Jet Propulsion Laboratory
California Institute of Technology

Starshade Milestone 3
Optical Edge Segment Scatter Performance

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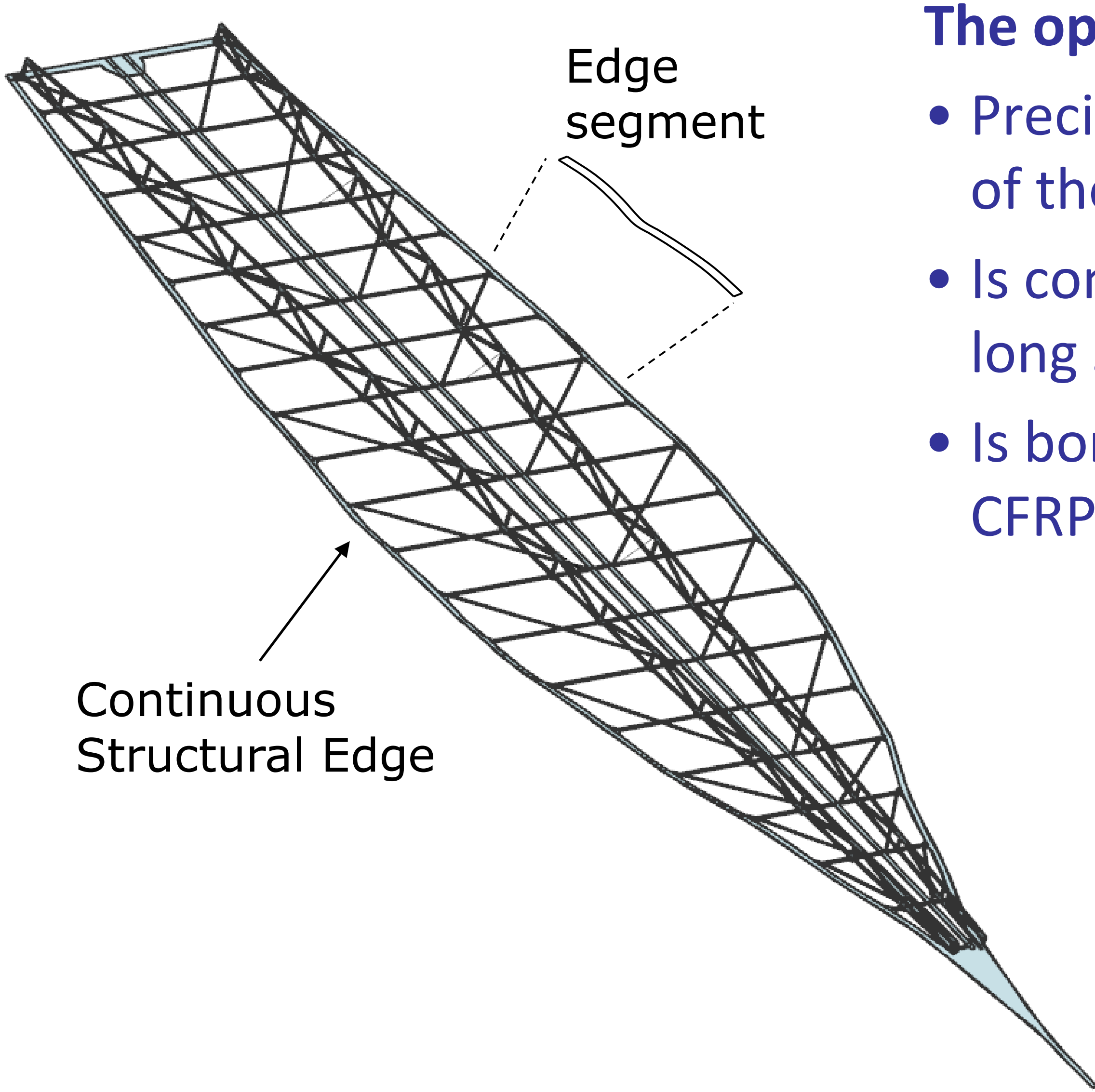
Milestone Definition

- *"Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles."*
- We interpret as follows:
  - Applies to full range of wavelengths and sun angles for WFIRST Starshade Rendezvous (SRM) and Habex missions.
  - Azimuthally averaged brightness at and beyond the inner working angle (IWA), which is nominally the angle from center to the outer tips of the starshade.
    - This is consistent with the planet being equally likely to appear anywhere around the IWA.
  - Testing includes:
    - Bend and release cycling
    - Deployed thermal cycling consistent with the expected number of thermal cycles.

Milestone Review was held with ExoTAC Jan 15, 2020

- ExoTAC concluded that Milestone 3 has been met.
- Some minor changes and clarifications to the report have been completed.
- A key result was that environmental testing, including thermal cycling and stowed bending and release did not significantly change the edge scatter performance.
- Some scatter degradation is observed due to the manufacturing process. This will be the focus of future work.
- After post-environmental testing had completed, we received game-changing coated edge coupons that improve glint performance by an order of magnitude. These will be fully characterized and tested in future work.

Optical Edge Design Overview

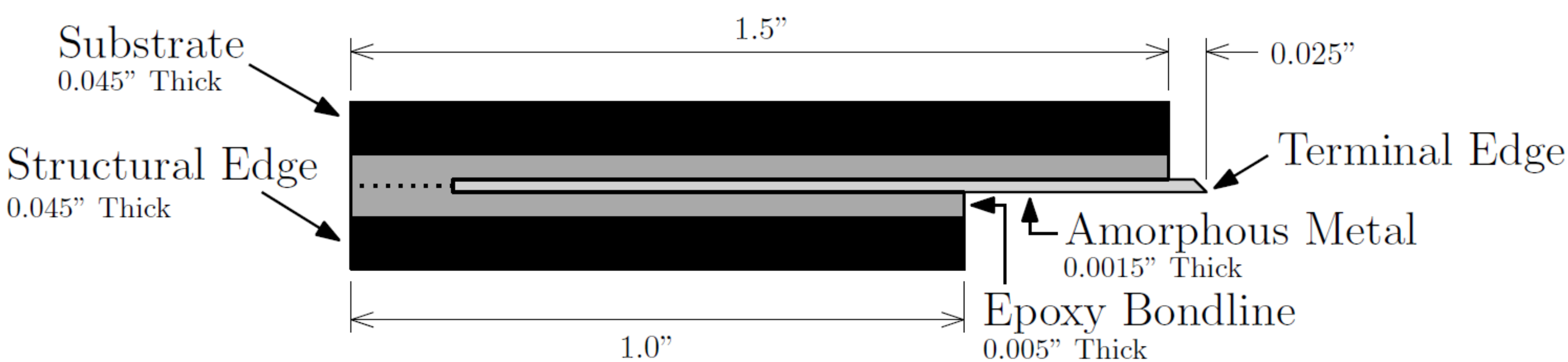


The optical edge:

- Precisely defines the perimeter of the petal
- Is constructed with 0.75-1.1m long segments
- Is bonded to the continuous CFRP structural edge

Optical Edge Cross Section

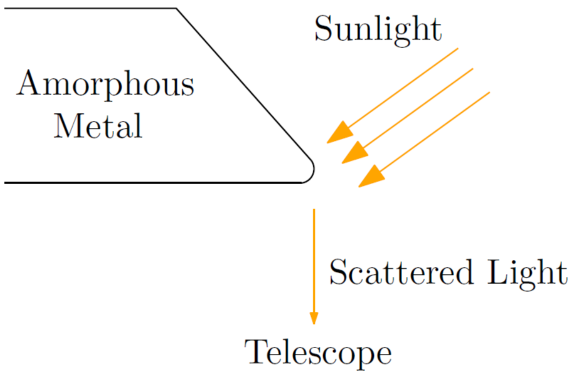
- The terminal edge is photochemically etched amorphous metal foil
- Substrate is used to lock in the etched shape before bonding it to the larger structure
- The structural edge is the outer perimeter of the petal structure
- A two step bonding operation using EA9394 is implemented
  - Glass beads used to enforce 0.005” bondline

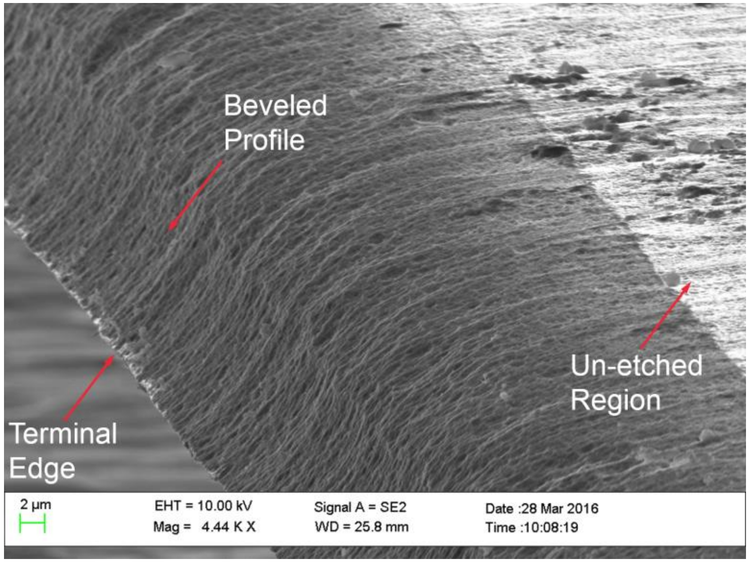


* Not to scale

Amorphous Metal

Minimizing the terminal radius reduces scattered sunlight





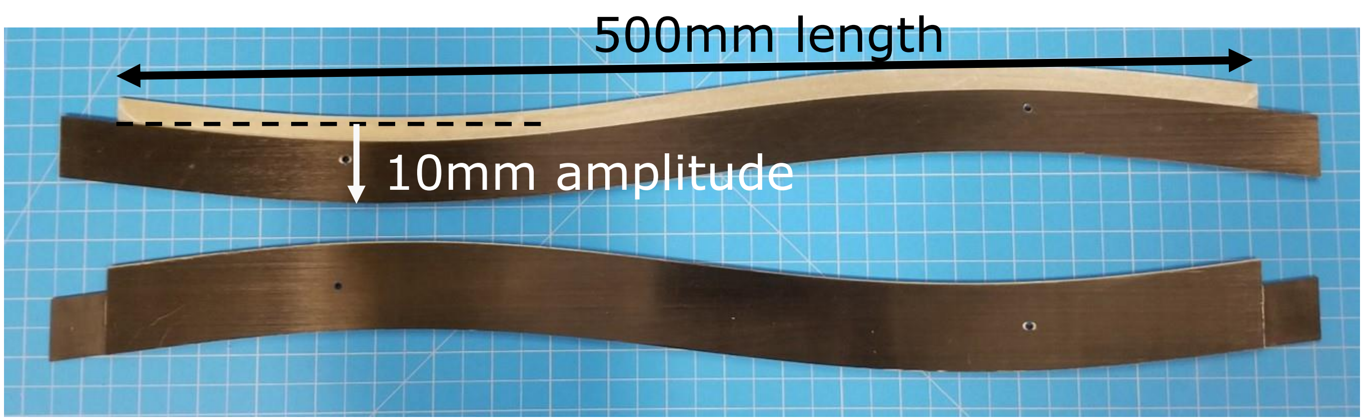
Etched amorphous metal yields a terminal radius of <1µm radius

Test Articles

ExoPlanet Exploration Program

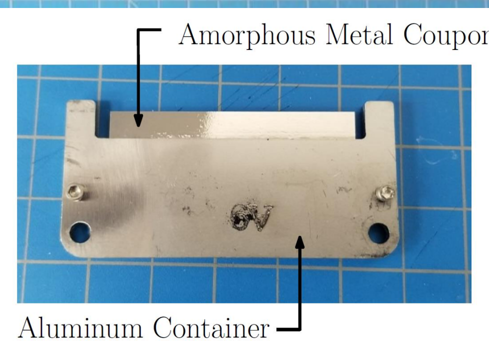
500mm long segment

- Half scale in length, but all other dimensions (thicknesses and widths) are full scale
  - Segment can be lengthened without affecting stresses in the cross section
- 10mm amplitude sine wave mimics curvature of petal



25mm x 50mm coupons

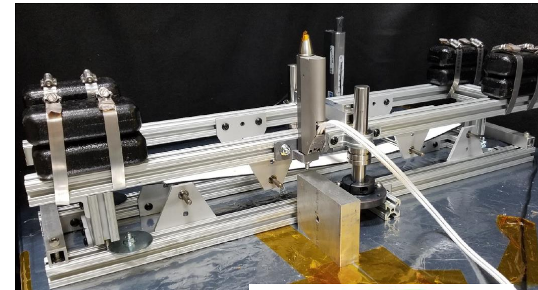
- Manufactured in parallel with segments

