Jet Propulsion Laboratory
California Institute of Technology

Starshade Edges- Design, Calibration and Performance

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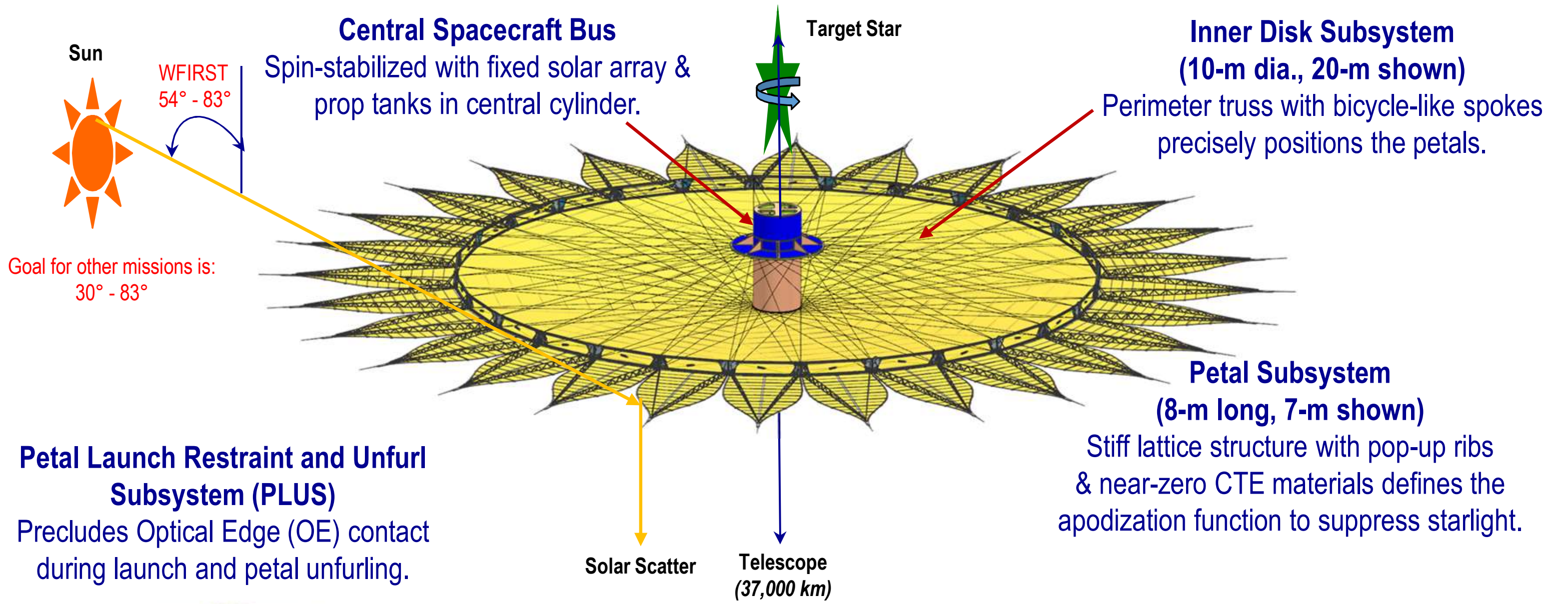
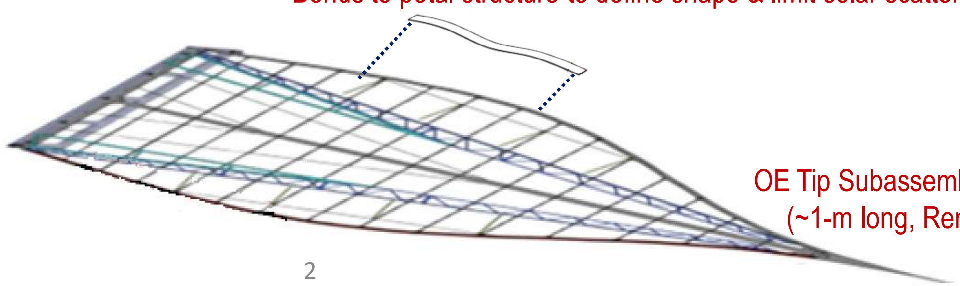
Starshade Mechanical Architecture Overview



Petal Launch Restraint and Unfurl Subsystem (PLUS)
Precludes Optical Edge (OE) contact during launch and petal unfurling.



Outline of talk

Glint

- Starshade glint- introduction
- Starshade edge design
- Modeling edge scatter
  - Reflection
  - Diffraction
- Model versus measurements
- 'Stealth' edges
- Scatter measurement

Edges

- Starshade edge materials
- Edge construction and assembly
- Segment-level testing
- Preliminary results on segments*

Optical tests on edges are part of a plan to bring starshade edges at the segment level up to TRL5

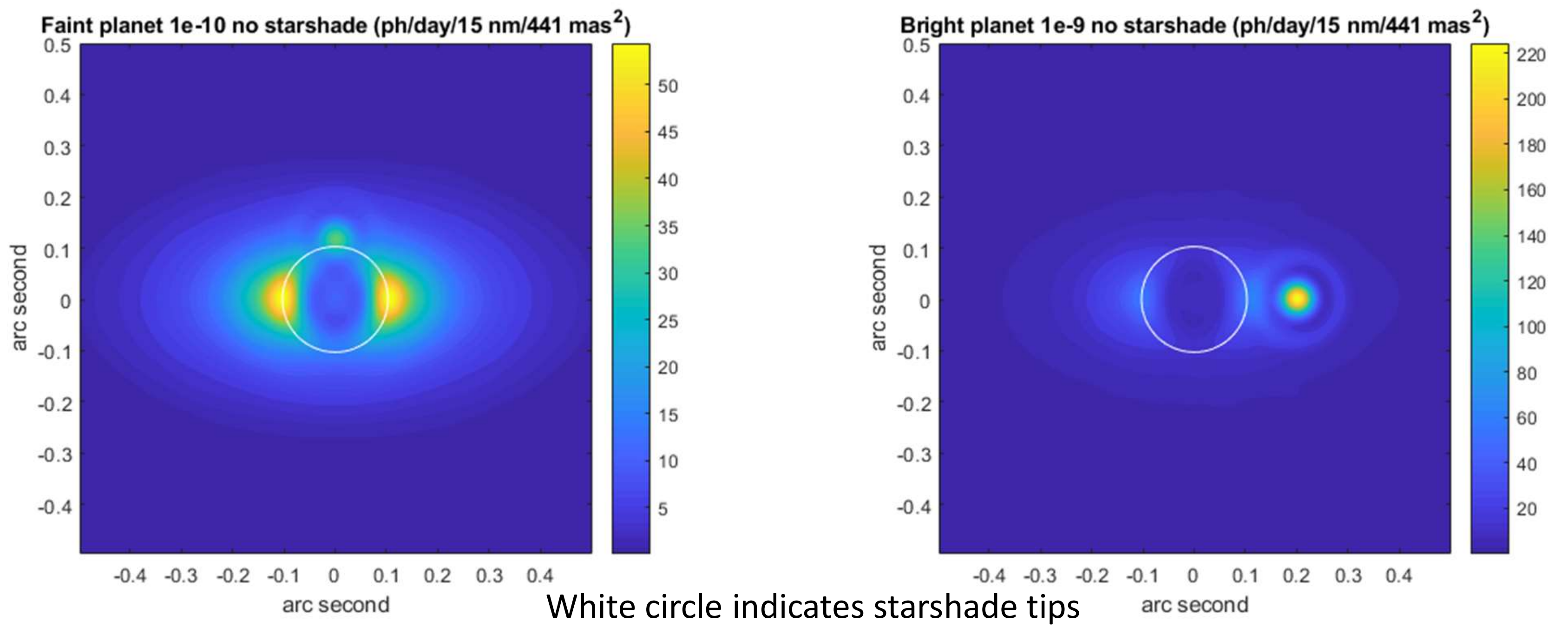
*Note other work on starshade edges which will not be covered here.
For example:
TDEM-12 "Starshade Stray Light Mitigation through Edge Scatter Modeling and Sharp-Edge Materials Development", Casement et al., (on ExEP web site) and "Starshade design driven by stray light from edge scatter," Casement et al. Proc. SPIE 8442 (2012).

Model images of Tau Ceti with a perfect starshade

1x1 arcsec images of a 1e-9 and 1e-10 planet around Tau Ceti, observed with a perfect starshade. Model pixel size is 3 mas.
Exozodi is 1 solar zodi, inclined 60 deg.
1e-9 contrast planet is at 200 mas (in x), with exozodi and solar glint.

1e-10 planet is at 120 mas (in y), with exozodi and solar glint
The overall background is local zodi.
Imager FOV is 9 arc sec diameter.

Images created using SISTER (Sergi Hildebrandt)

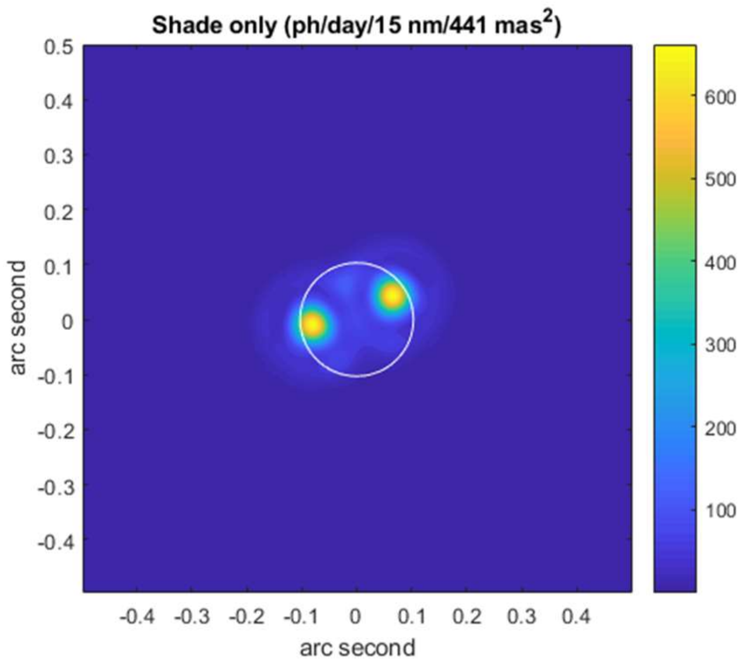


White circle indicates starshade tips

Model images of Tau Ceti with a real starshade

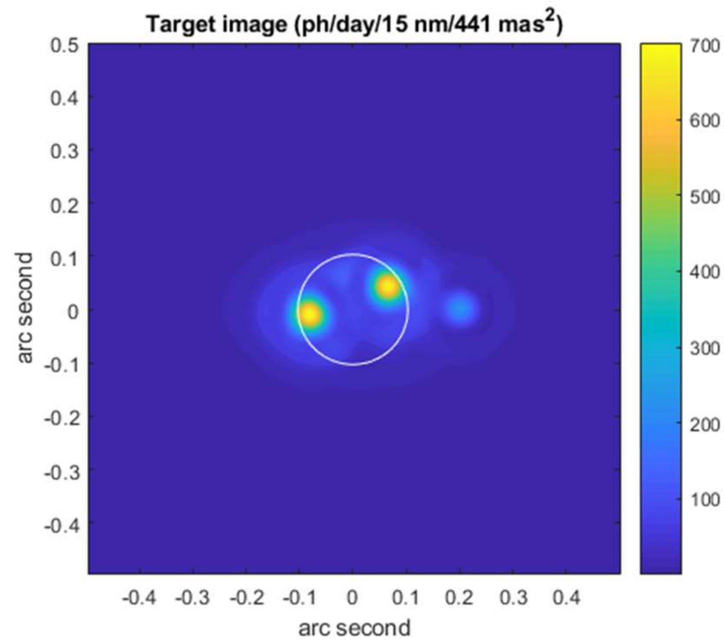
Tau Ceti observed with a 26 m diameter starshade at 26 Mm.

