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Single Surface Membrane Optical Shell Technology - Current Status -

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Wednesday, August 1, 2007

Presented at the Mirror Technology Days-2007
Albuquerque, New Mexico

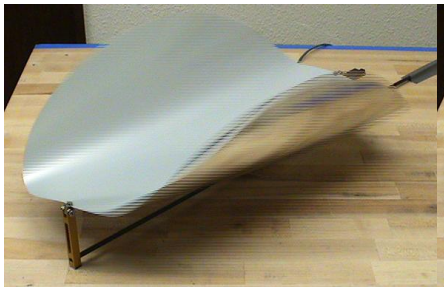
Acknowledgements

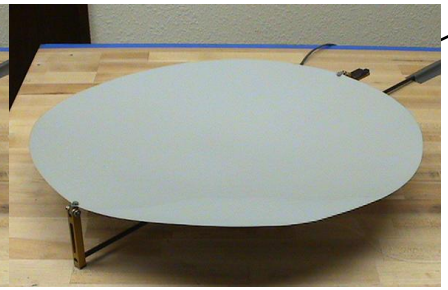
- **PI/PII 2005 NASA SBIR**
  - "Precision Membrane Optical Shell (PMOS) Technology For Lightweight LIDAR Apertures"
  - COTR Phase I: Dr. McGill, Contract # NNG06LA19C
  - COTR Phase II: Dr. Kathy Marx, Contract # NNG07CA10C

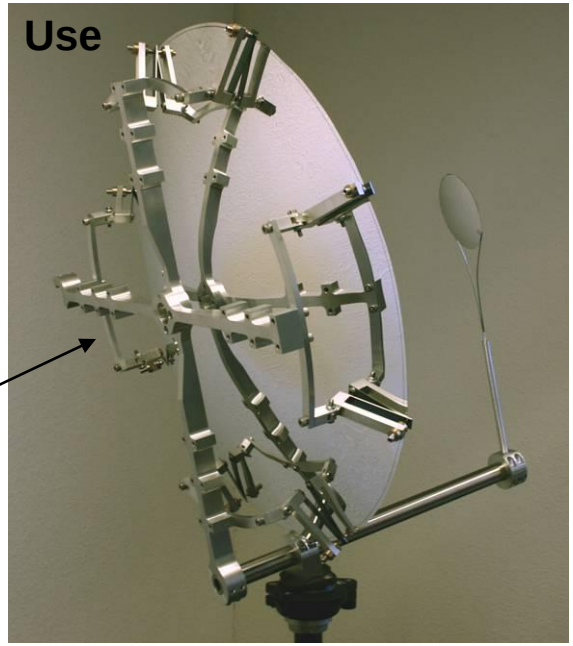
- **2006 NASA PI SBIR**
  - "Extremely Lightweight, Segmented Membrane Optical Shell Substrate Technology (MOST) for Future IR to Optical Telescopes"
  - COTR: Dr. Bill Jones, NASA-MSFC, Contract # NNM07AA42C
  - Co-COTR: Dr. Philip Stahl, NASA-MSFC

- **Colleagues at Mevicon Inc.**
- **Other Projects**

Overview
Membrane Shell Technology







- **Inherent Stiffness:** Derived from curvature
- **Low Areal Density:** Multiple sources
- **Compact Stowage:** Rolling
  - No folding/creasing
  - No discrete hinge mechanisms
- **Deterministic Self Deployment**
- **Zero Energy Self-Rigidization**
- **Scalability**
- **Cost /Schedule Advantages**

- **Low Areal Density**
  - Thin film based (≈40g/m^2 @ 25 µm thick)
  - Single surface
  - Minimal support structure
  - Minimal deployment and rigidization support hardware requirements
- **Cost /Schedule Advantages**
  - Fabrication time
  - Materials
  - Transportation costs (mass & volume)

Application Areas

Solar

Power
- Higher Gain PV
- Solar Dynamic

Propulsion
- STP/SOTV
- Solar Sails

Terrestrial
- Water
  - Purification
  - Distillation
- Solar Cooking

RF Aperture

- SATCOMM
- RADAR
- Science

S-Band to W Band

THz

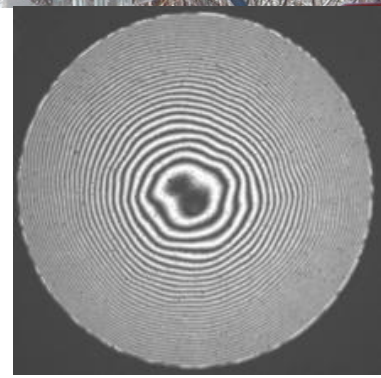
Emergency Use
- Transportable
- Expandable

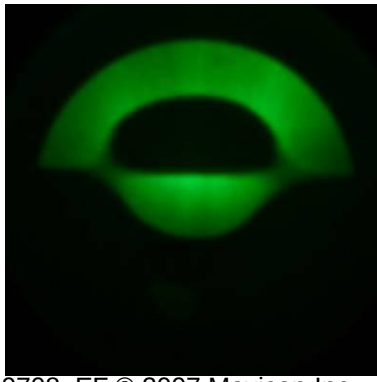
Optics

- IR
- LIDAR
- LaserComm
- Imaging

- Telescopes
  - Ultra-lightweight
  - Ultra-compact

Solar Sails, MLI, Sunshields, …





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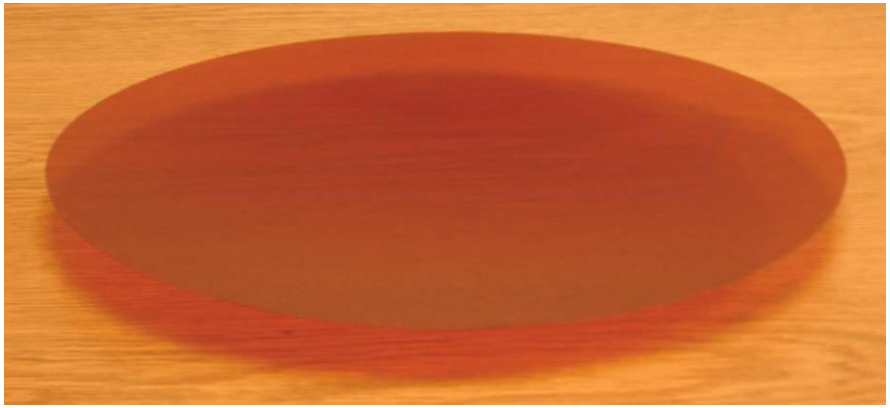
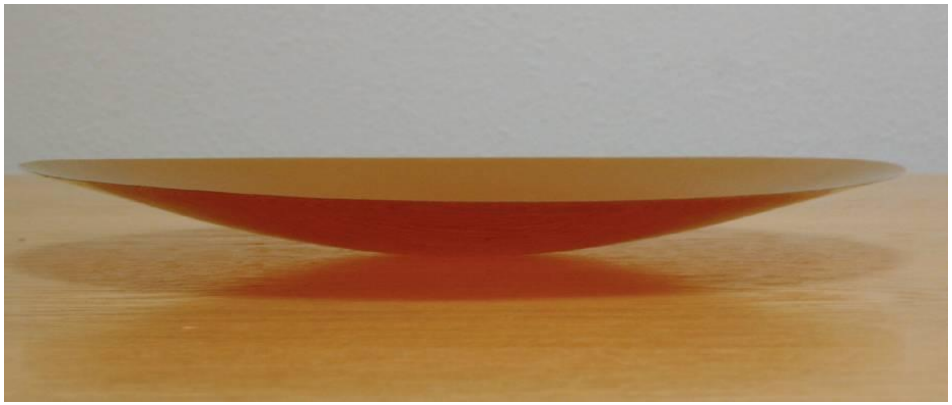
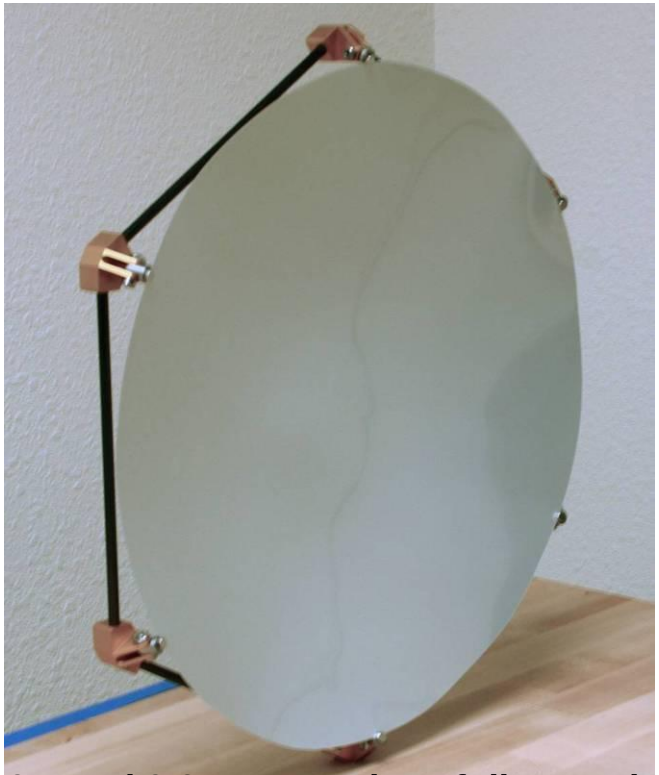
Strength Through Curvature







0.4 and 0.6 m examples of discrete boundary mounting on lightweight structures

Background: Space Heritage Materials

- **Material Types**
  - Polyimides (Kaptons, . . .)
  - Polyesters (Mylars, . . .)
- **Space Use Examples**
  - MLI Blankets
  - Sun Shields (Skylab . . . JWST)
  - Blanket Type Solar Arrays
  - RF Aperture Shields
  - Flex Circuits

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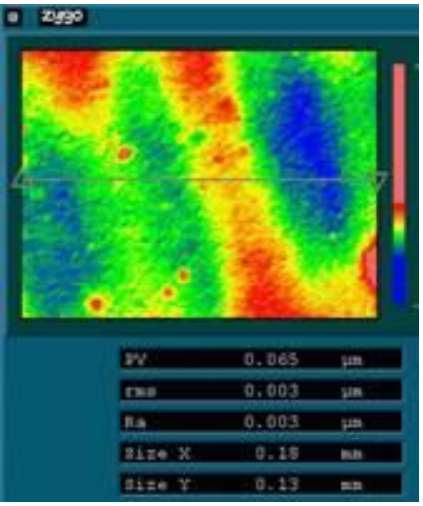
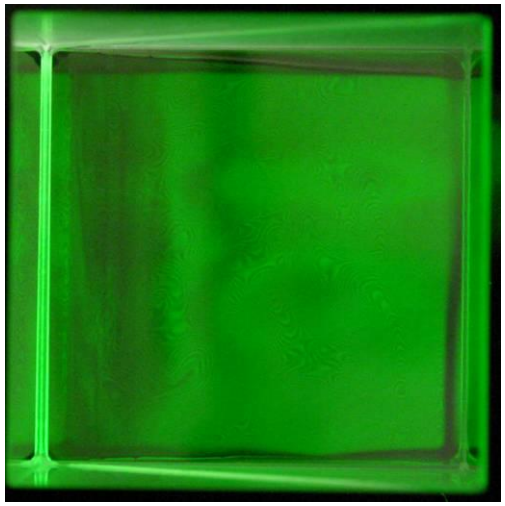
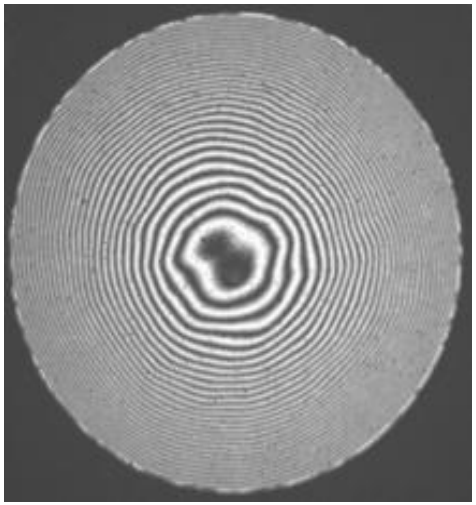
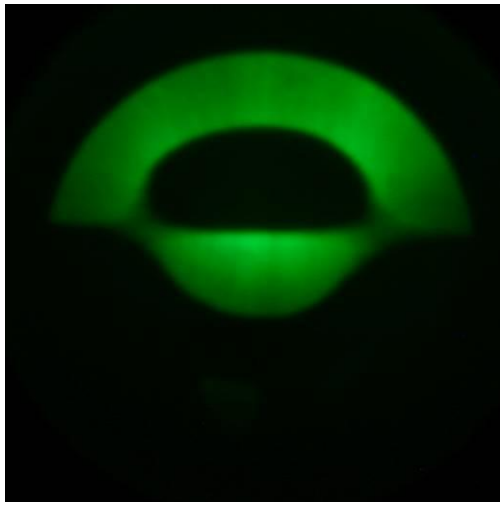
Optical Quality Materials

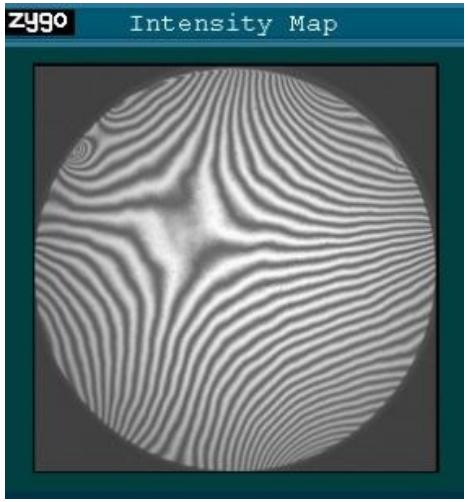


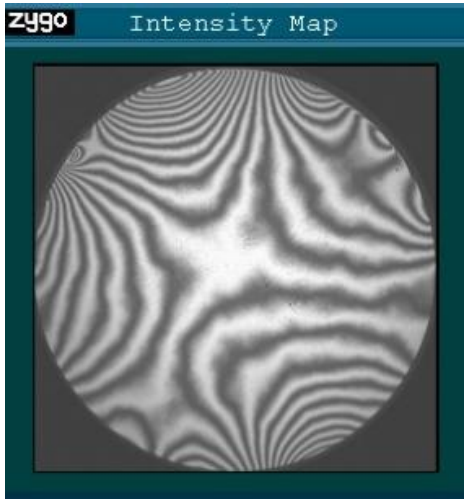


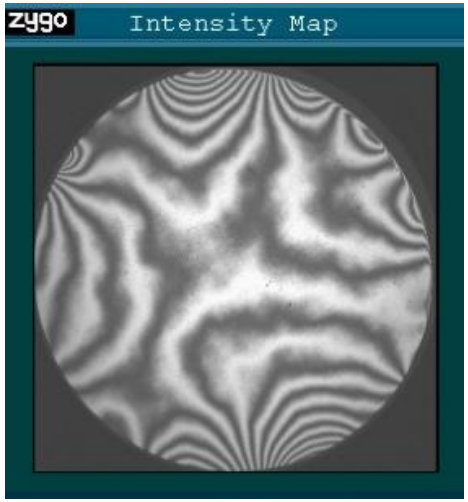




Optical Grade Reflective Films (from left to right 3 to 5 nm rms micro roughness, minimal thickness variation, demonstrated interferometric optical measurements showing 20 nm rms or less surface figure, very promising preliminary optical shop and interferometric test results on powered surfaces)







Demonstrated Optical Level Boundary Control (example from 10 cm flat)

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Process Compatibility

With Wide Range of Materials & Coatings

- Shown material/coating combos are the ‘standard’ stocked materials
  - Many other materials/coatings demonstrated as well.

