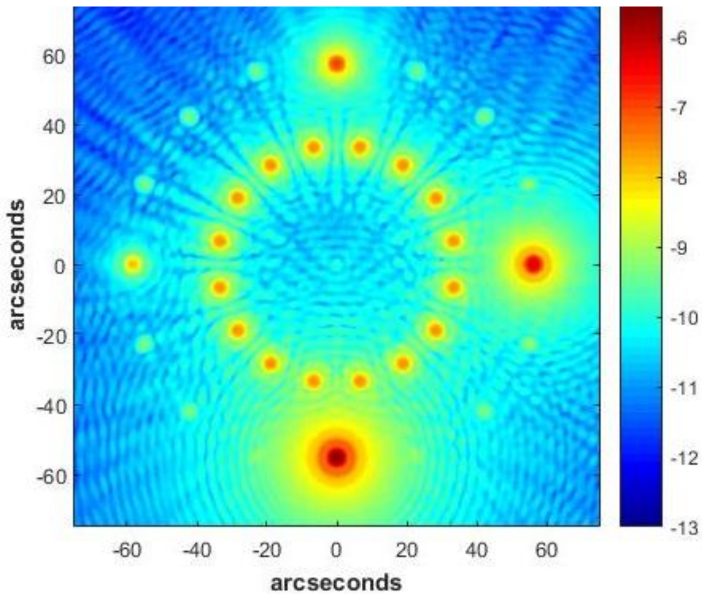
Approved for public release; NGAS Case 15-2567 dated 12/21/15.

Evaluating the Diffraction Integral
Model Comparison: Princeton, JPL, CU, NGAS

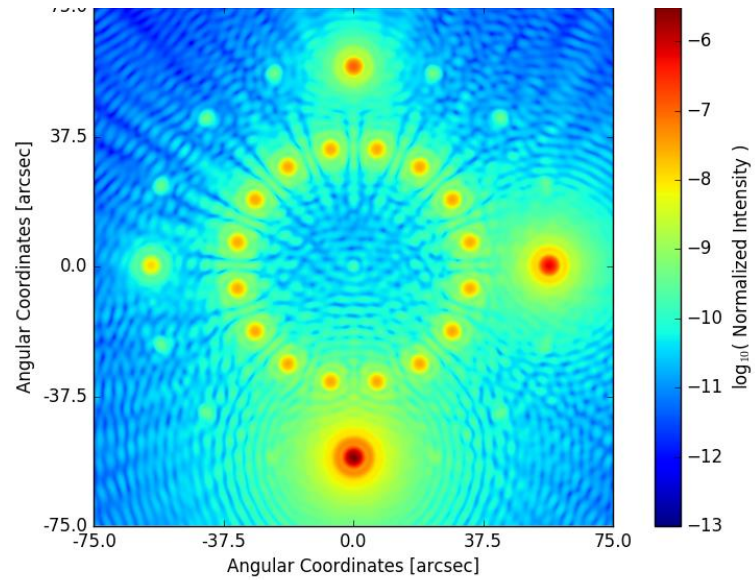
- Each group takes a different approach to evaluating the diffraction integral:
  - Princeton integrates over two dimensions using a gray pixel approximation
  - JPL applies Stokes' theorem to solve the double integral as a single integral over the boundary of the starshade
  - CU uses the Dubra-Ferrari 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
- **After initially seeing > factor of 10 difference in predictions, mainly due to non-physics issues, groups are now consistent to a few percent.**

