Advancing Technology for Starlight Suppression via an External Occulter

N. Jeremy Kasdin*, D. N. Spergel
Princeton University

D. Lisman, S. Shaklan, M. Thomson, P. Walkemeyer, V. Bach, E. Oakes,
E. Cady, S. Martin, L. Marchen
Jet Propulsion Laboratory
California Institute of Technology

B. Macintosh, R. Rudd
Lawrence Livermore National Laboratory

J. Mikula, D. Lynch
NASA Ames Research Center

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Photo Courtesy of Robert Vanderbei

What is an Occulter?

July 11, 1991

August 11, 1999

A Prototypical Mission for Earthlike Planets (2009 AMCS)

Technology Challenges

To design and build an occulter that satisfies the requirements and constraints on:

- Precision edge shape
- Deployment accuracy
- Validated optical models (software and lab)
- Sensing and Formation control
- Thermal stability
- Dynamic stability
- Solar Glint

. . . and develop verification and validation approaches.

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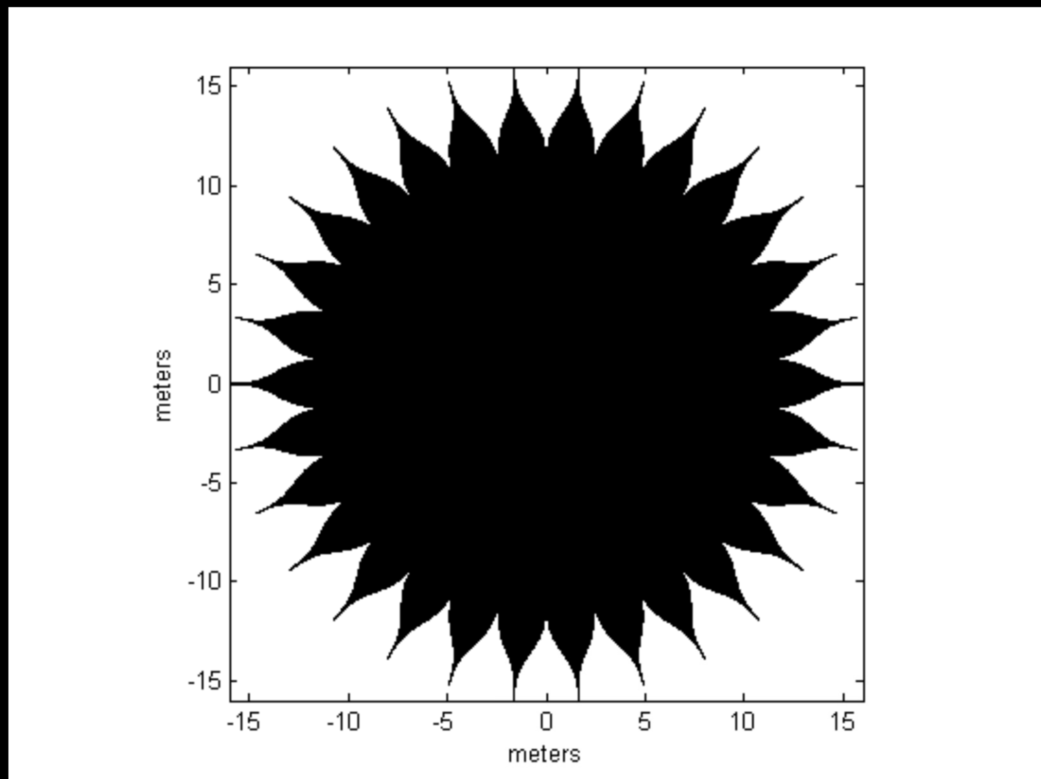
2010 TDEM – Petal Manufacturing



DI22 Occulter:
32 m diameter,
90 mas IWA
6 m petals,
1.5 m telescope

Objective:

Measure the width of the optical edges of a full scale petal at a sufficient number of locations and with sufficient accuracy to show that, using modeling, a full size occulter with that petal would achieve a contrast of 3×10^{-10} or better at the IWA with 95% confidence.

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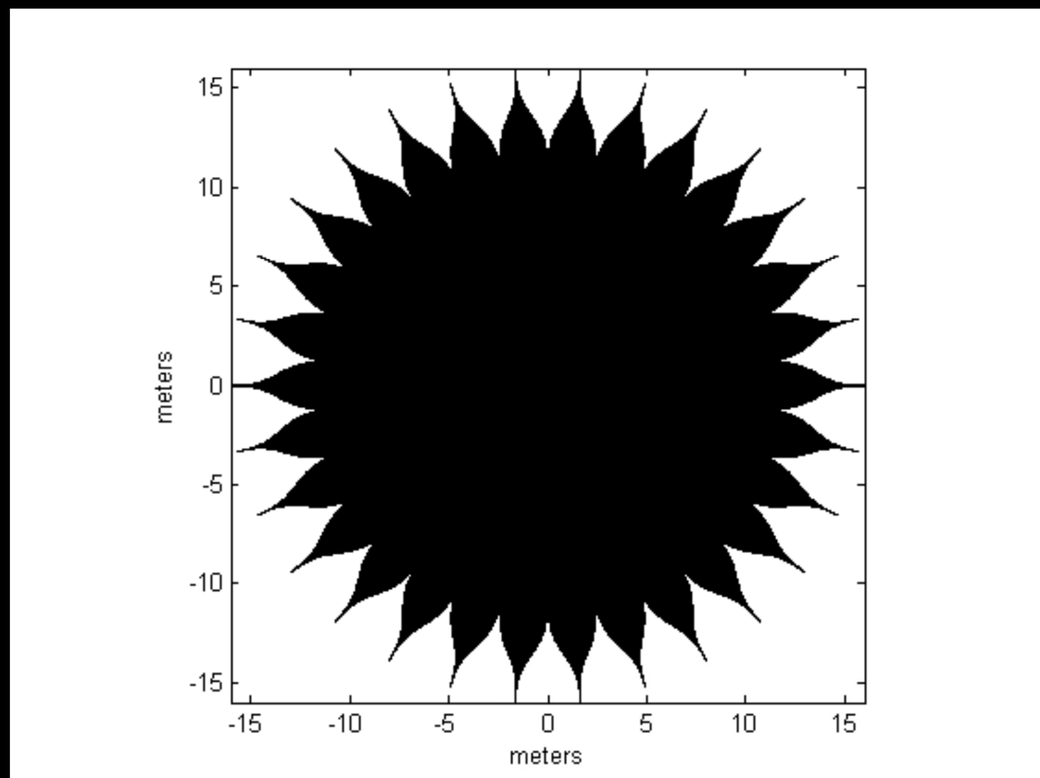

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Our goal is to do better than 2×10^{-11} !

Occulter Petal Shape Requirements

See Shaklan, et al., 8151-38.

Based on current knowledge regarding manufacturing capability, net contrast due to manufacturing errors is expected to be better than 2 x 10^{-11} (with remaining contrast due to dynamic and deployment errors).

All requirements are met with a 3-sigma shape error along petal of ~28 microns excluding petal bending.

	TDEM Design 6 m petals, 32 m tip-to-tip 1.5 m diam. telescope		THEIA Design 10 m petals, 40 m tip-to-tip 4 m diam. telescope		
	90 mas	75 mas	75 mas	60 mas	3-sigma
MANUFACTURE					
Proportional width	10	5	10	10	ppm
Segment placement	12.5	8	25	25	um
Segment shape	75	60	75	75	um
Contrast	**1.6E-11**	**1.5E-11**	**4.2E-12**	**8.9E-12**	
DEPLOYED SHAPE					
Proportional width	5	5	5	5	ppm
Segment displacement	5	3.5	5	5	um
In-plane Quadratic bend	1	1	2	2	mm at tip
Out of plane quadratic bend	10	10	20	20	mm at tip
Contrast	**2.0E-12**	**5.7E-12**	**3.1E-13**	**1.2E-12**	
DEPLOYED POSITION					
Radial Shift	0.50	0.24	0.50	0.50	mm
Lateral Shift	0.50	0.24	0.50	0.50	mm
Rotation about petal spine	0.25	0.25	0.25	0.25	deg
Elliptical truss def.	1.00	0.75	1.00	1.00	mm
Contrast	**2.2E-11**	**2.5E-11**	**1.3E-11**	**2.3E-11**	
THERMAL					
Proportional width	35	15	35	35	ppm
Base to tip gradient	30	30	30	30	ppm
Random batten length	7.5	7.5	7.5	7.5	ppm
In-plane Quadratic bend	1	1	2	2	mm at tip
Out of plane quadratic bend	10	10	20	20	mm at tip
Radial Shift	0.2	0.13	0.2	0.2	mm
Lateral Shift	0.2	0.13	0.2	0.2	mm
Contrast	**1.3E-11**	**1.8E-11**	**4.8E-12**	**8.3E-12**	
FORMATION FLYING	1	0.25	1	1	m
Contrast	**3.3E-12**	**4.5E-12**	**2.0E-12**	**4.7E-12**	
DYNAMICS ALLOCATION	**5.0E-12**	**5.0E-12**	**5.0E-12**	**5.0E-12**	
EDGE SCATTER ALLOCATION	**2.0E-11**	**2.0E-11**	**2.0E-11**	**2.0E-11**	
RESERVE	**1.8E-11**	**6.8E-12**	**5.1E-11**	**2.9E-11**	
TOTAL	**1.0E-10**	**1.0E-10**	**1.0E-10**	**1.0E-10**	

By adopting a spinning occulter, error is dominated by mean rather than rms and is relaxed significantly.