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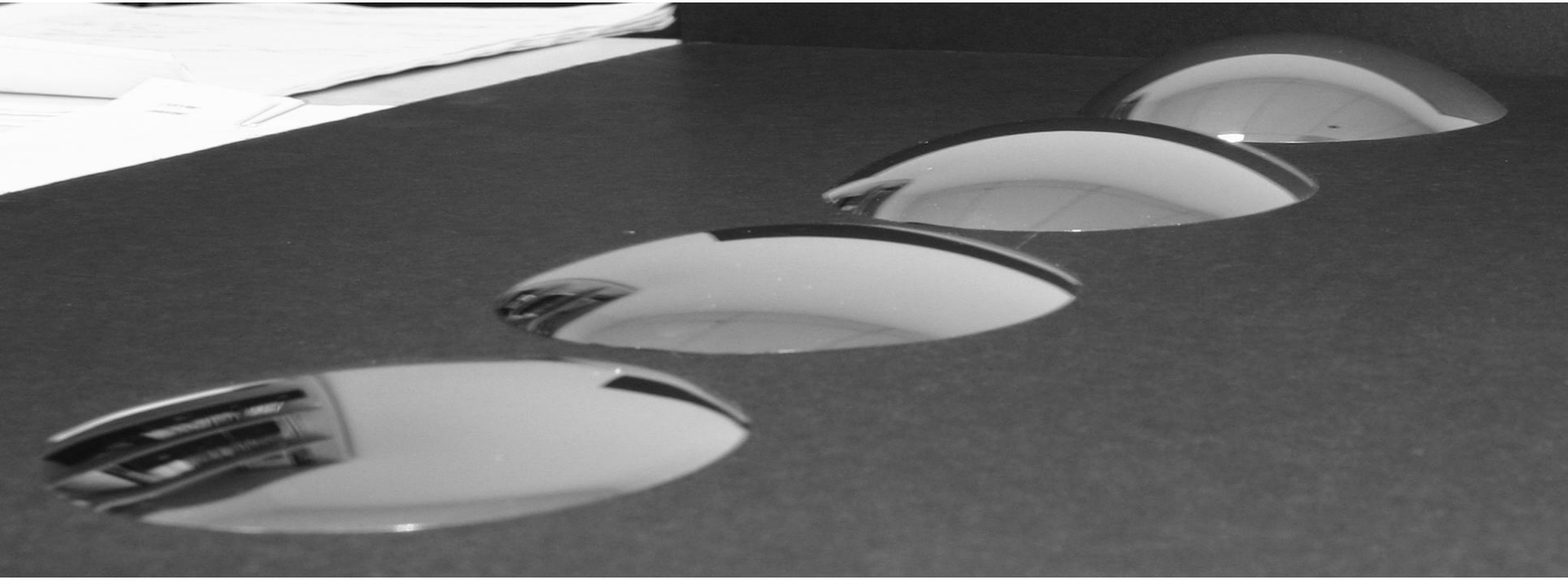
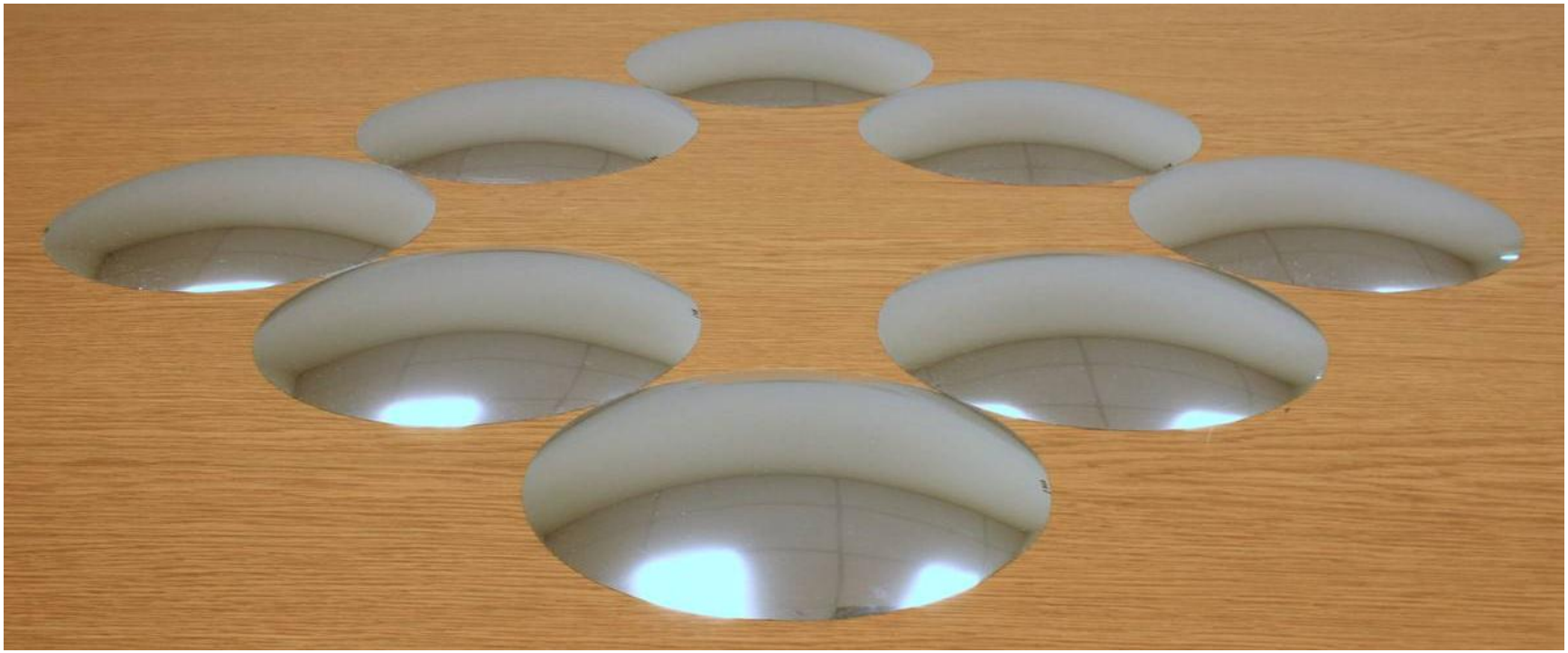
Process Compatibility
With Wide Range of Materials & Coatings

Flexible Process Can Produce Range of Depths



- Variety of prescriptions can be made with the same fixture
- Yields strong cost/schedule advantage
- Shown examples vary in R# from 2.2 to 0.9

Efficient Process



Multiple example 0.2m shells

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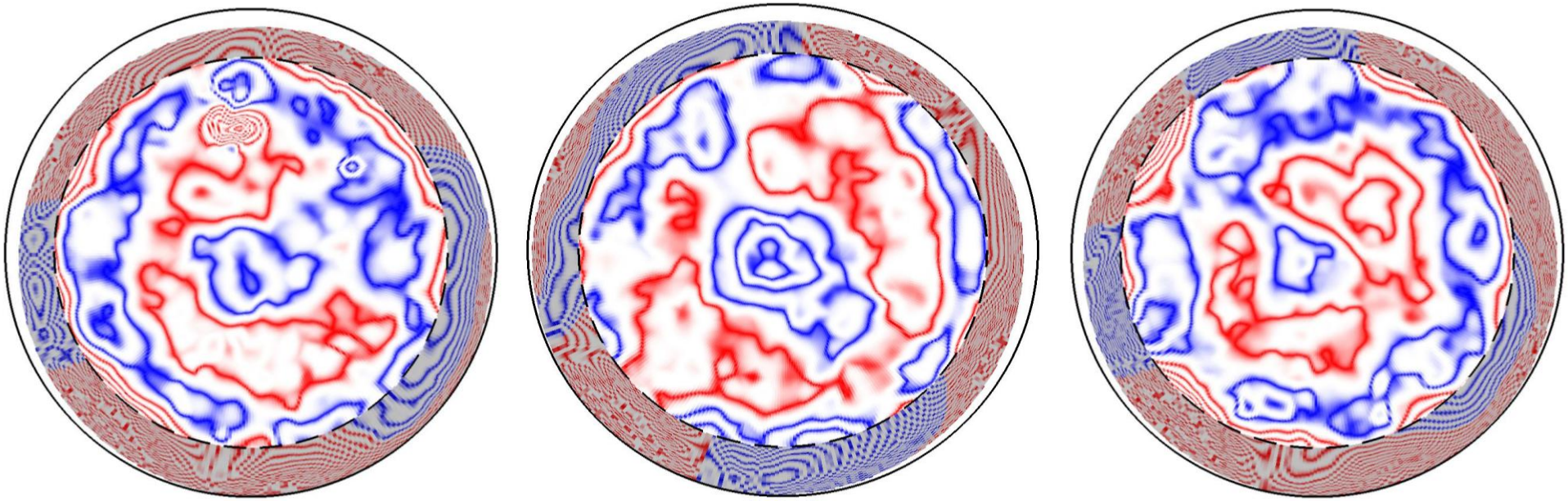
Current Global Figure Metrics



Prescription
- On-Axis,
- 0.2 m aperture
- ROC = 0.22m (fast)

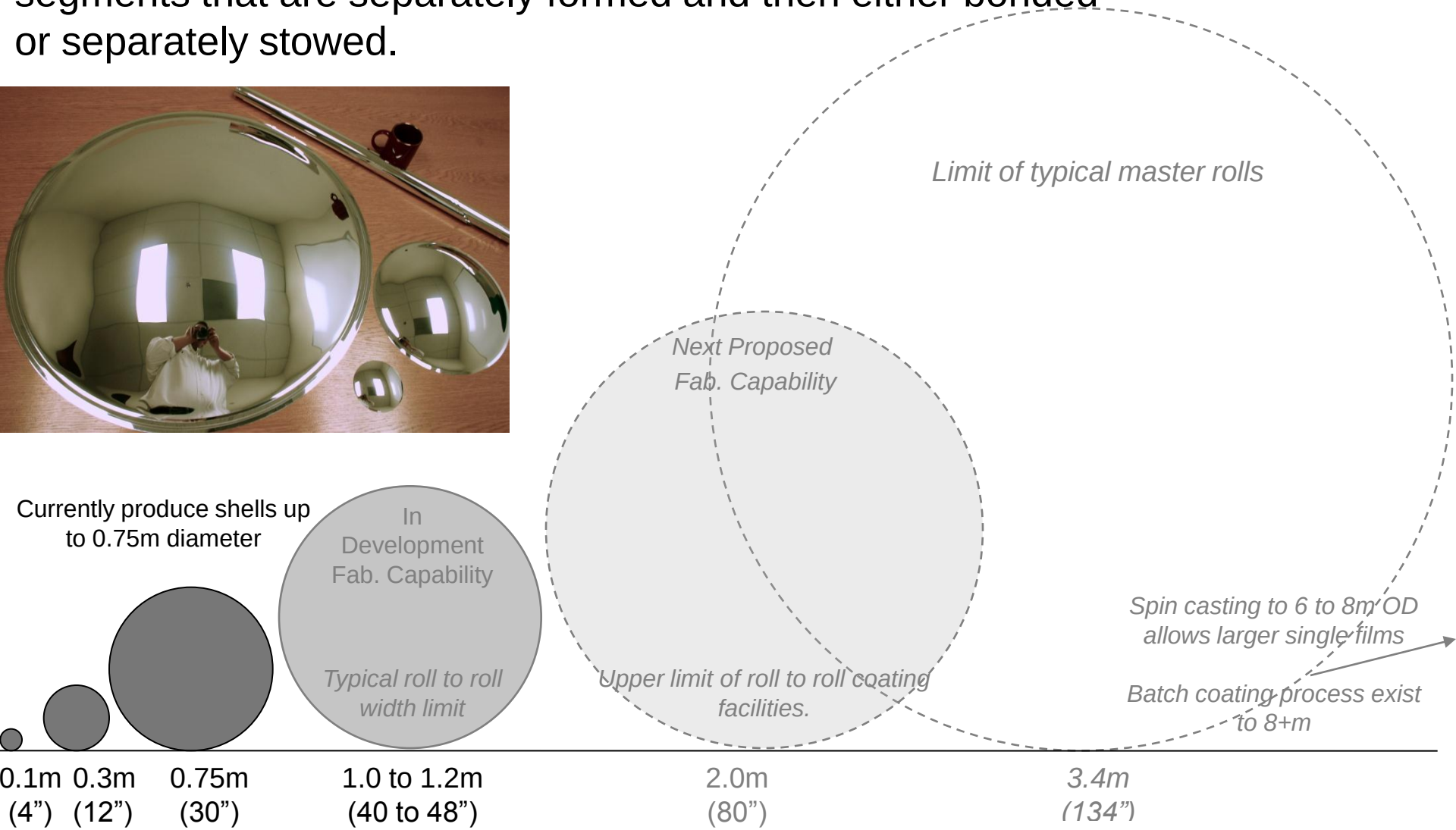
Figure Error (over 80% diameter)
- 7.6 to 7.8 um rms, 7 to 10x Peak Valley
- 10 um contour settings, boundary corrected
- Dominated by spherical aberration terms
- Noise floor
  - Photogrammetry: About 1-2 um rms
  - Material : About 1-2 um rms

Scalable Process

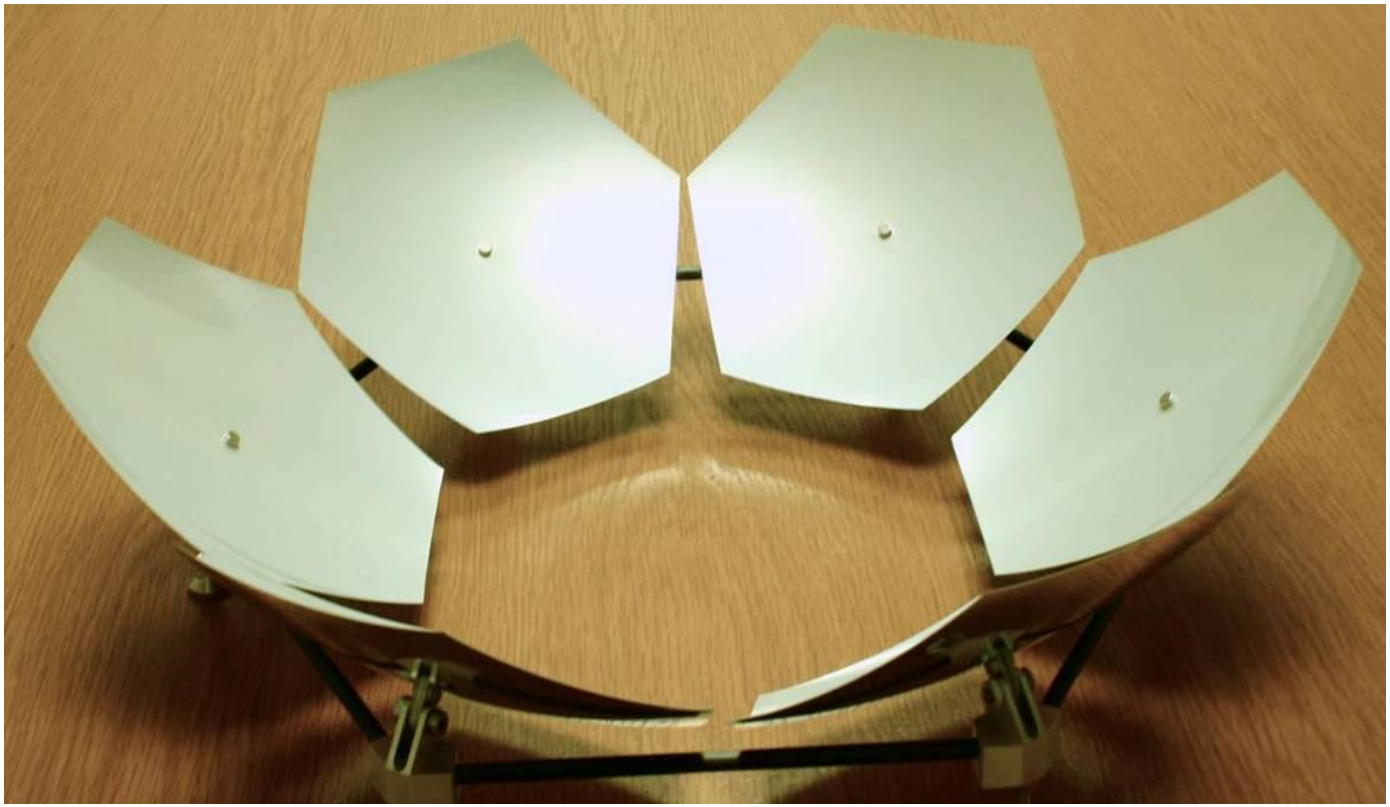
Example Shells: 0.1 m, 0.3 m, and 0.75 m (stowed 0.75 m and coffee mug for scale)
Plans for 1.1 and 2.0 m fabrication hardware in development