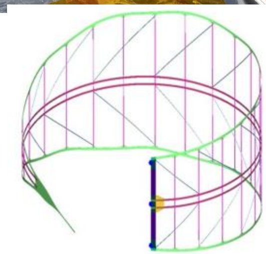


Experiments

Stow/Deploy Cycles

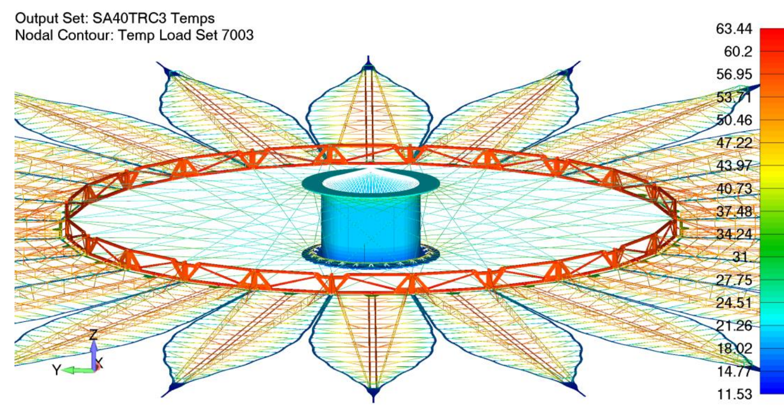
- Simulate the number of bend & release cycles that a flight article will experience
- Test articles stow 10x to a radius of 1.125m (stowed truss radius) using a 4pt bending fixture
  - Loads shown to be conservative relative to petal analysis





Deployed Thermal Cycles

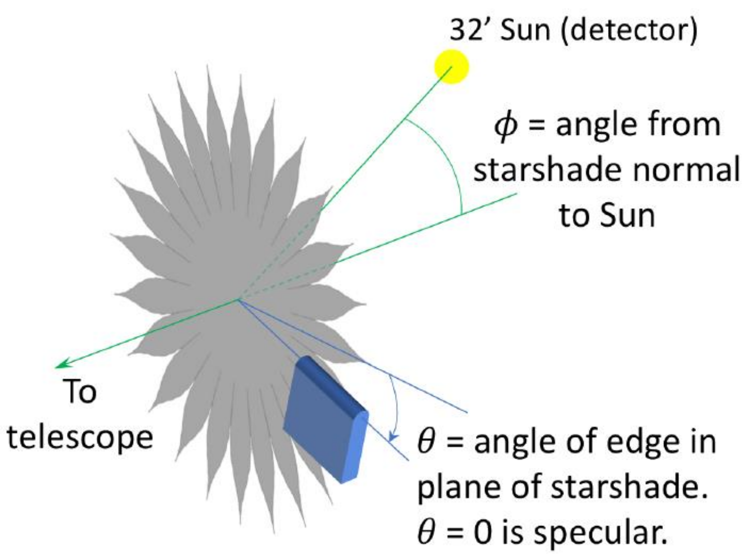
- Test Temperatures: +105°C / -125°C
  - Based on starshade system analysis
- Results in 25°C margin on hot, 29°C margin on cold side based on system thermal model
- Minimum of 25x cycles on each test article

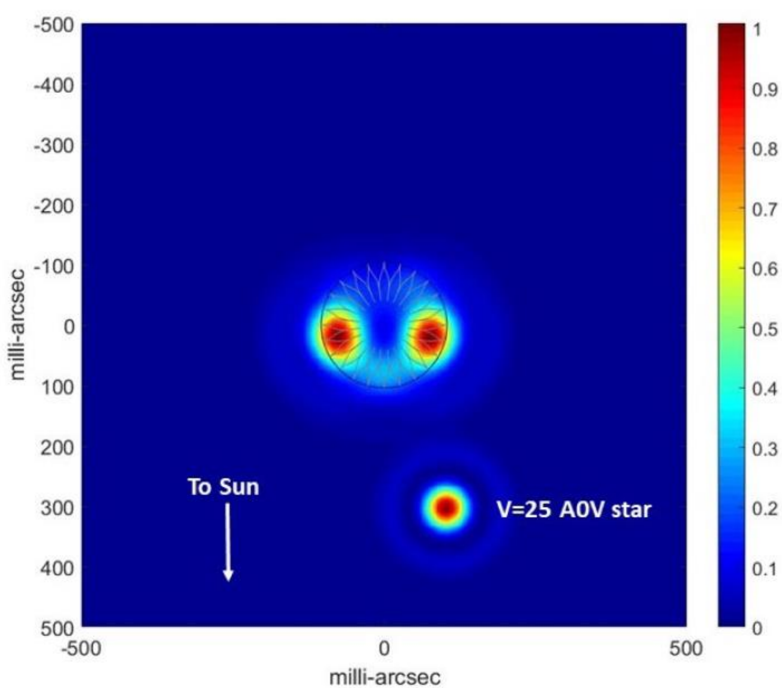


Representative system model, some components removed for clarity

Glint Geometry and Lobe Shape

- Based on testing over several years, we found that specular edges result in reduced overall scatter.
- Specular edges lead to two glint spots concentrated on the edges that are 'broadside' to the solar illumination.
- The reflection is polarization-dependent and we account for this in our calculations, and measure it with the multi-angle scatterometer (MAS). We measure 'S' polarization with the single-angle scatterometer (SAS).





Glint for Different Starshade Missions

$$Glint \propto \frac{L\lambda}{Z^2}$$

- L is total length of the starshade petals (scales linearly with diameter, varies with design).
- λ is wavelength. Glint is brightest in the red channels.
- Z is distance between the starshade and telescope
- Glint is nominally flat over the range of Sun angles (40-83 deg) with an ~ 50% uptick at the high end.
- Glint is a combination of reflected and diffracted light.

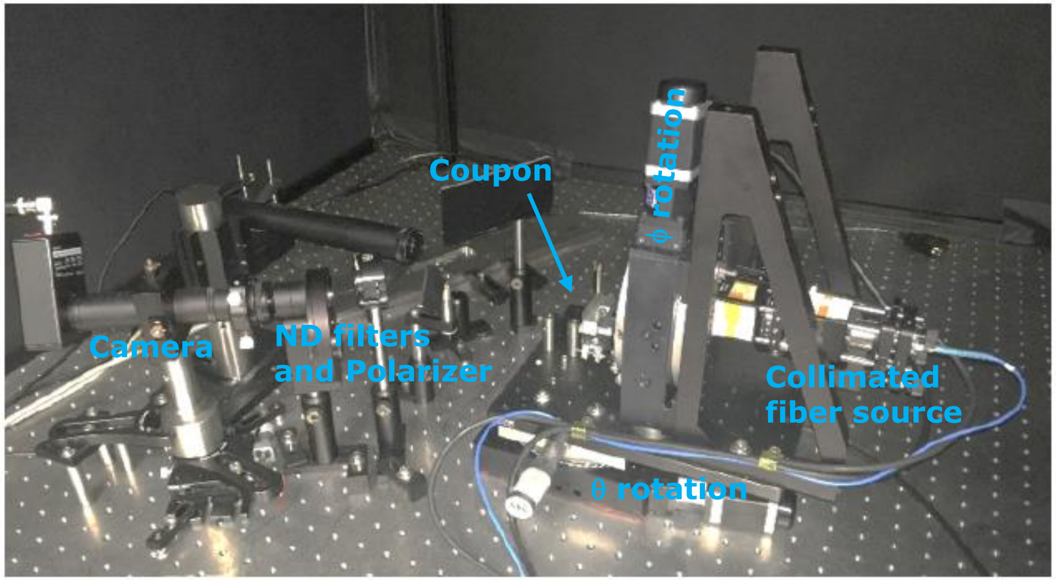
Table 1: Starshade Missions

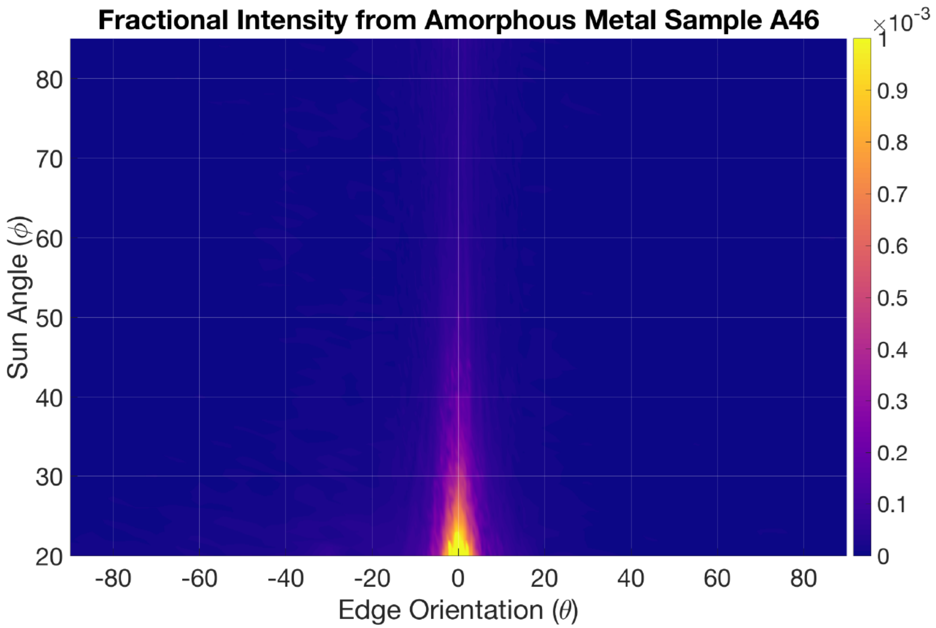
Mission	Bandpass	Starshade Diam.	Distance	Star-Sun Angle
SRM ('blue')	425-552 nm	26 m	37.2 Mm	54° - 83°
SRM ('green')	$\boxed{\text{615-800 nm}}$	26 m	$\boxed{\text{25.7 Mm}}$	54° - 83°
HabEx	300-1000 nm	52 m	76 Mm	40° - 83°

SRM "green" band is the driving case.

Optical Scatter Measurement Instrumentation: Multi-Angle Scatterometer (MAS)

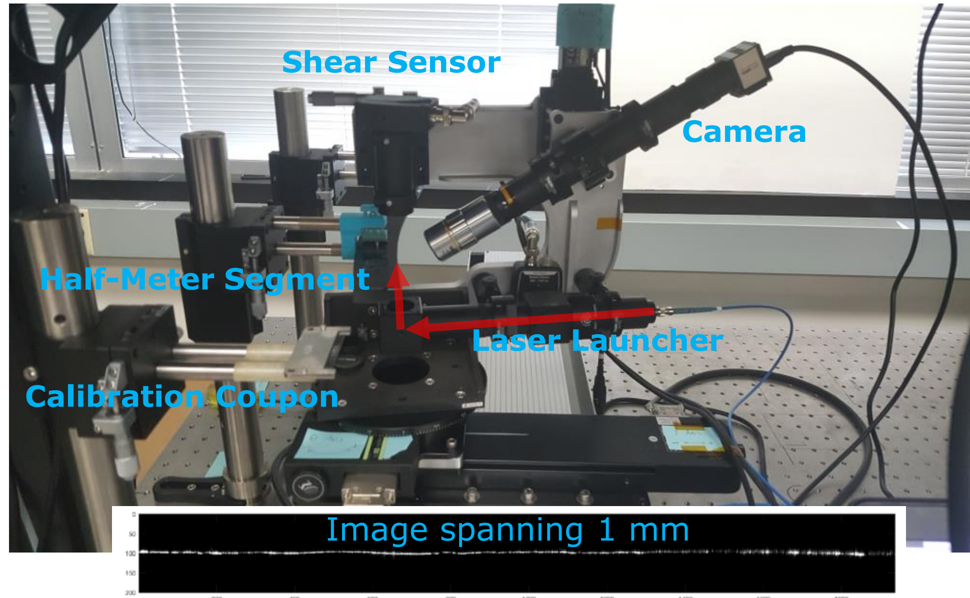
- The MAS measures a 3 mm region of a 50 mm long coupon.
- It rotates the sample in (θ,ϕ) to measure the scatter function.
- It is set up with a 30 arcminute field to mimic the angular size of the sun.
- It produces a scatter 'heatmap' showing the fractional scatter vs. angle.
- The fractional scatter is calibrated against the direct beam when the edge sample is removed.

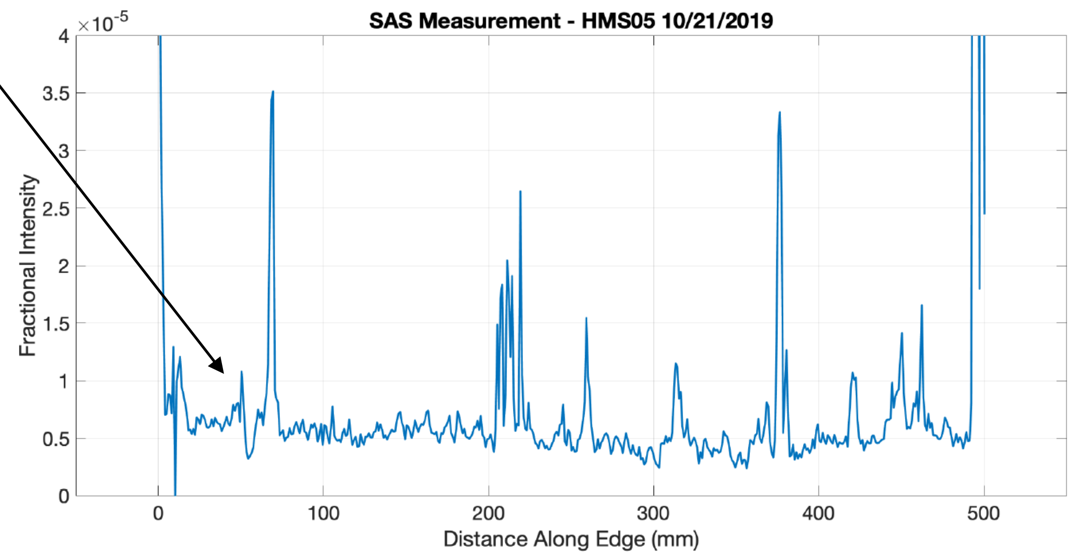




Optical Scatter Measurement Instrumentation: Single-Angle Scatterometer (SAS)

- The SAS measures the scatter over a fixed range of angles (nominally 30 deg wide) spanning 45 – 75 deg.
- It measures along the length of an edge segment or coupon with ~ 10 um resolution.
- Measurements are typically averaged over 1 mm.
- Typically measure the ‘S’ polarization
- SAS does not measure an absolute scatter value: by measuring coupons, we determine the scale factor between the MAS and SAS.