Starshade only- starshade radius is 100 mas



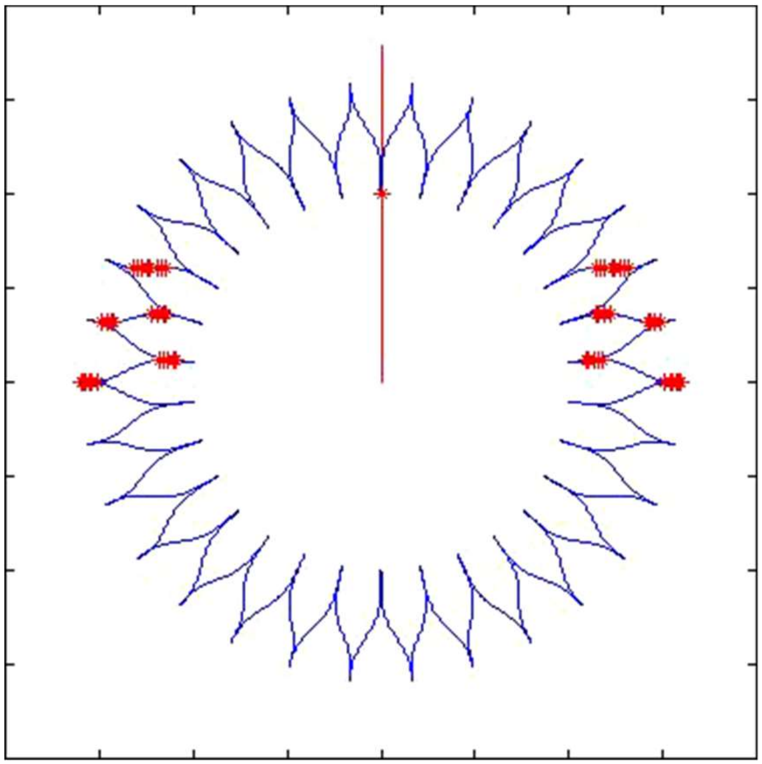
Photons/day/15 nm/21 mas pixel

1e-9 planet in quadrature at 200 mas

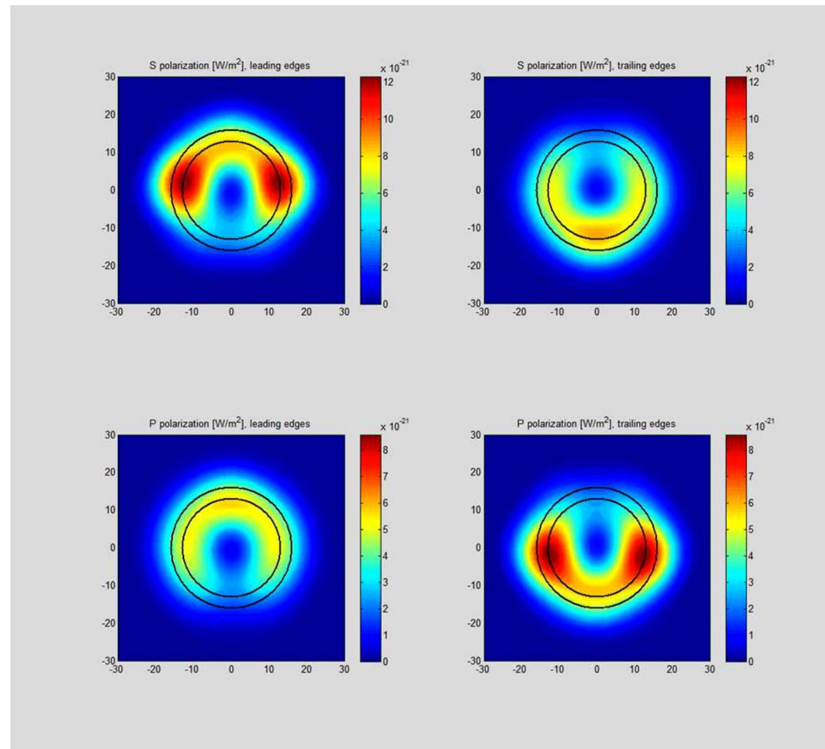


Models of glinting from the starshade edges

Model based on a specular edge

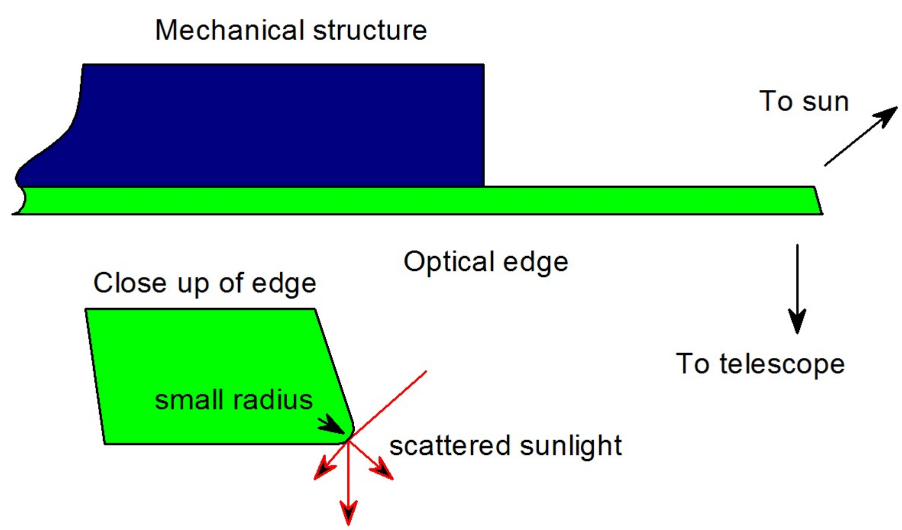


Model based on a measured edge



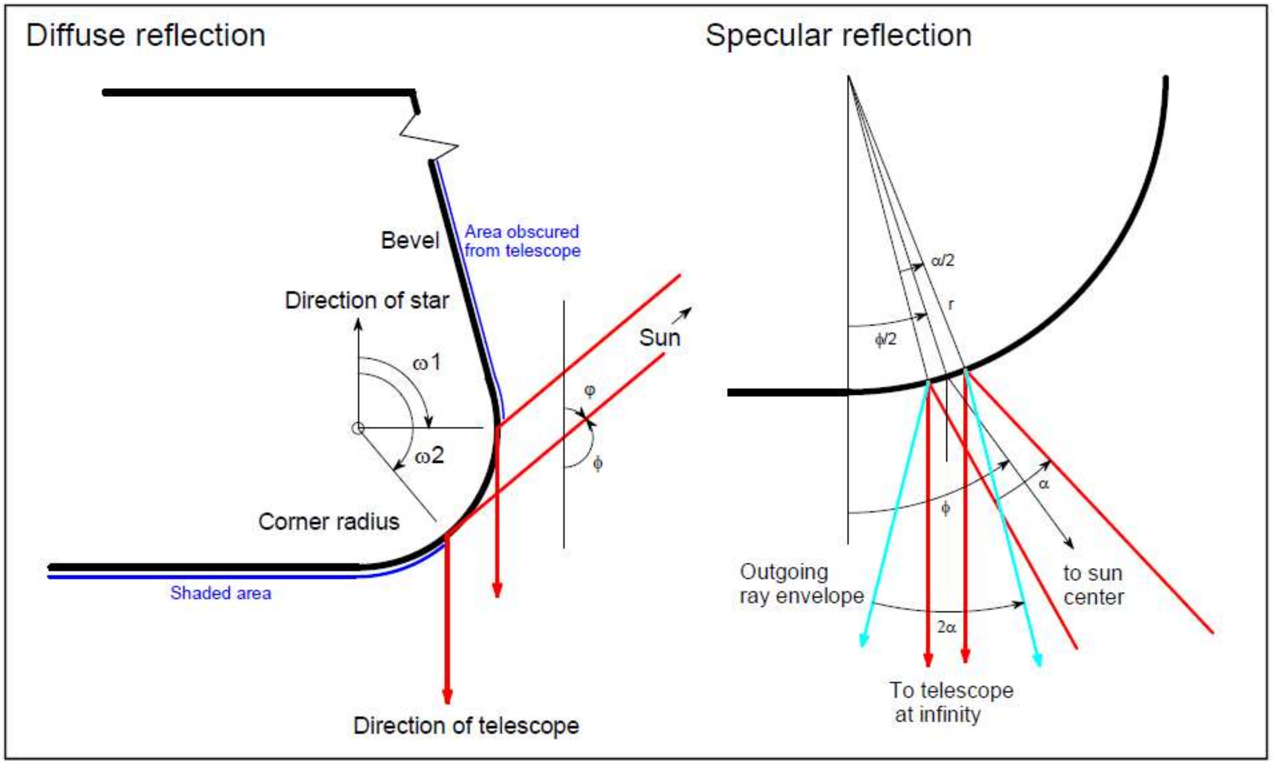
Starshade edge design

- Edge has a small radius at the tip.
- Edge tapers away from the line of sight to the telescope
  - Limits area illuminated by sunlight
- For a sharp edge the solar scatter is dominated by diffraction
- For a rounded edge, the solar scatter is driven by the radius of curvature (ROC) and the reflectivity