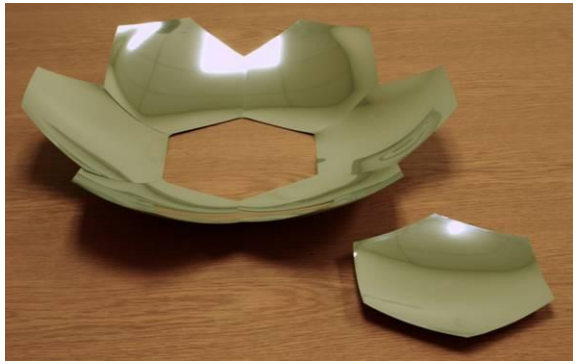
Scalable Process

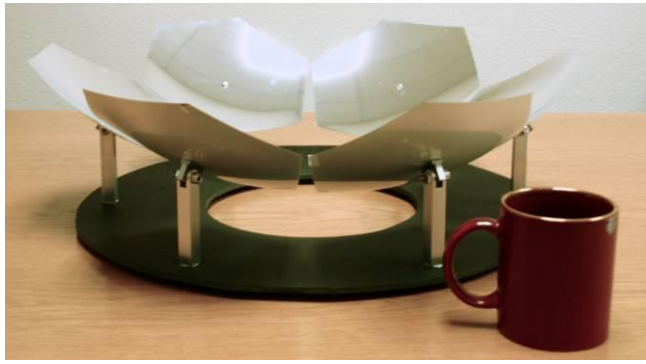
Multiple paths exist. Direct formation scalable to 8m with investment in new tooling. Other approaches include segments that are separately formed and then either bonded or separately stowed.



Scalable Process: Segmentation



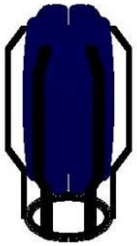


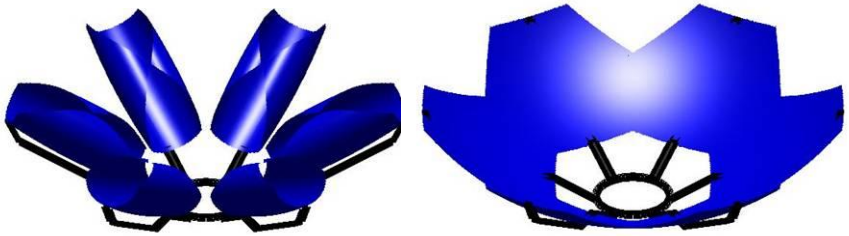


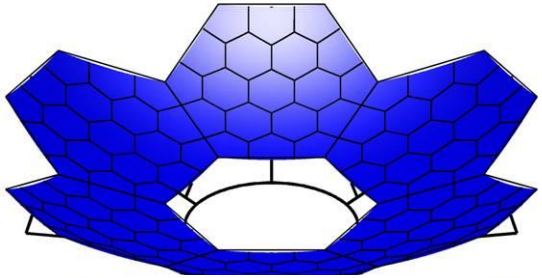
Example 0.5m aperture constructed from 0.2m hexagon segments

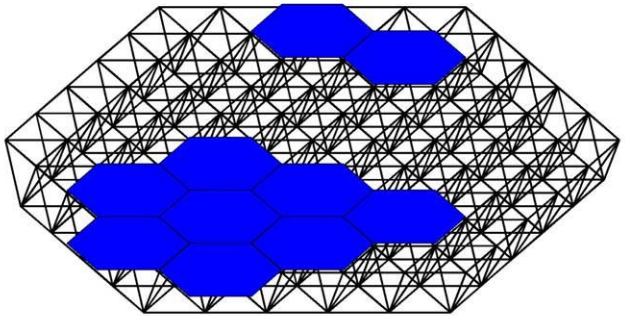
Multiple Scaling Paths

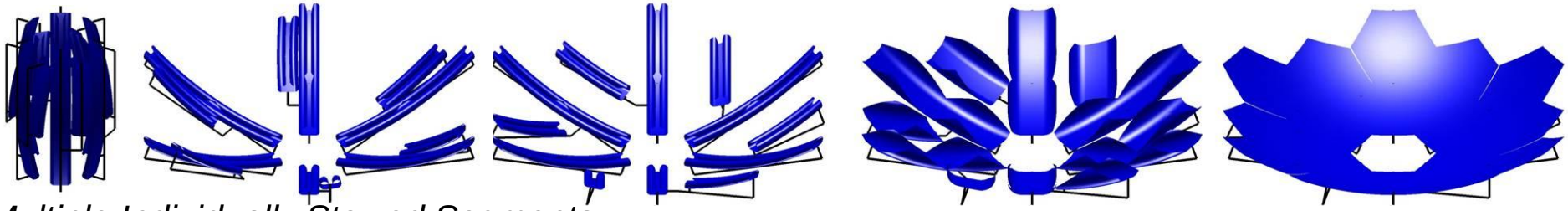
- **Ever Larger Continuous Surfaces**
  - **0.1, 0.3, 0.75 . . . (*1.1, 2.0,*** *3.4, 8.0 m)*
- **Segments (also ever larger)**
  - **Individually Stowed/Deployed**
    - **Rolled**
    - **Stacked**
  - **Joined (yields larger)**
    - **Continuous Surface**
    - **Larger Segments**





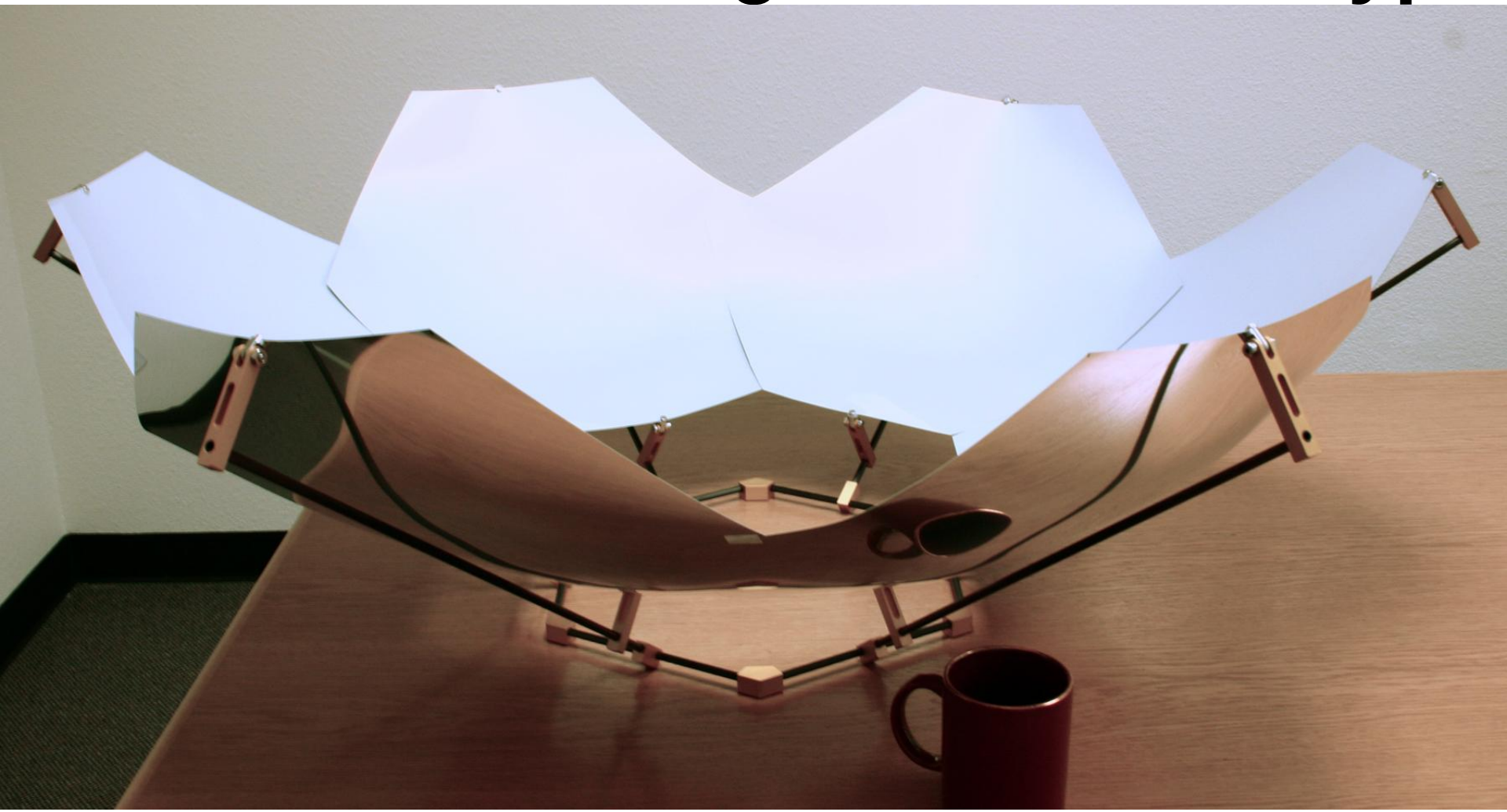






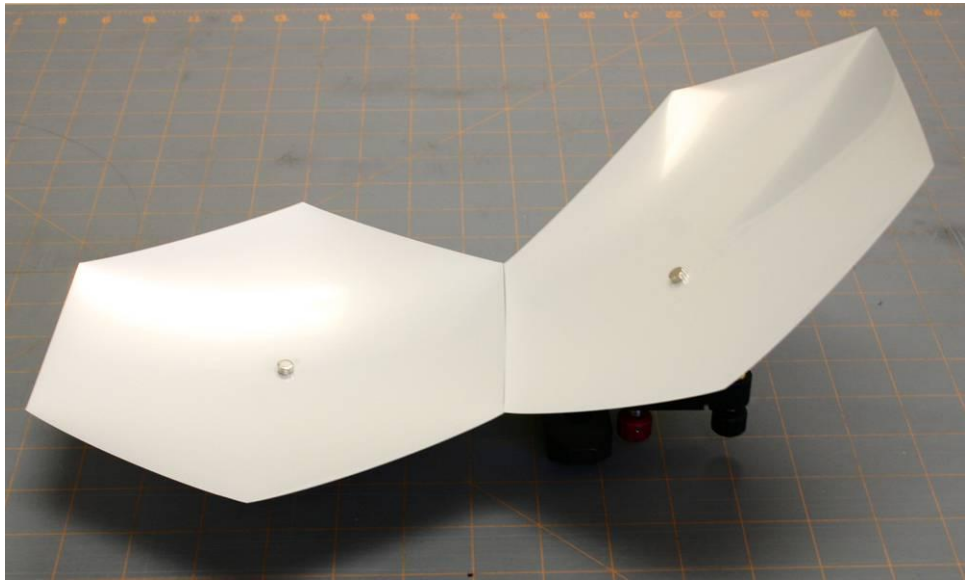
Multiple Individually Stowed Segments

1.0m Segmented Prototype

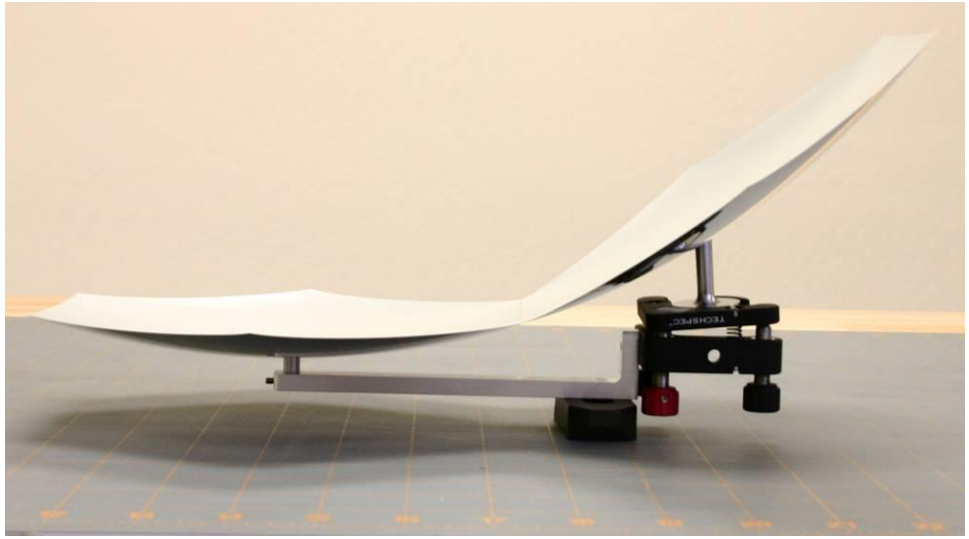


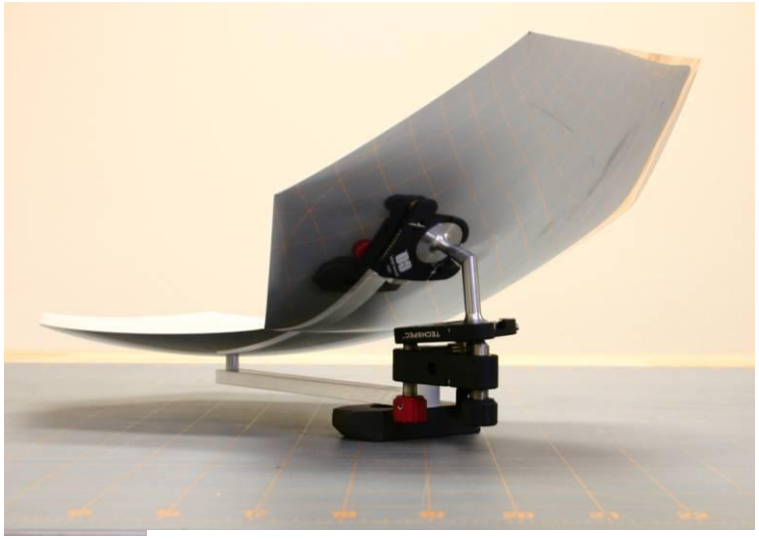
- Segments (0.5m c2c, 0.6m ROC, F/0.6)
- System (1.0m diameter, 0.6m ROC, F/0.3)