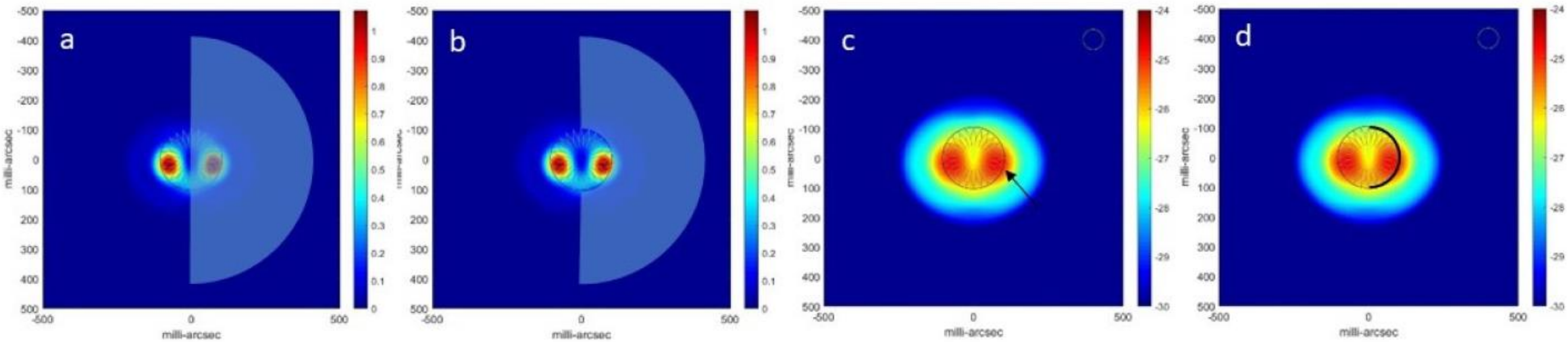
Experiment Error Budget

- The largest source of error is the long-term (months) repeatability of the MAS (10%).
- Other significant errors are mainly due to the finite sizes of the data sets and intrinsic differences between samples (including segment assembly issues).
- Assuming the error sources are uncorrelated, the overall performance is estimated to be 17.6%.
- This translates to a 95% confidence level of 0.28 visual magnitudes.

Table 5: Sources of Error in Estimating Solar Glint Lobe Brightness

Parameter	error (1-σ)	Notes
INSTRUMENT		
MAS repeatability	10 %	std. dev. of Instrument repeatability on a coupon (3 mm spot)
MAS scatter calibration	5 %	Knowledge of open beam ND filter OD
MAS length scale	2 %	Accuracy of distance from coupon edge to aperture (300 mm)
SAS Repeatability	0.9 %	std. dev. of instrument repeatability on a coupon (3 mm lengths)
COUPONS		
Mean coupon scatter (MAS)	7.6 %	SEM of coupon-to-coupon variability integrated over full range of angles
Mean coupon selection ratio ρ (MAS)	4.8 %	SEM of the ratio of coupon cone scatter to coupon full scatter
Mean coupon scatter (SAS)	6.4 %	SEM of coupon-to-coupon integrated scatter
Mean MAS to SAS ratio	3.8 %	SEM of relative cone scatter of same 3 mm spot measured on each instrument
SEGMENTS		
Mean segment scatter (SAS)	4.5%	SEM of segment-to-segment average scatter
ANALYSIS		
Imaging Code (SISTER) MUF	5 %	Consistency between analytical model and SISTER glint lobe
TOTAL		
Root Sum Square Error	17.6 %	Estimated 1 σ error on glint lobe brightness
Delta Mag 95% confidence	-0.28	1.65 σ

Glint Lobe Analysis



- TOTAL LIGHT PER LOBE
- Integrate all the scatter over half the plane
- Convert integrated flux into equivalent visual magnitude.

- TOTAL LIGHT PER LOBE OUTSIDE IWA
- Integrate all the scatter over half the plane starting at the IWA (103 mas for the green band)
- Convert to equivalent V.

- BRIGHTEST PHOTOMETRIC PIXEL OUTSIDE IWA
- Convolve to λ/D-diameter photometric resolution
- Convert flux to equivalent V.

- AVERAGE MAG AT IWA
- Convolve to λ/D-diameter photometric resolution
- Determine average flux level at IWA.
- Convert average to equivalent V.

Lobe Brightness Results

ExoPlanet Exploration Program

- Results include SCSR = 1.41 (delta mag = -0.37)
- Bold column includes experimental 95% confidence delta mag = -0.28

Table 6: Estimated Glint Lobe Magnitude in WFIRST Rendezvous 425-552 nm Band

ϕ	Lobe mag	r>IWA mag	IWA Phot. min. mag	IWA Phot. Avg. mag	**IWA Phot. 95% conf.**	IWA, V>25 Compliance
53	25.8	26.8	26.7	27.6	**27.3**	100%
63	25.9	26.9	26.9	27.7	**27.5**	100%
73	25.7	26.7	26.7	27.5	**27.3**	100%
83	25.2	26.2	26.2	27.0	**26.7**	100%

Table 7: Estimated Glint Lobe Magnitude in WFIRST Rendezvous 615-800 nm Band

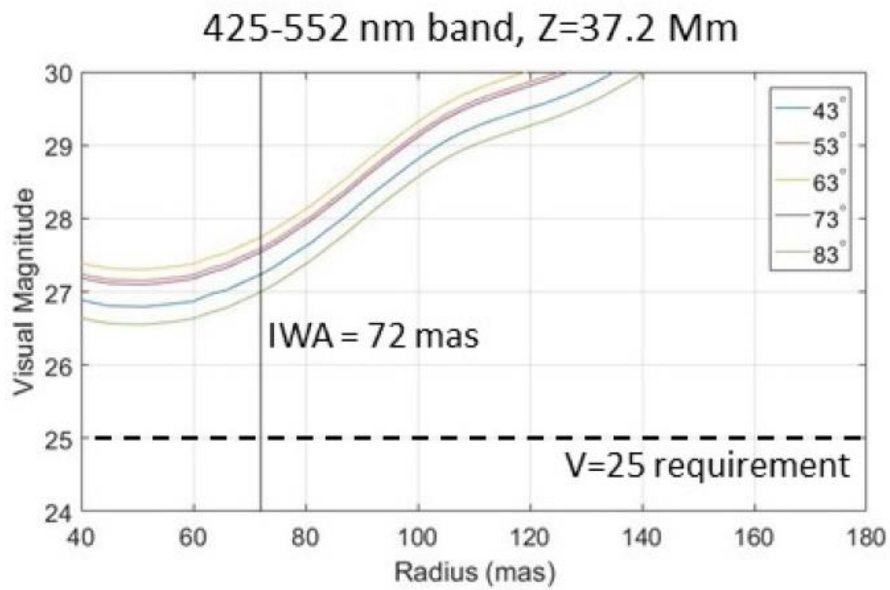
ϕ	Lobe mag	r>IWA mag	IWA Phot. min. mag	IWA Phot. Avg. mag	**IWA Phot. 95% conf.**	IWA, V>25 Compliance
53	23.7	24.7	24.6	25.5	**25.2**	67%
63	23.8	24.9	24.8	25.6	**25.4**	71%
73	23.6	24.7	24.6	25.4	**25.2**	64%
83	23.1	24.1	24.1	24.9	**24.6**	40%

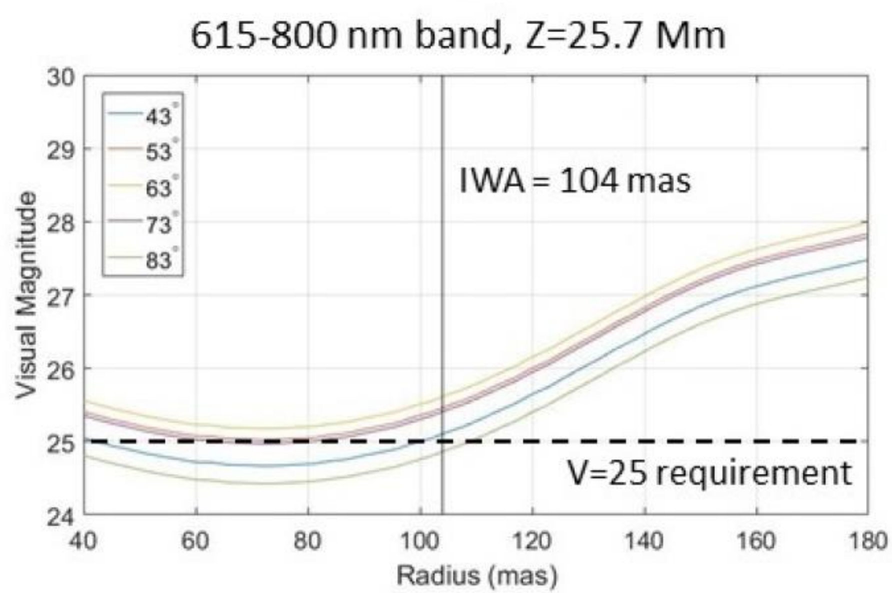
Table 8: Estimated Glint Lobe Magnitude for HabEx 300-1000 nm band

ϕ	Lobe mag	r>IWA mag	IWA Phot. min. mag	IWA Phot. Avg. mag	**IWA Phot. 95% conf.**	IWA, V>25 Compliance
35	25.0	26.4	26.4	27.5	**27.2**	100%
45	25.6	27.0	27.1	28.1	**27.8**	100%
55	25.9	27.3	27.4	28.4	**28.1**	100%
65	26.0	27.4	27.5	28.4	**28.2**	100%
75	25.8	27.1	27.3	28.2	**27.9**	100%
85	25.2	26.6	26.7	27.6	**27.3**	100%

Lobe Brightness vs. Working Angle

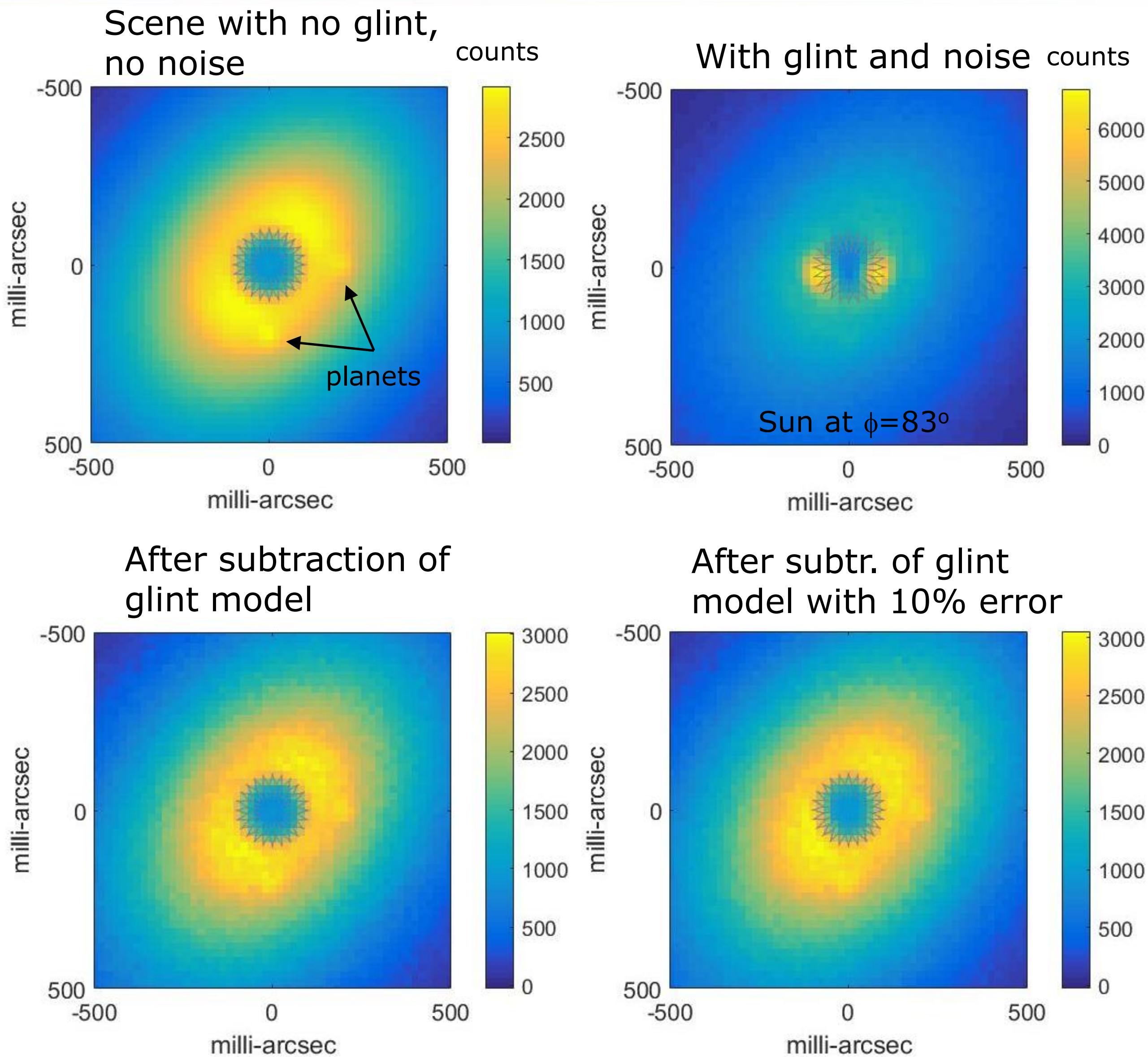
- All of the glint is generated within the IWA.
- The telescope resolves the glint spots into sidelobes that extend beyond the IWA.
- There is a 1 stellar magnitude drop after ~20 mas (blue band) and ~30 mas (green band).
- Similar behavior but 2.5 mag fainter for HabEx (not shown here).