Flawed Starshade – Tip Truncation

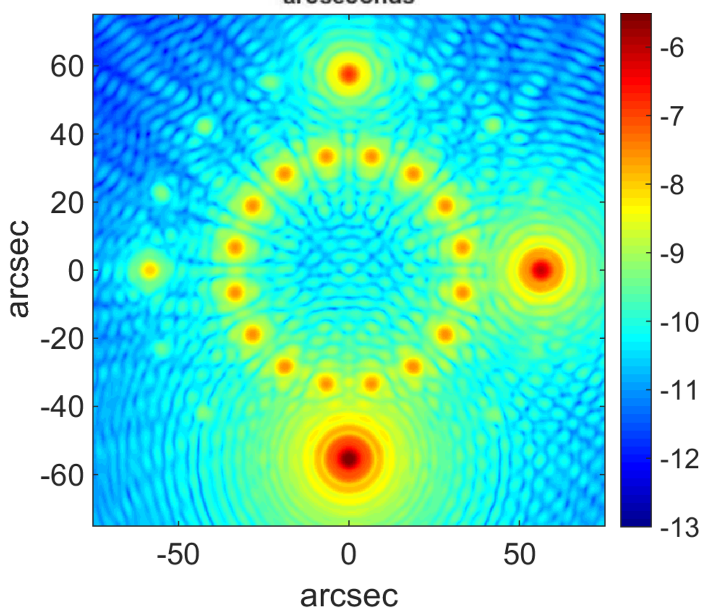
JPL



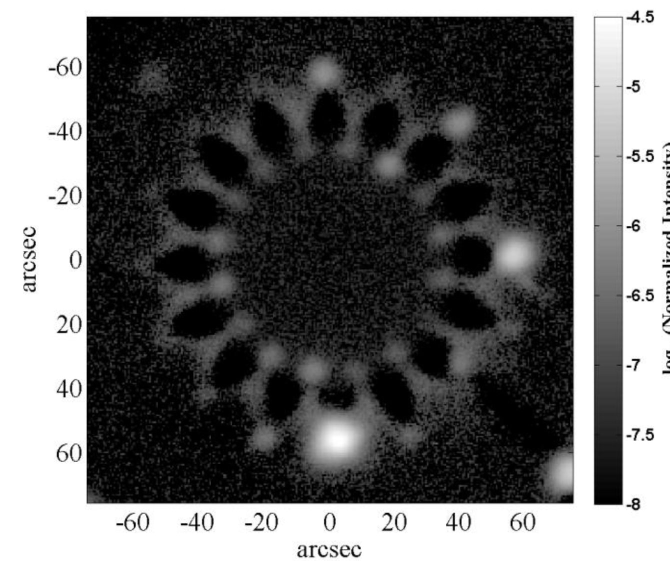
CU



NGAS



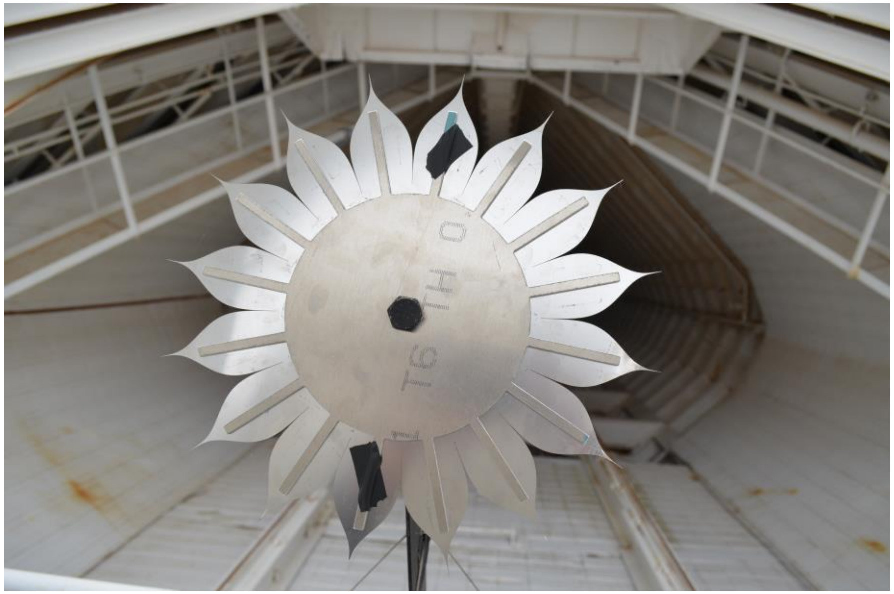
Field Test

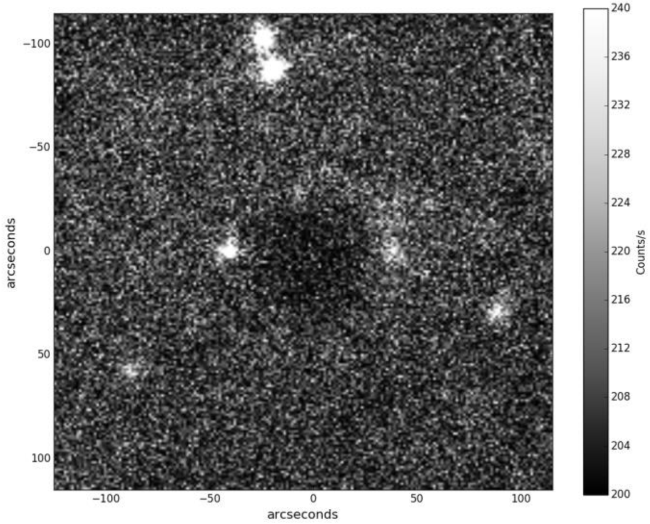


Starshade Testing at McMath Solar Telescope

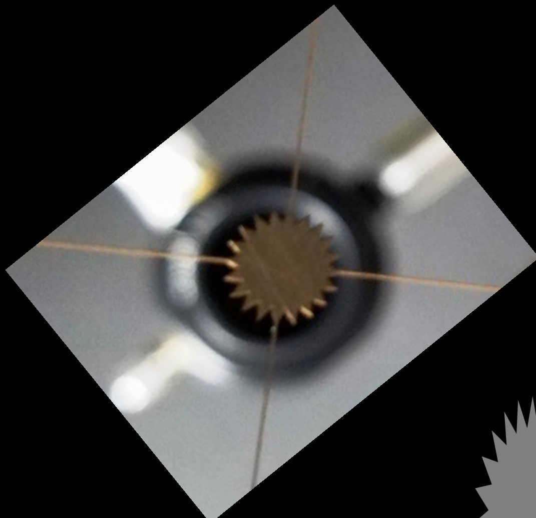
NORTHROP GRUMMAN

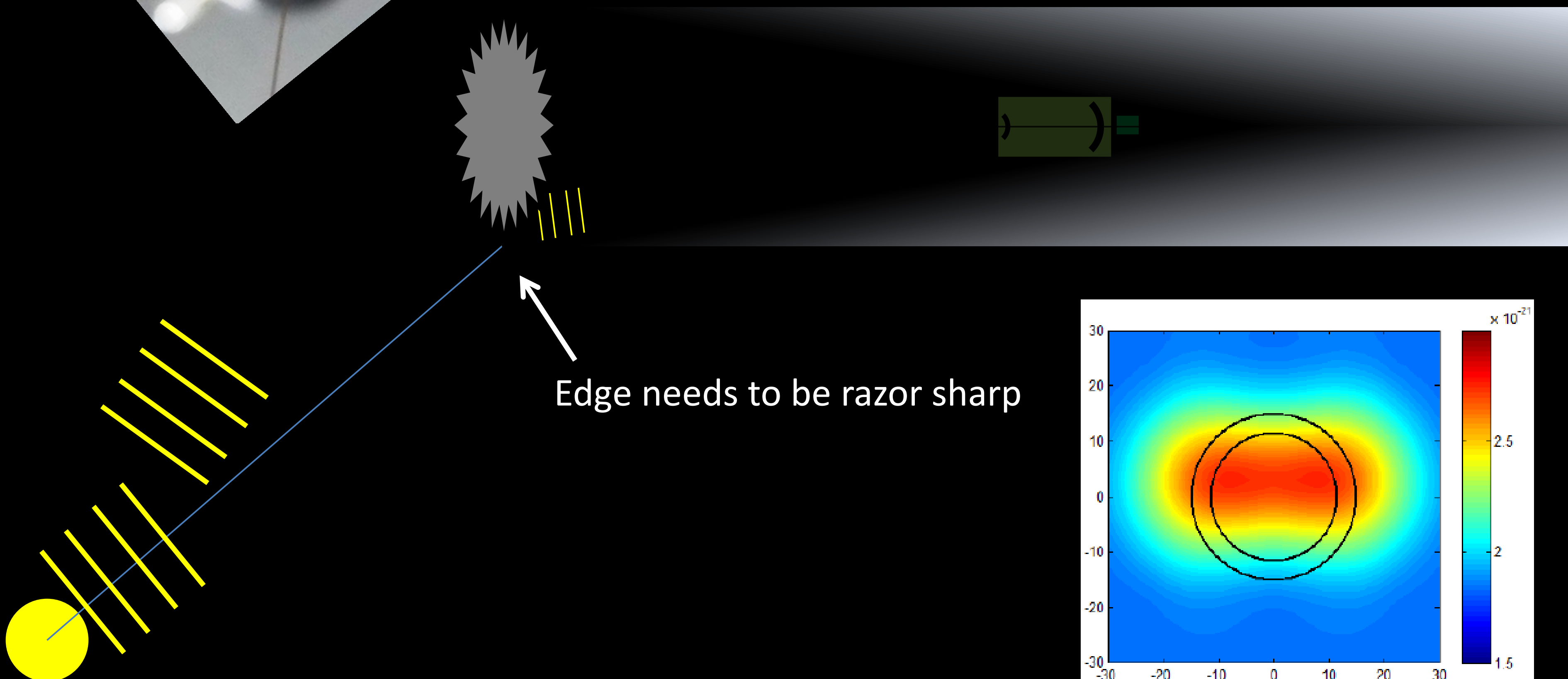
A . Harness, speaking in this session.