Two Segment Prototype Assembly



- **Initial Demonstration – Test the basic repeating structure of a single ring (7 hexagons) segmented reflector**
- **Segmentation requires rigid body adjustment of the outer hexagon to align it with center hexagon**
- **To save cost, off-the-shelf optical alignment part provides tip-tilt and piston motion of the segment's center attachment point**
  - **Currently manual adjustment**
  - **Three 100 pitch threads**





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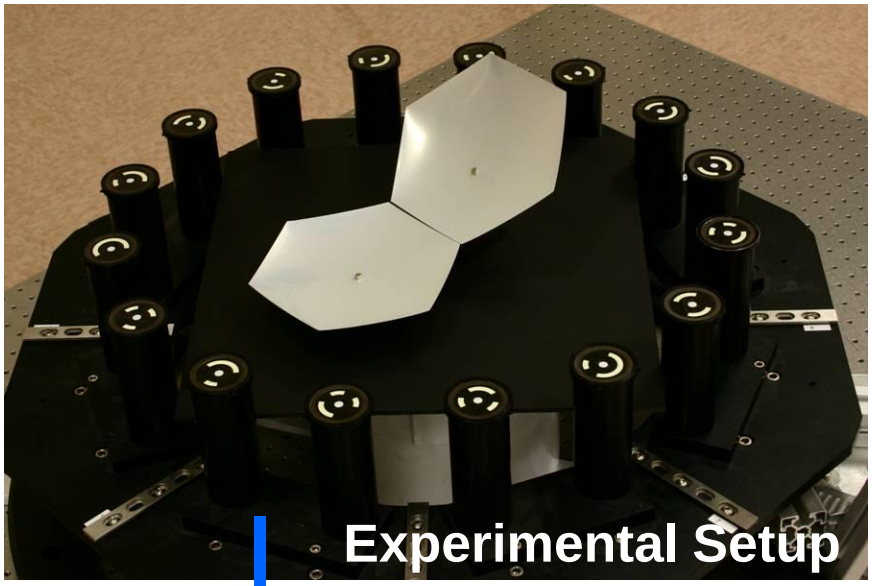
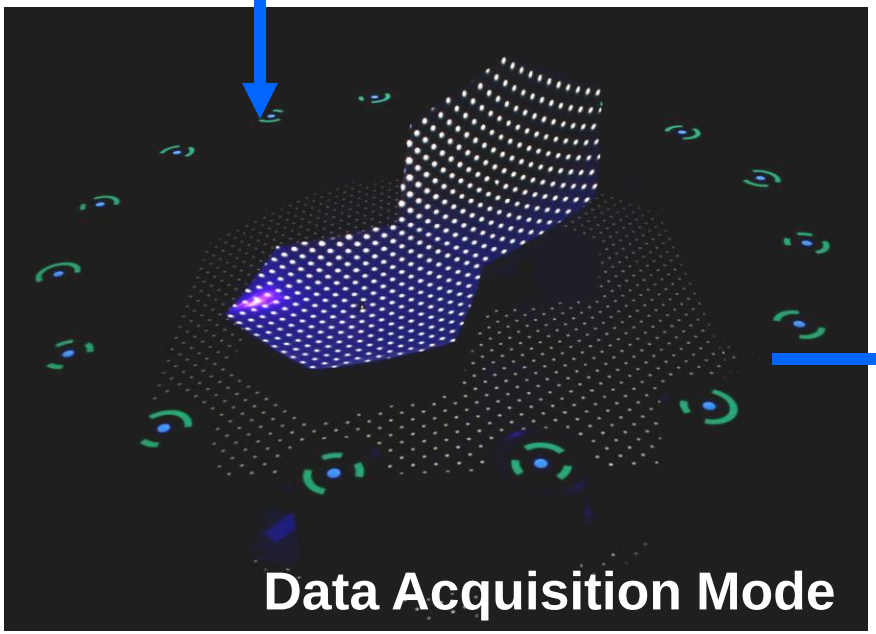
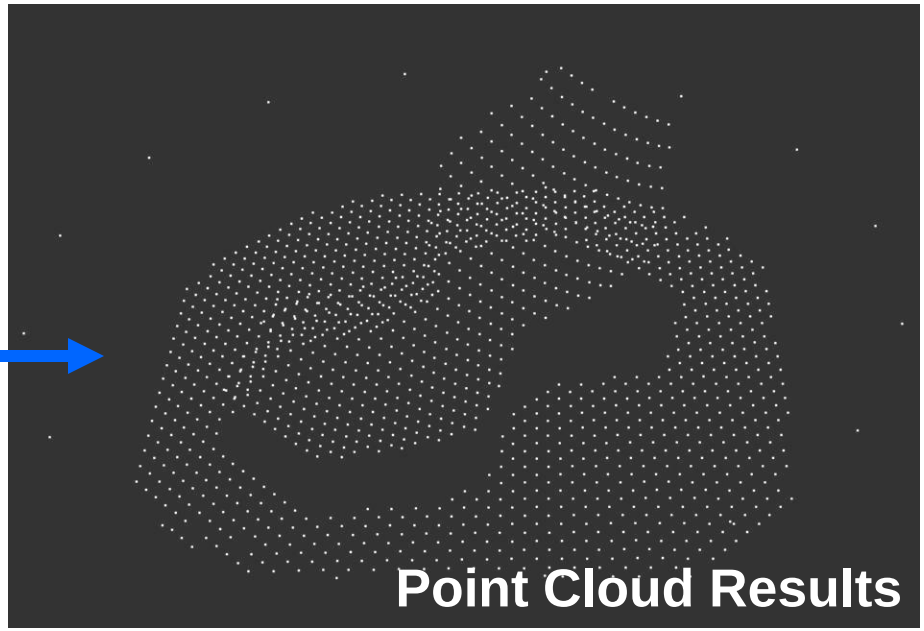
Photogrammetry Tests



- Two segment assembly was placed into Mevicon's 0.5 m photogrammetry test setup
- Photogrammetry was used to measure point locations on the two hexagons
  - 16 coded targets around the segments
  - Projected dots onto segment's surface
  - 16 image locations used in processing
- Currently, post-processing point locations to generate surface error plots





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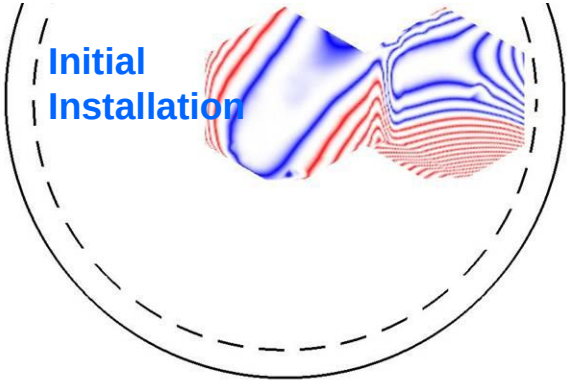
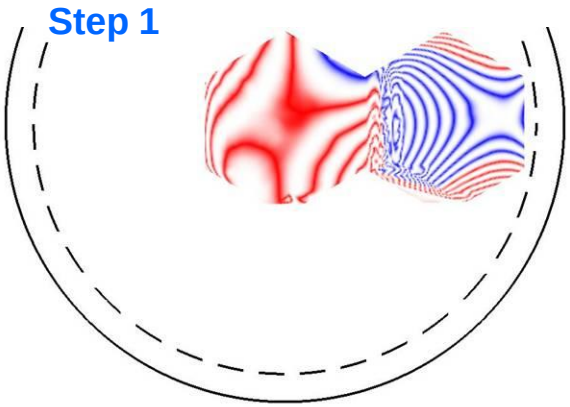
Closed Loop Control Test

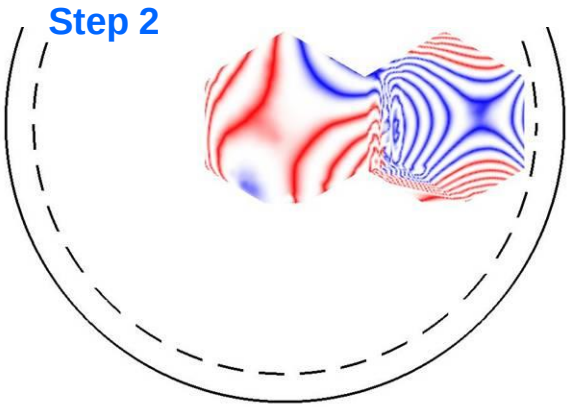


Test sphere reference, ∅ 0.46 m,
Sphere, R 0.284m, R# 0.7m
RMS = 1.4 mm, PV = 9.8 mm
500 μm Contours, Ri-Ro 0.0%-90.0%

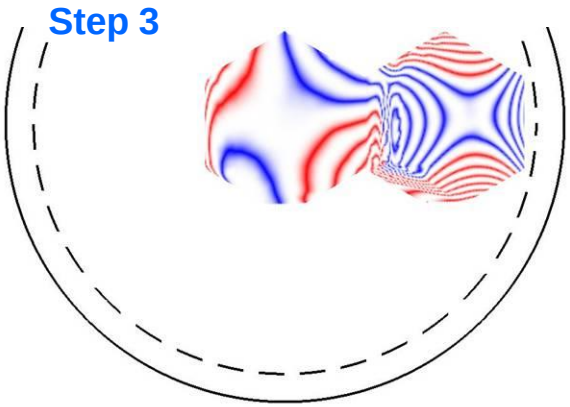
- **Using adjustment screws, aligned side hexagon with center hexagon**
- **Initial surface error (left) shows tilt and piston error between center and side hexagon**
- **First adjustment corrects most of the tilt error**
- **Next two adjustments reduce the piston error between segments**
- **Reduction in surface rms from 1.4 mm to 832 microns**
- **Residual error dominated by gravity induced astigmatism**



Test sphere reference, ∅ 0.46 m,
Sphere, R 0.267m, R# 0.6m
RMS = 1.3 mm, PV = 7.2 mm
500 μm Contours, Ri-Ro 0.0%-90.0%



Test sphere reference, ∅ 0.46 m,
Sphere, R 0.263m, R# 0.6m
RMS = 990 μm, PV = 6.2 mm
500 μm Contours, Ri-Ro 0.0%-90.0%



Test sphere reference, ∅ 0.46 m,
Sphere, R 0.260m, R# 0.6m
RMS = 832 μm, PV = 5.5 mm
500 μm Contours, Ri-Ro 0.0%-90.0%

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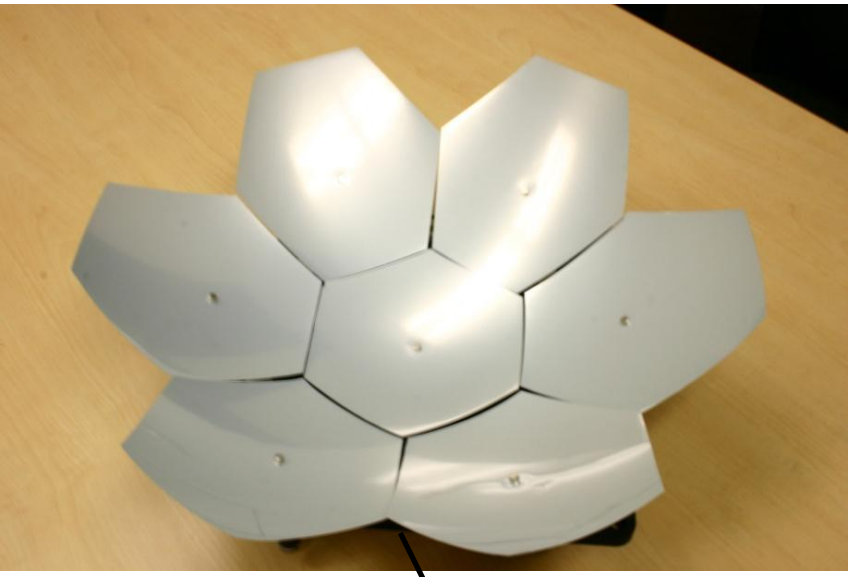