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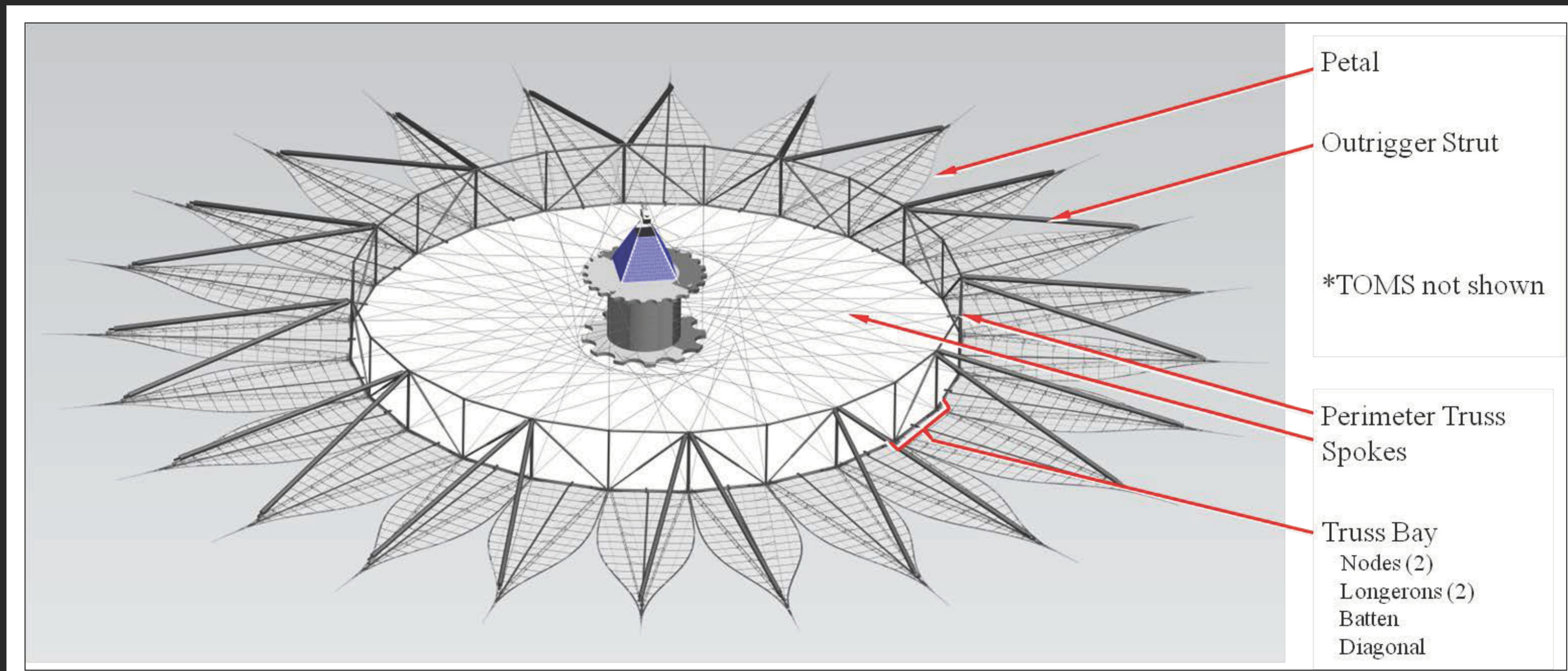
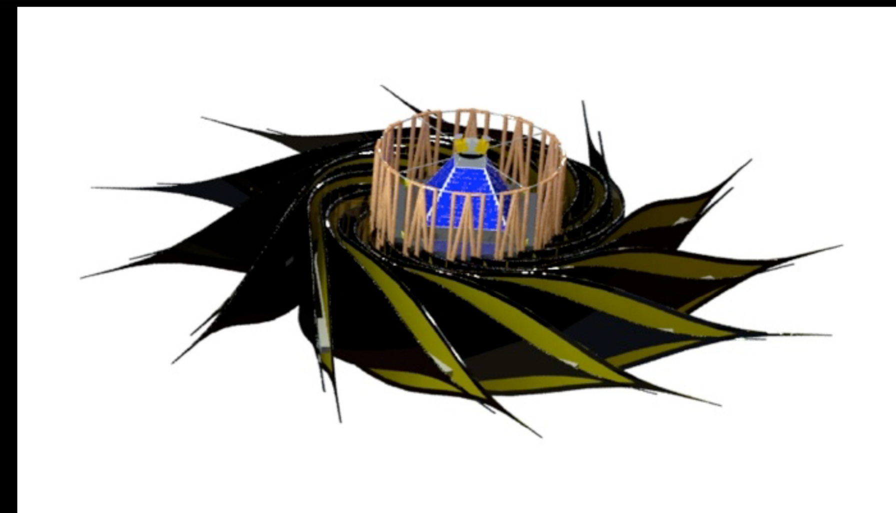
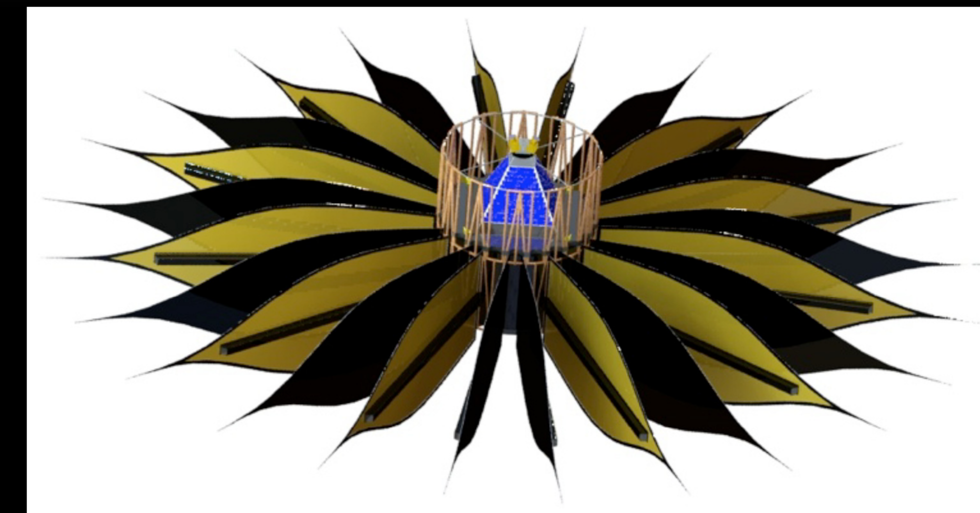
Starshade Mechanical Design



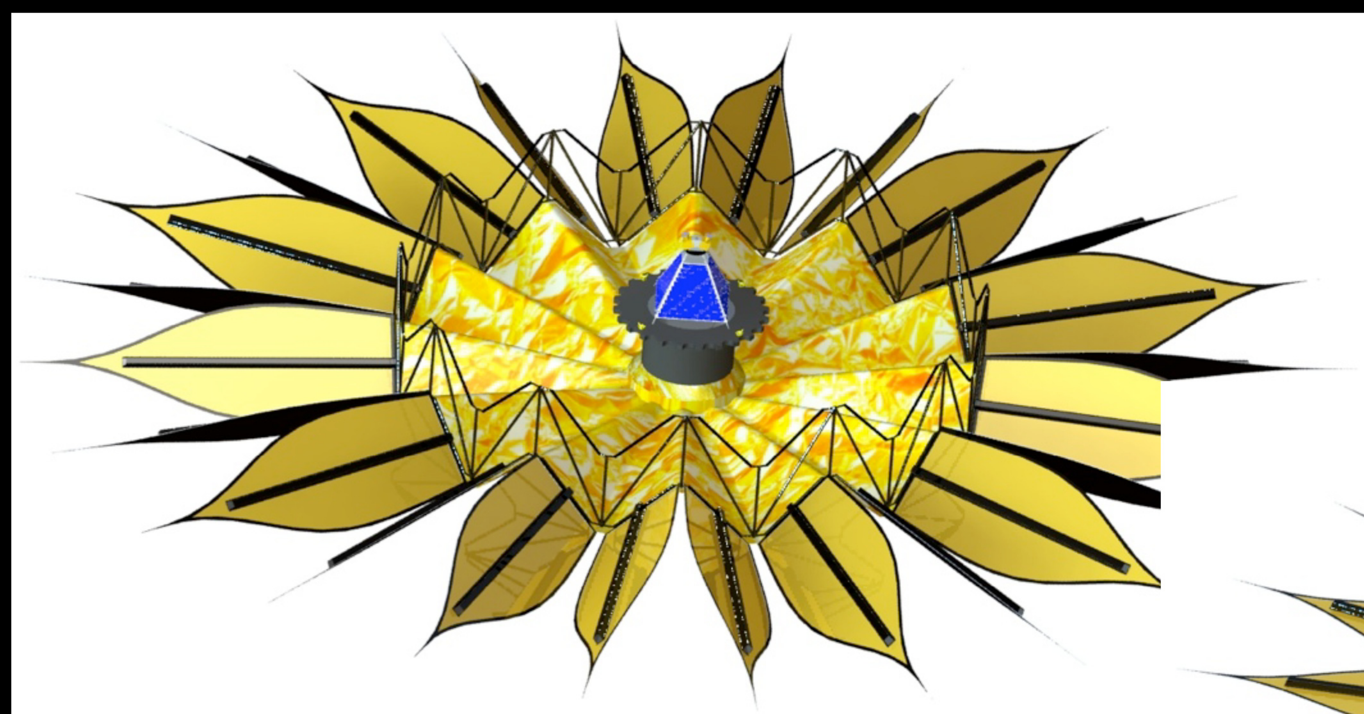
Deployed Starshade, including Petals, Truss, and Spacecraft