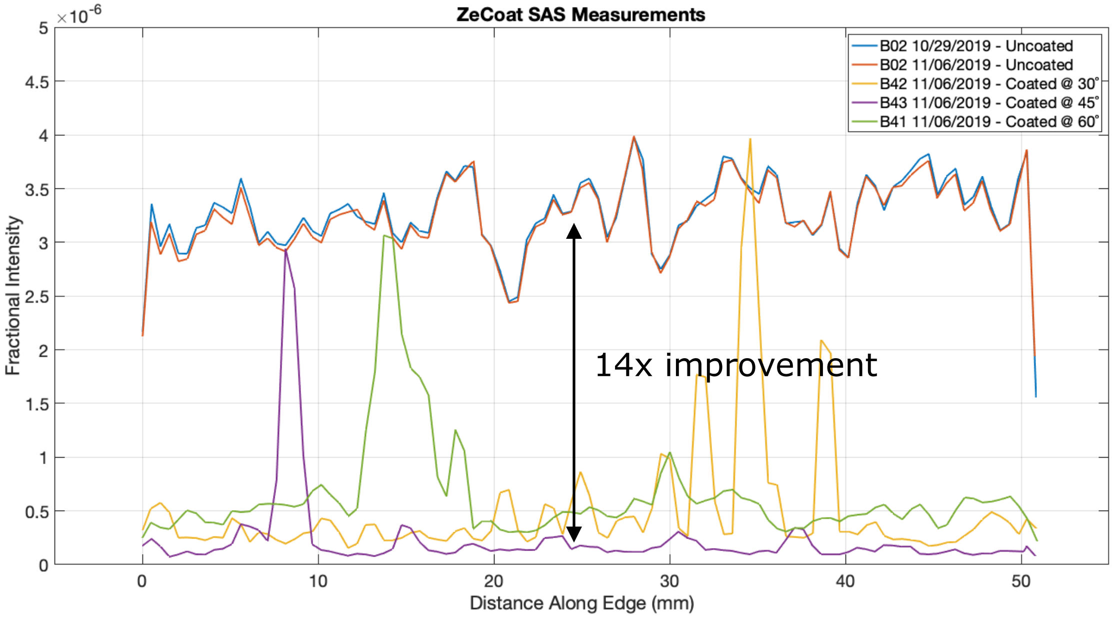
SRM Performance Assessment Example
(Earth-like planets around Tau Ceti)

- V=3.49, Dist = 3.65, L=0.52L_{sun}
  - EEID = 197 mas.
  - Earth at quadrature would be 1.92e-10 contrast. V=28.
- Exozodi density = 4, inclined 46.5 deg, P.A. = 52 deg.
- Observing band 620-800 nm.
- 1 day exposure, throughput = 0.1, shot noise and dark current only, 20 mas pixels.
- For SRM, the glint lobes are bright but their shot noise is not prohibitively large.
- In this example, the accuracy of the subtraction is not critical, but in some cases the requirement could be <10% glint lobe estimation error.

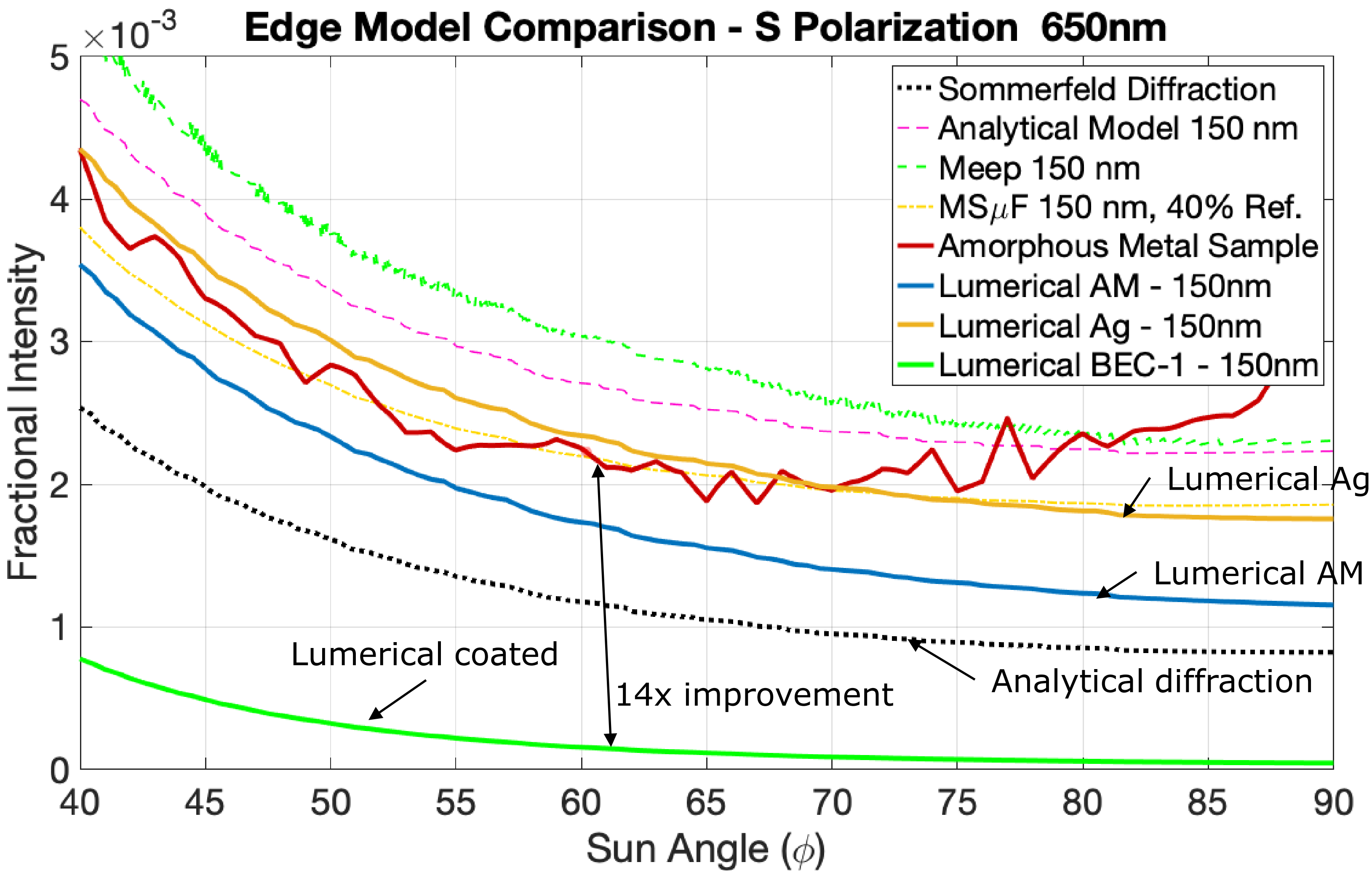


Coated Edge Performance

- Zecoat coated amorphous metal coupons with a thin hybrid-dielctric coating.
- We measured them in the SAS. They are at least 10x darker than uncoated edges.
- This is darker than the theoretical diffraction limit.
- The coating has a reflection component that is cancelling the diffraction – we think.
- We have been modeling this using Finite Difference Time Domain software and verify the observed improvement (see next slide).
- We are modifying the MAS to have adequate sensitivity to measure the coupons.



FDTD Models of Coated Edge Scatter



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Conclusions

- 500 mm long edge segments had on average 1.41x more scatter than unmounted coupons.
  - Difference is partially attributed to damage/defects caused by a non-optimal assembly process: primary issue may be epoxy on the terminal edge.
- No significant degradation from environmental testing (3% observed).
- Experimental precision was 0.28 mag (95% confidence), mainly due to instrument repeatability and small sample sizes.
- Average glint level at the IWA is fainter than V=25 for Habex and for SRM in the 'blue band' 425-552 nm.
- The average glint level in the SRM 615-800 at a sun angle of 83 deg is V=24.6. The compliance fraction is 0.4.
- Solar glint is the brightest source of instrument scatter. Mitigation is possible: edges coated with a thin AR coating have shown >10x reduction in scatter and are actively being pursued.

Backup Material

Test Article History

- Of the six assembled prototype edges, four were used for MS3 testing
- Coupons were not put through bend and release testing due to their small size.

	Bend and Release		Deployed Thermal Cycles	
	# Cycles	Bend Direction	# Cycles	Temperature (C)
SN05	10	Tension	25	+105/-125
SN06	10	Compression	50	
SN07	10	Compression	25	
SN08	10	Tension	25	
Coupons	N/A	N/A	50	

Overall Experiment Flowchart

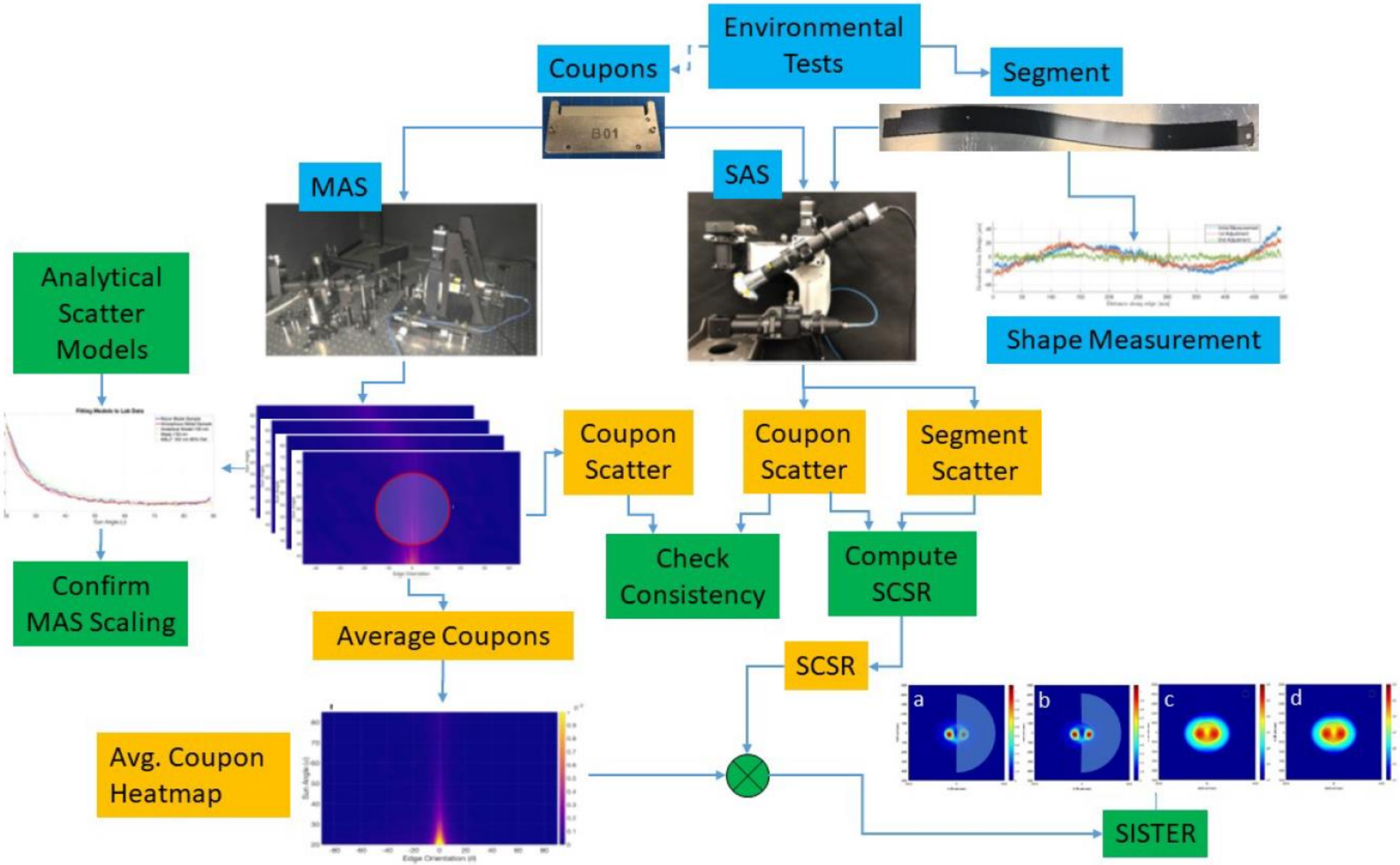


Figure 12: Overall experiment implementation. Orange boxes are data. Blue boxes are hardware. Green boxes are software and analysis tools.