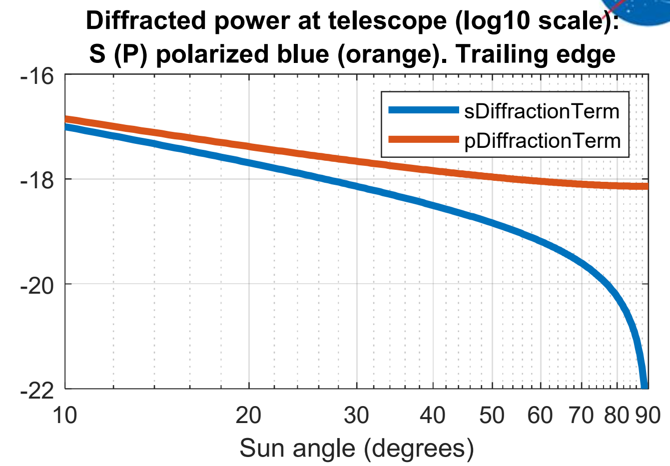
Scatter modeling- Geometric

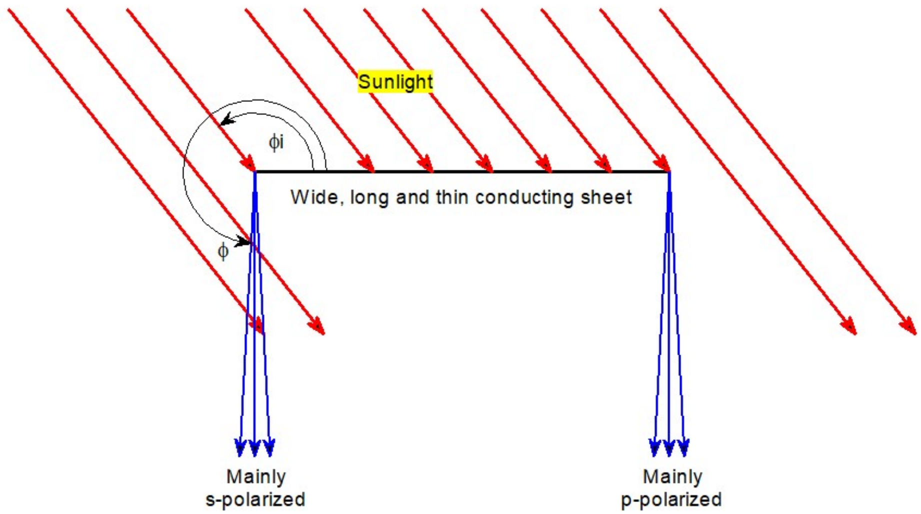
- Two modes of geometric scatter- diffuse and specular
- In diffuse reflection limiting the whole illuminated area scatters light towards the telescope (and elsewhere)
- In specular reflection only a limited area reflects light towards the telescope.
- To get the full picture, this has been modeled in three dimensions.

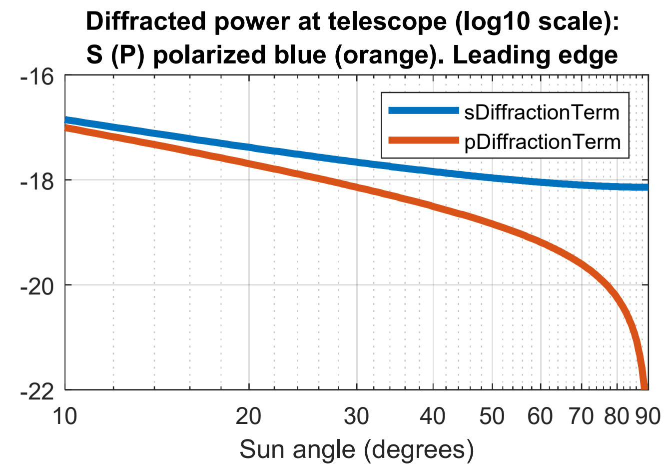


Scatter modeling- Diffraction

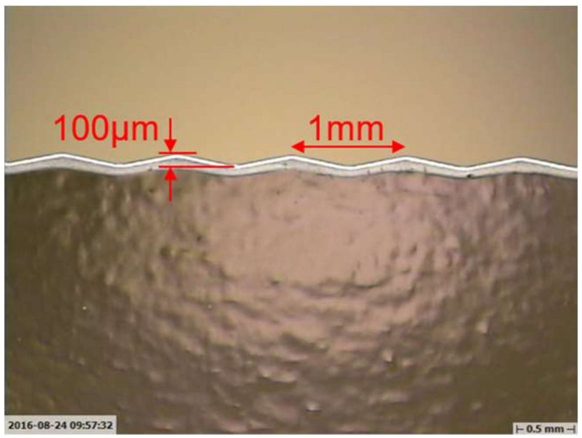
- Diffraction – akin to specular in that it is highly directional
- Arnold Sommerfeld's (1895) total field solution for diffraction from a semi-infinite conducting sheet.
- Light from the leading edge is dominated by the S polarization (electric vector aligned with edge)
- Light from the trailing edge is dominated by the P polarization (electric vector perpendicular to edge)



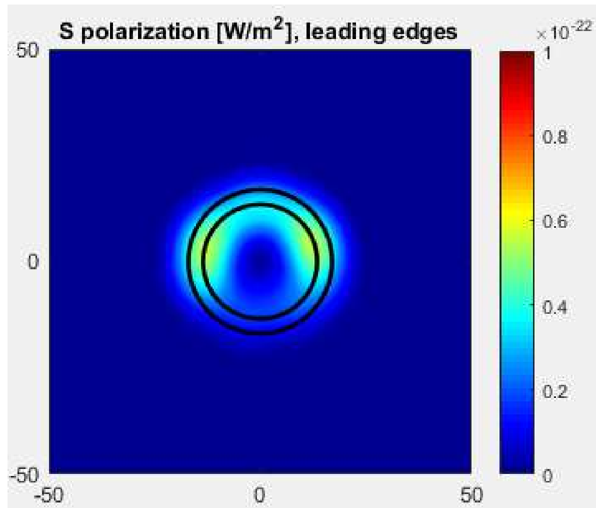




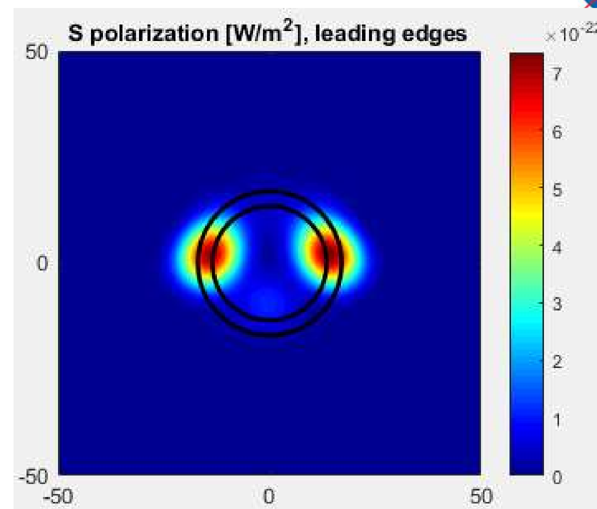
Stealth edges



Stealth edge



Standard edge



Model uses data from scatterometer for Gillette razor blade, amorphous metal blades would be expected to be similar. In this model, sections of the edge making an angle within +/-9.2 degrees of normal to the sun angle are eliminated, effectively becoming perfectly dark. So this is a best possible case.

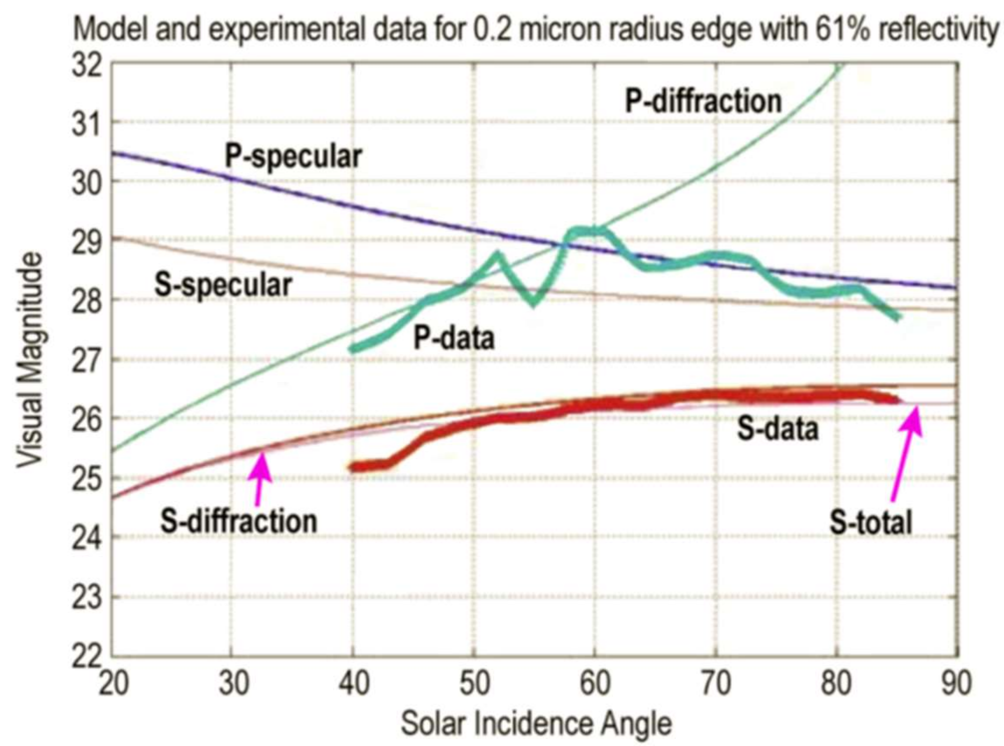
The residual scatter peak is a factor of ~14 less than the standard edge (about 2.9 magnitudes fainter).

Average power from edge scatter in the two cases is 1.4 10^{-19} W/m^2 and 2.7 10^{-20} W/m^2, so a factor of 5.2 less for stealth (about 1.8 magnitudes fainter).