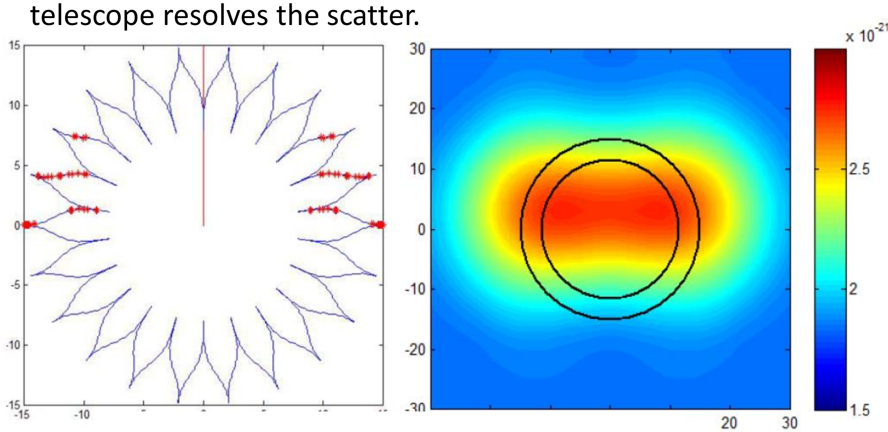
Solar Glint



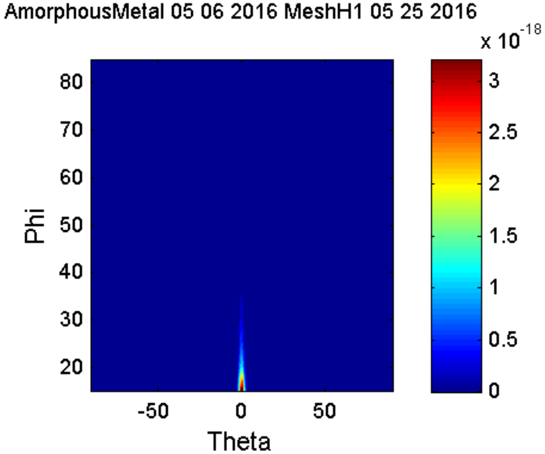

Edge needs to be razor sharp
x 10^-21
30
20
10
0
-10
-20
-30
-30 -20 -10 0 10 20 30
2.5
2
1.5

Serrated edge "hides" from the Sun

Sun is above and behind plane. Reader is at the telescope position. Red marks show straight segments with specular component to telescope. Intensity pattern is how telescope resolves the scatter.