Linking MAS and SAS measurements

- The MAS measures the scatter over all relevant angles, while the SAS measures scatter over the acceptance cone of its microscope.
- For a set of representative coupons, there is good consistency between the cone and the full range of angles measured on the MAS (SEM = 4.8%) .
- There is good consistency between the SAS and the MAS (SEM = 3.8%)
- **Thus, for coupons there is good consistency between the SAS and on-sky performance.**

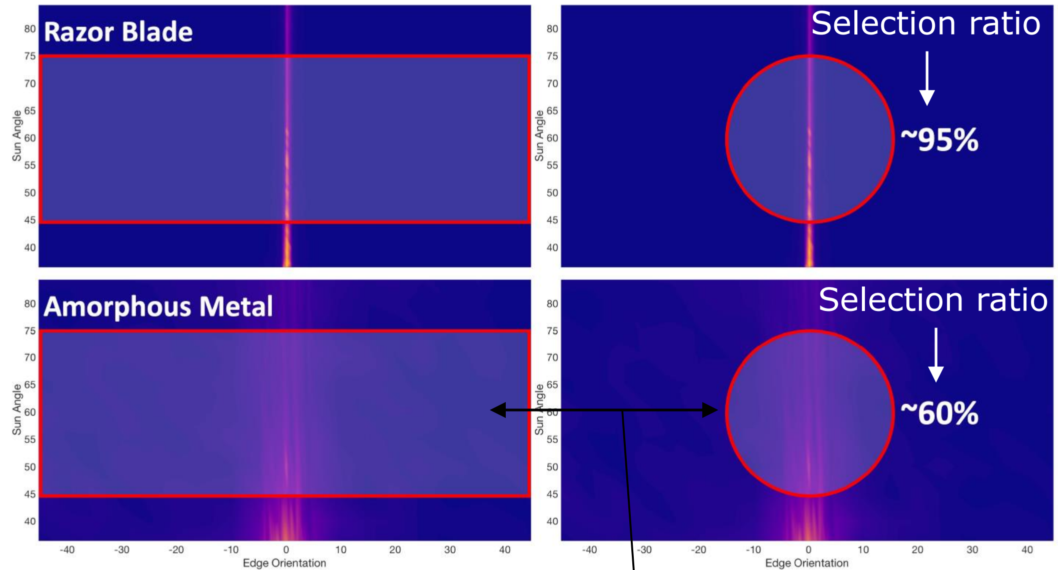


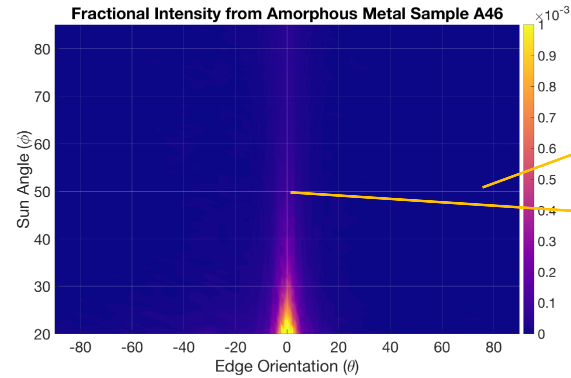
Table 3: Selection ratio for amorphous metal edge coupons

Coupon	MAS full	MAS cone	MAS ρ	SAS	MAS cone / SAS
A14 10/07/2019	6.8	4.6	0.67	4.3	1.05
A21 10/07/2019	7.3	5.0	0.68	4.6	1.08
A23 10/07/2019	8.8	5.2	0.60	4.8	1.09
A26 10/18/2019	7.3	3.1	0.42	3.6	0.86
A58 04/29/2019	8.4	4.7	0.56	3.9	1.19
B02 05/08/2019	6.6	4.1	0.62	3.4	1.20
B03 10/18/2019	5.5	2.6	0.48	3.0	0.87
B27 10/22/2019	4.9	3.4	0.69	3.6	0.92
B28 10/19/2019	3.6	1.6	0.45	2.1	0.77
B29 10/19/2019	4.6	3.1	0.66	3.4	0.90
B30 08/08/2019	4.1	2.4	0.57	2.5	0.95
B31 08/07/2019	5.3	3.8	0.71	3.9	0.96
B32 08/07/2019	6.0	4.2	0.70	4.3	0.98
MEAN$\pm$SEM	6.08$\pm$0.46	3.66$\pm$0.31	0.60$\pm$0.03	3.66$\pm$0.23	0.98$\pm$0.04
FRAC	**7.6%**	8.6%	**4.8%**	6.3%	**3.8%**

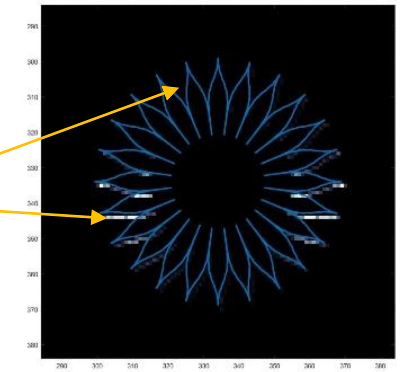
Relating the MAS Heat Map to On-Sky Performance using SISTER

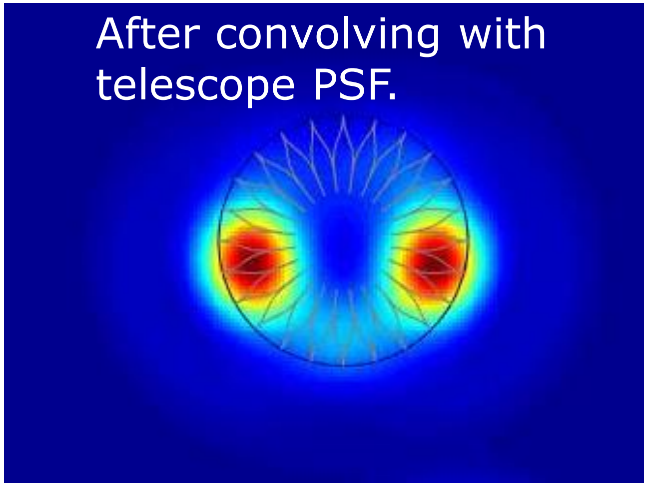
- SISTER = Starshade Imaging System Toolkit or Exoplanet Reconnaissance
- Reads the starshade petal locus file, determines orientation of edges relative to the Sun.
- Reads the MAS heat map and picks out the cell matching each edge locus orientation, scaling the cell for the distance of the starshade, the length of the segment, and the wavelength.
- Multiplies by the solar spectrum.
- Convolves the pattern with the telescope PSF.
- Calibration is performed using a 1 m long edge segment and a heat map generated from an ideal half-plane analytical model (diffraction only).

Heat map



High-Res scatter pattern





- Comparison between the SISTER imaging result and a spreadsheet prediction using the analytical model was consistent to 0.05 mag (5%).

Link Between Coupons and Segments

- Segments define on-sky performance.
- The SAS measures segments and coupons.
- The relative performance is called the Segment to Coupon Scatter Ratio (SCSR).
- We found that post-environment, the segments were 1.41x brighter than coupons (measurement SEM = 7.8%).
- **We also found no significant difference (3%) between pre-and post environment performance.**

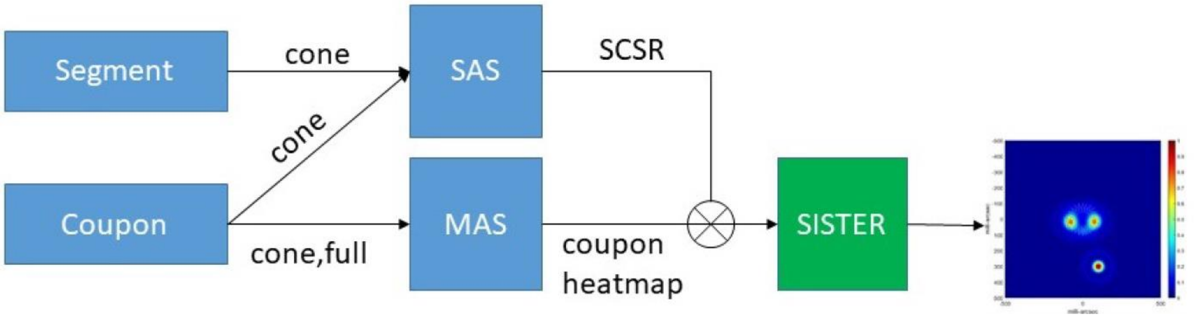
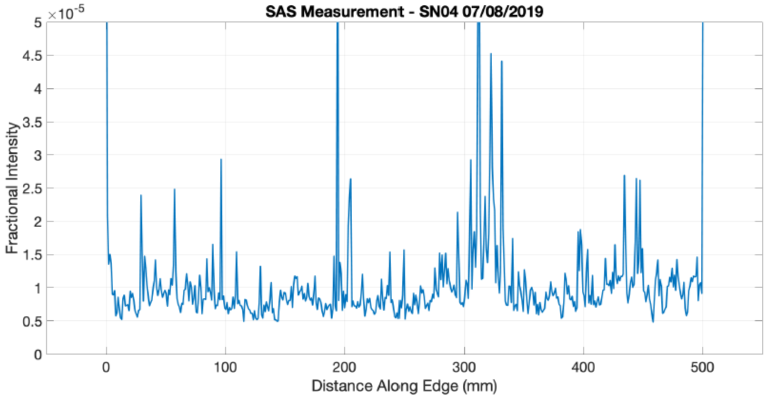
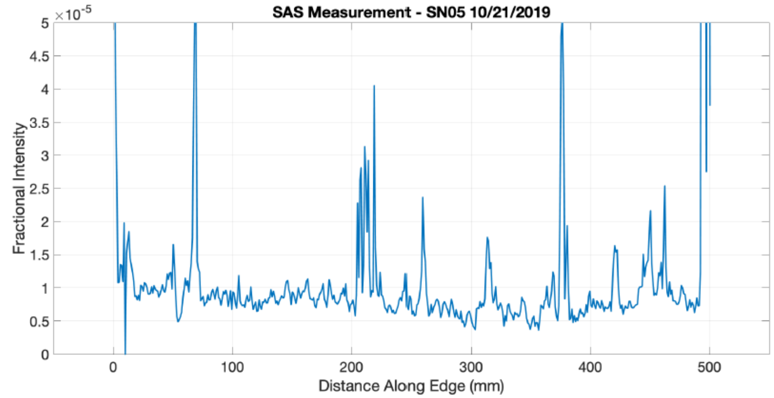


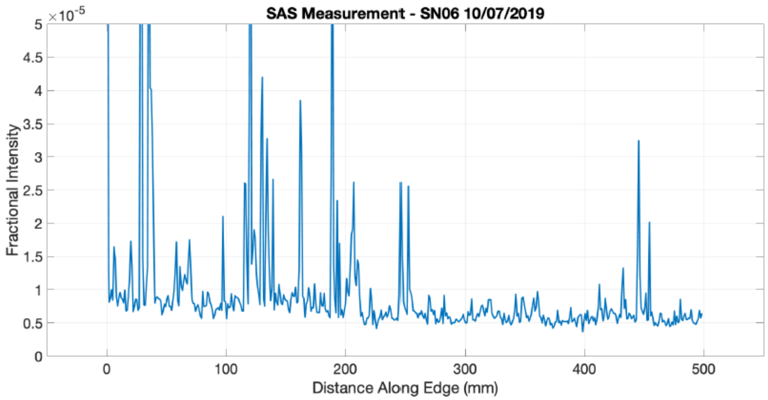
Table 4: SAS Coupon and Segment Measurements

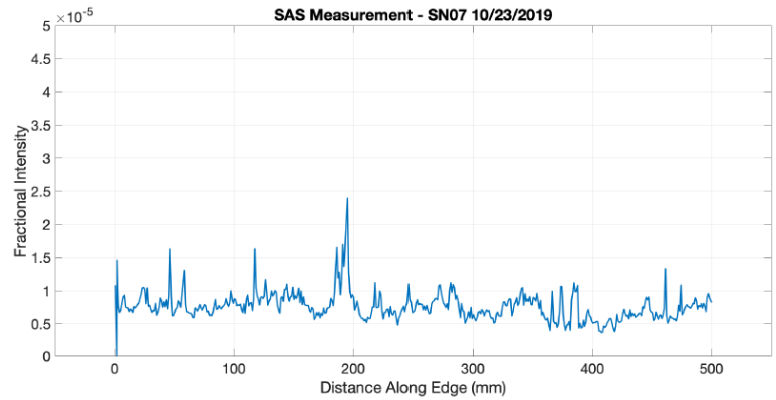
Coupon Name	Date	1e6*Scatter
A14	2019-10-22	6.1
A21	2019-10-22	6.8
A23	2019-10-22	7.1
A26	2019-10-21	5.3
A58	2019-10-18	5.9
B02	2019-10-21	5.0
B03	2019-10-18	8.8
B27	2019-10-22	5.5
B28	2019-10-22	3.8
B29	2019-10-22	5.1
B30	2019-10-22	4.2
B31	2019-10-22	7.2
B32	2019-10-22	6.8
MEAN±SEM (SEM%)		5.97±0.38(**6.4%**)
Segment Name		
SN05	2019-10-21	9.2
SN06	2019-10-07	8.7
SN07	2019-10-23	7.5
SN08	2019-10-23	8.3
MEAN±SEM (SEM%)		8.44±0.38 (**4.5%**)
Segment to Coupon Scatter Ratio (SCSR)		1.41 ±0.11 (7.8%)