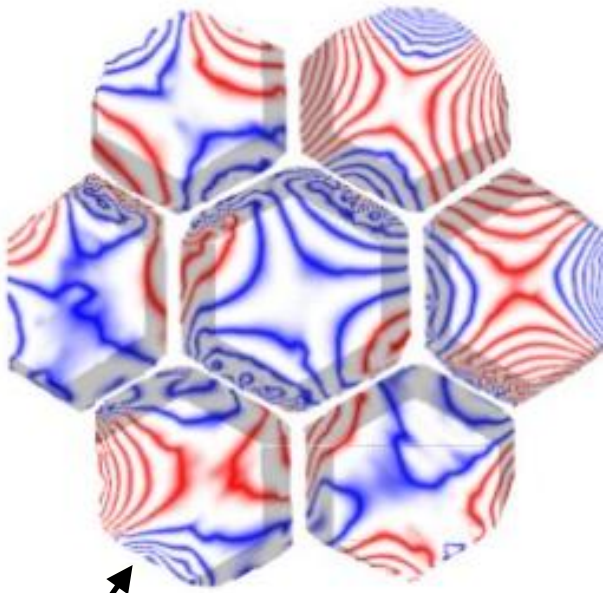

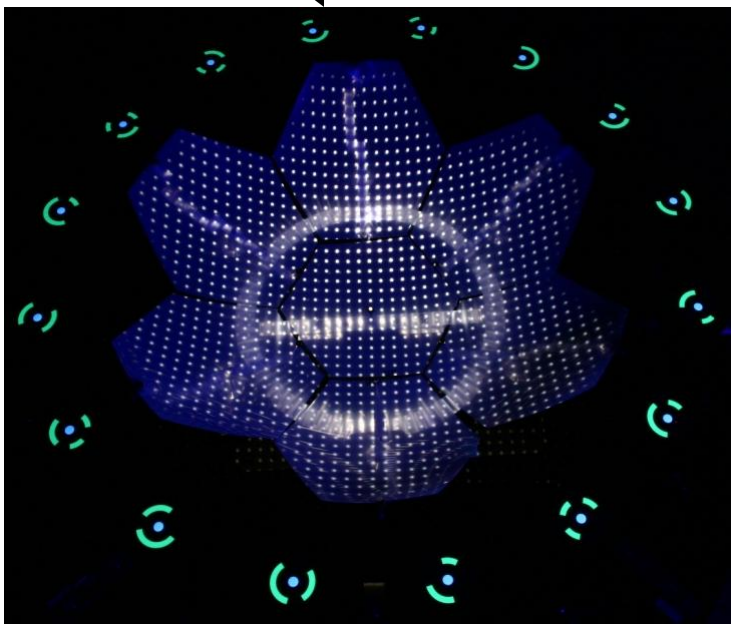

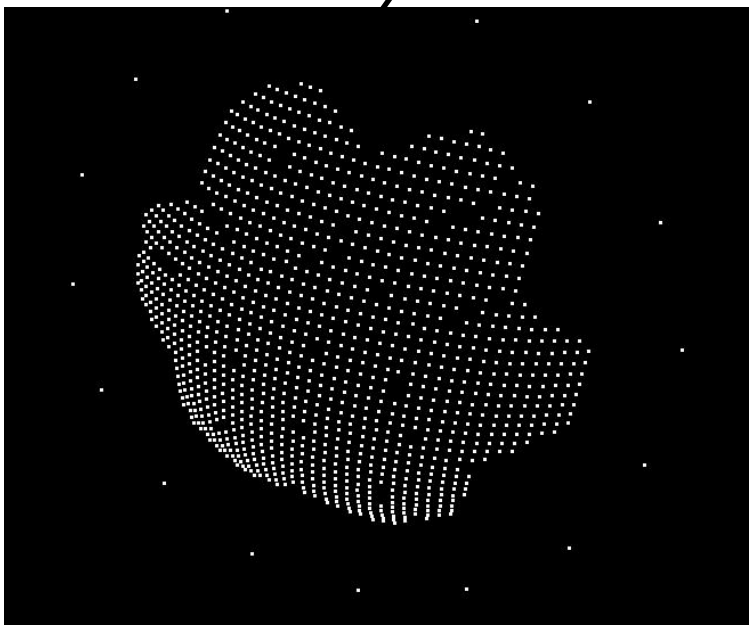

Example Test Image → Point Cloud

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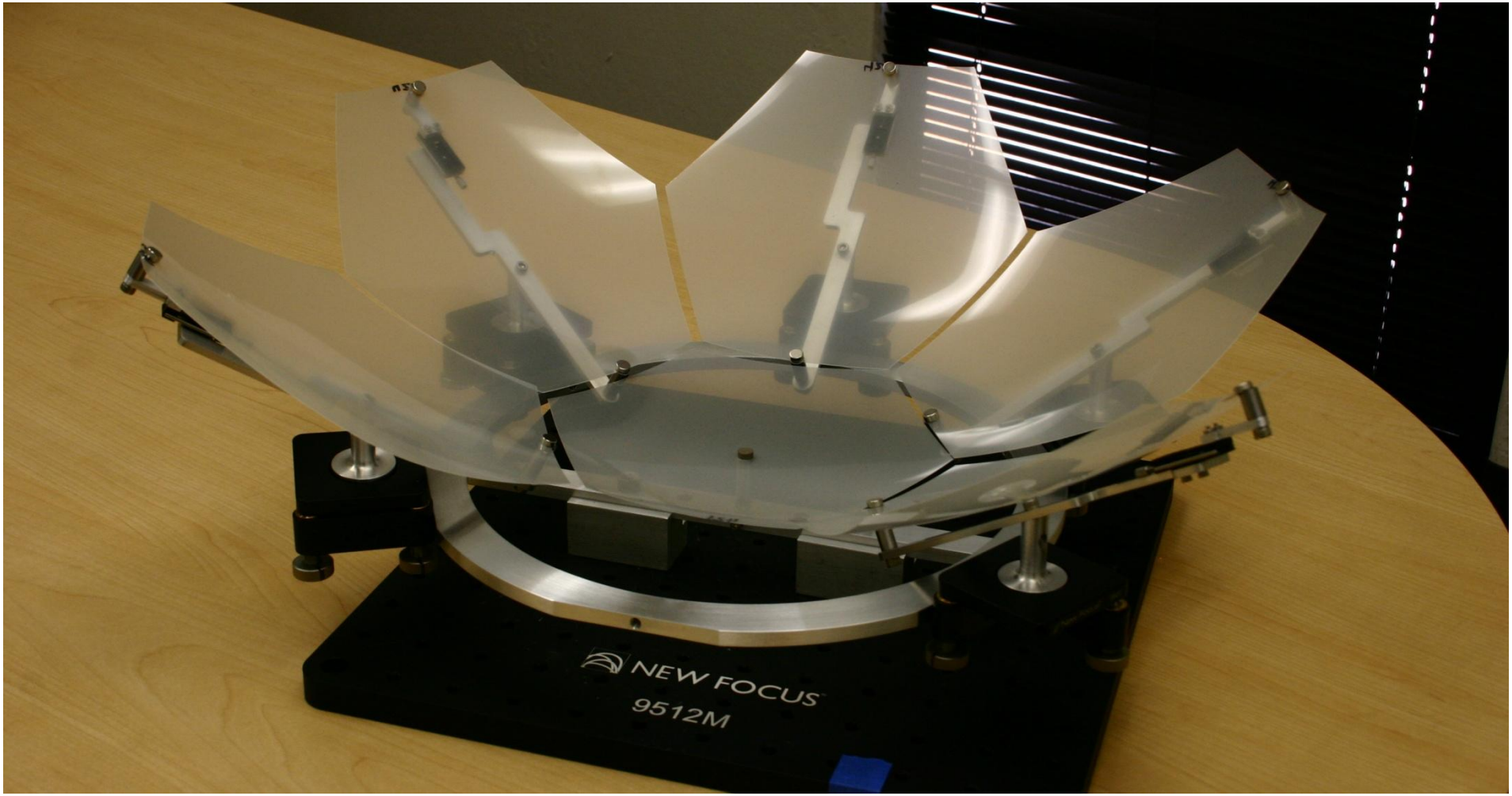
Improved N=7 Segmented Two Point Mount Prototype



1 shell and mount removed to enhance clarity

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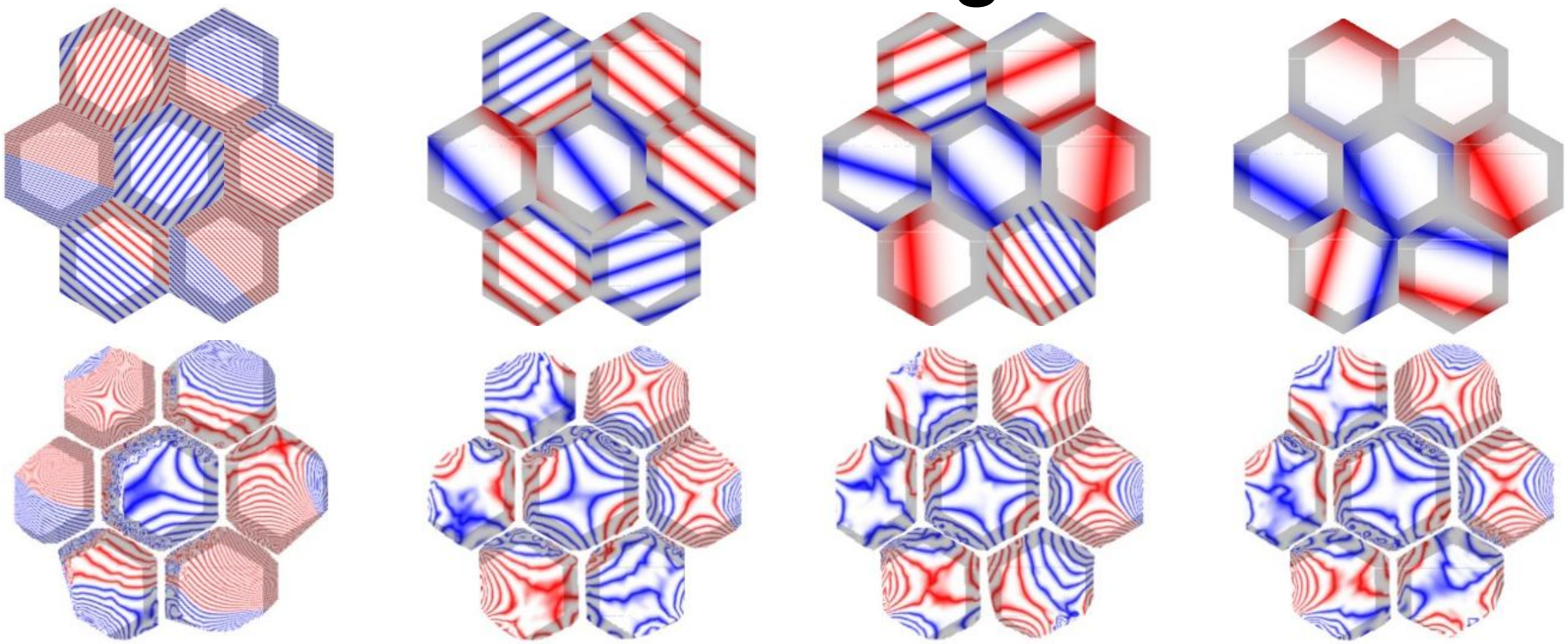
Improved N=7 Segmented Two Point Mount Prototype Rigid Body Alignment Results



Test 428_001, ∅ 0.19 m,	Test 428_005, ∅ 0.19 m,	Test 428_010, ∅ 0.19 m,	Test 428_013, ∅ 0.19 m,
Sphere, R 0.278m, R# 2.1m	Sphere, R 0.287m, R# 2.2m	Sphere, R 0.288m, R# 2.2m	Sphere, R 0.287m, R# 2.2m
RMS = 4.1 mm, PV = 52.6 mm	RMS = 1.0 mm, PV = 7.1 mm	RMS = 818 μm, PV = 8.6 mm	RMS = 788 μm, PV = 7.2 mm
500 μm Contours, Ri-Ro 0.0%-70.0%	500 μm Contours, Ri-Ro 0.0%-70.0	500 μm Contours, Ri-Ro 0.0%-70.0	500 μm Contours, Ri-Ro 0.0%-70.0%

Example progression in manual adjustment of rigid body alignment of 2 point mount, 7 segment spherical system. Initial error was decreased by more than a factor of 5 in an rms sense (from 4.1 to 0.788 um rms)

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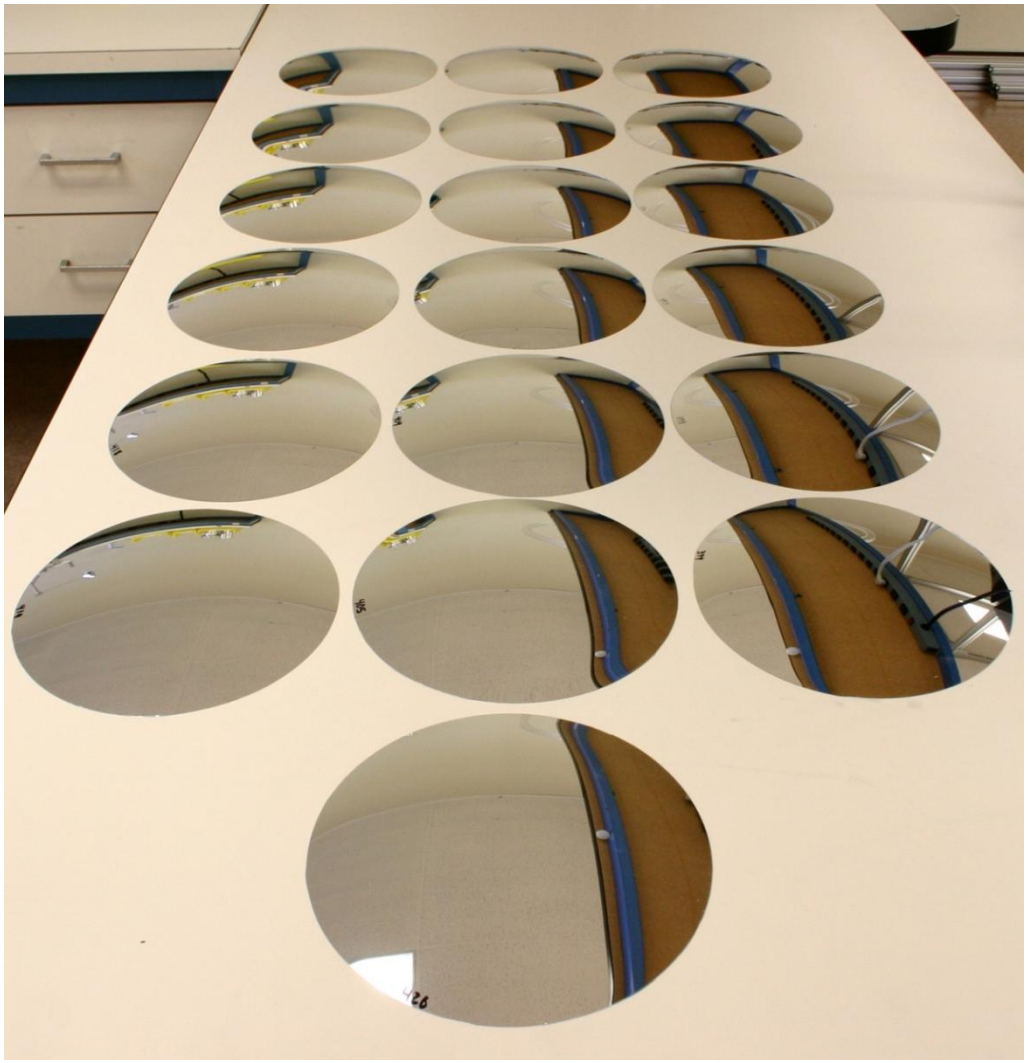
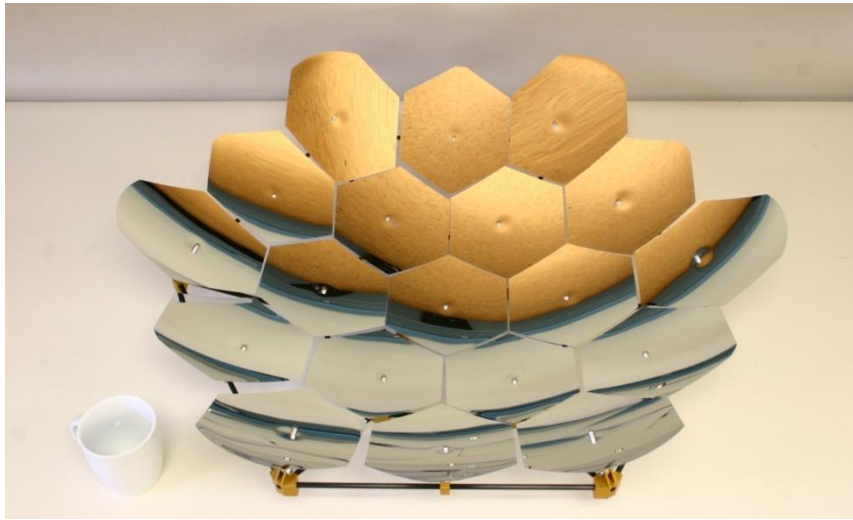
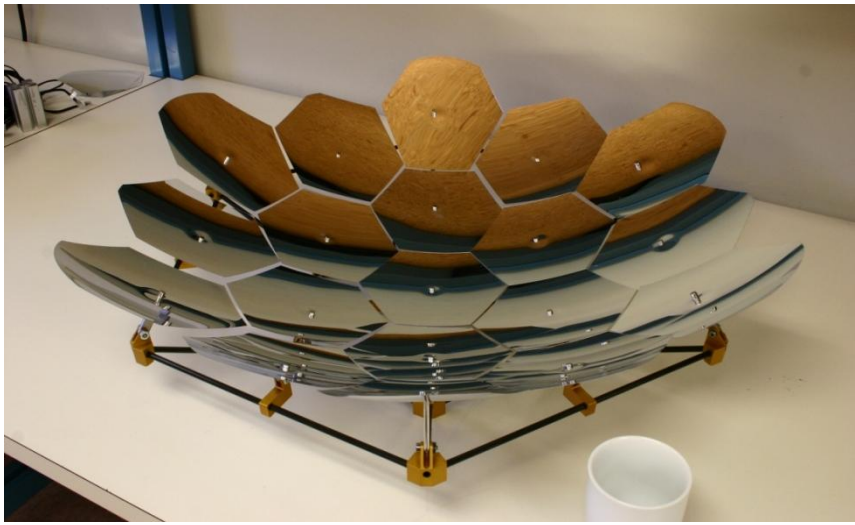
N=19 Segmented Prototype