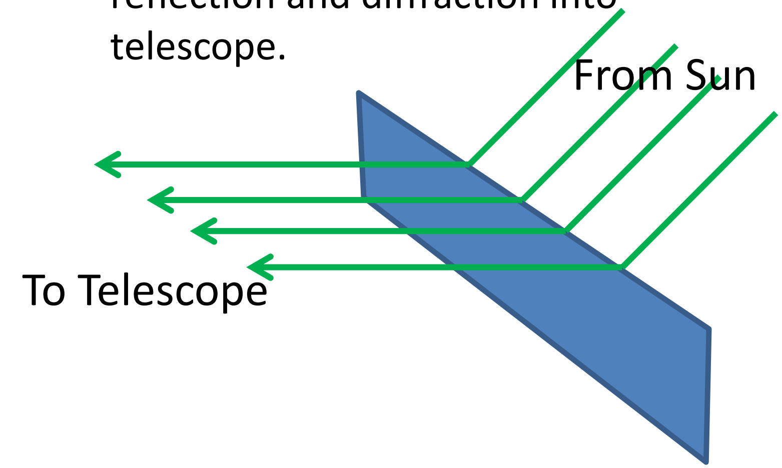


Scatter into telescope (W/m/m^2) for AmorphousMetal 05 06 2016 MeshH1 05 25 2016

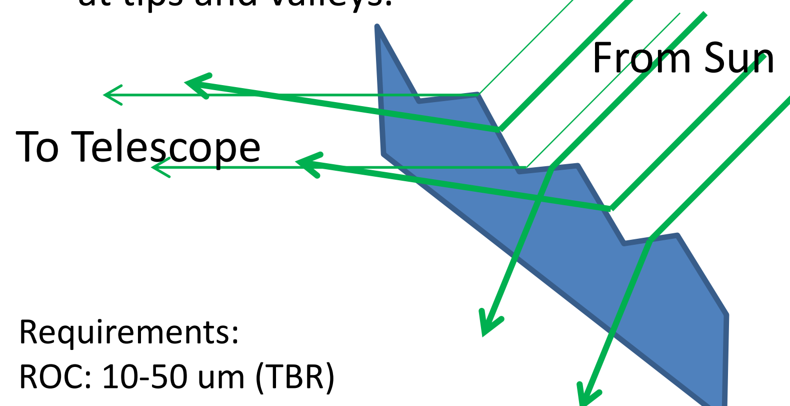


Measured scatter from an etched metallic edge shows that the edge is strongly specular with scatter contained within a few degrees of normal. This sets a requirement of several degrees on the serration angle and the starshade orientation angle. Scatter from tips and valleys of the edge will be reduce by > 1 order of magnitude compared to the straight edge.

Straight edge segment: specular reflection and diffraction into telescope.



Serrated edge: no specular component except minor area at tips and valleys.

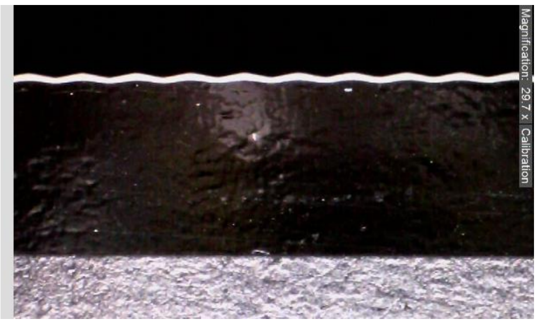


Requirements:
ROC: 10-50 um (TBR)
Specularity: FWHM < 5 deg (TBR)
Reflectivity: < 80% (TBR)
Serration angle: 10-30 deg (TBR)
Serration period: 1-10 mm (TBR)

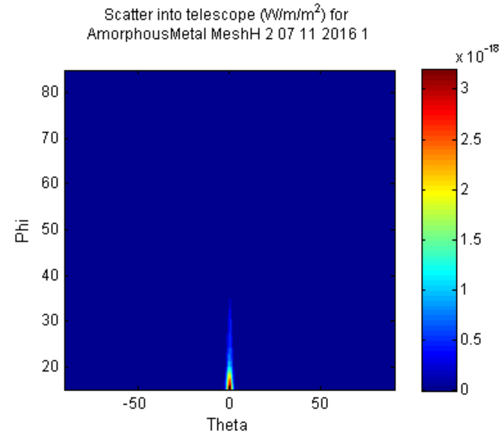
Starshade Optical Edges

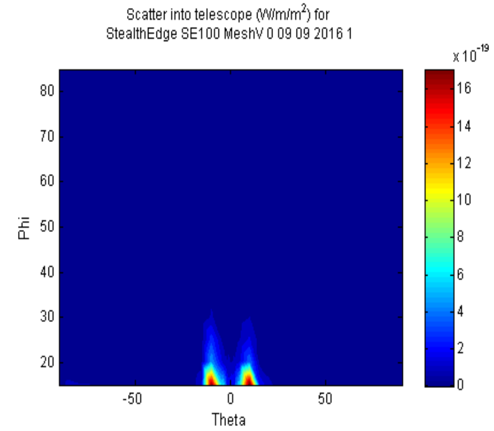
- New idea: “Stealth Edges”
- Using specular edges, introduce high frequency ripple that diffracts sunlight away from the telescope. It won’t affect diffraction of starlight.