Drawback- starshade cannot rotate- makes thermal management of the shade harder.

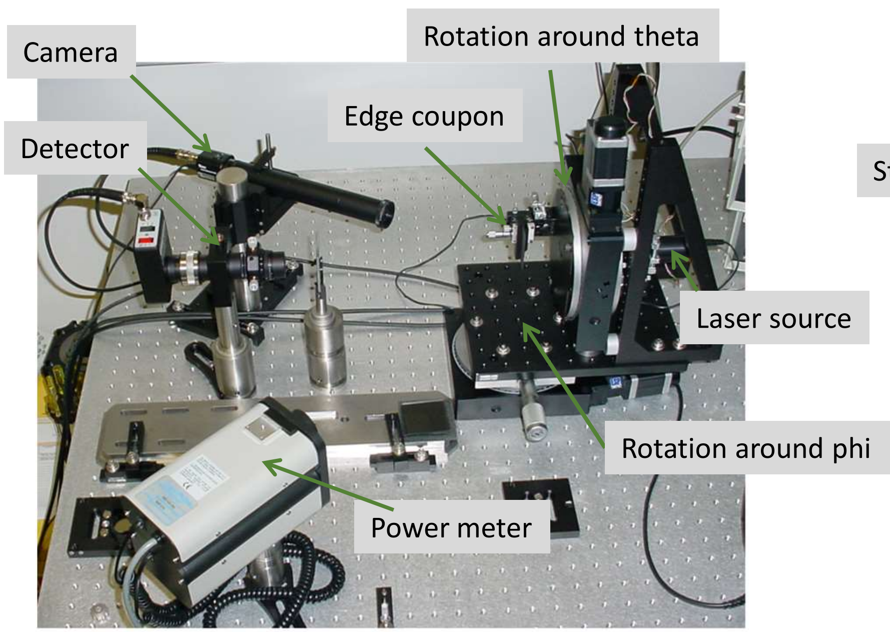
Scatter model

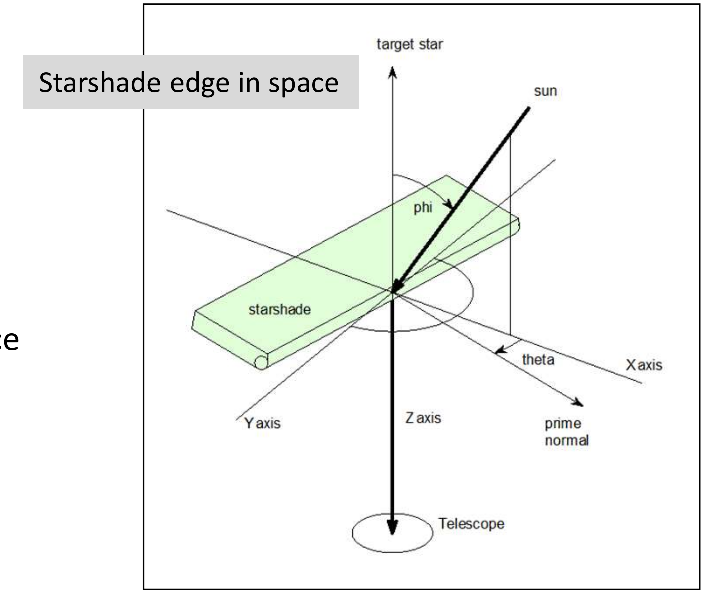
- Trailing edge assumed shaded
- S-diffraction dominates
- P-diffraction very weak; 5x less than S-diffraction at 40°
- S-specular is weak, but has a linear dependence on the edge ROC
  - So, at larger angles it may dominate S-diffraction
- Plot also shows lab data for S and P scatter with good agreement to model

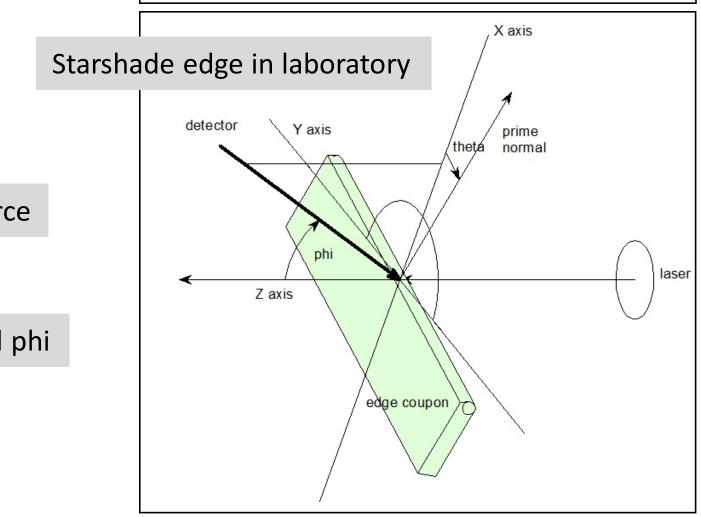


Scatterometer

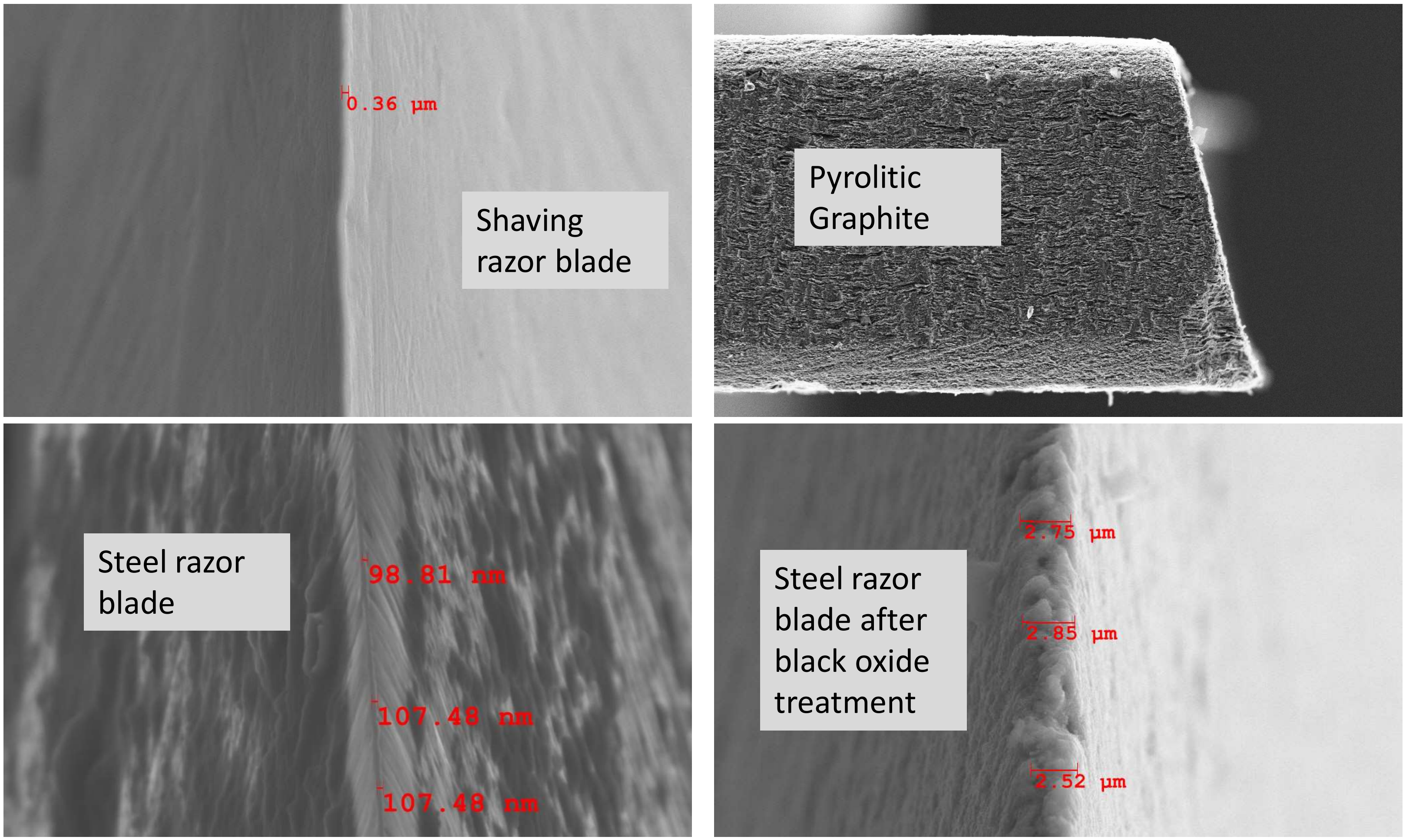
- Measurements of scatter from edge coupons
- Geometry scalable to the flight situation
- Accurate for both specular and diffuse scatter
- Measures down to ~10^{-23} W/m^2 equivalent in space
- Optical chopping eliminates background light
- Separate measurements for s and p polarizations





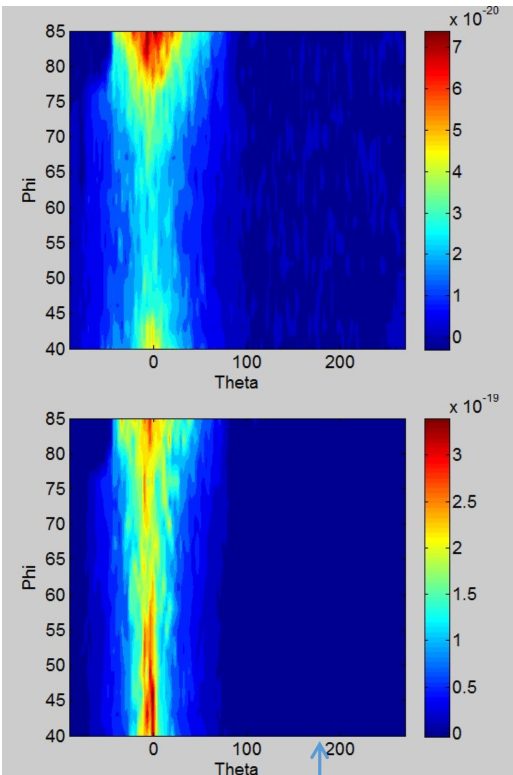


Sample edges: scanning electron microscope images



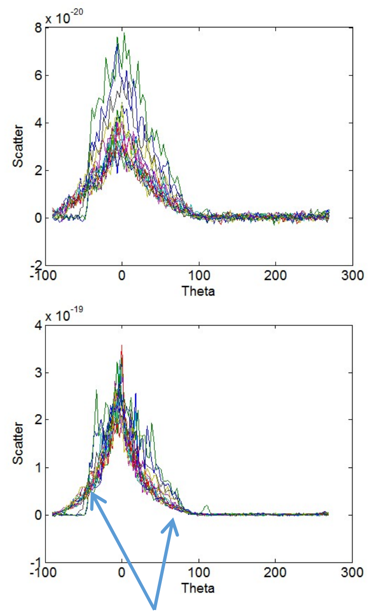
Measured scatter: Pyrolitic Graphite

Scan of θ and ϕ



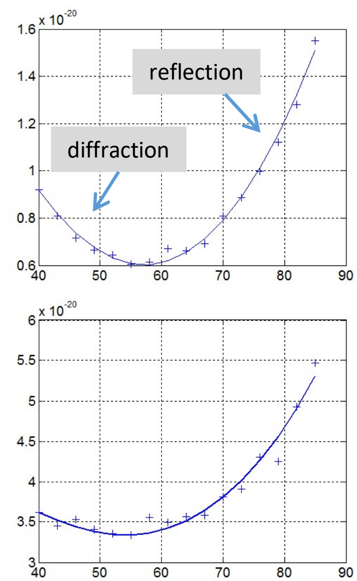
No apparent trailing edge diffraction: edge is self-shading