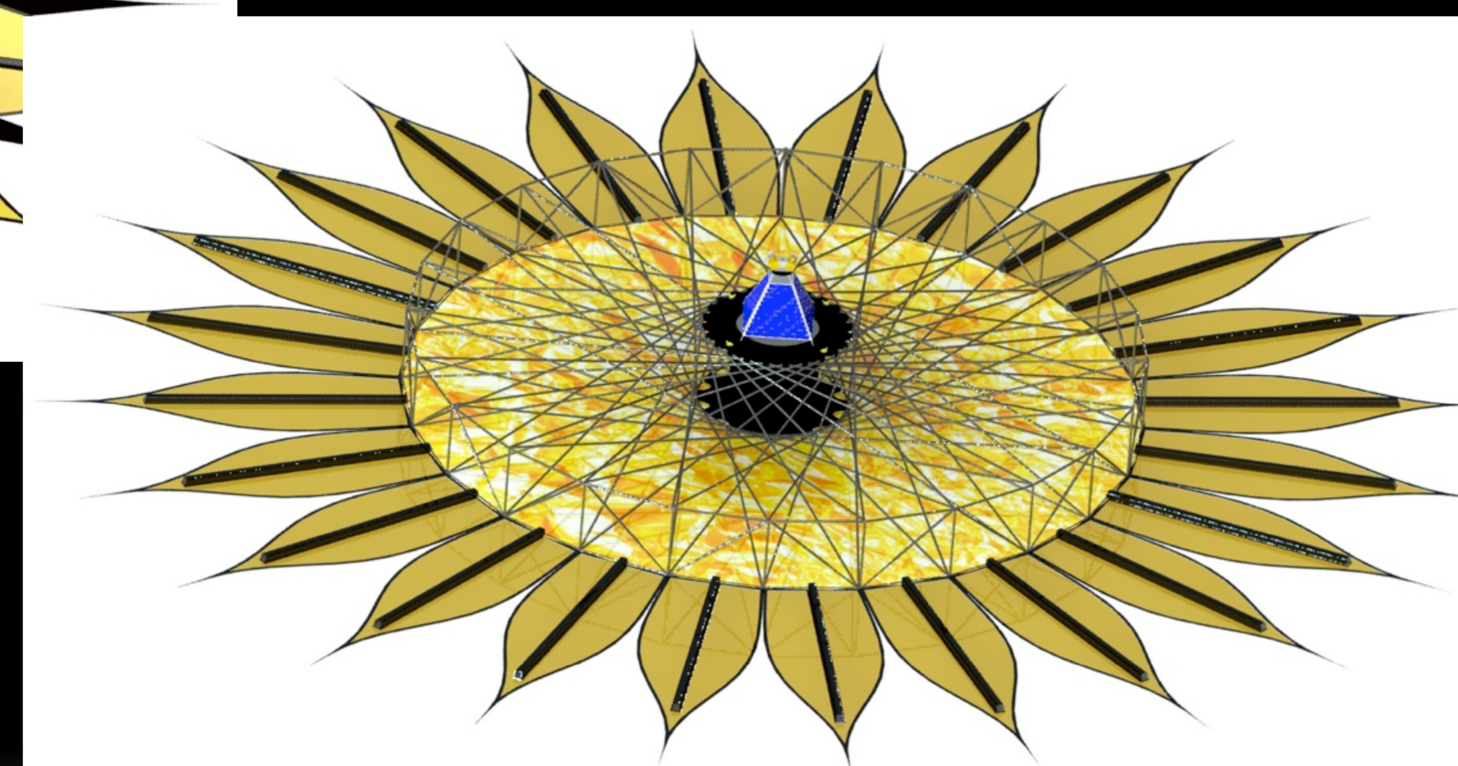
- Launch with single, existing launch vehicle (5m fairing)
- Petal areal mass density < 2.6 kg/m^2
- Petal 1^{st} mode > 1 Hz
- Occulter system 1^{st} mode > 0.2 Hz
- Gravity sag < 1.5 cm
- Petal position and figure tolerances per table:



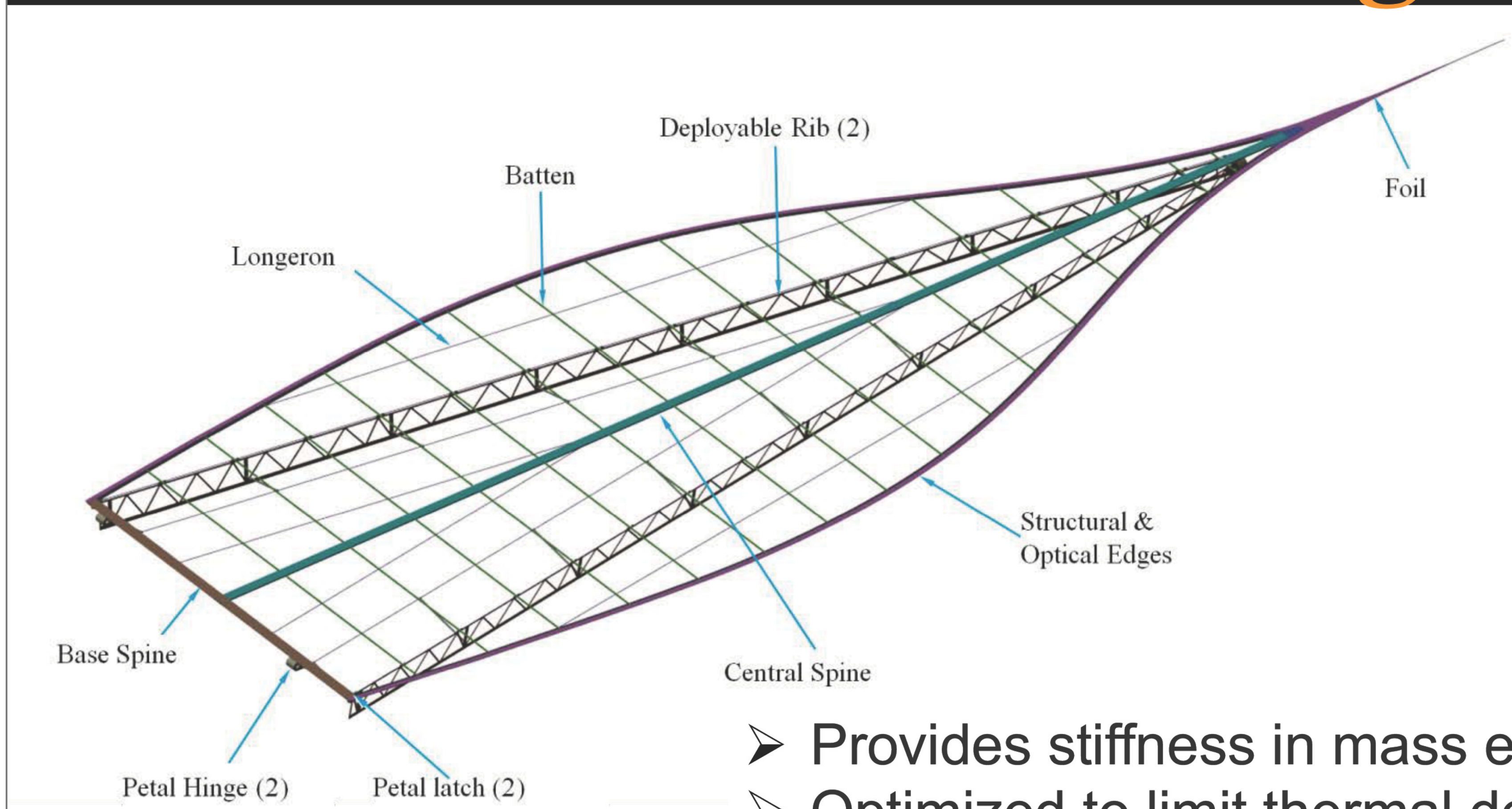


Starshade Stowage and Deployment





Petal Mechanical Design



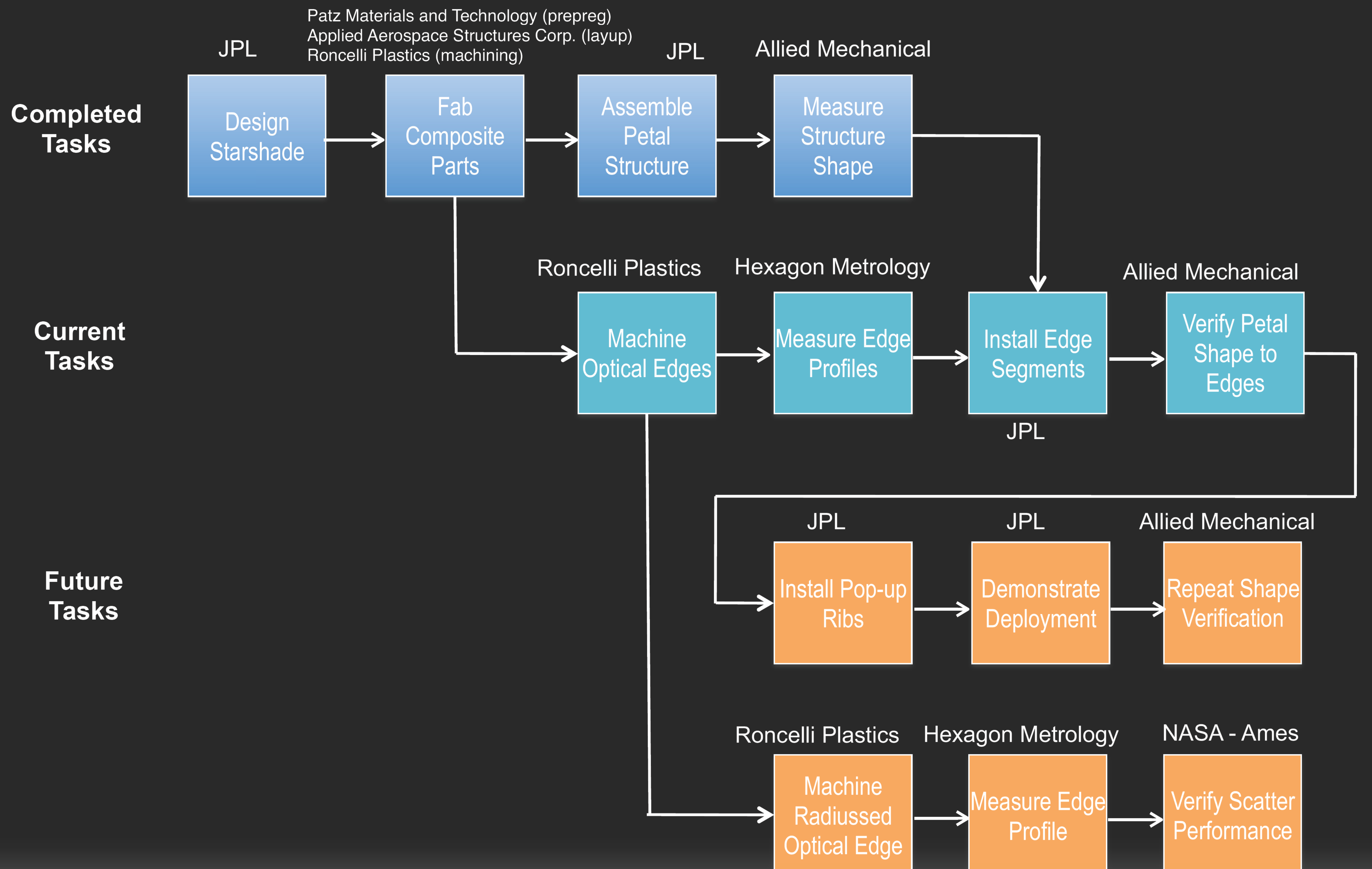
- Provides stiffness in mass efficient manner
- Optimized to limit thermal deformations – battens (lateral members) control width
- Battens made from carbon pultruded rods with finely controlled
- Out of plane stiffness augmented with pop-up ribs and outrigger struts
- Optical edge is replaceable & installs as multiple segments (1 at tip + few per side)
- Minimum tip width is 1 mm
- Blanket system (not shown) controls temp, makes optically black & mitigates micrometeorite induced light leakage

Aluminum Initial Proof of Concept

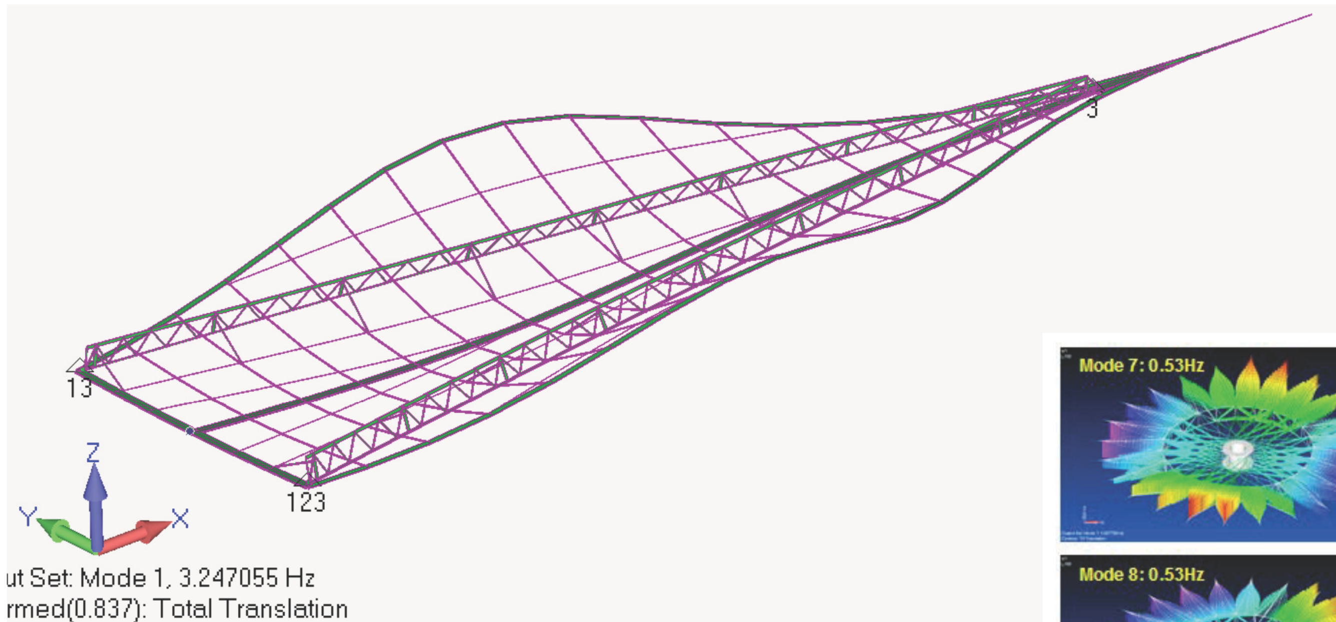
Starshade Petal
Proof of Concept

Deployment
Test

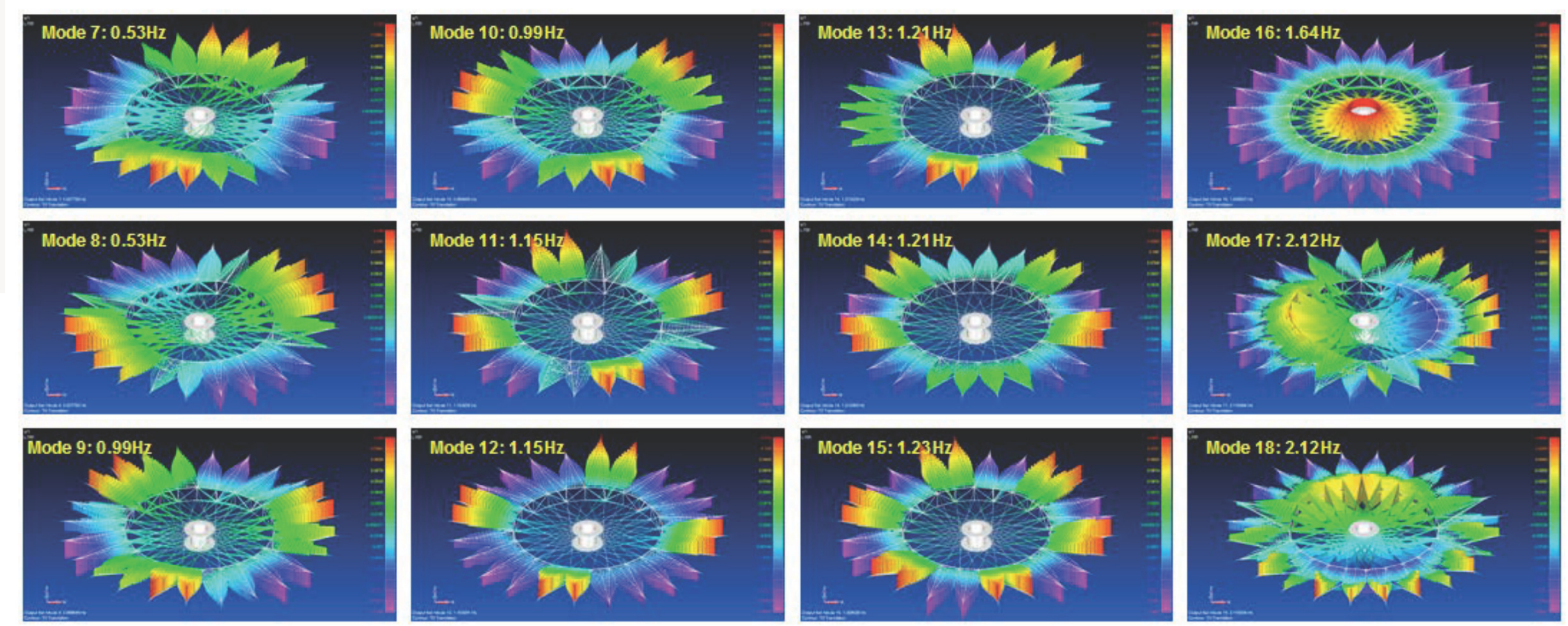
Precision Composite Petal Manufacturing



Preliminary Thermal/Mechanical Model

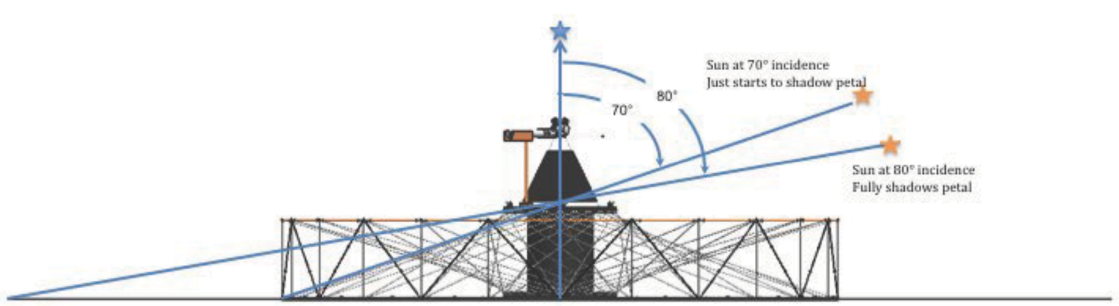


Petal 1st mode (3.2 Hz) mode-shape.