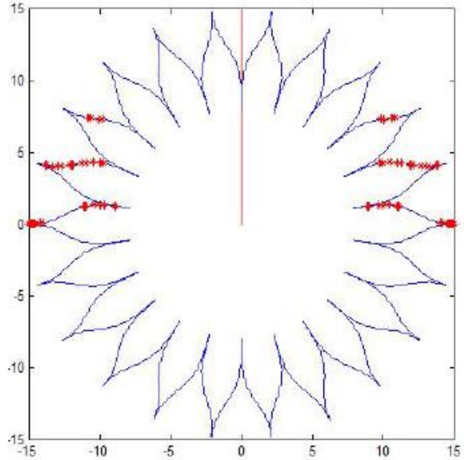
100 um amplitude, 1 mm period

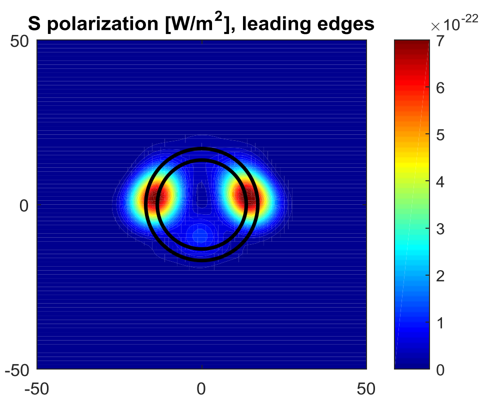


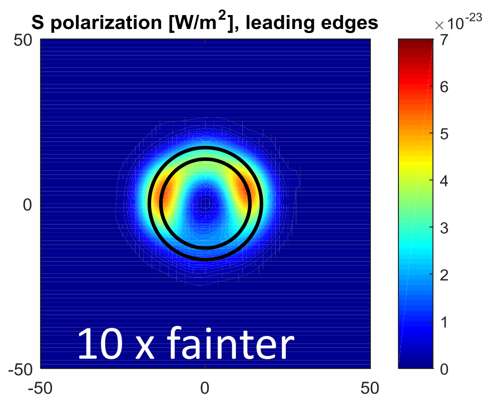
Etched amorphous metal.
Edge RoC ~ 1 μm





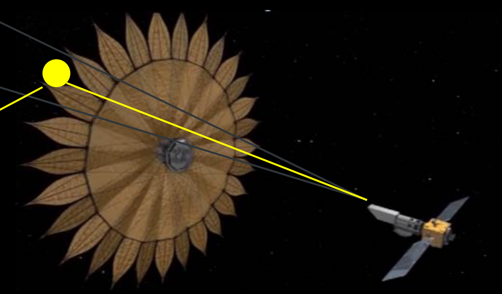






Keep the Edges Clean!

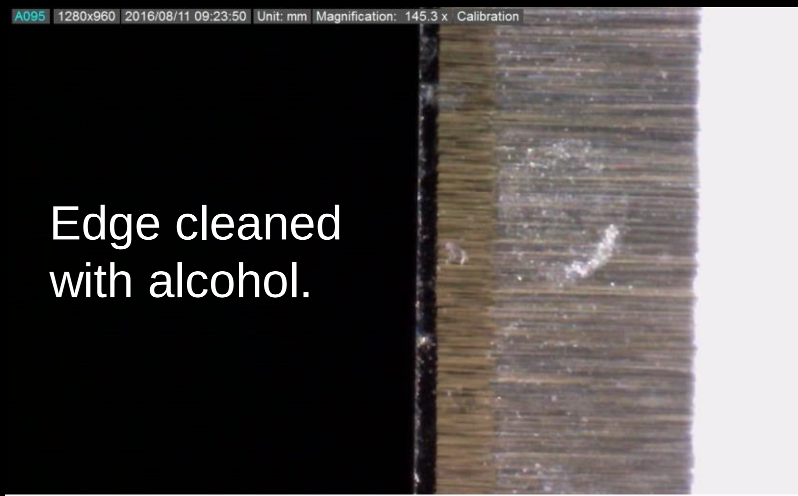
An Earth-size planet at 10 parsecs projects as a 1 mm diameter particle on the edge of the starshade.

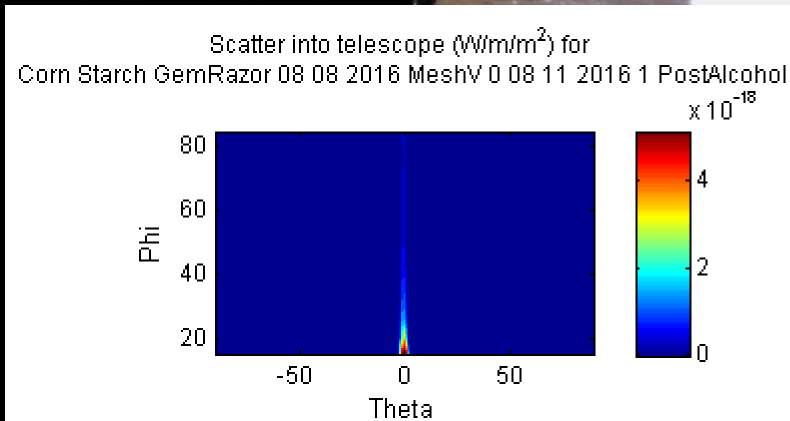


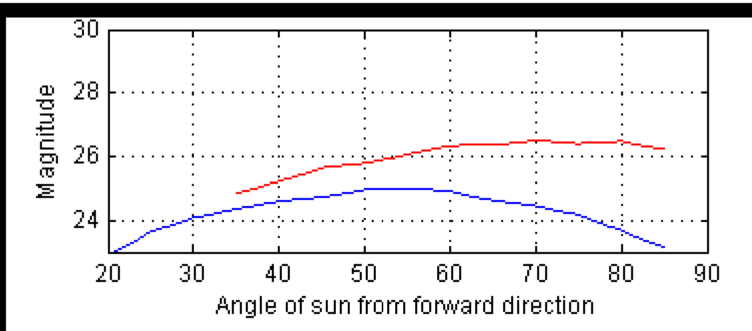
Equivalent to 10,000 particles of dust 10 um in diameter, spread over about 40 m of the starhade edge.
Will it accumulate on the edges?