Range of scatter for each sun angle ϕ



Wide angle range: ~Lambertian scatter

Integrated scatter around whole edge



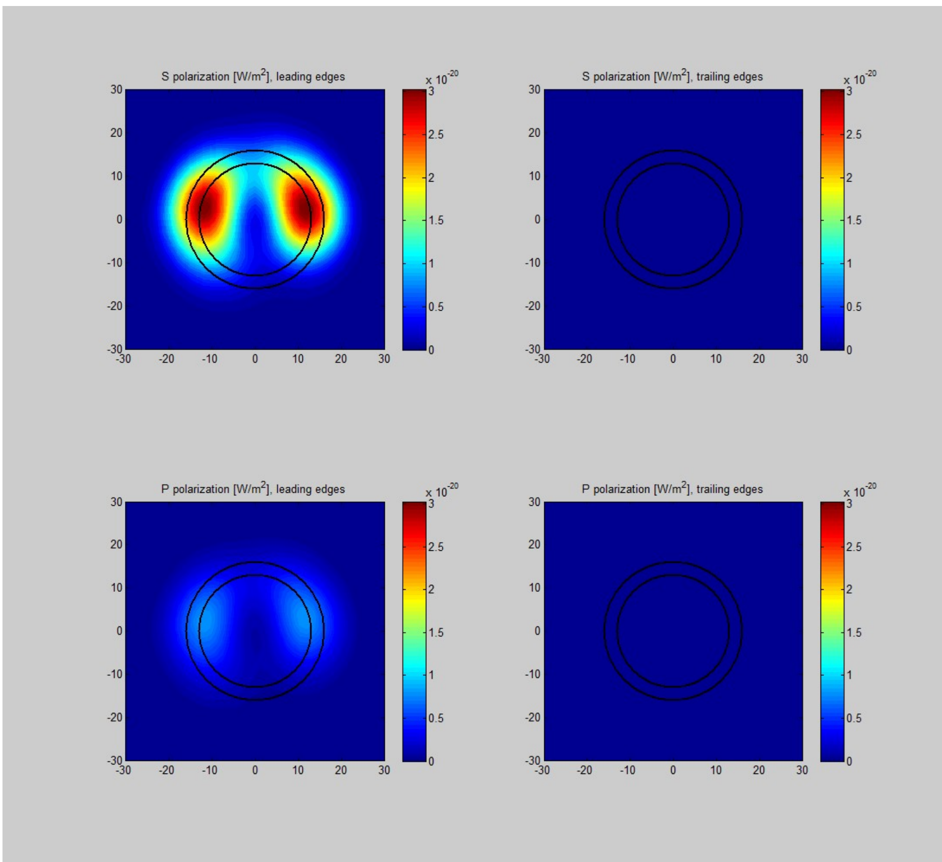
p-polarized

s-pol ~6x > p-pol

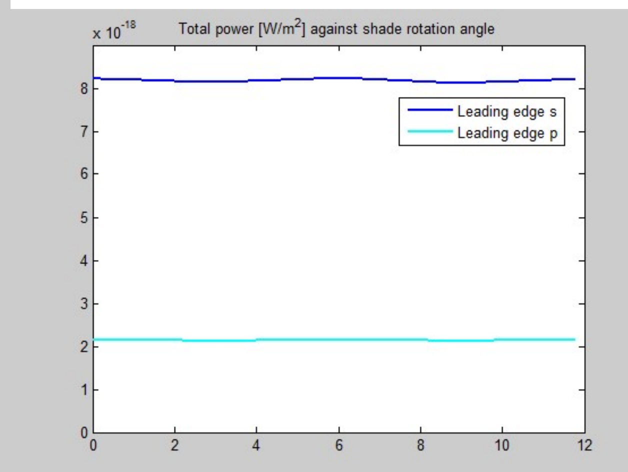
s-polarized

Starshade image

Pyrolitic graphite edge

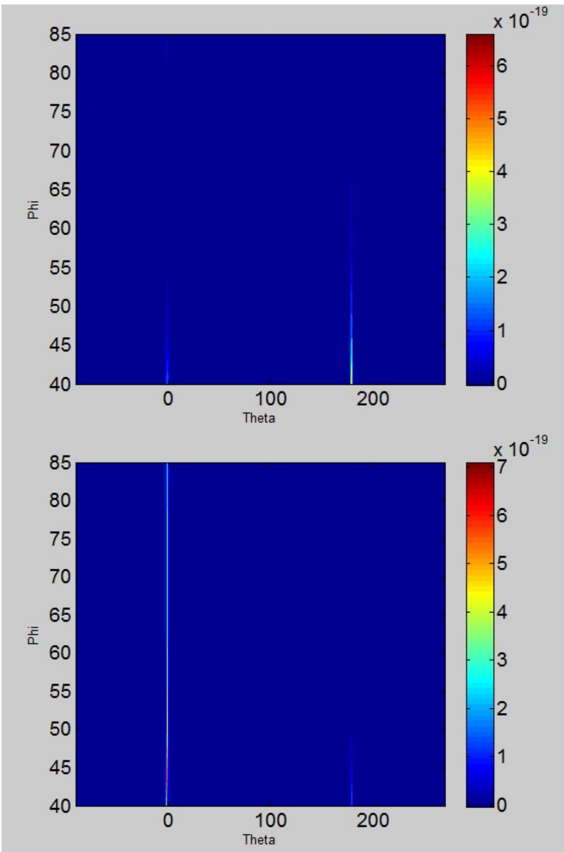


Trailing edges are well shaded



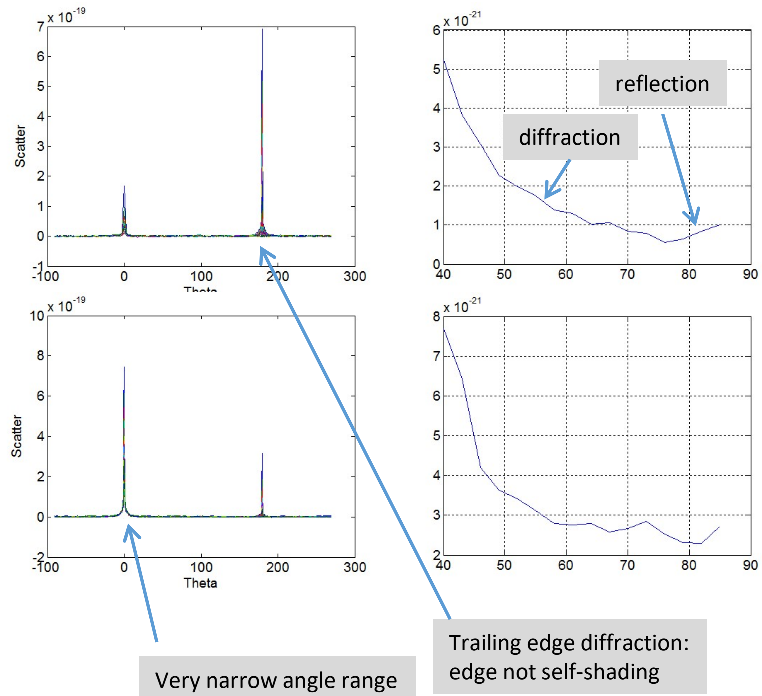
Measured scatter: Shaving razor blade

Scan of θ and ϕ



Range of scatter for each sun angle ϕ

Integrated scatter around whole edge

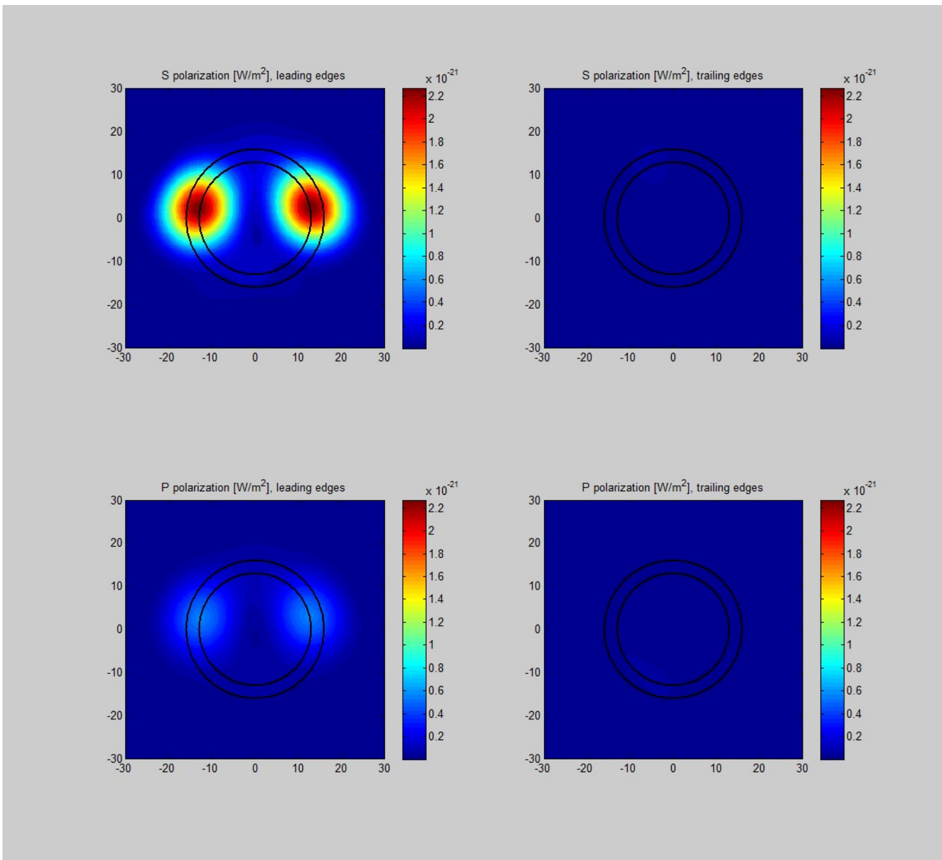


p-polarized

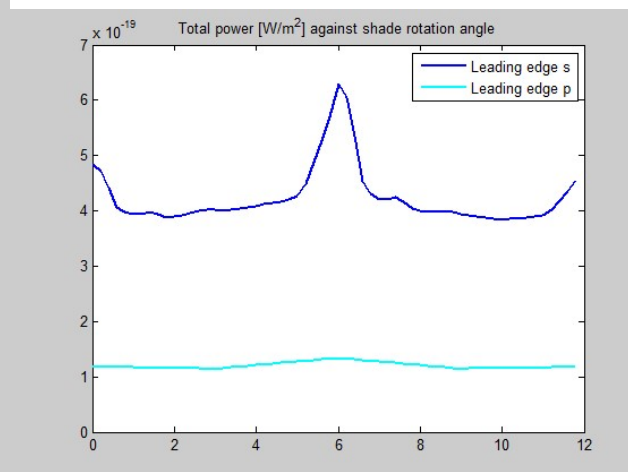
s-polarized

Starshade image

Shaving razor blade



Trailing edges are not shaded



Starshade Edges

Motivation

- Razor blades in scatterometer showed in-spec performance
- Sharp, specular edges are preferred.
- Require curved rather than straight edges.

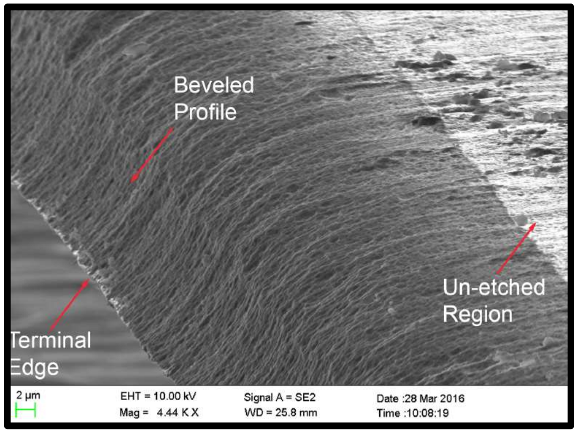
Chemical etching of metal sheet

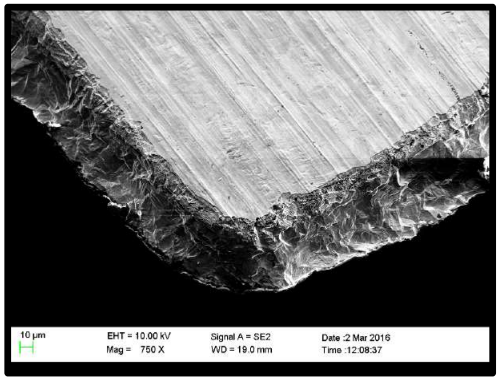
- Can meet in-plane profile requirements via a photoresist process
- Inherently leaves beveled edge