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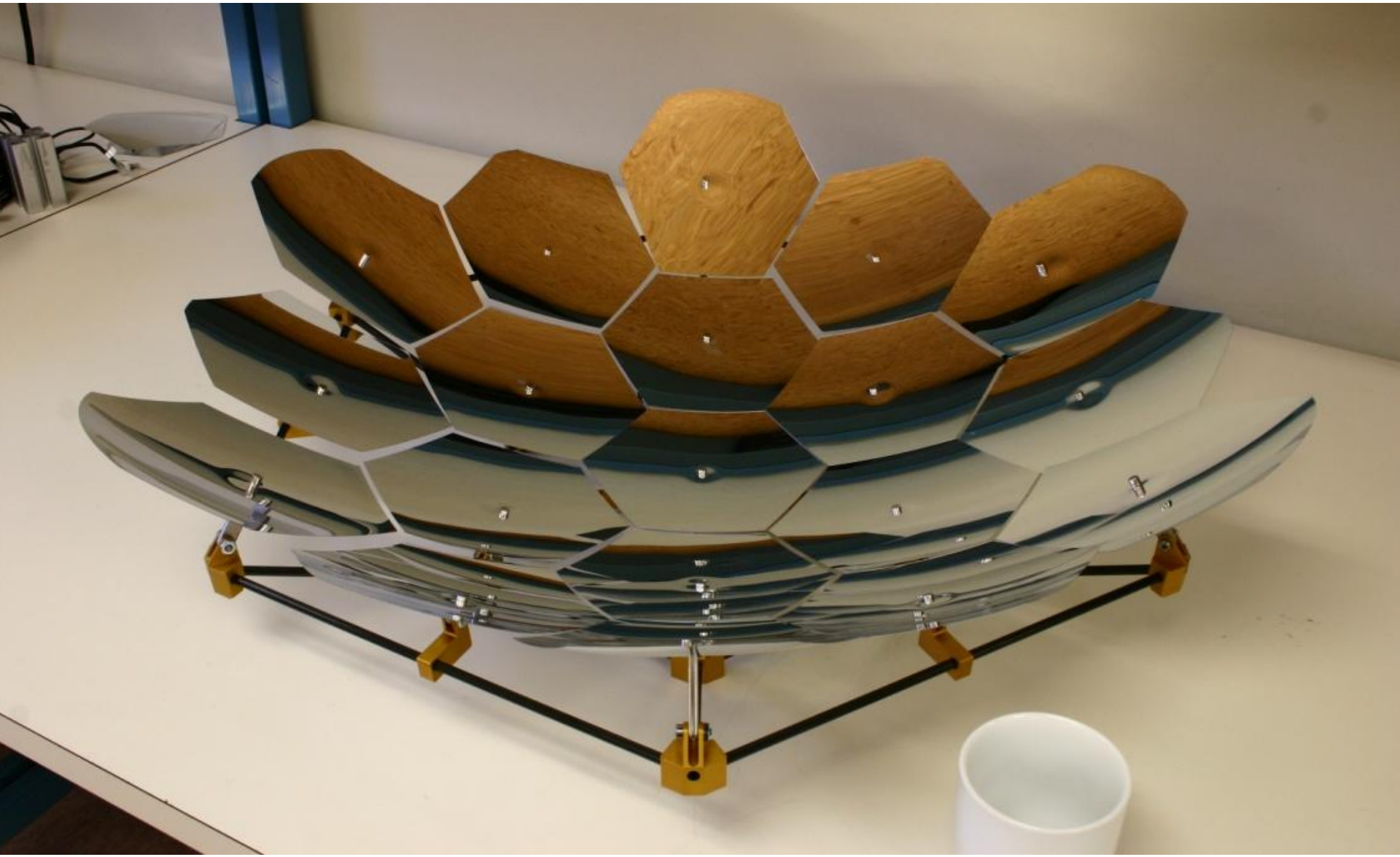
N=19 Segmented Prototype



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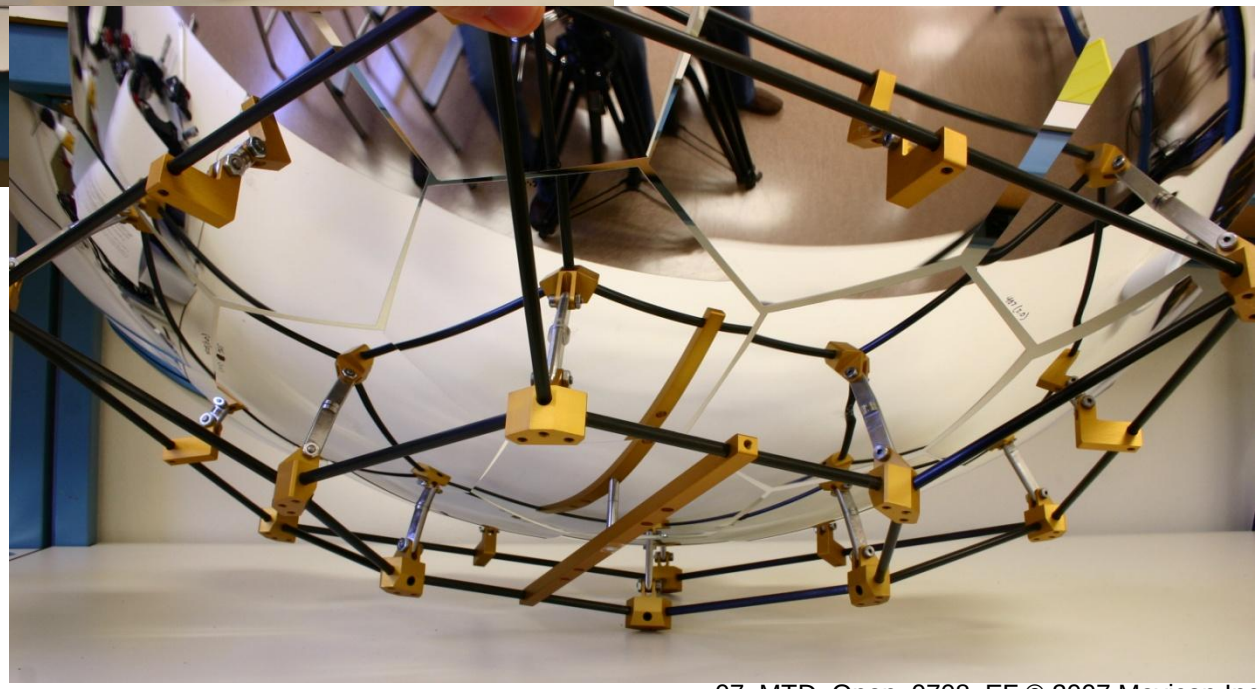
N=19 Segmented Prototype Backside



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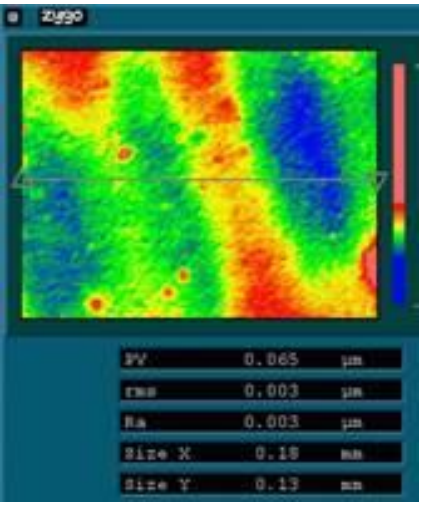
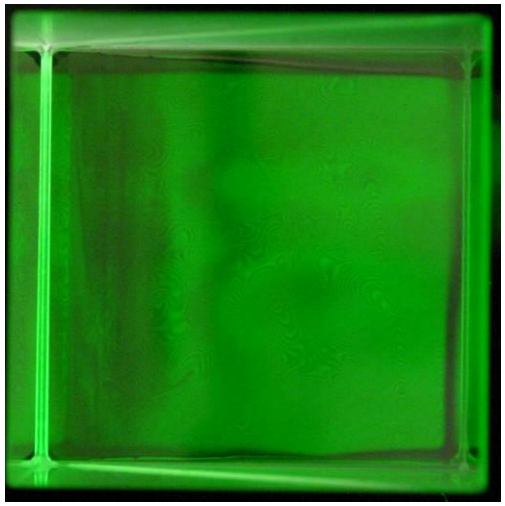
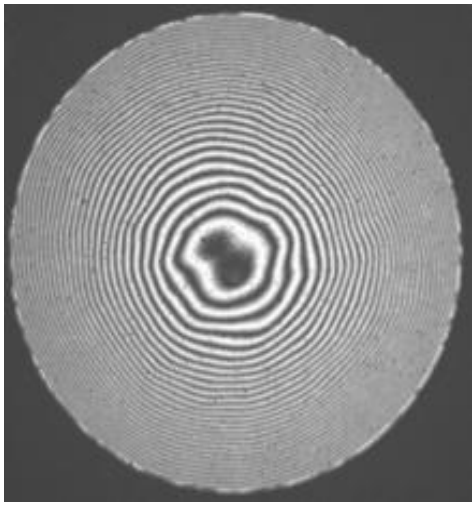
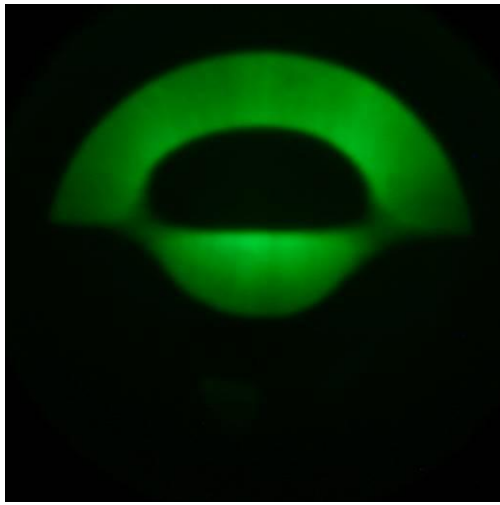
Optical Quality Materials

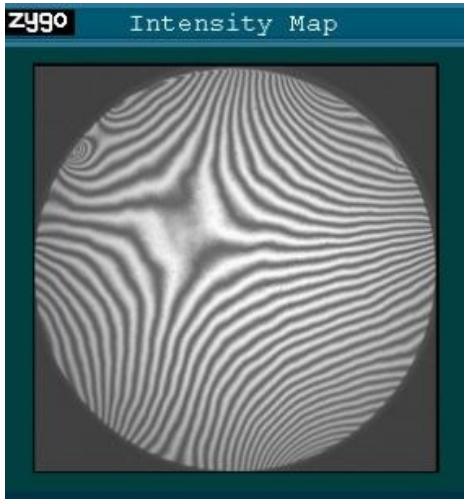


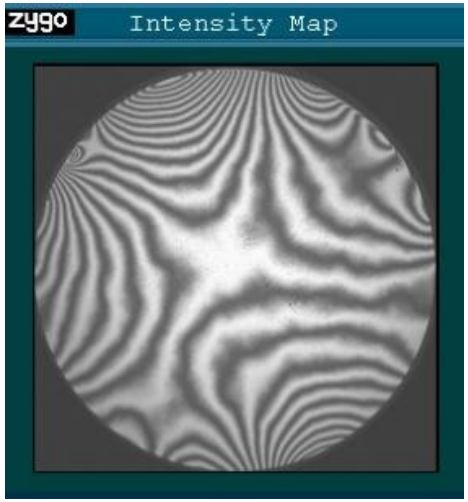


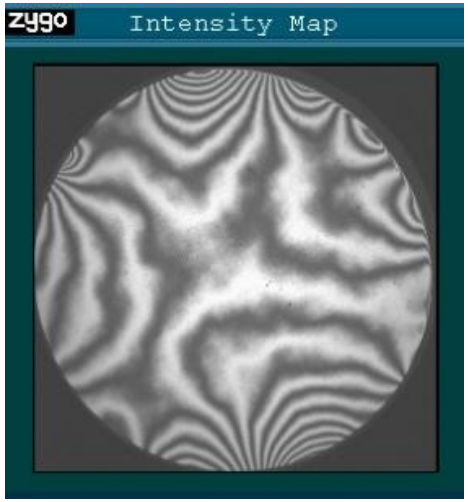




Optical Grade Reflective Films (from left to right 3 to 5 nm rms micro roughness, minimal thickness variation, demonstrated interferometric optical measurements showing 20 nm rms or less surface figure, very promising preliminary optical shop and interferometric test results on powered surfaces)

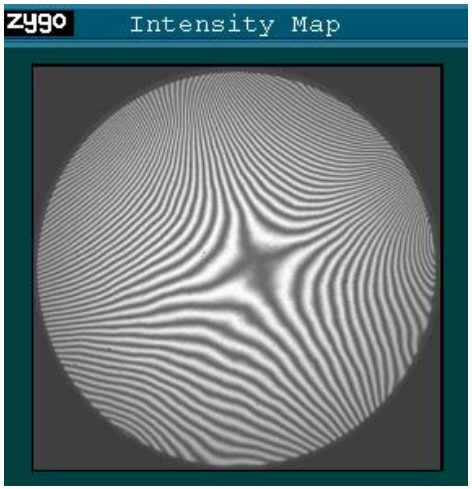


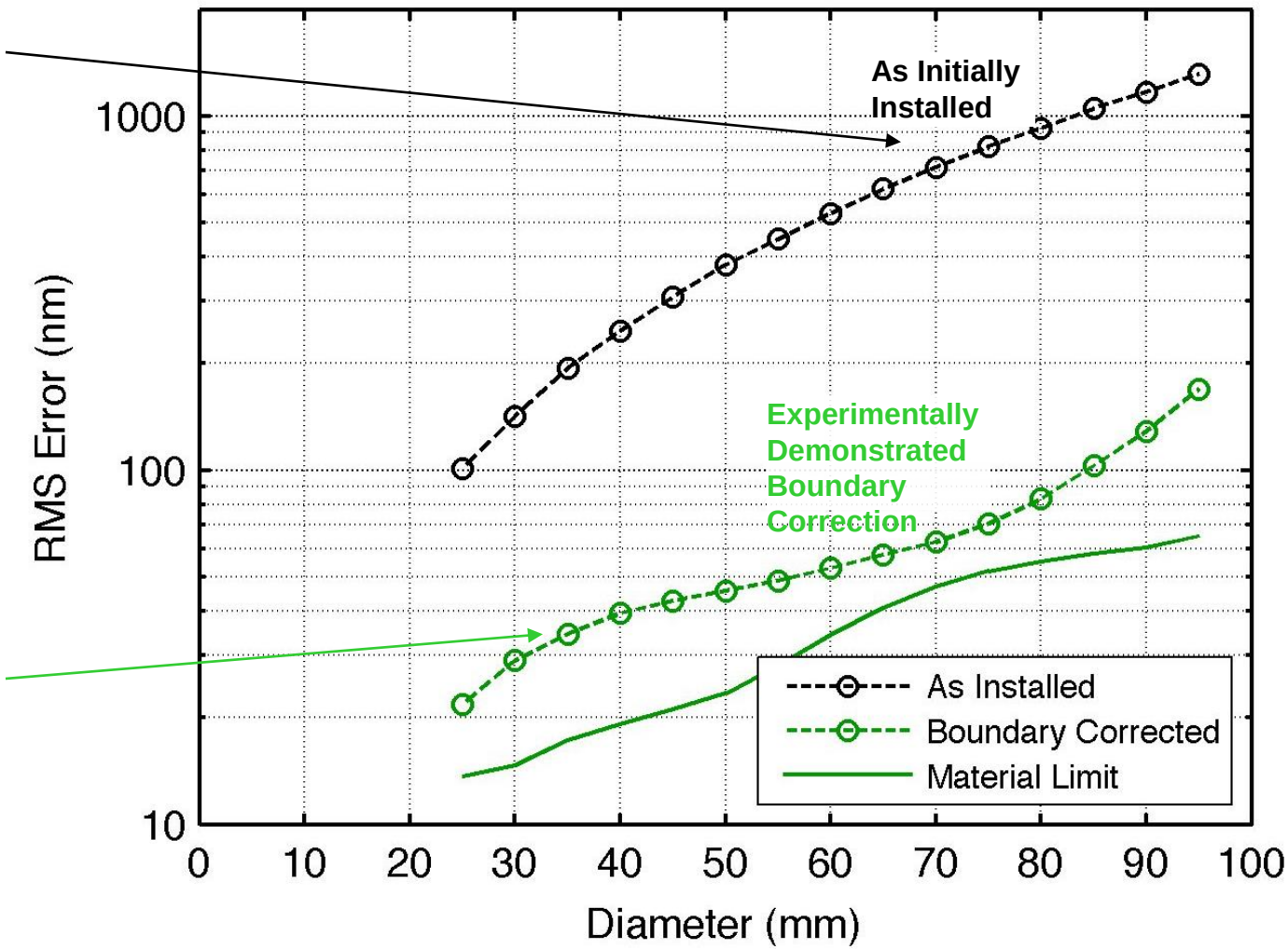




Demonstrated Optical Level Boundary Control (example from 10 cm flat)