Scatter from Contamination

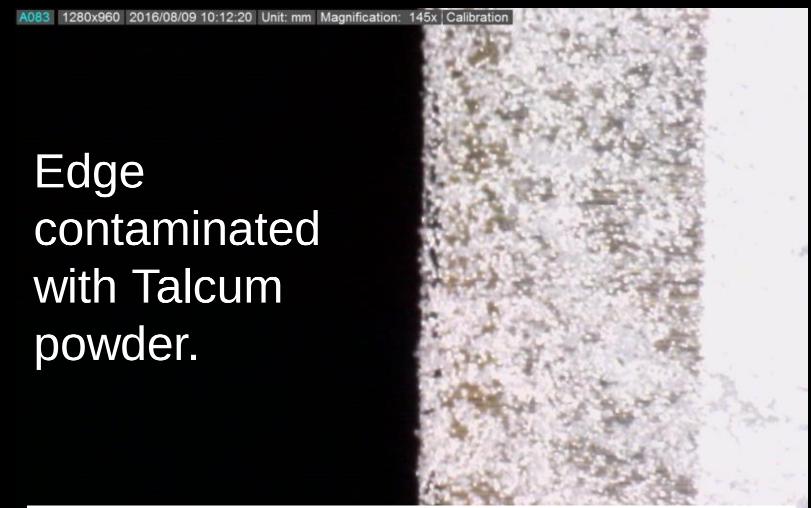
Edge cleaned with alcohol.

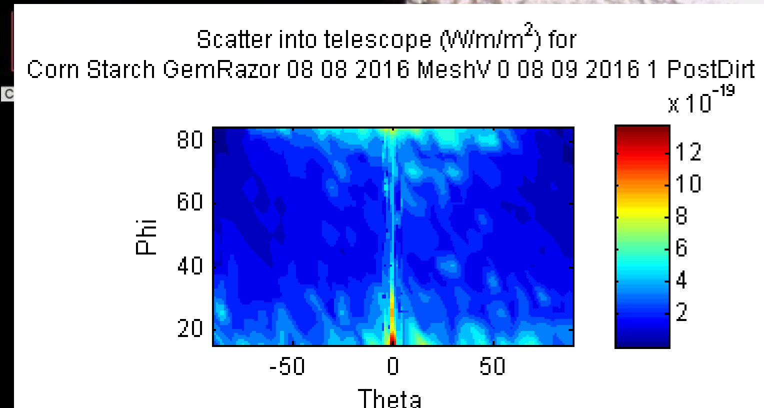


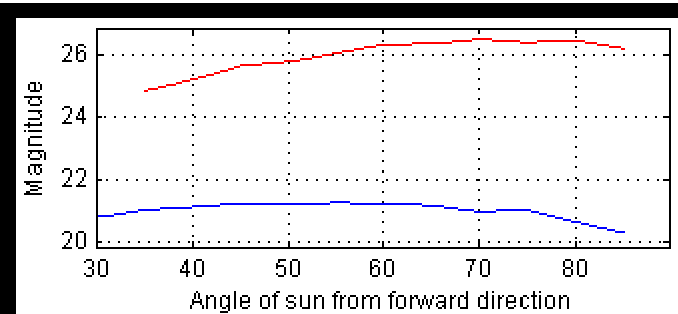




Edge contaminated with Talcum powder.







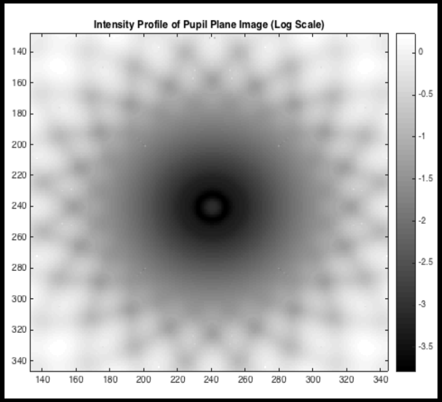
Formation Flying Sensing Accuracy Activities

Status

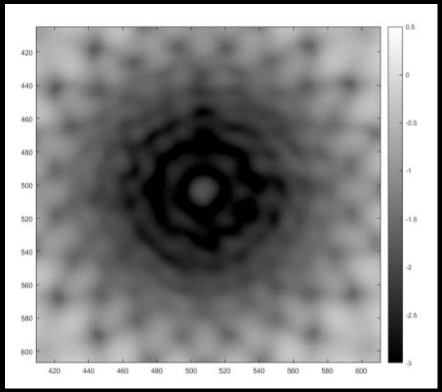
- Developed an approach to use WFIRST LOWFS for formation sensing.
- Completed detailed modeling of the sensor.
- Demonstrated pupil-plane and image-plane signal measurement in mini-testbed

Planned

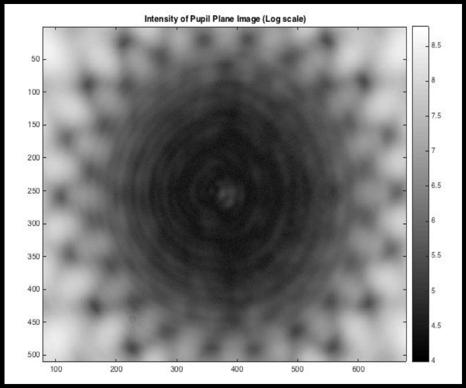
- Demonstrate feedback control with milli-arcsecond bearing precision in scaled testbed with sensor and GNC
- Demonstrate autonomous move from science observation, through transition, to acquisition, and finally re-establish science-precision control using sensor model verified in testbed