Material Choice

- Many materials explored
- Amorphous metals (metal glasses) produce durable edges with small grain size
- Small grain boundaries in amorphous metal results in an even and smooth edge of <1 μm radius
  - Large scale deformation due to release of internal strain leads to integration challenges

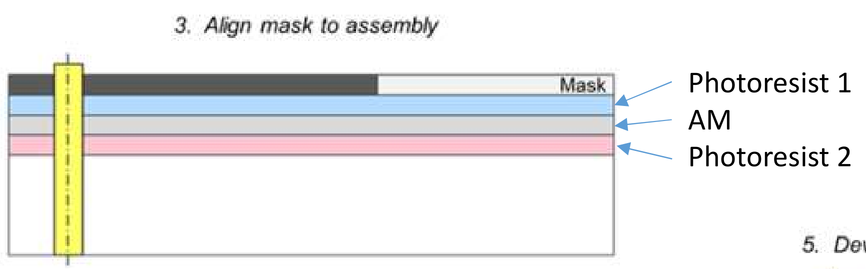
Amorphous Metal

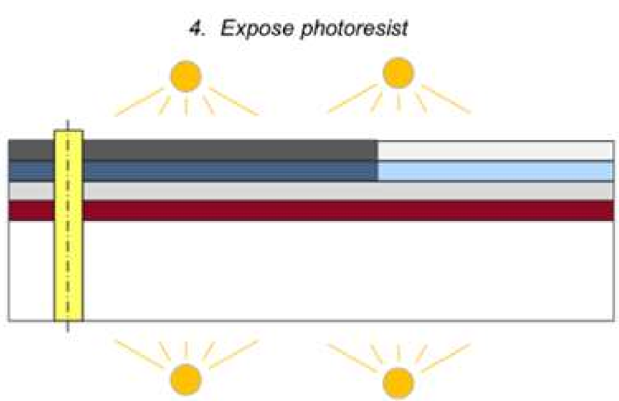


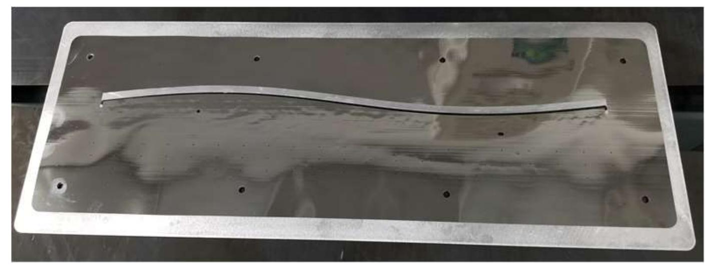


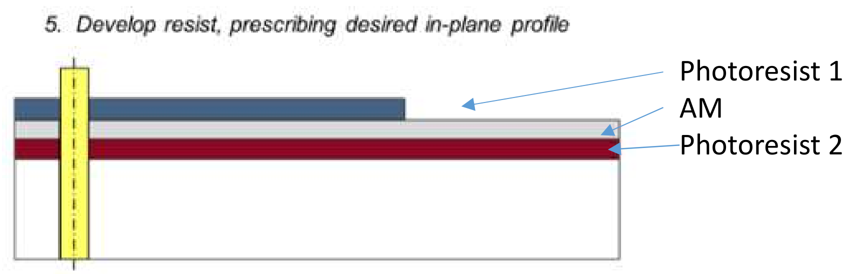
Stainless Steel

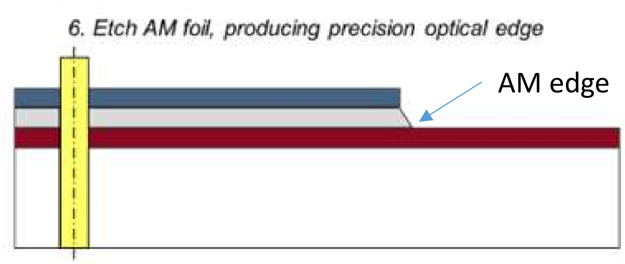
Starshade edge manufacture

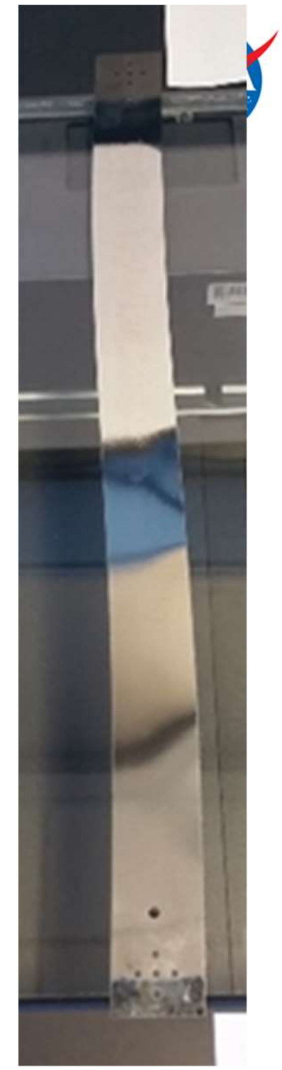






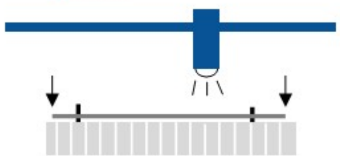






Starshade edge segment construction

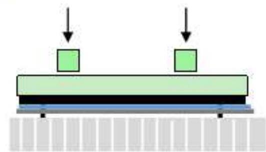
1. Place AM on vacuum table, measure with MicroVu.



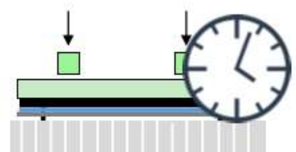
2. Screed epoxy (blue) onto Substrate (black), clean up edges

3. Place substrate on AM. Clean up squeeze out.

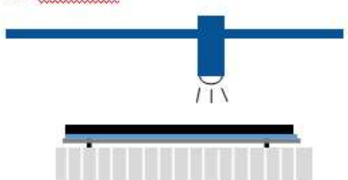
4. Apply load to fixture. Clean up squeeze out.



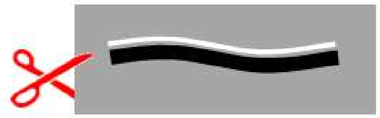
5. Cure for 3 days at room temp.