Optical Boundary Control





- **5 to 10x Improvement in Experimental Figure Error of 100mm tensioned flat**
  - **900 nm → 80 nm at 80mm Aperture**
  - **100 nm → 20 nm at 25mm Aperture**
- **Control Authority Approaching Material Thickness Variation**

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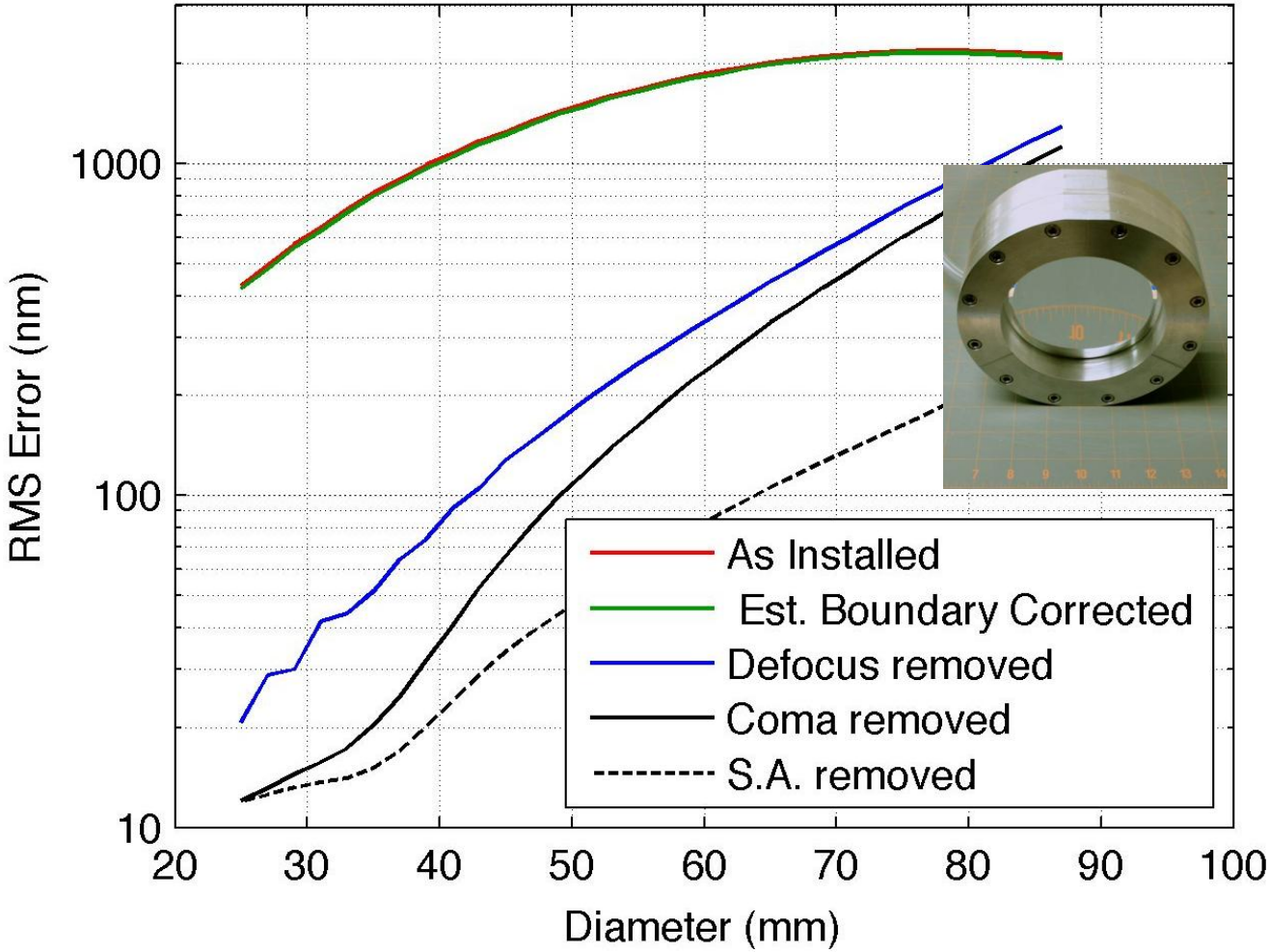
Very Recent Interferometric Measurement of Spherical Surfaces

Full Aperture (100mm OD)

Zoomed In (50mm OD)



Interferometric measurement of a thin-film spherical surface

Pressurized, Tensioned Flat
Diameter: 100 mm
Radius of Curvature: 730 mm
R/7.3, F/3.6

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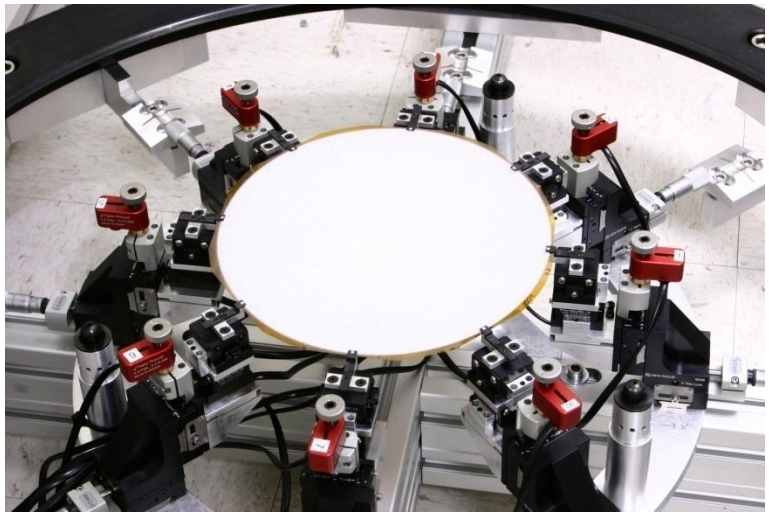
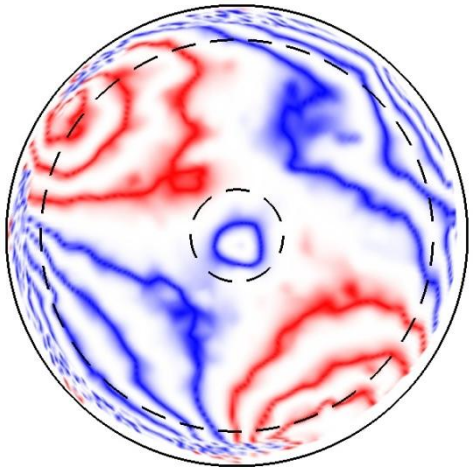
Active Boundary Control

- **Fully automated control**
- **0.2 m aperture, R# 0.75**
- **3 to 4 µm rms repeatedly achieved over 75 to 80% of diameter**
- **Results primarily limited by coating, fabrication, and material noise floors**

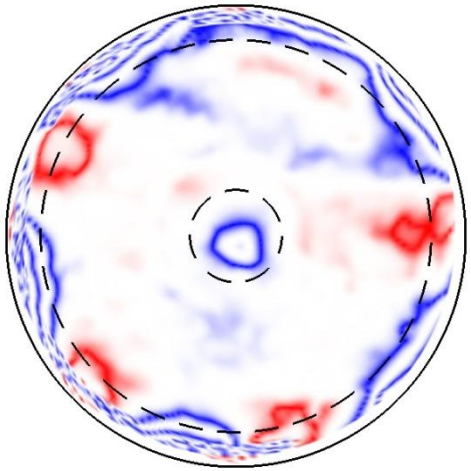


0.2m diameter shell correction result



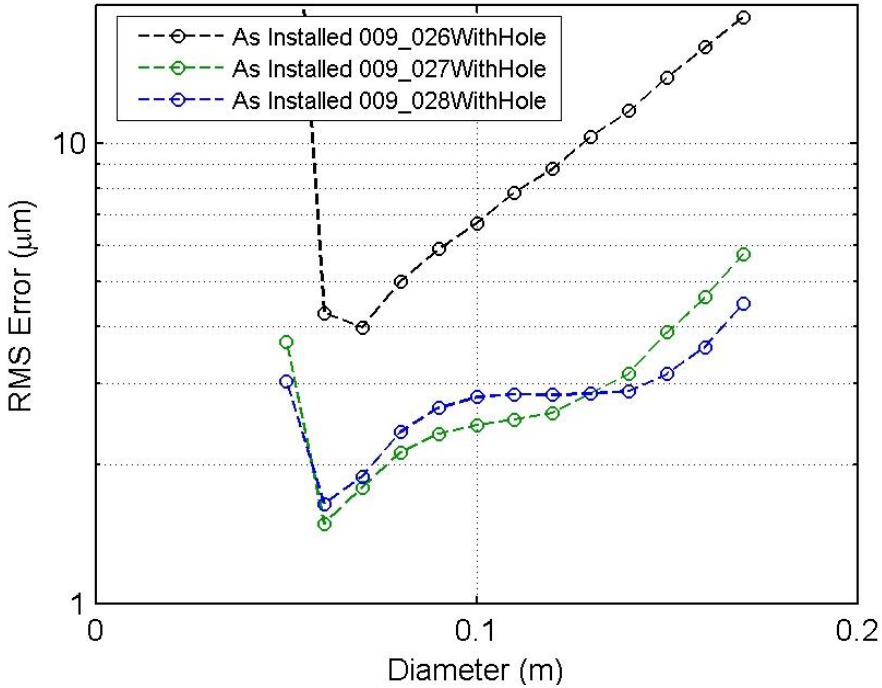
Test 009_026, ∅ 0.2 m,
RMS = 18.5µm, R 0.148683 m, R# 0.74
λ 20 µm, Ri-Ro 20%-85%, Pitch 6.5 mm

As Installed



Test 009_028, ∅ 0.2 m,
RMS = 4.4µm, R 0.148701 m, R# 0.74
λ 20 µm, Ri-Ro 20%-85%, Pitch 6.5 mm

Post Correction



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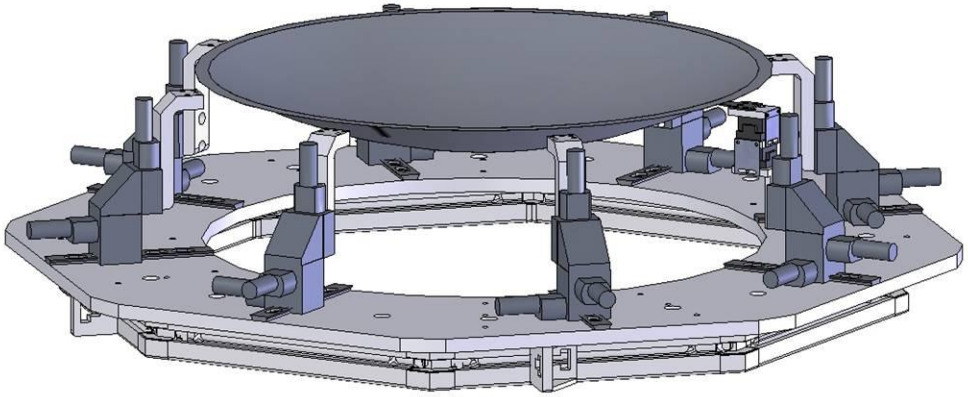
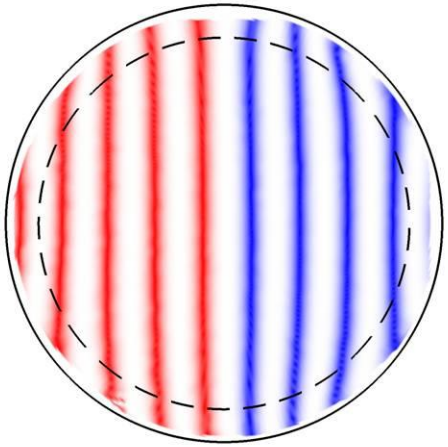
Zernike Control Authority



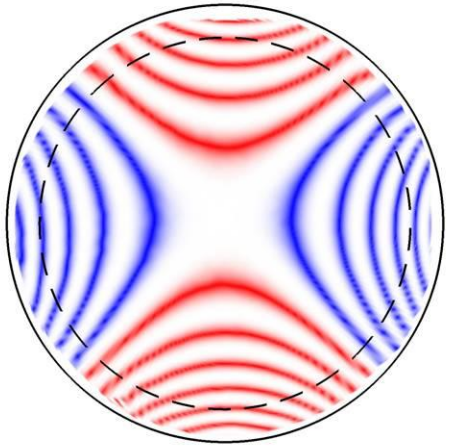
Experimental Data, 1 Contour = 400 µm

- **Demonstrated ability to enforce Zernike mode shapes on shell via boundary control proves ability to reject Zernike error components of an aberrated shell**
- **Experimentally, 1 to 2 iteration actuation steps used to approach numerically predicted best match to ideal coefficient shape**
- **85% of shell diameter used for fitting and actuator prescription calculation**

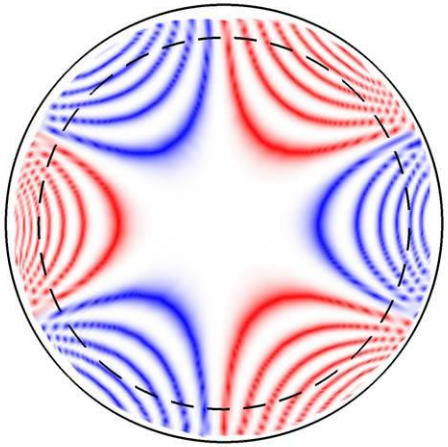
Demo'd authority (±2 mm-surface) = 16,000 waves (P-V-wavefront) at λ = 500 nm



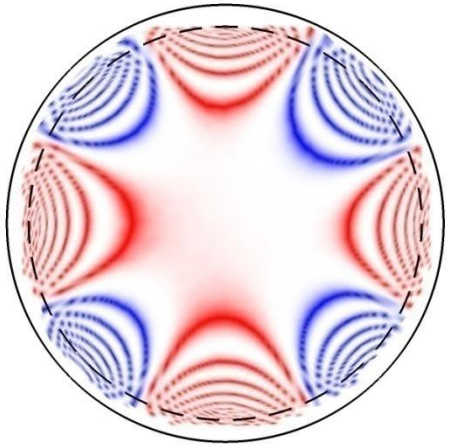
Tip/Tilt (Z11)



Astigmatism (Z22)