Simulation of Ideal Starshade

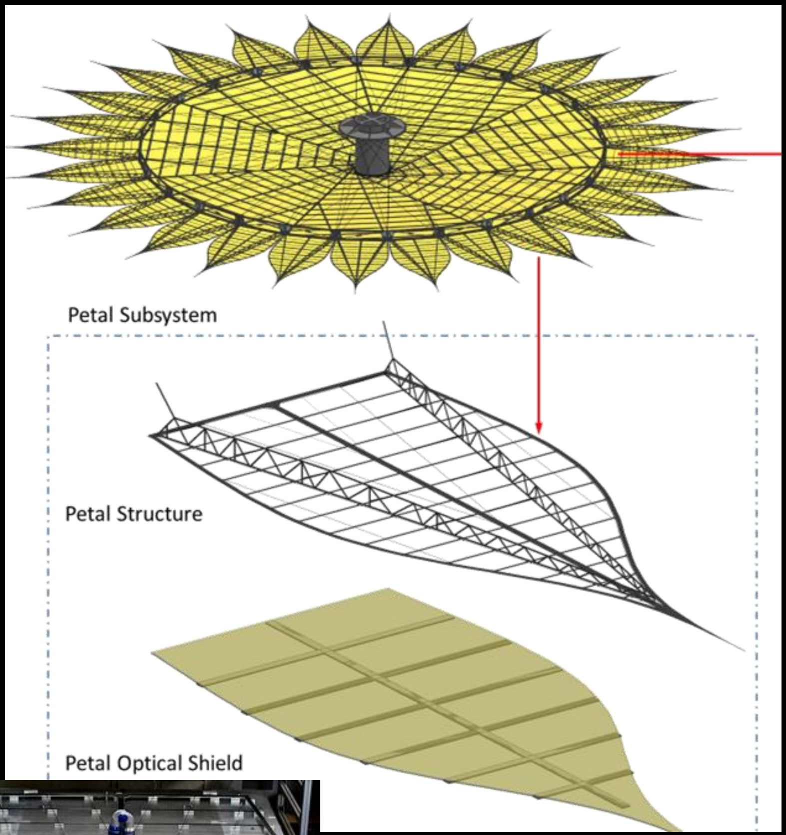


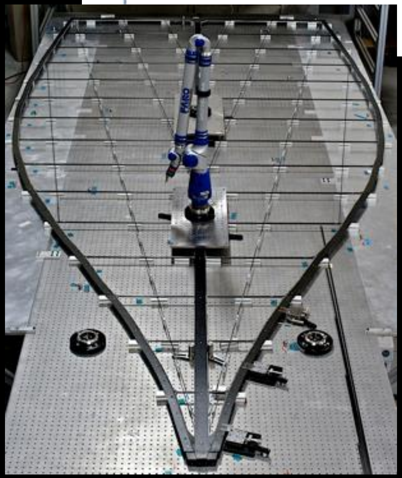
Simulation of As-Built Starshade



Measured shadow of laboratory starshade

Petal Fabrication Activities





Status

- Design of 7m petal with flight-like materials underway *(Princeton and JPL TDEM-12)*
- Designing flight-like interfaces to integrate petal to overall structure
  - Base hinges
  - Launch tie downs
  - Petal unfurling mechanism
  - Optical edge and tip interfaces

Planned

- Fabricate a full-scale petal with optical edges and optical shield *(Princeton and JPL TDEM-12)*
- Demonstrate stowing and unfurling the full-scale petal to verify shape tolerance requirements *(Princeton and JPL TDEM-12)*

Thuraya → Starshade

Inner Disk Deployment Activities

Status

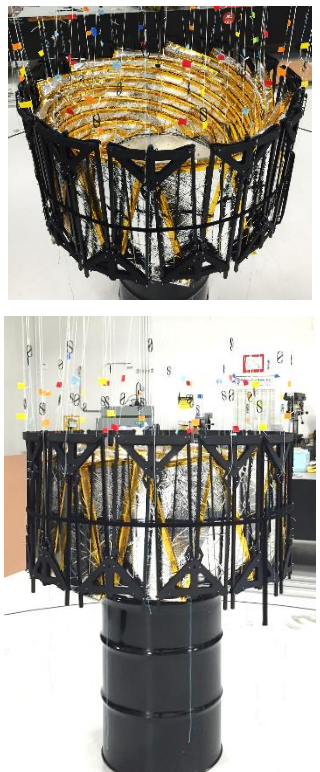
- Completed rebuilding half-scale (10m) perimeter truss testbed with upgraded design and more flight-like parts
- New petal interface integrated

Planned

- Build flight-like spokes
- Verify inner disk deployment tolerances
- Integrate optical shield *(JPL TDEM with NGAS support)*