6. Remove assembly and re-measure on MicroVu

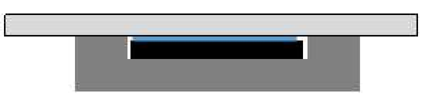


7. Remove excess AM



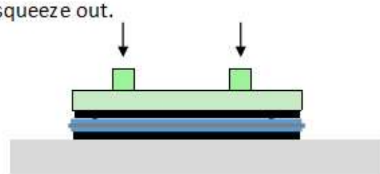
8. Place assembly on structural edge alignment fixture

9. Screed epoxy onto structural edge

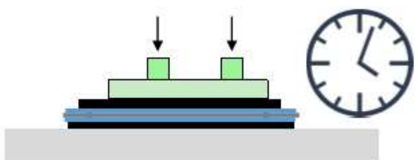


10. Place structural edge on assembly using tooling. Clean up squeeze out.

11. Apply load to fixture. Clean up squeeze out.

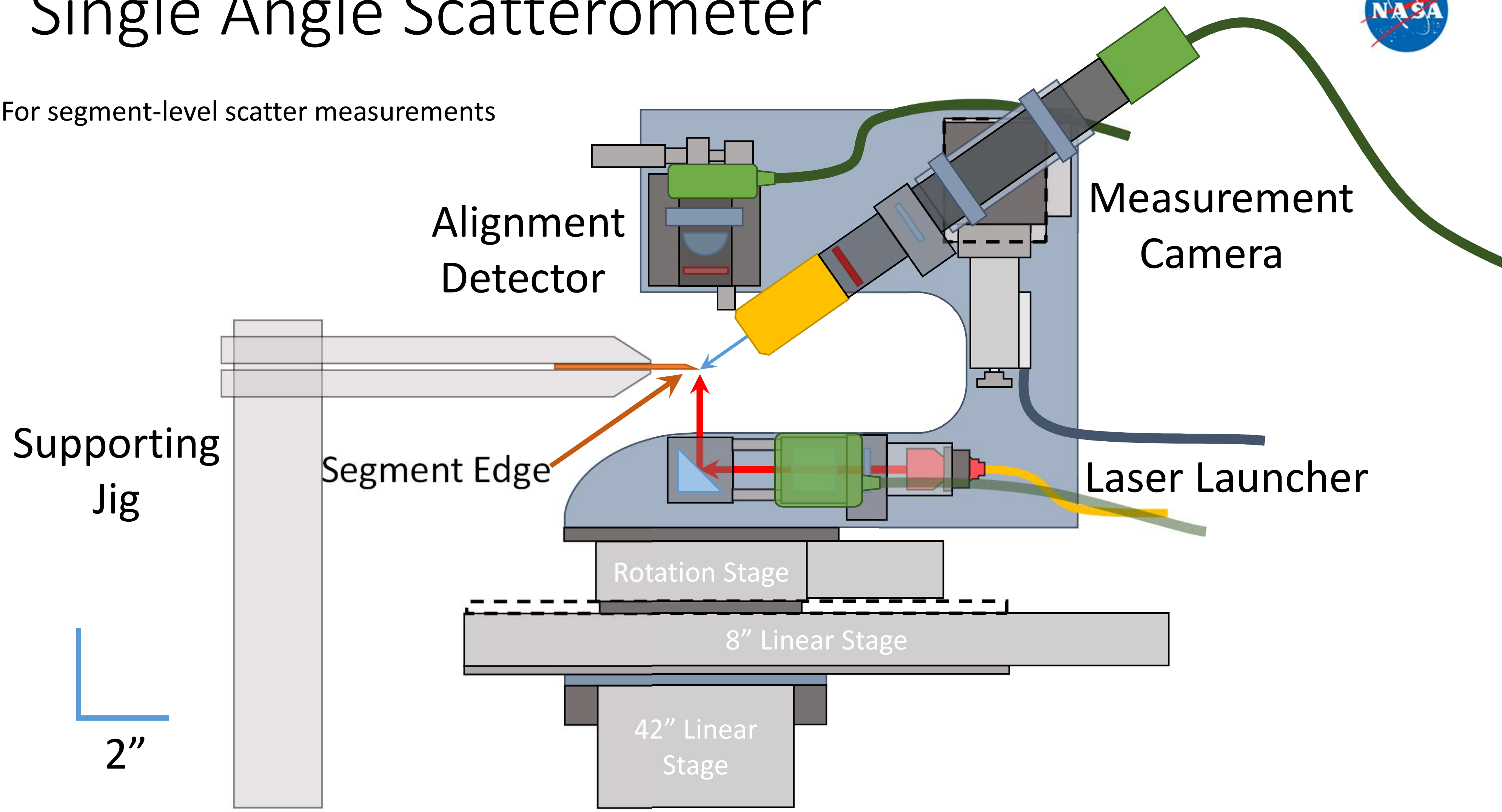


12. Cure for 3 days at room temp. Post cure at 100C for 2 hrs.



Single Angle Scatterometer

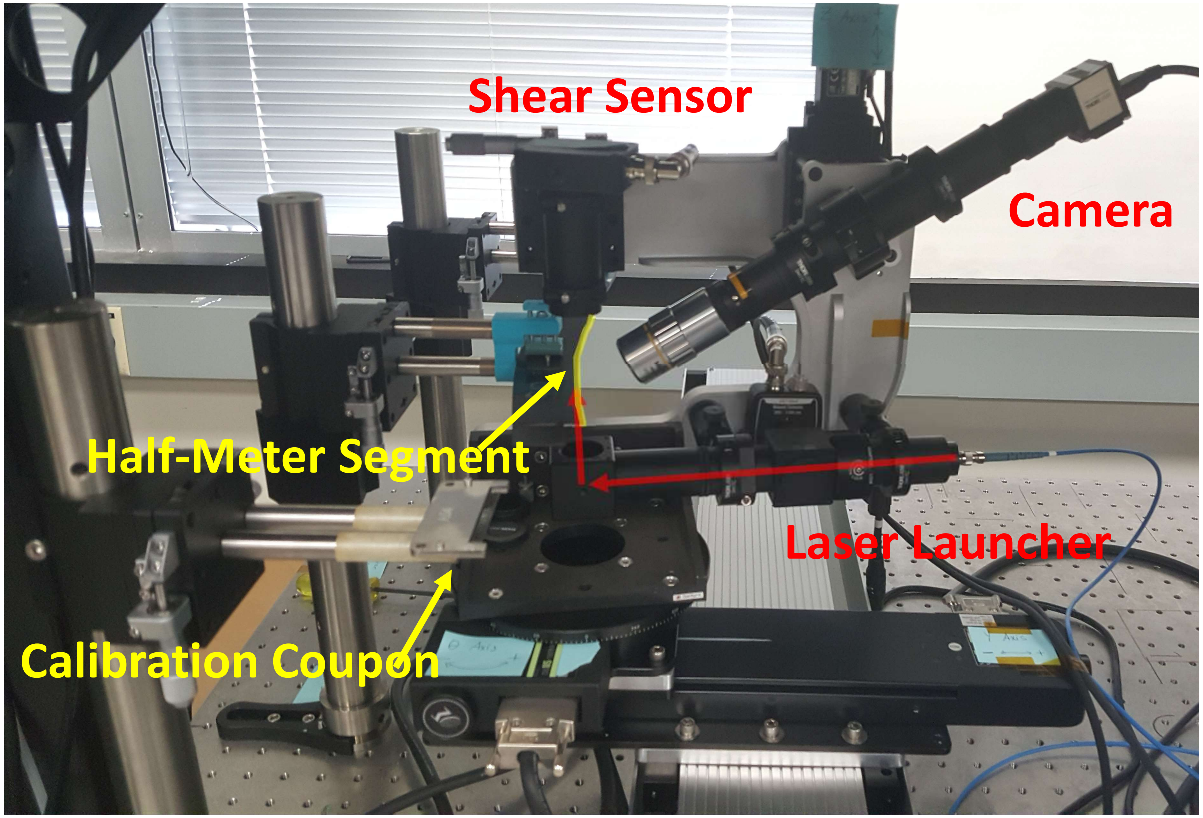
For segment-level scatter measurements



Single Angle Scatterometer

Features:

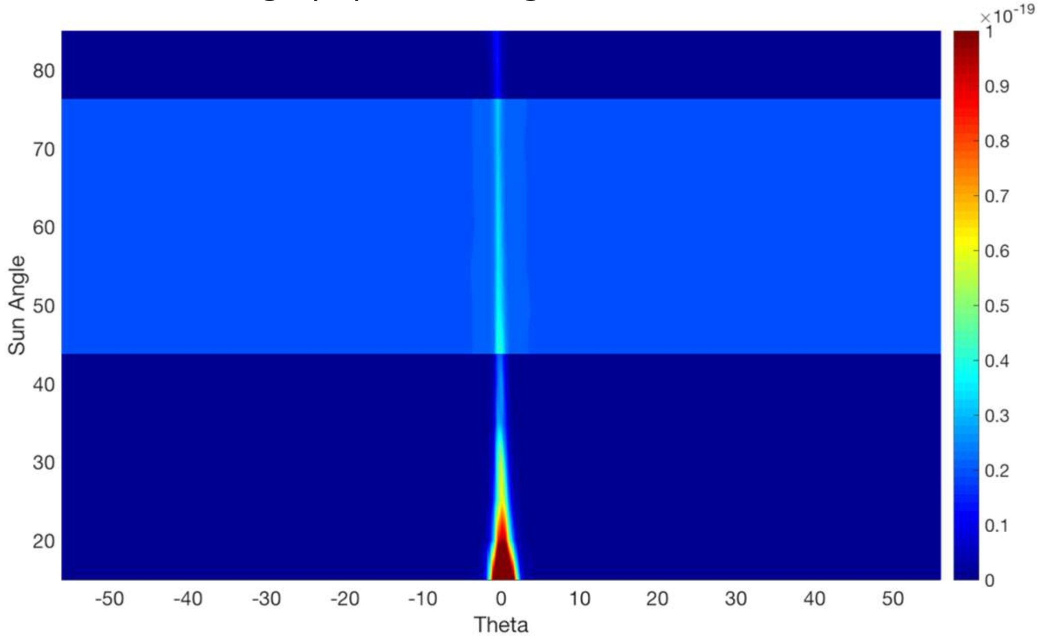
- Autofocus
- Automatic vertical centration
- Follows the direction of the edge based on design data and live measurements
- Views and measures 1 mm long sections
- Saves all images
- Uses calibration coupon to relate segment scatter to regular scatterometer measurements
- GUI allows return to measurement points
- Has a separate imaging function for viewing any suspect areas of the edge (not shown)