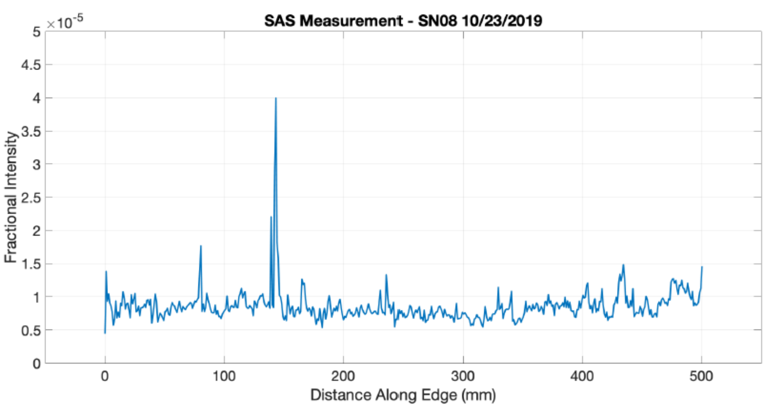
Segment Scatter Plots
Post-Environmental Testing

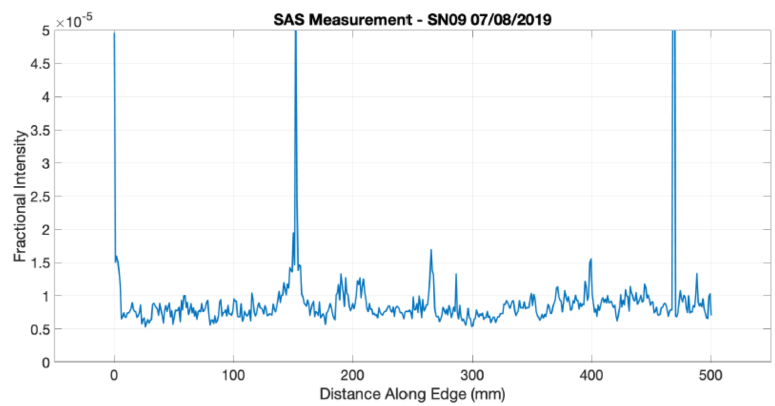




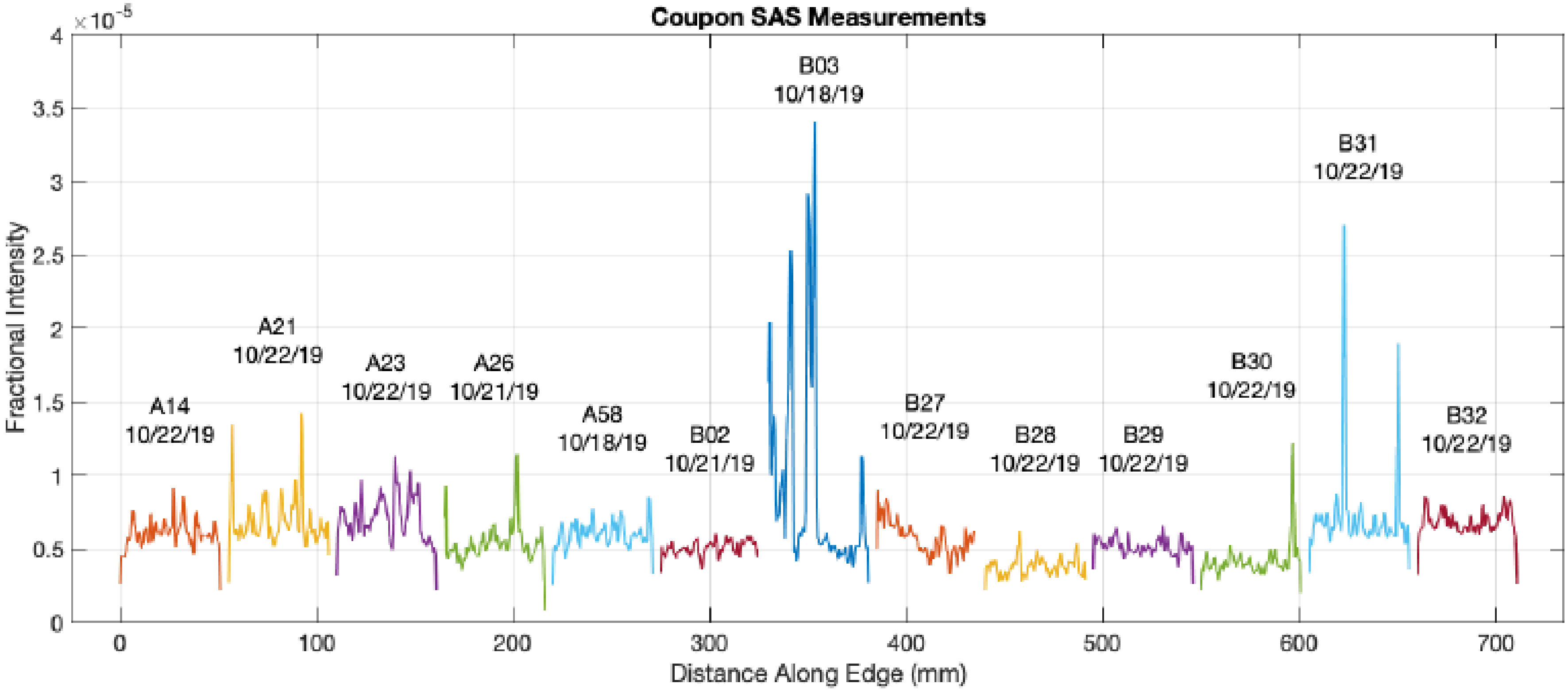




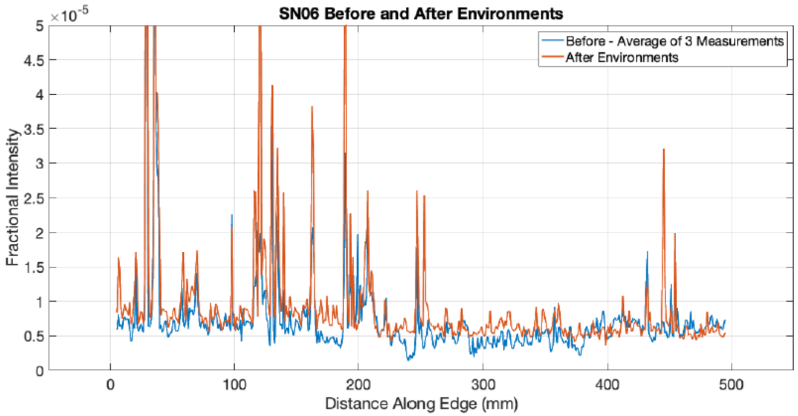


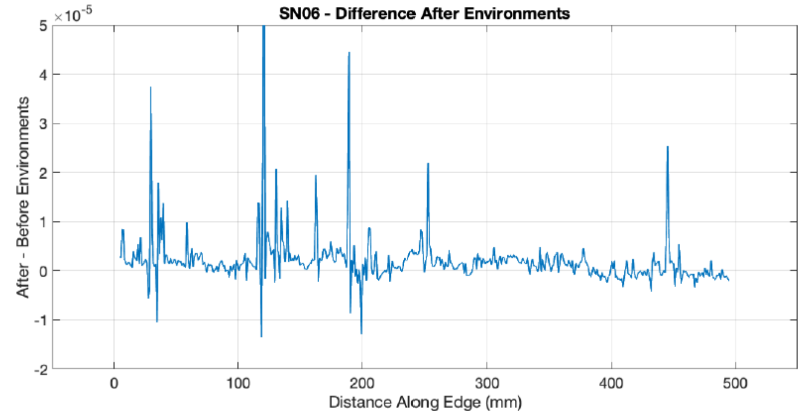


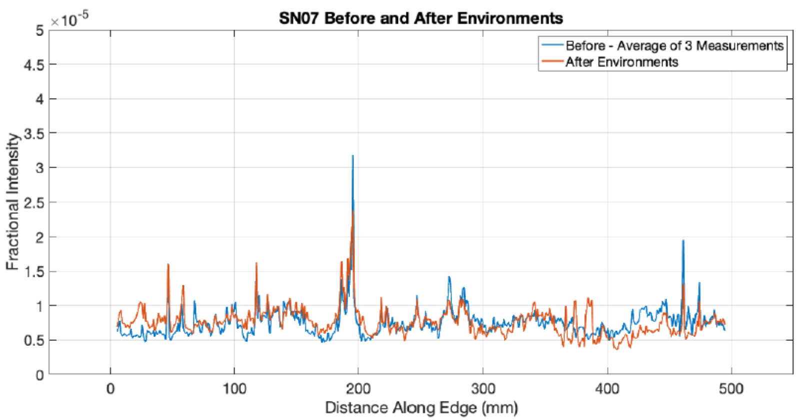
Coupon Measurements

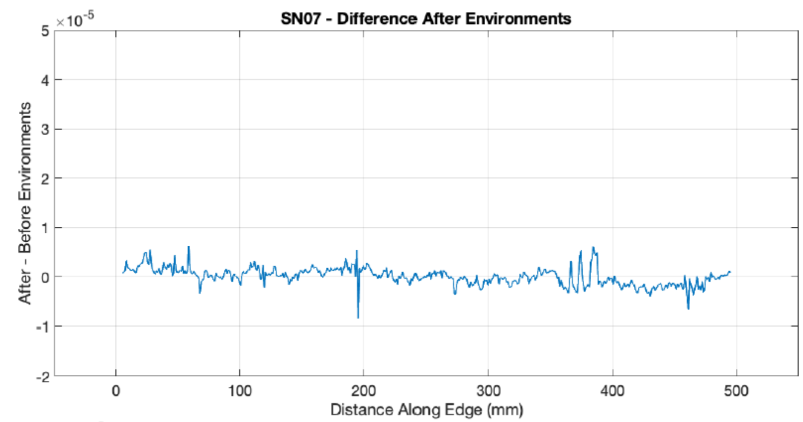


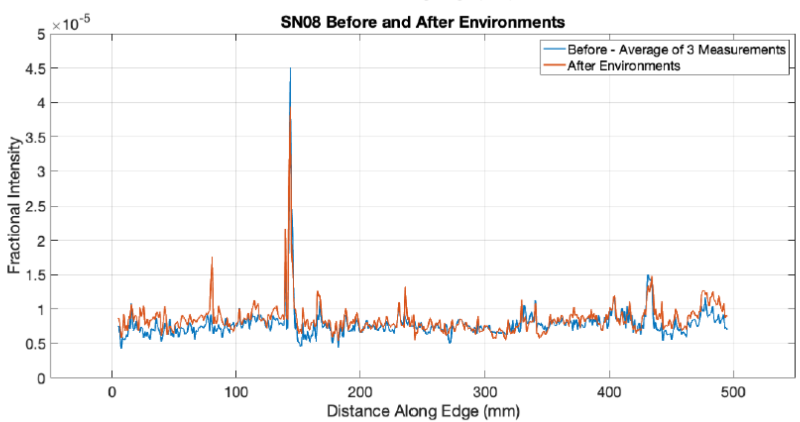
Segment Scatter
Before and After Environmental Tests