Occulter system normal frequencies and shapes–petals act as rigid bodies.

Steady-State Thermal Deformations well within Specifications

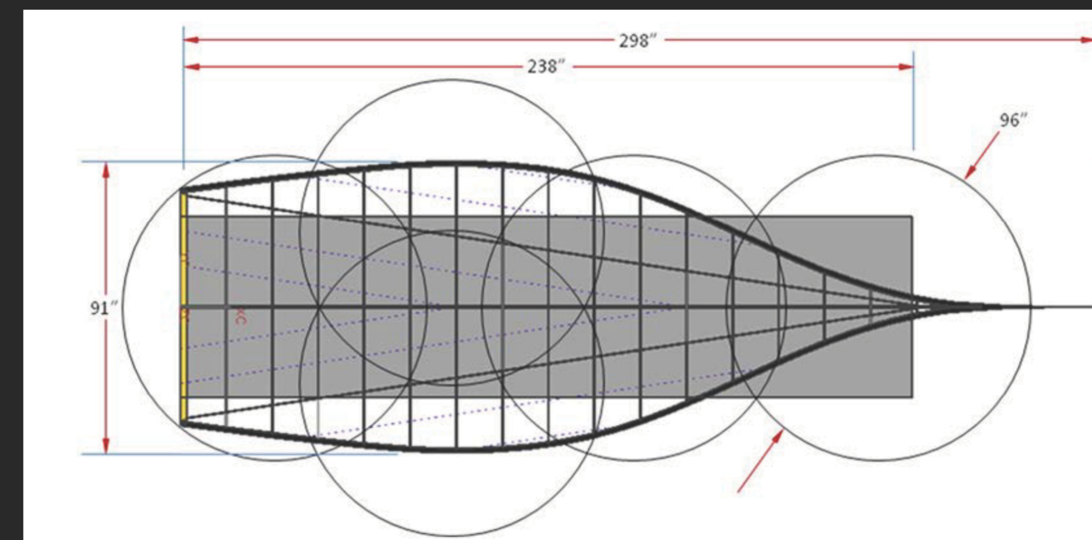


Deformation Type	Worse-case parameters	Max temp deviation with unc'ty (K)	Max deformation (ppm)	Tolerance Allocation (ppm)	Margin against allocation (%)	Notes
Uniform - proportional width	$\varepsilon^* = 0.1$ $\theta = 30°$ to $85°$	100	20	35	43	ΔT is relative to reference temp. set midway between extremes
Non-uniform - monotonic gradient	$\varepsilon^* = 0.7$ $\theta = 80°$	30	6	15	60	Allocation applies at extreme temp. points
Non-uniform - semi random	$\varepsilon^* = 0.7$ $\theta = 70°$	15	3	7.5	60	Allocation applies as envelope about average batten temp.

Metrology

Fiducial balls on structural edge measured with 5 micron repeatability with Coordinate Measuring Machine at Allied Mechanical.

A 4 ft. Faro Platinum Coordinate Measuring Machine used to measure the static petal edge shape during assembly.



Arm Positioning

Final optical edge width of assembled petal measured at Allied Mechanical with CMM.

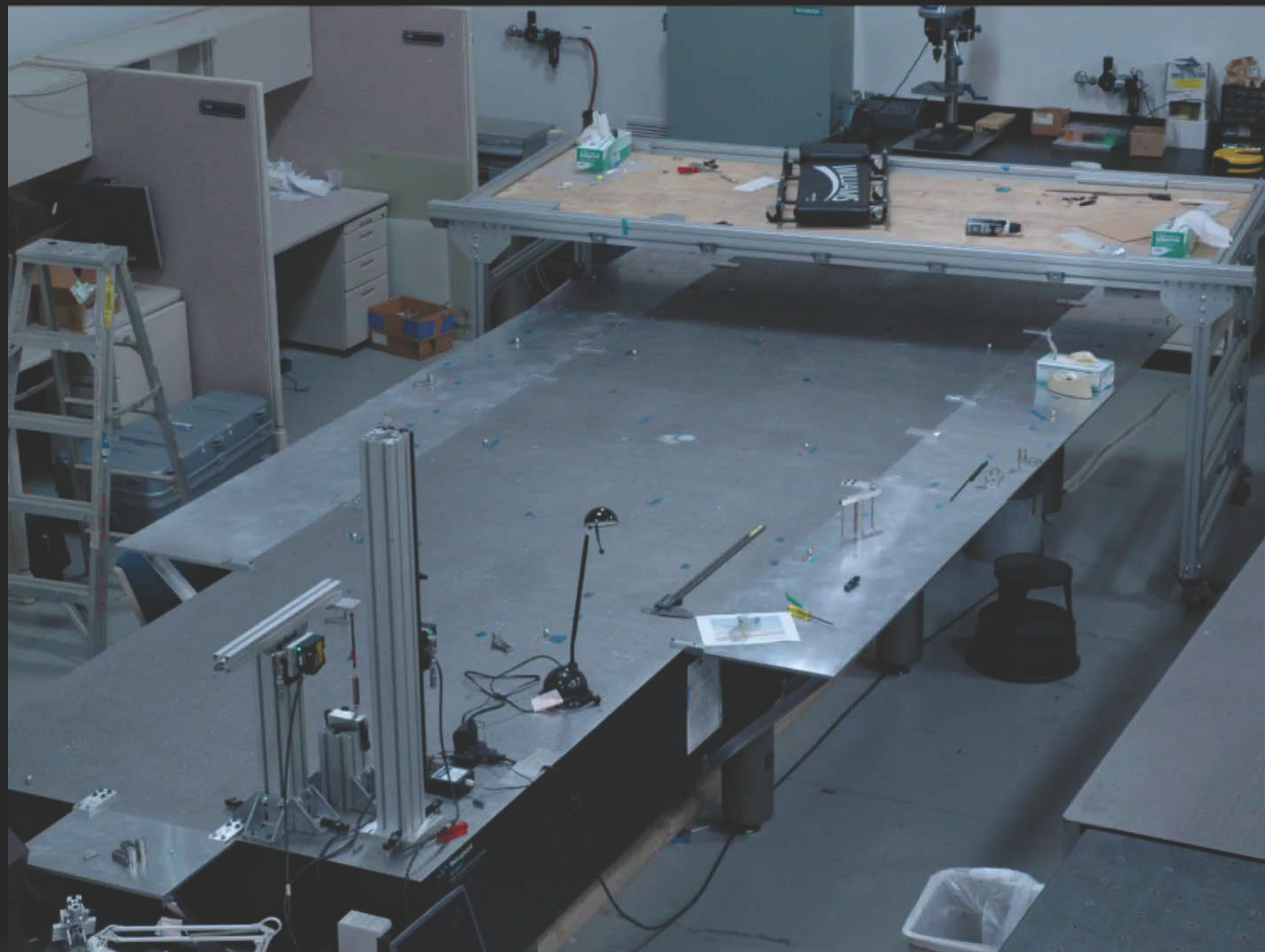
Analysis used to compute contrast from equivalent starshade made up of as-built and measured petal.