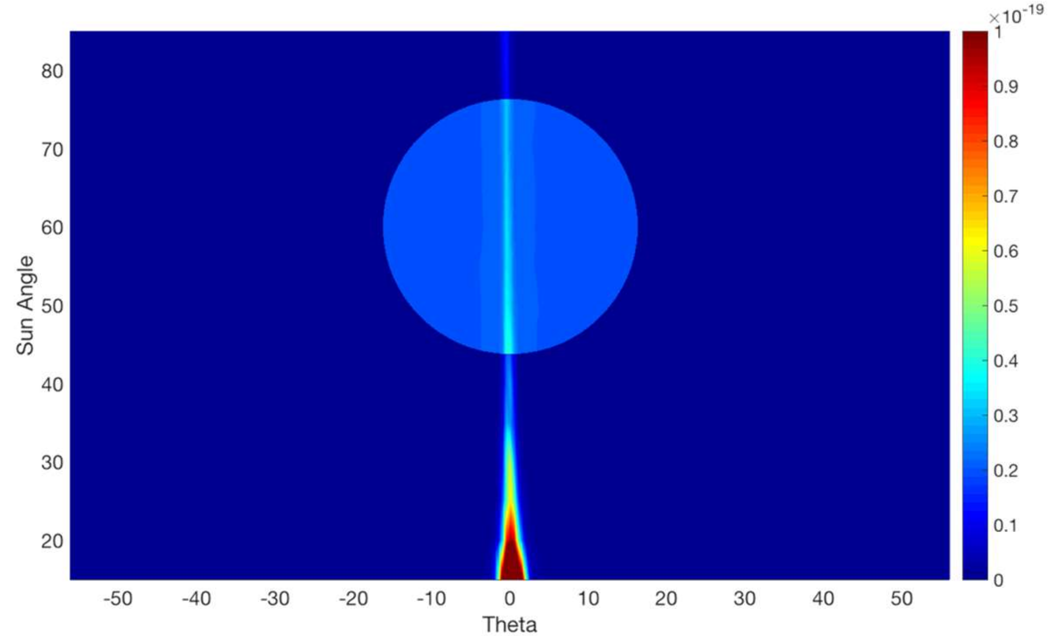


SAS vs Multi-Angle Scatterometer (MAS)

MAS captures all the light from the edge. SAS captures a selected region, representative of the edge.

Highly specular edge– Gem Razor A5





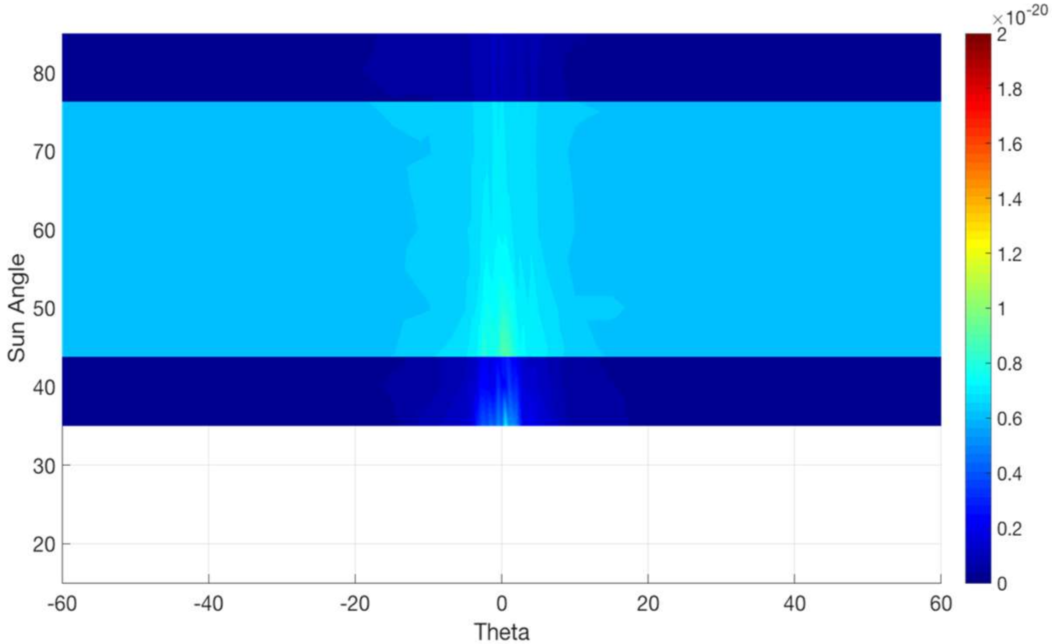
Integrated Light: 6.8705e-19

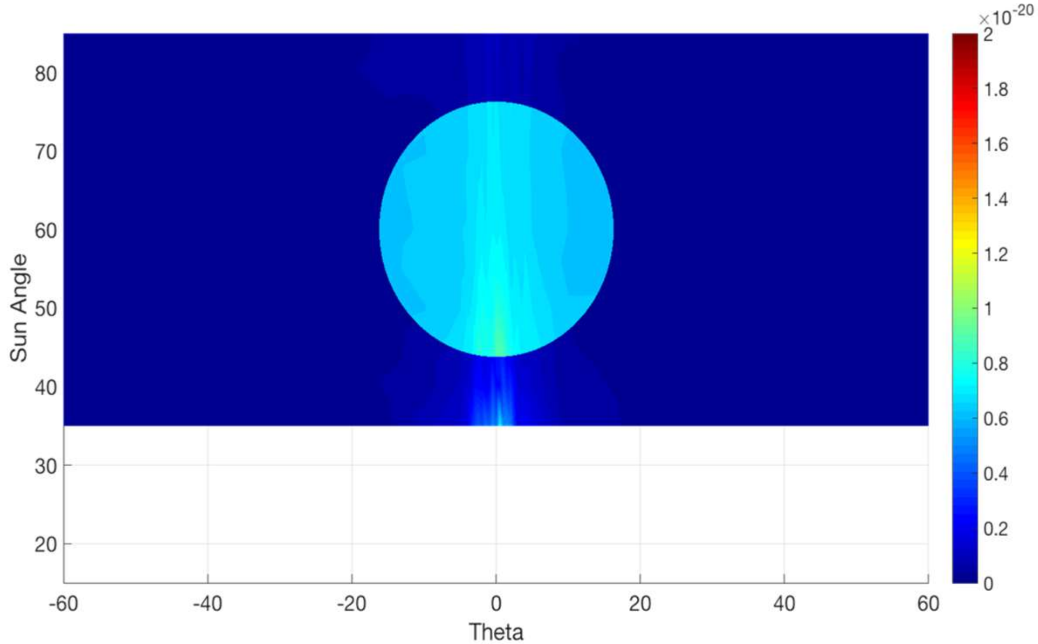
Integrated Light: 6.5477e-19

Circular Aperture Captures **95.3%** of the available light

SAS vs. MAS

Specular edge– AM Coupon B02





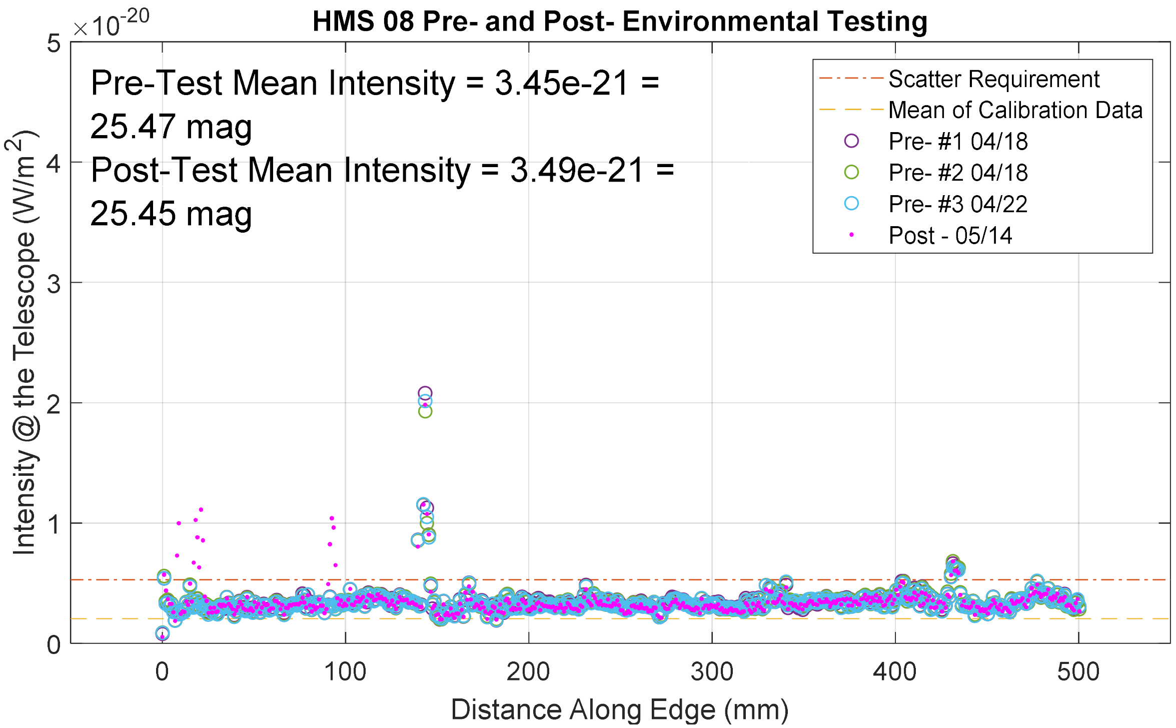
Integrated Light: 7.9540e-19

Integrated Light: 4.7888e-19

Circular Aperture Captures **60.2%** of the available light

Edge segment environmental testing

- So far:
  - Bend and release test- stowed to deployed configuration
  - Deployed thermocycling: +40 to -100 C
- Next steps:
  - Stowed thermocycling +40 to -50 C (TBR)
  - Creep testing



Summary

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Solar Scatter

- Starshade solar scatter can be limited by creating sharp, specular edges
- The solar scatter is then dominated by diffraction and arises from particular regions on the shade.
- Stealth edges can mitigate this but require a starshade that does not rotate.
- The Scatterometer was developed to measure edge scatter in a system that can relate lab measurements to space.
- Scattering models were developed and shown to agree well with measurements

Edge segments

- Etching is used to produce long, precisely shaped sharp-edged foils.
- These foils are then assembled into segments which will make up the starshade edge
- A single angle scatterometer (SAS) has been developed to measure the entire edge of each segment.
- Data from the SAS can be calibrated against reference data from the MAS.
- Tests now in progress show highly reproducible results for segments subjected to environmental testing.
- These segments show negligible change in scatter performance after testing