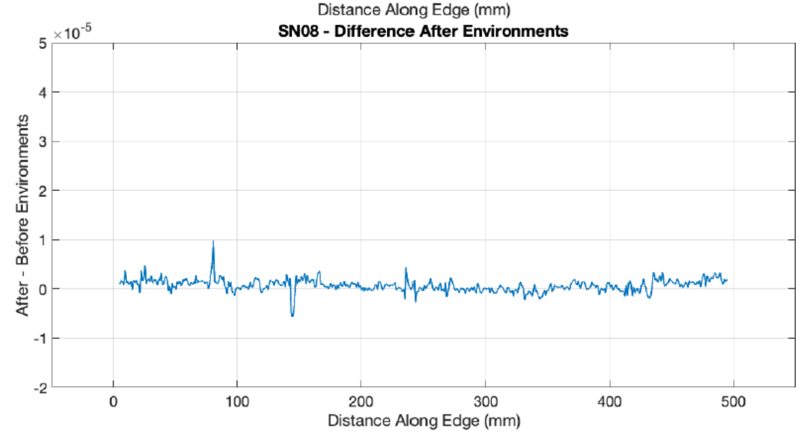










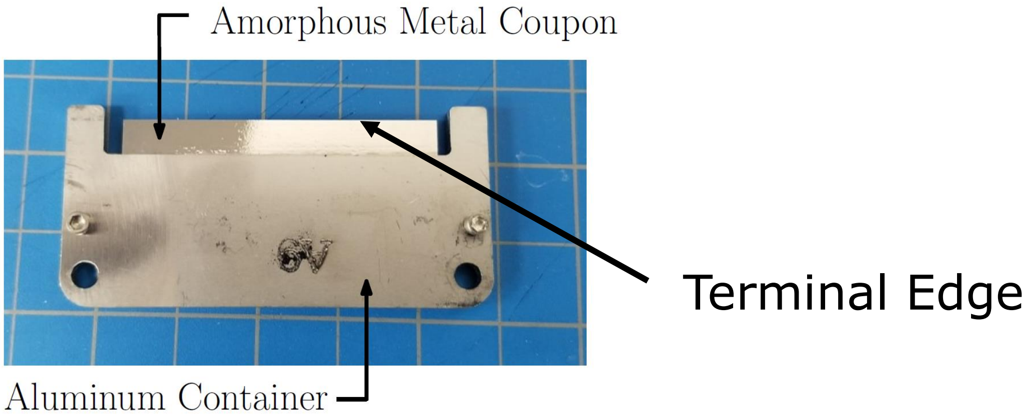


Test Articles: Two types

500mm long segment

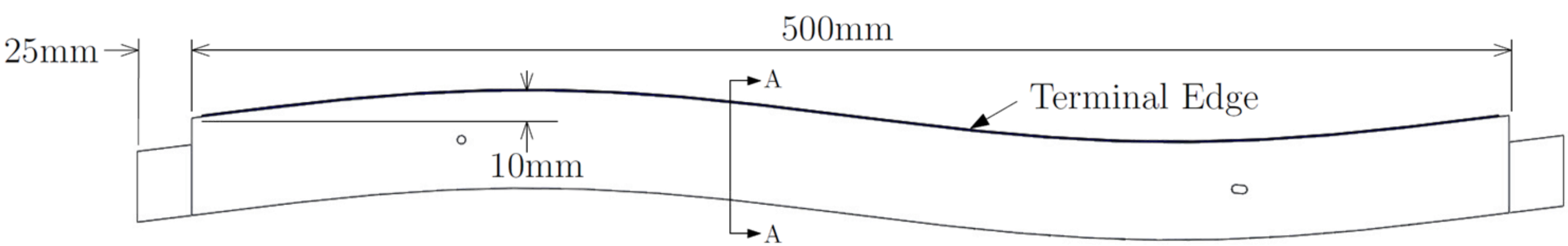
25mm x 50mm coupons

- Manufactured in parallel with segments

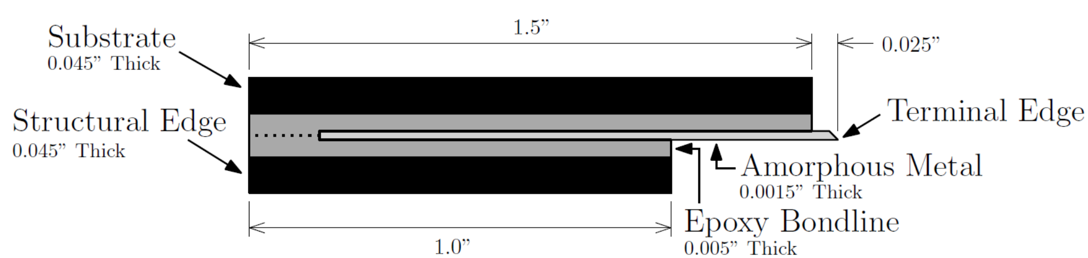


Segment Layout

- Half scale in length, but all other dimensions (thicknesses and widths) are full scale
  - Segment can be lengthened without affecting stresses in the cross section
- 10mm amplitude sine wave mimics curvature of petal
- Structural edge tabs protrude 25mm on each end to mimic continuous nature of petal



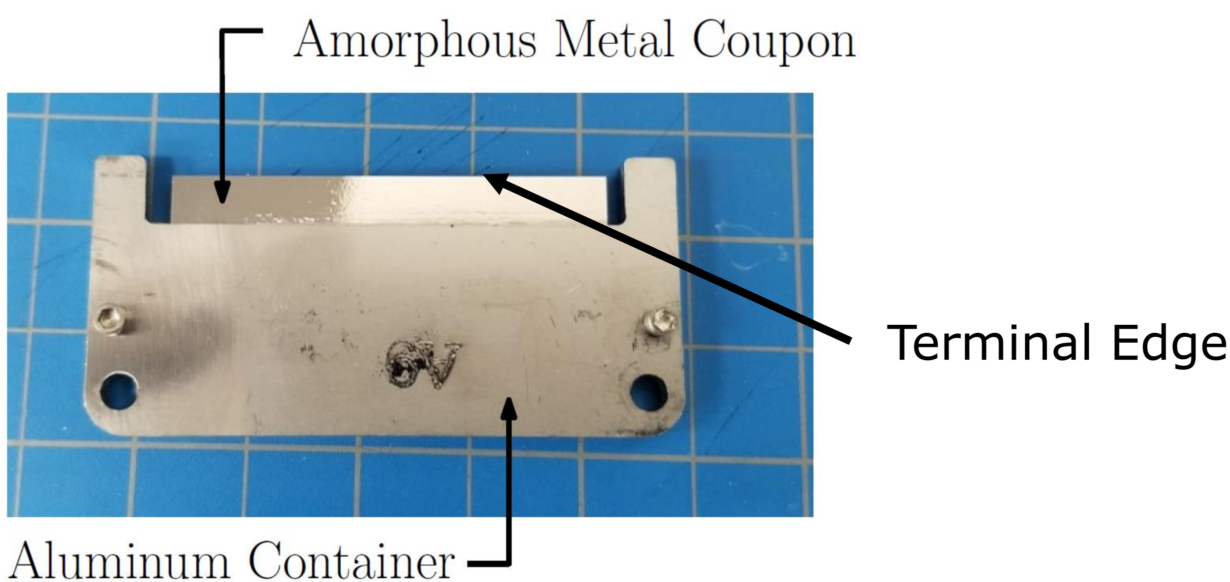
- Cross section is identical to previous



Section A-A

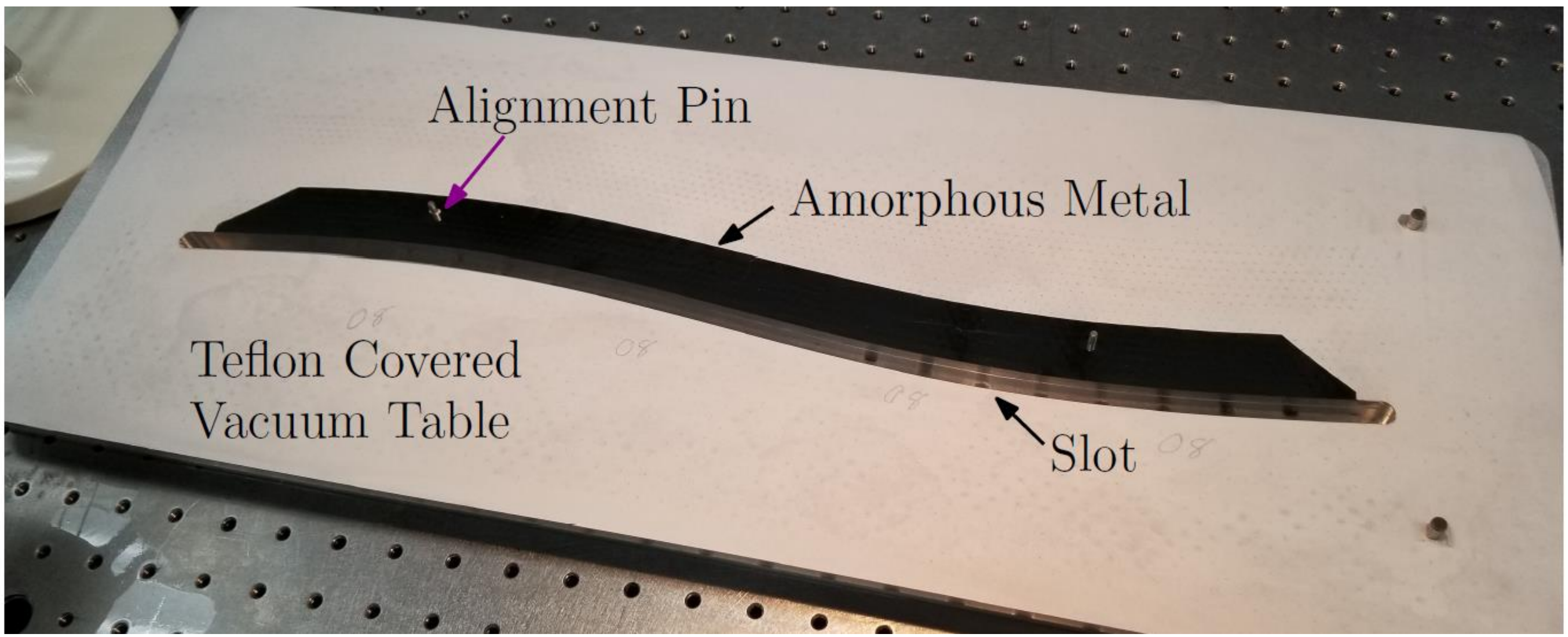
Coupon Fabrication

- 25mm x 50mm coupons were manufactured to enable characterization of edge over all possible sun angles.
- Coupons were etched in the same batch as the segment amorphous metal
- Coupons are clamped in an aluminum container to enable safe handling while retaining access to the terminal edge



Segment Fabrication

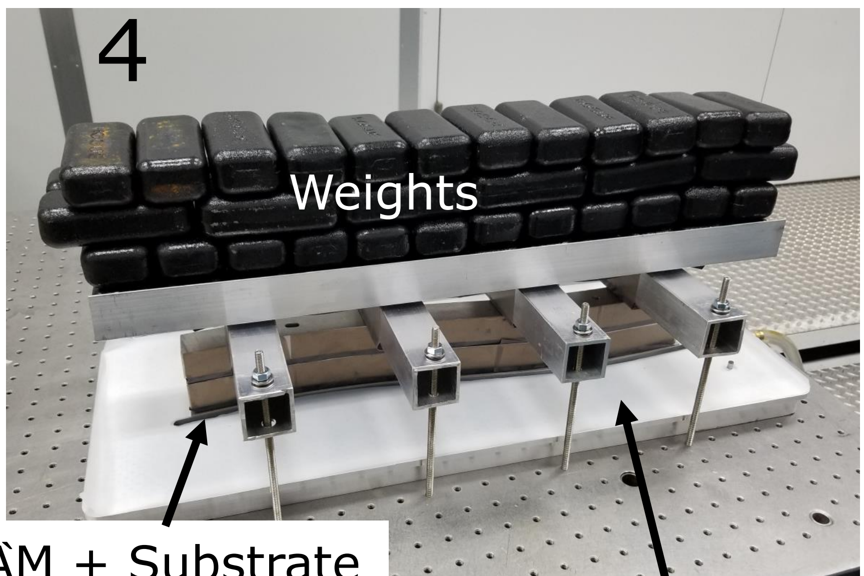
1. The terminal edge is chemically etched from the amorphous metal foil.
2. The foil is secured using a vacuum table and is cleaned prior to bonding



Segment Fabrication

3. The substrate is abraded and cleaned, and epoxy applied by screeding.

4. The substrate is then placed on top of the amorphous metal and pressure applied using weights.



`AM + Substrate (not visible)

Vacuum Table

CFRP substrate post-screeding operation

5. A similar process is used to adhere structural edge to substrate + AM assembly

4 Point Bending Fixture – Notes on Loading

4pt bending loads were compared to a stowed petal FEA to verify the bending moment and shear loads are appropriate

4 Point Bending

$$M_{max} = F \cdot x \qquad V_{max} = F$$

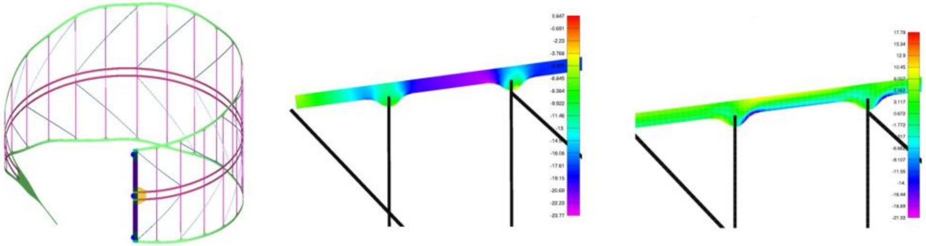
F: Force applied to a pin, estimated from bulk material properties

X: Distance along segment

$$M_{max} = 33.7\ in \cdot lbs$$
$$V_{max} = 7.3\ lbs$$

Stowed FEA Model

Loads modeled throughout deployment cycle. Max moment and shear along edge checked

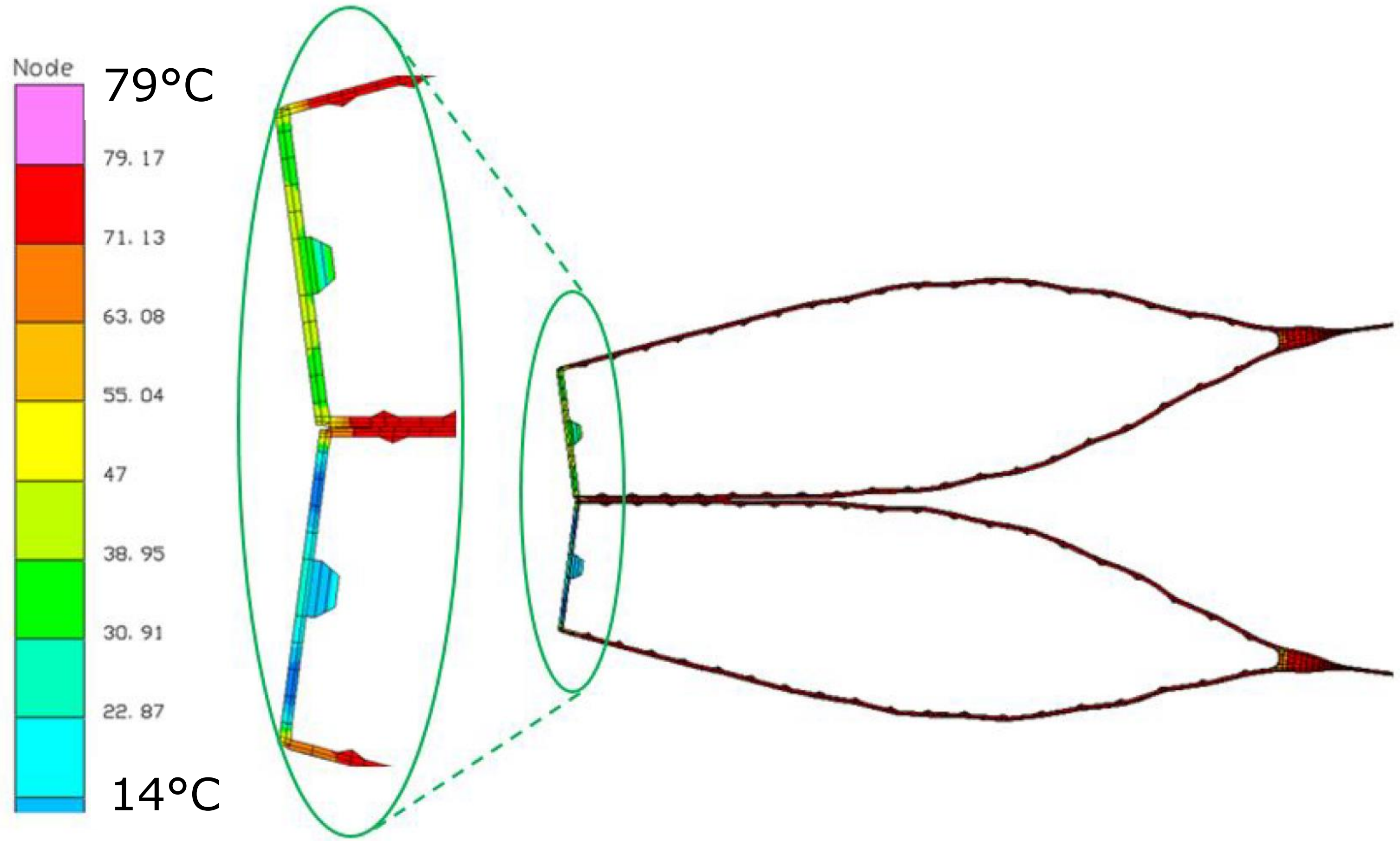


$$M_{max} = 31.5\ in \cdot lbs$$
$$V_{max} = 2.5\ lbs$$

Conclusion: The test article conditions are considered to be representative and conservative for the flight petal.