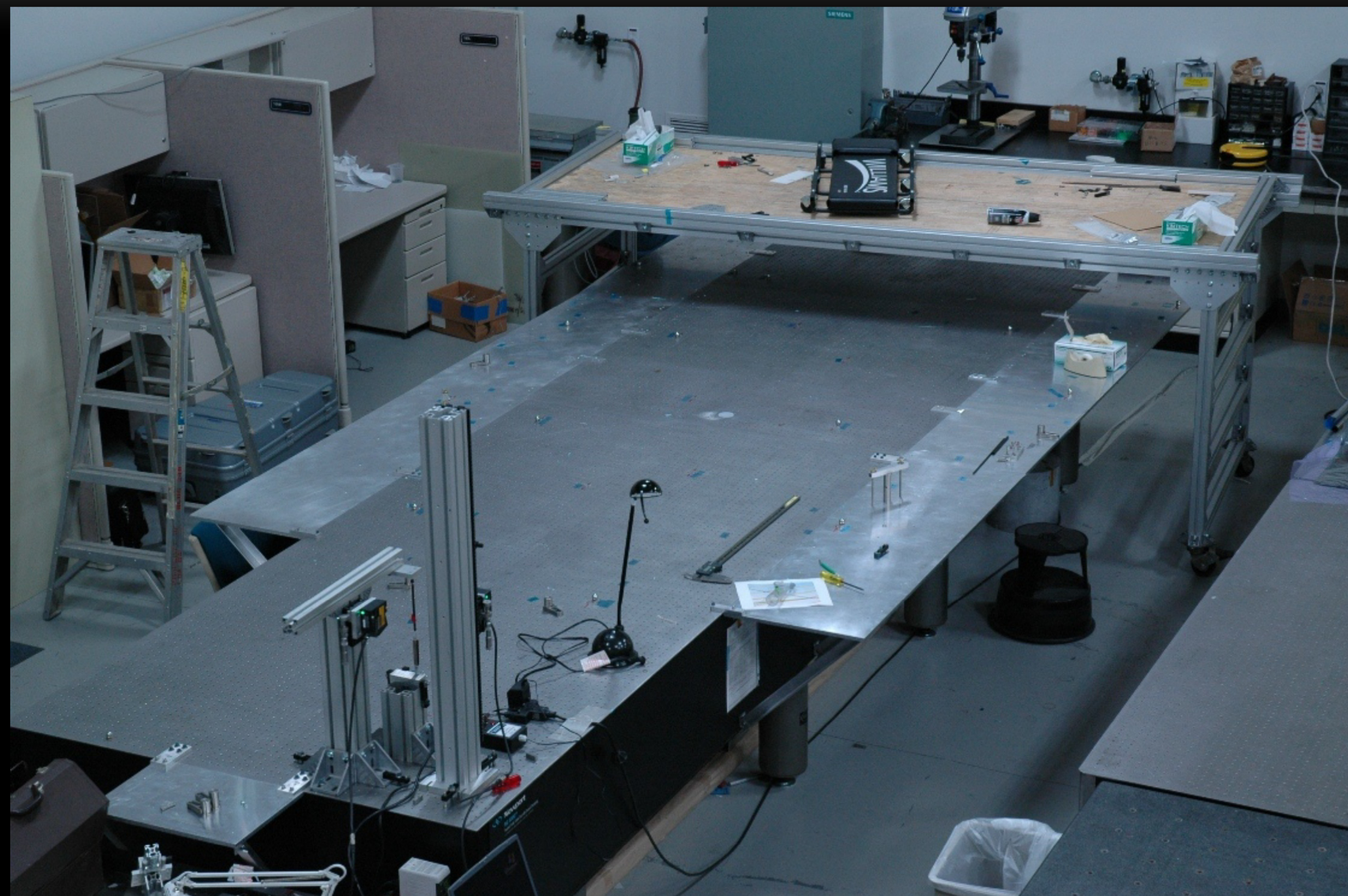
Computing Contrast

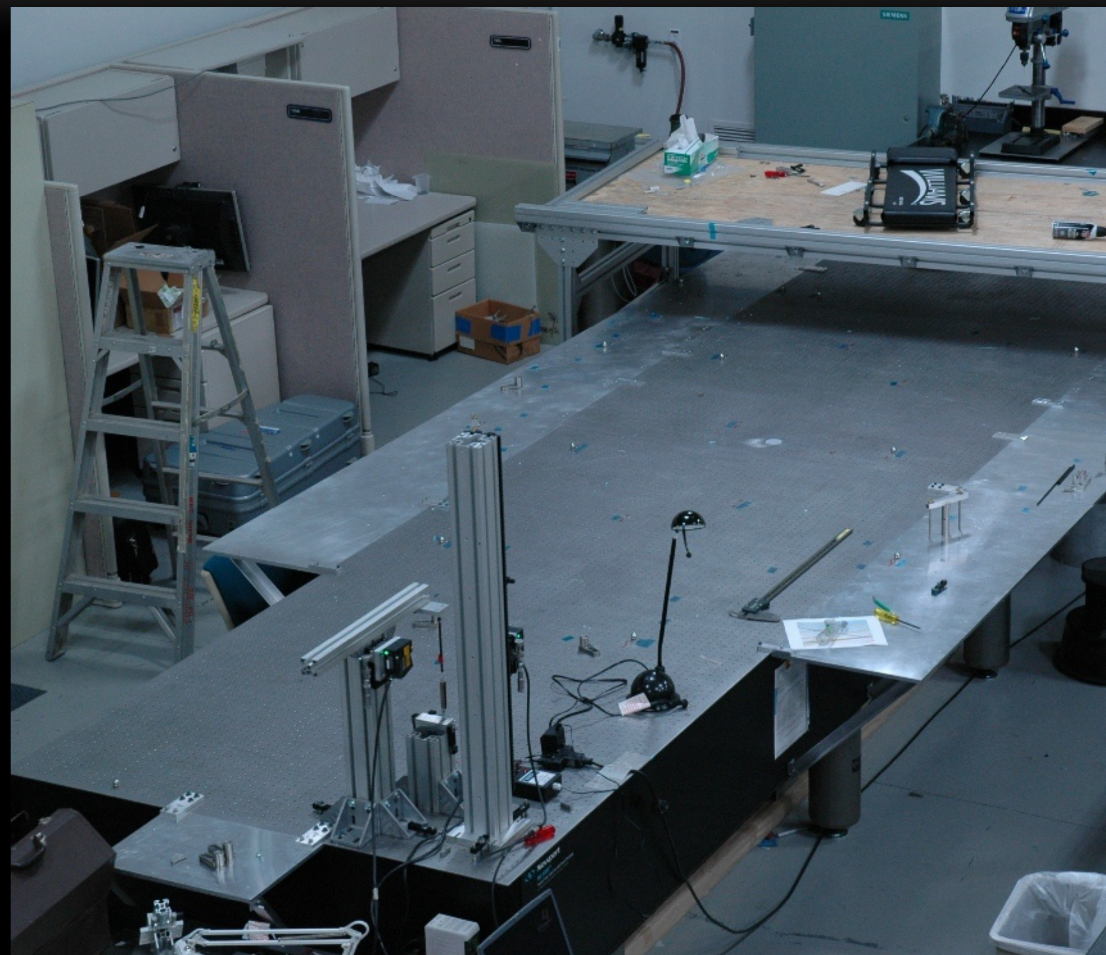
- Measure petal width at roughly 200 points along optical edge using CMM at Allied Mechanical.
- Interpolate to a sufficient number of points to approximate well the Fresnel integral.
- Numerically construct an occulter with all petals of the same measured shape assuming perfect positioning around the truss.
- Use our standard simulation tool to compute the point spread function of a 1.5 m telescope perfectly positioned in the shadow of the occulter at two wavelengths, 550 nm and 1000 nm.
- Compute the contrast at the designed for inner working angle and verify it meets the 3 x 10^$^{-10}$ requirement.
- Repeat a sufficient number of times to reduce Type I and II error probabilities to less than 5%.

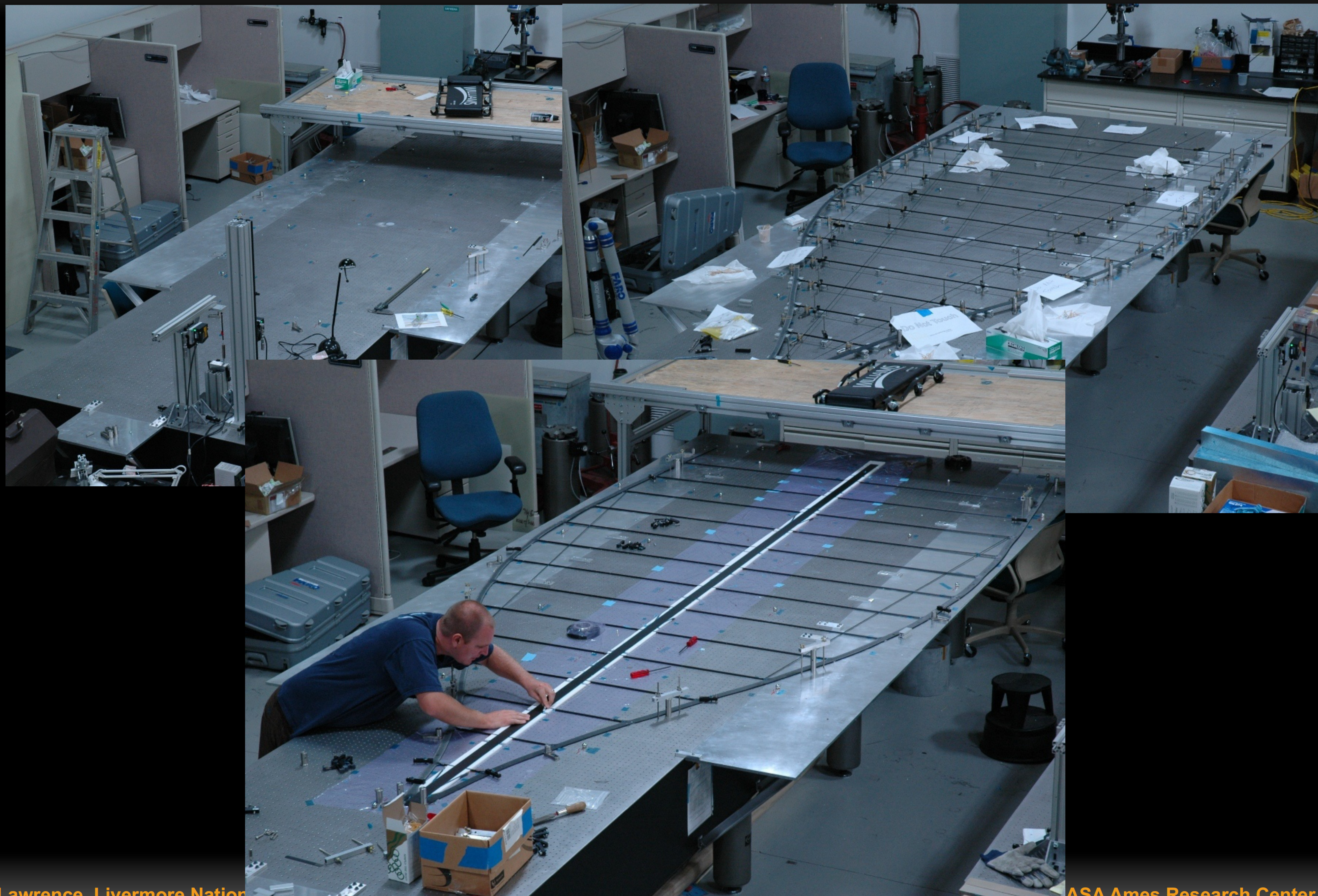
Result does not verify statistics of petal manufacturing, but does validate design and prove feasibility of occulter petal manufacturing and metrology.