Flight-like Optical Shield Proto-type

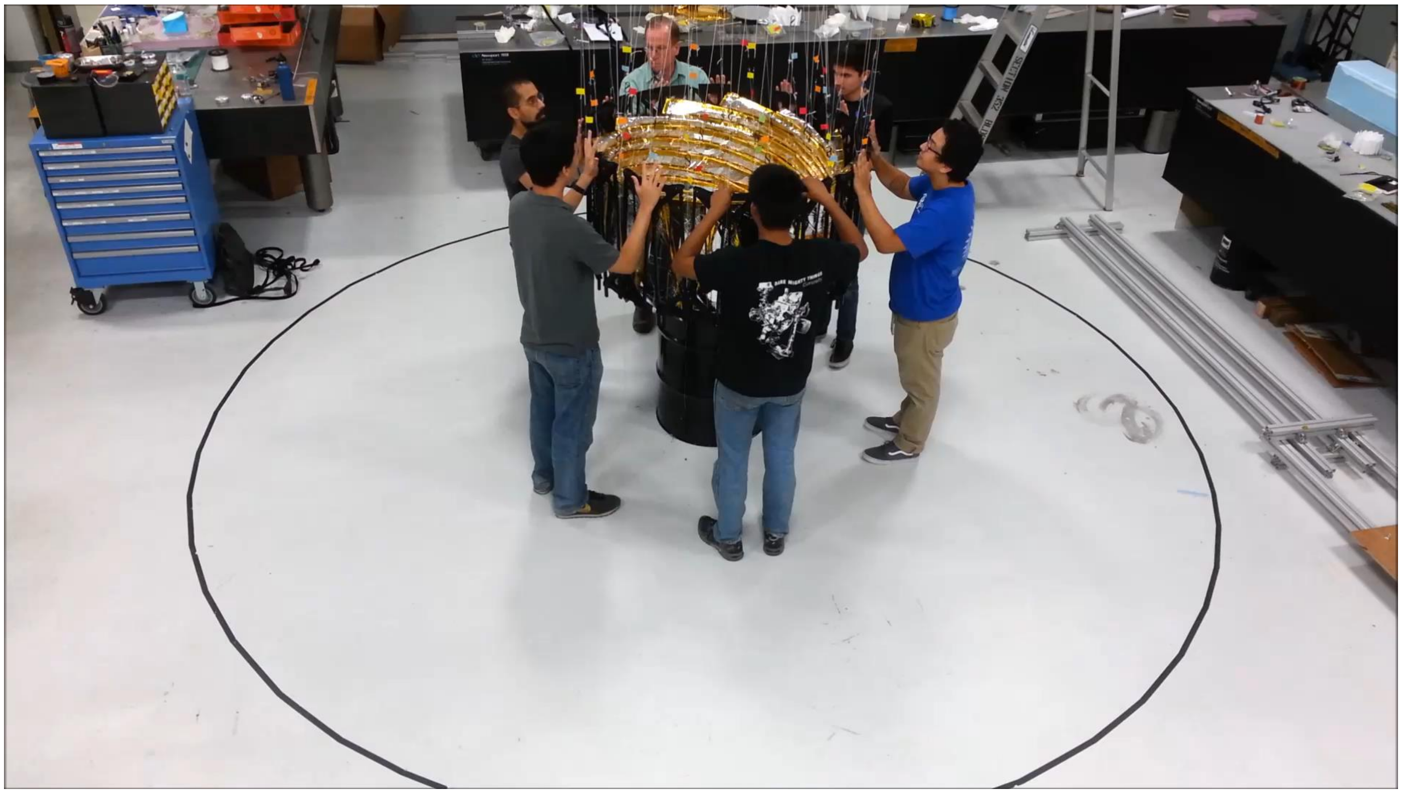
- New flight-like optical shield
- 5-m diameter (half scale for Rendezvous mission)
- Comprises flight-like gores of mylar-foam-mylar sandwich panel design
- Includes deployment & offloading features including carbon fiber deployment rods



Stowed 5m flight-like optical shield inside truss

Deployed 5m flight-like optical shield inside truss

5m Optical Shield w/solar array deployment video



Petal Launch restraint and Unfurling System (PLUS)

- Developed with SBIR partners Tendeg/Roccor
- Simulated petal spines wrapped around a full-scale simulated perimeter truss & spacecraft
- Petal Launch Restraints embedded in petals allow for test-bedding of launch restraint furling
- Future features will include:
  - Hub rotating mechanism to allow for petal **un**furling
  - Unfurling system breadboard testbed
  - Rev2 petal launch restraint system

Petal Launch Restraint ‘stack’

State-of-the-Starshade Lab' September 2016

Optical Shield testbed 1.0
(1/10 scale, 2m diameter)

TDEM Petal, TRL 4
(6m length, ~2.4 wide)

~1m diameter desert optical
verification test starshade

Inner Disk
Subsystem 2.0
Awaiting
integration

Inner Disk Subsystem 1.0
with furled petal

Petal Launch Restraint &
Unfurl Subsystem (PLUS) 1.0
with furled petal

5m flight-like
optical shield build-up

Conclusion

- Technology program is addressing all the technology gaps through a combination of
  - Sub-scale diffraction experiments at flight Fresnel number
  - Model validation activities in the laboratory and in long-baseline tests
  - Edge scatter and contamination experiments on edge coupons
  - Formation flying sensing experiments at flight Fresnel numbers
    - Easy to do in air as contrast is ~1e-3
  - Full scale petal construction to flight requirements
  - Half-scale truss construction and deployment testing
  - Half-scale petal deployment demonstration
  - Half-scale optical shield stowage and deployment demonstration
- The mechanical parts will be tested to TRL-5 and will be integrated into a half- or full-scale testbed to TRL-6.

5m Optical Shield w/Deployment Sequence

4x gores populated with flexible solar cells

- First deployments of 5m flight-like optical shield with solar array segment
- Includes 4 gores of flexible solar panels