Driving Cases

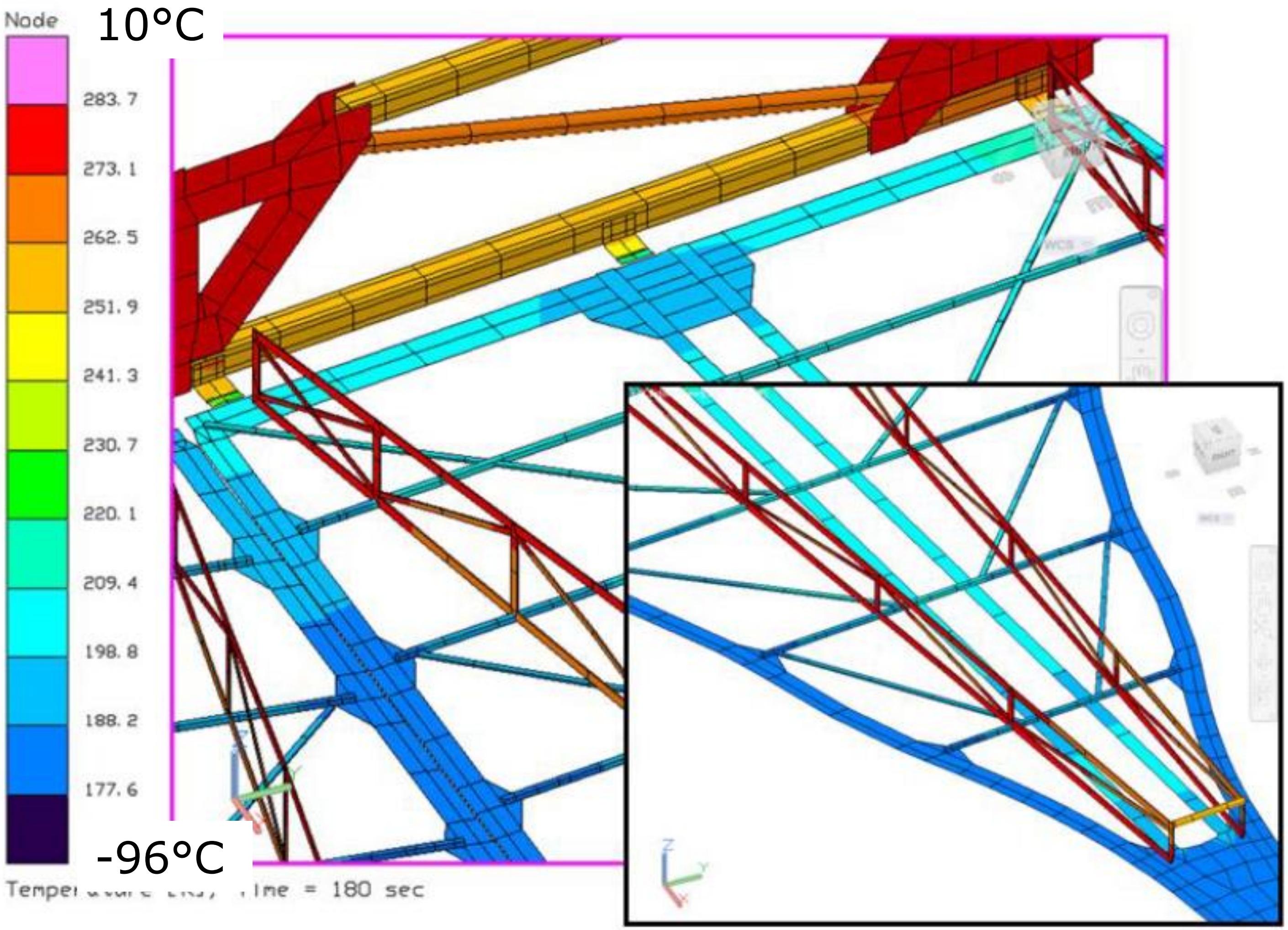
Hot Condition: 80°C at 0° sun angle



Only 2 petals shown, details omitted for clarity

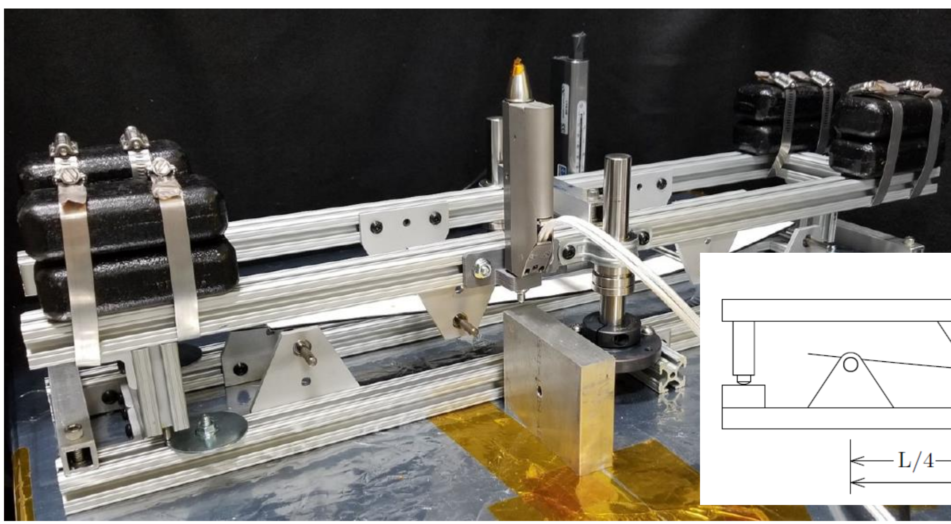
Driving Cases

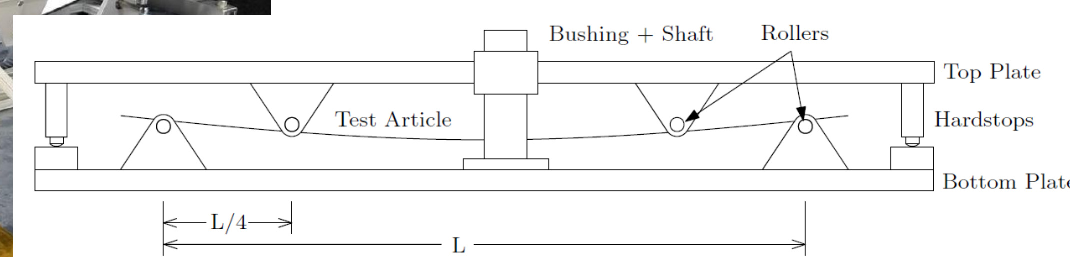
Cold Condition: -96°C at 83° sun angle



4 Point Bending Fixture

- Custom fixture using mostly commercial-off-the-shelf components
- Amount of curvature controlled by adjustable hard stops
  - Displacement driven, not force driven
- Loading rate controlled to 0.5mm/sec using motorized micrometers to simulate quasi-static stowage rate
- Half of assemblies tested with AM in compression, half in tension
  - Required due to inverse bending direction of “inner” and “outer” petals

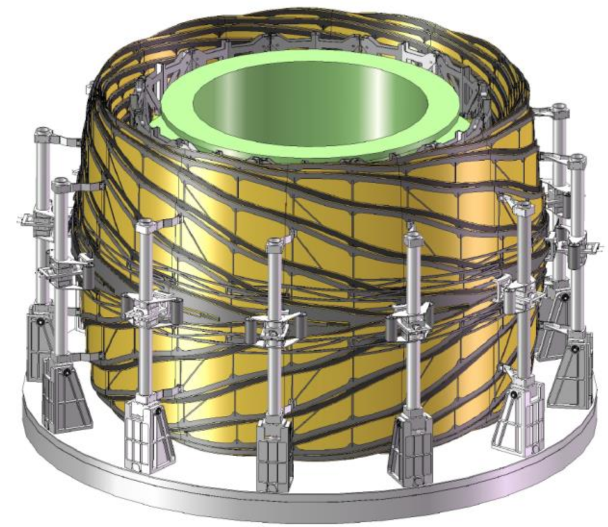




Bend and Release Cycles

Goal of Test: Simulate the number of bend & release cycles that a flight article will experience

- The petals are stowed around a central hub that has a 2.25m diameter
- A flight article is estimated to see fewer than 10 deployment before flight

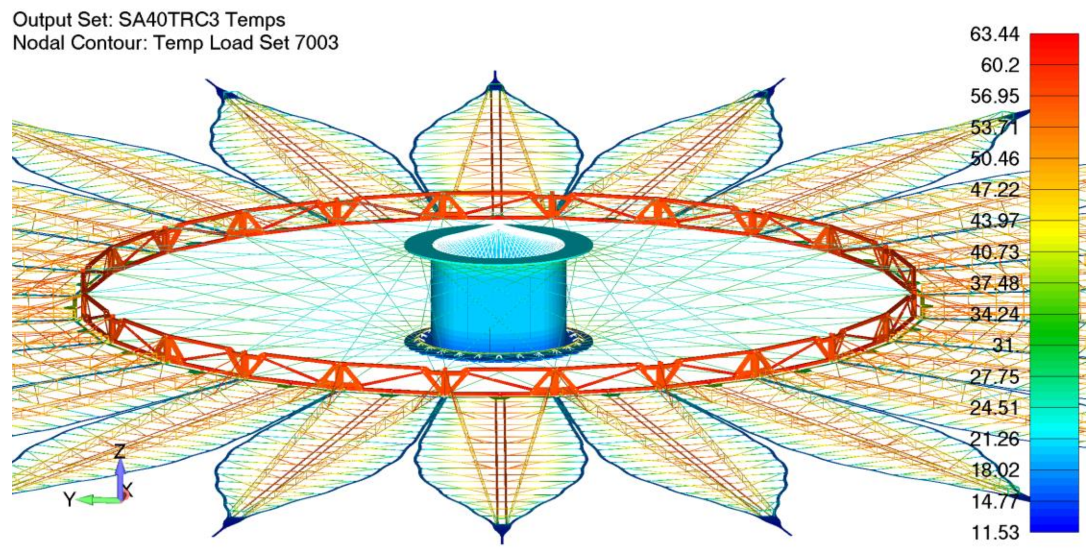


Test Parameters:

- Articles stowed using a 4pt bending fixture that creates a max curvature of 2.25m
- 10x cycles

Deployed Thermal Cycle

- Deployed thermal cycling is a stressing environment due to the mismatch in CTE between the AM (8.4ppm/°C) and CFRP (~0ppm/°C).
- FEA model used to determine test temperatures
  - Incorporates petal structure, optical shield, other blanketing
  - A 3 layer optical shield is modeled on the telescope side
  - Spin rate of 1/3 RPM
- Relevant sun angles
  - 40° – 83° for operational cases
  - 0° and 180 ° survivability case



Representative system model, some components removed for clarity

Notes on Structural Integrity

All segments that were thermal cycled showed bondline separation between the AM and CFRP Substrate

- Separation only occurred at the epoxy-AM interface
- Separation only occurred in the overhang region where there is a one sided bond

Mitigation efforts:

- Mechanically trap/encase amorphous metal to avoid separation
  - Subcontract in process with Tendeg
- Improve epoxy adhesion to the amorphous metal
  - Initial subcontract with BTG Labs completed. Plasma clean + primer application shows promise

Test Conditions

Actual Test Temperatures: +105°C / -125°C

- Results in 25°C margin on hot, 29°C margin on cold side
- JPL best practice is for 20°C margin on hot, and 15°C on cold

Test cycles: minimum of 25x

- Some samples experienced 50 cycles
- Expected number of thermal cycles per Starshade Rendezvous mission is <40
  - Based on number of target star reorientations which results in the starshade facing towards the sun