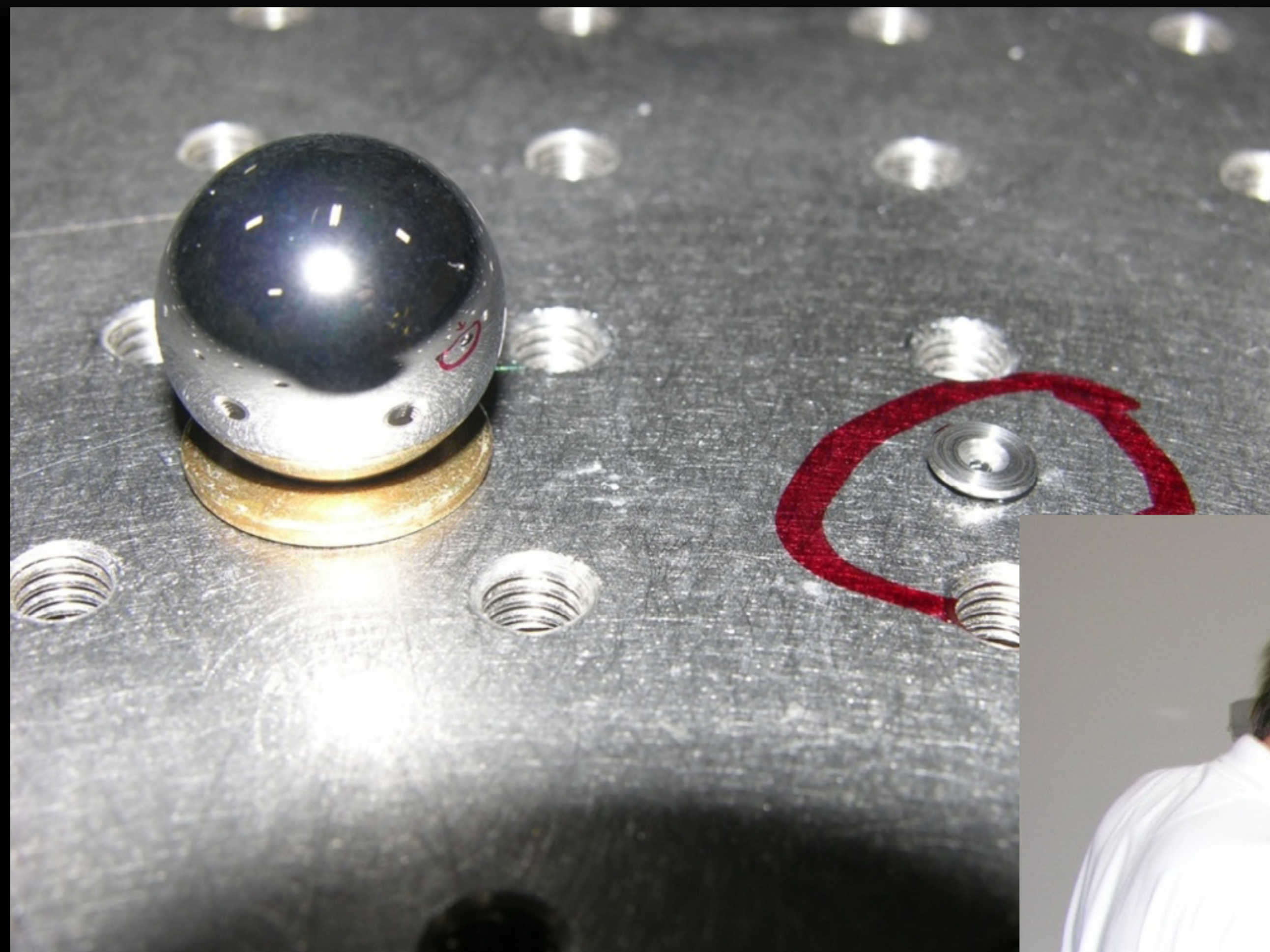
Progress to Date





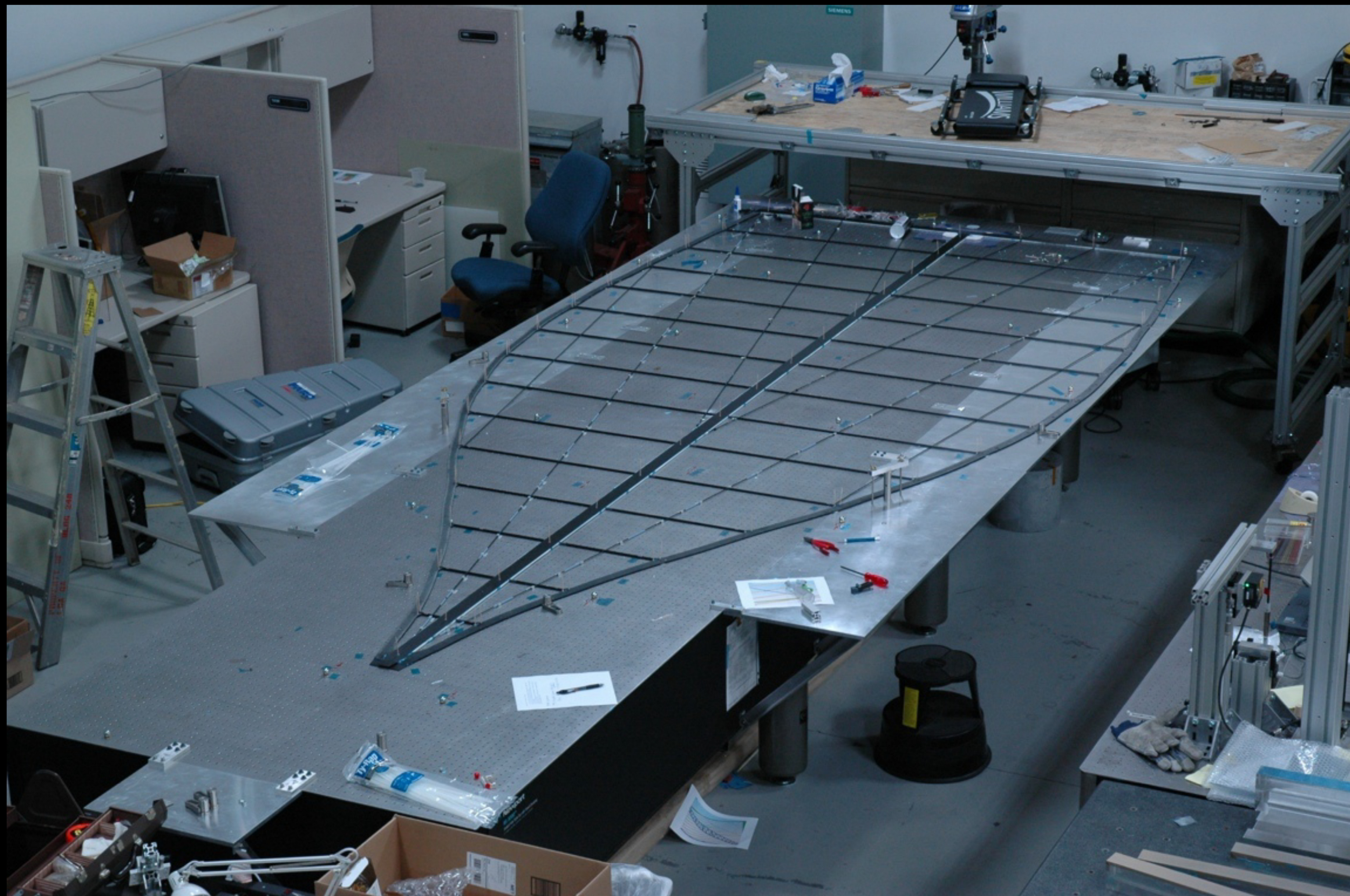






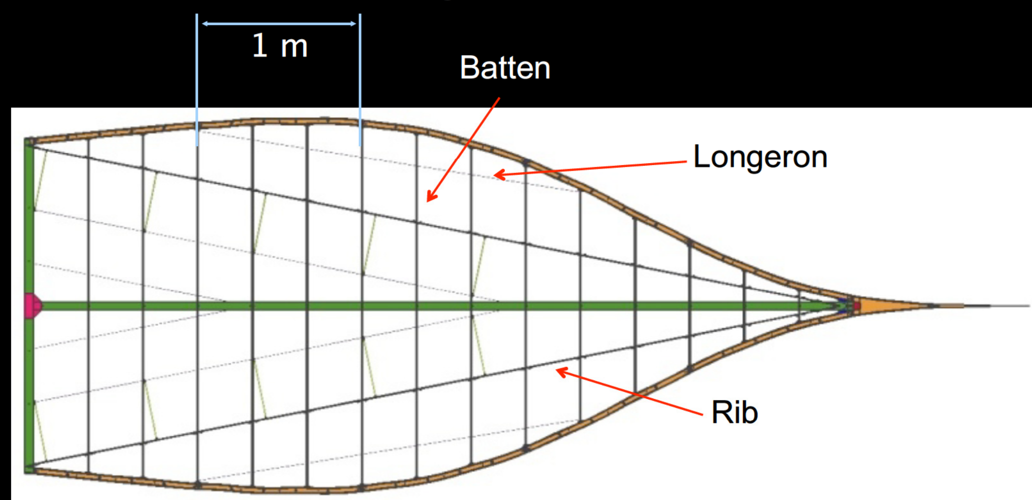

FARO
PLATINUM ARM

Final Structural Components Assembled

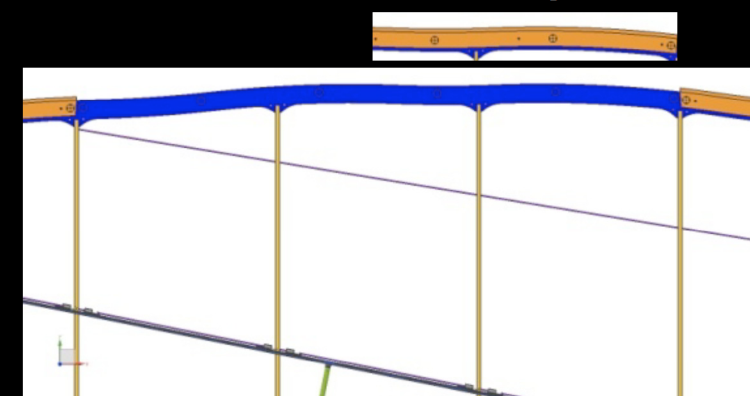


Optical Edge Manufacturing

2nd optical segment



Trial part



Due to cost, schedule and metrology constraints, final optical edges will be flat; they will not be machined with needed small radius of curvature.

Final Precision Optical Edges Now Being Machined

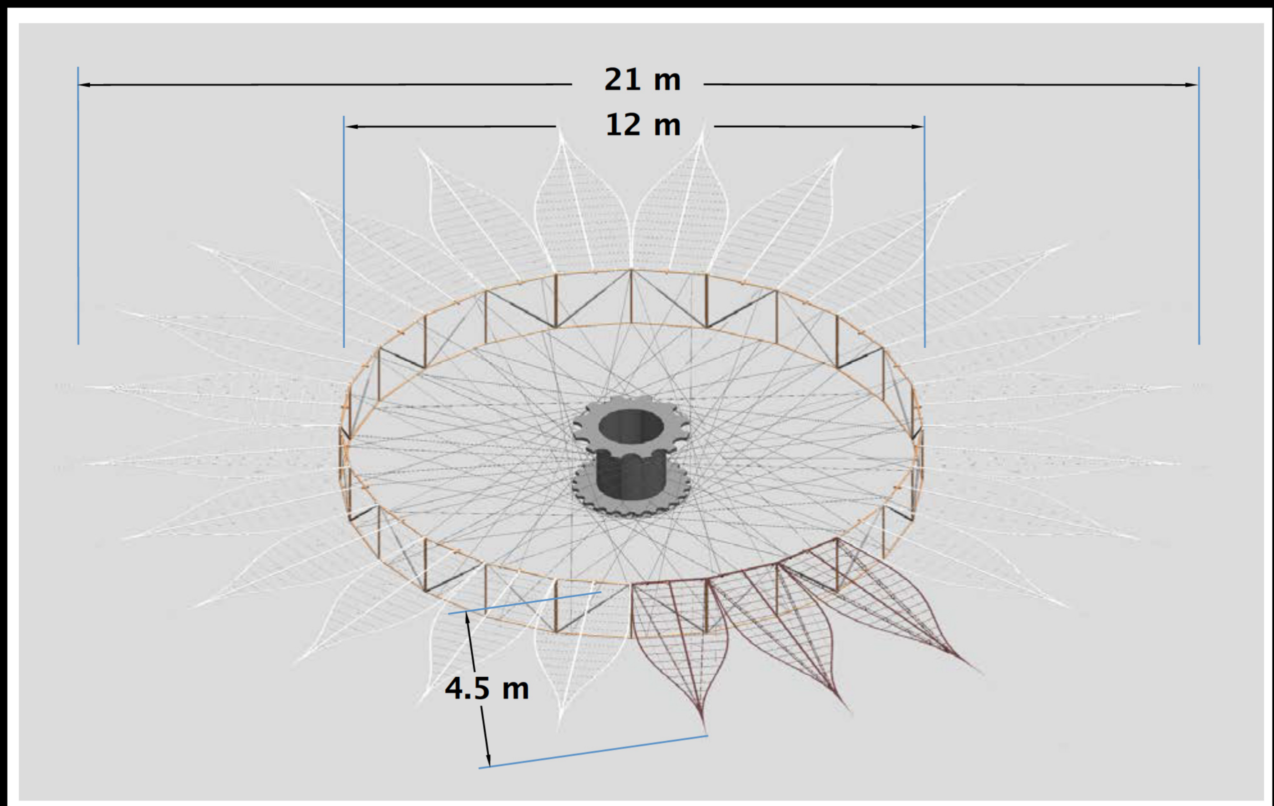
Conclusions

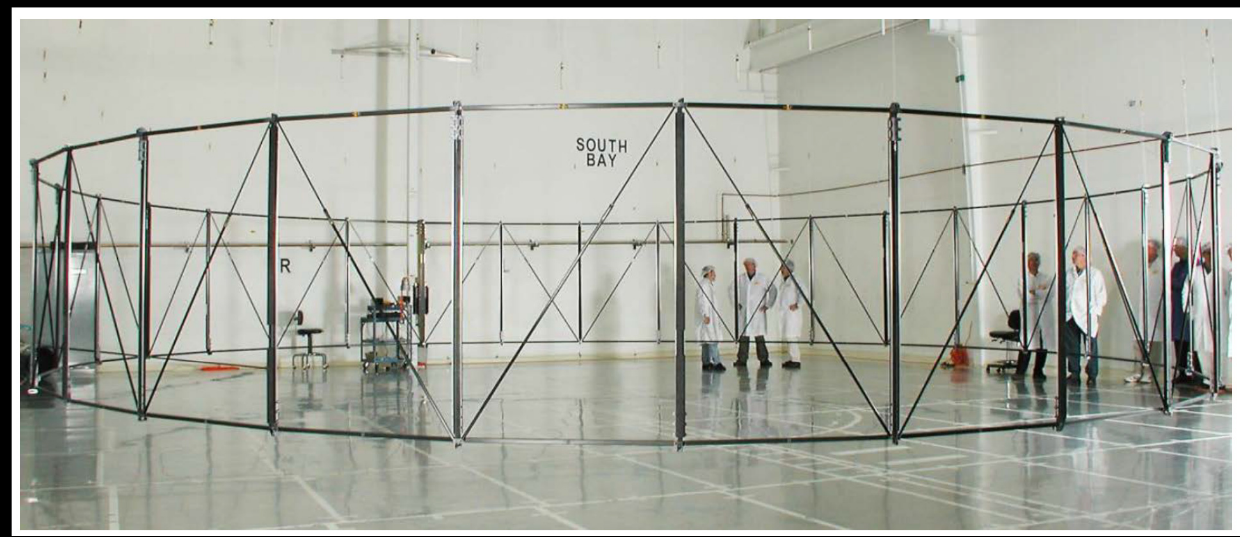
- We are on schedule to complete the TDEM milestone as planned.
- We have completed a thorough error analysis and budget and understand the allocation to various starshade tolerances.
- Current manufacturing capability is consistent with flight occulter performance requirements and should do better than 2×10^{-11}.
- Analysis shows that thermal deformations are consistent with 10^{-10} performance.
- Petal manufacture and assembly should be completed by September.
- Hope to do a deployment test of precision composite petal in Fall.

Within the cost and schedule constraints of the TDEM program we can design, build, and measure flight like petals to levels consistent with detecting Earth-like planets, retiring the manufacturing risk.

Next Step – TDEM 2

Verify starshade deployment functionality and interfaces by demonstrating repeated deployment of a 3 petal and truss subscale prototype consistent with a total instrument contrast of 10^{-10} (< 5 mm).





Existing Truss at Northrop-Grumman Astro

Thank You

This work was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.