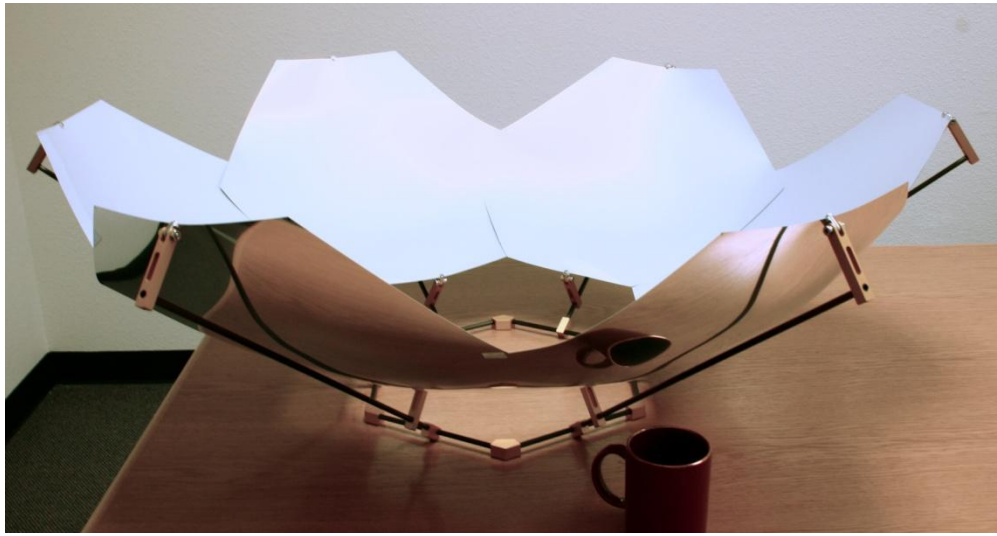
Trefoil (Z33)



Tetrafoil (Z44)

Upcoming Steps

- Basic Membrane Shell Technology
  - Continue to scale demonstrated apertures
    - Larger Single Surface Shells (1.1, 2.0m, …)
    - Segmentation (0.5m segments, R=1, R=2, …)
  - Continue to improve shell global figure
  - Address thermal/CTE concerns
    - Material selection
    - Shielding
    - Control
  - Readiness for Flight
- System Demo's (with Partners)
  - Lightweight primary optics
  - Full Telescope/OTA
    - Incoherent LIDAR
    - Far IR
    - . . .
    - Optical Imaging (Someday)
  - Environmental
- Transition to Field/Mission Use
- Adaptive Optics



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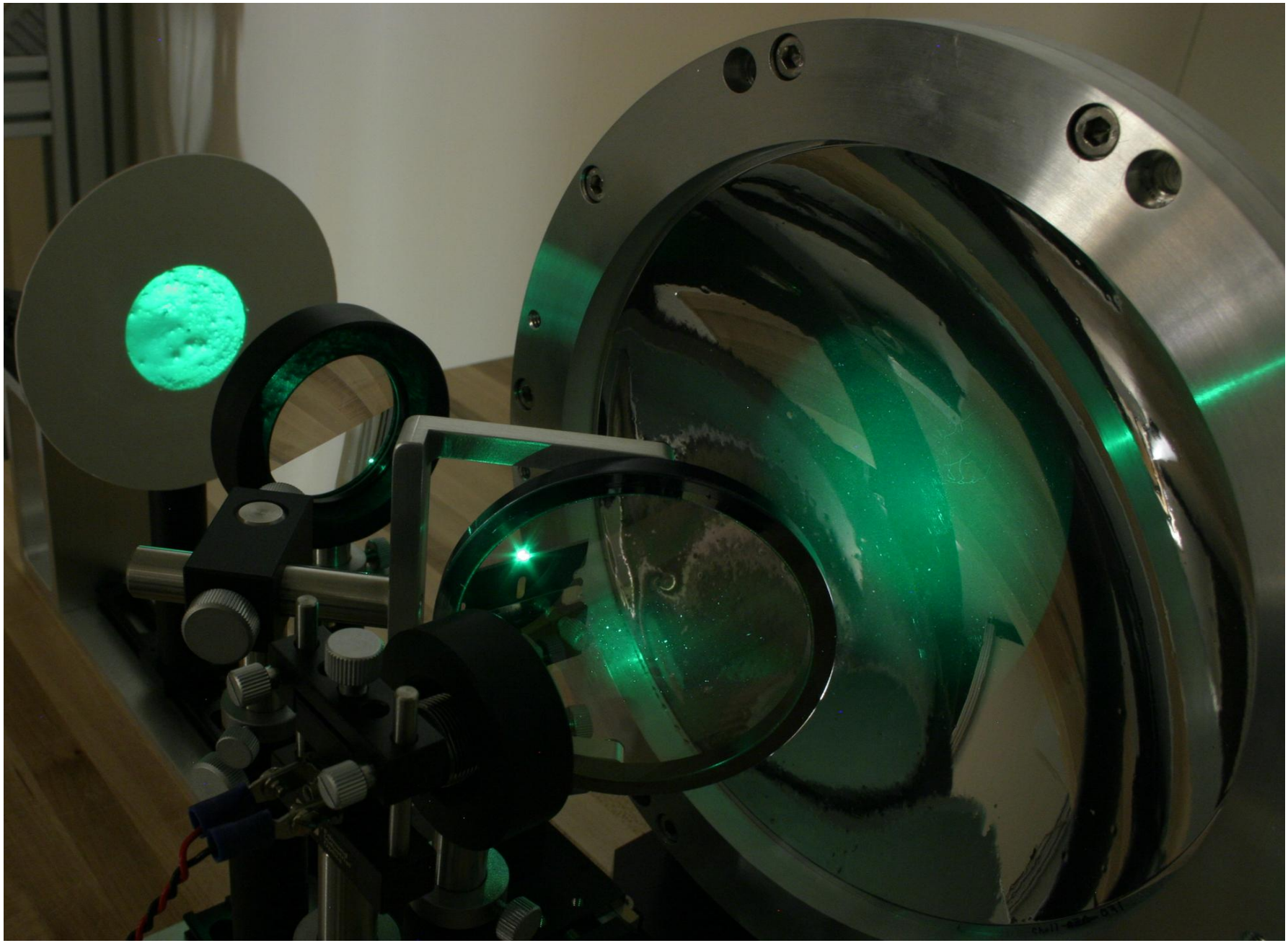


Structural Dynamics

Structural Dynamics
Analytical Fundamental Behavior

From Blevins, …

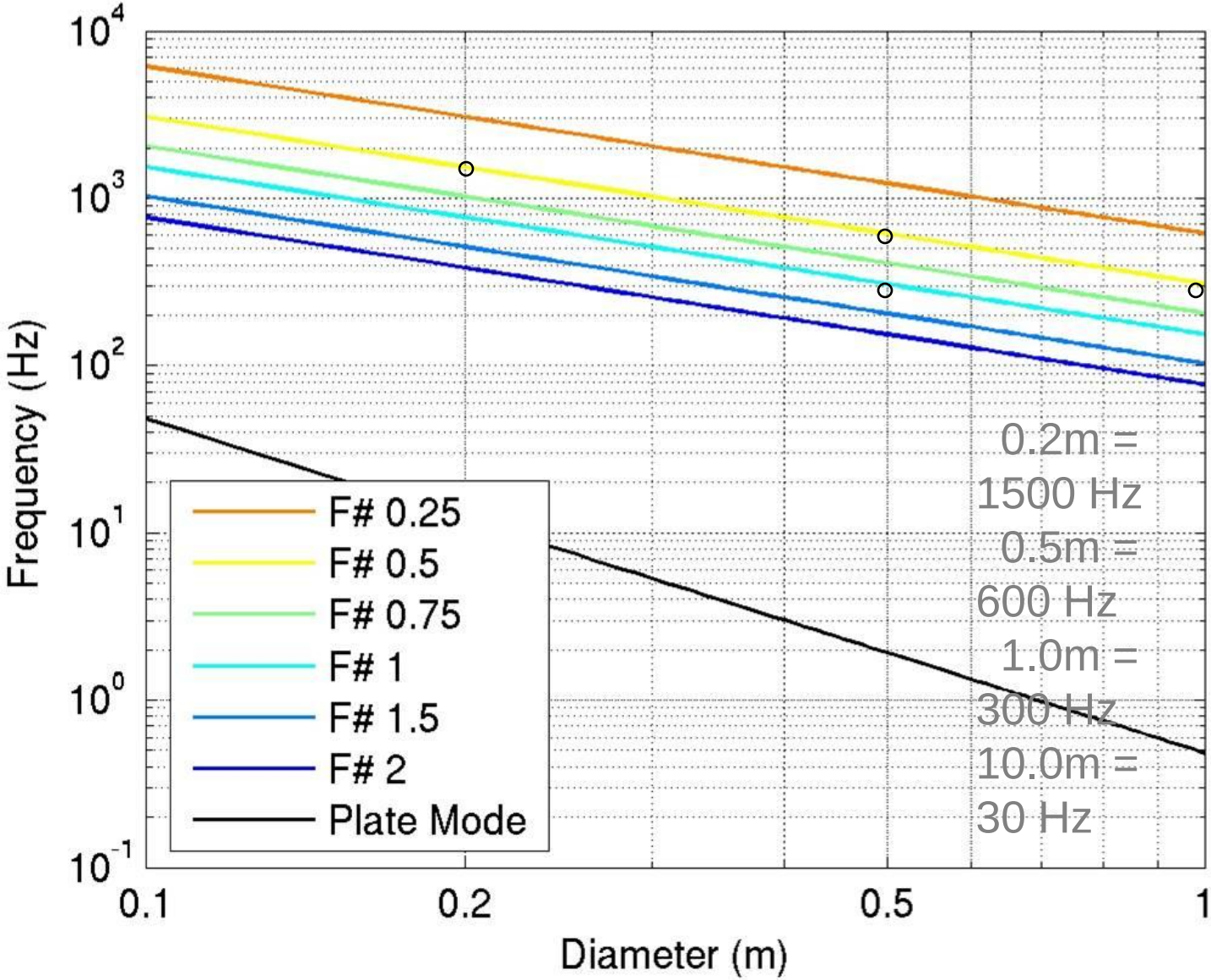
Plate Terms Shell Terms

$$\varpi_{i,j} = \sqrt{\frac{E}{\rho}\left(\frac{\lambda_{ij}^4}{12(1-\nu^2)}\frac{t^2}{r^4} + \frac{1}{R^2}\right)} \rightarrow \frac{1}{R}\sqrt{\frac{E}{\rho}}$$

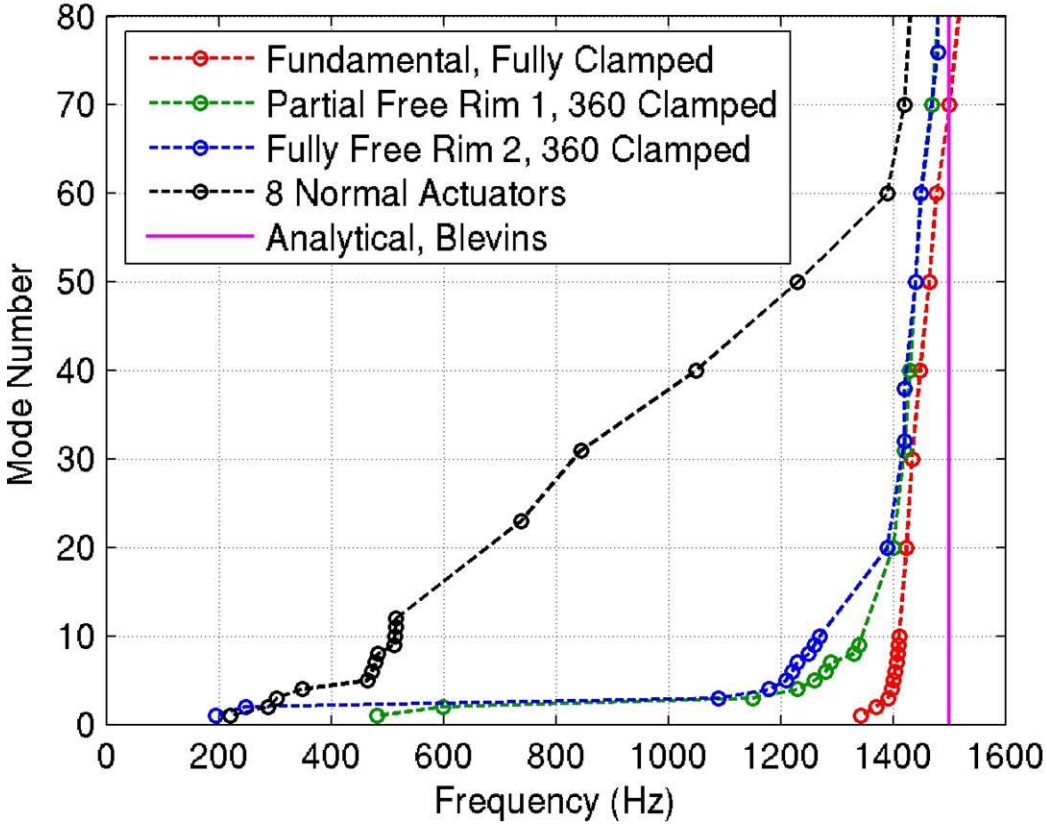
Implications:

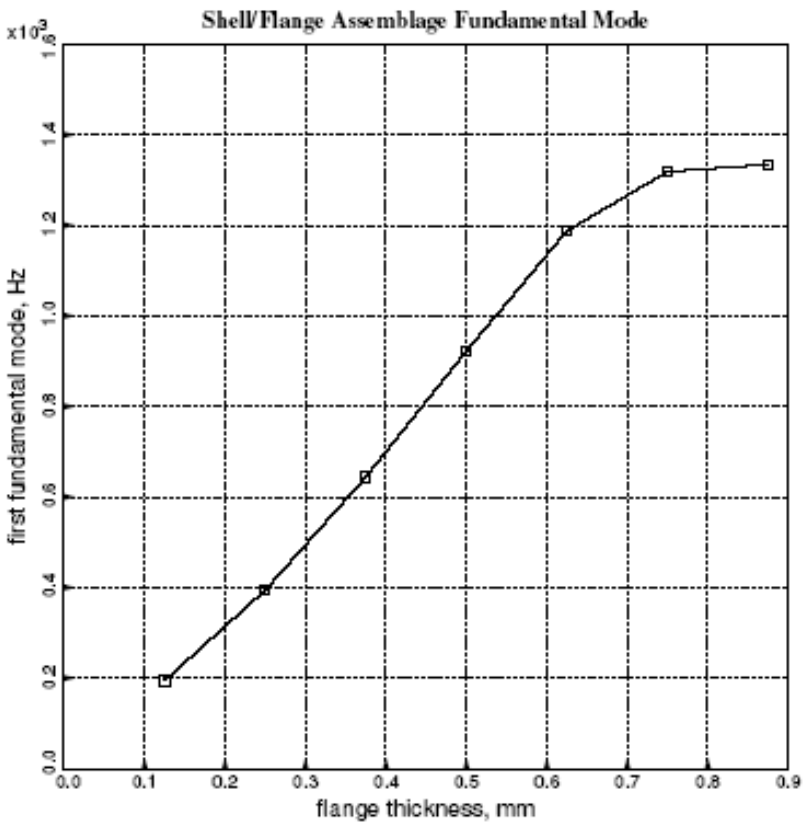
- Plate terms become insignificant if:
  - **Material thickness, t, is small and/or**
  - **Reflector aperture radius, r, is large**
- Modal density
  - **'DC' bias (they start high)**
  - **Closely spaced "plate" modes (thereafter)**
- Ideal NNS's are dynamically stiff **(F/0.5)**
  - **0.5 m diameter = 600 Hz**
  - **1.0 m = 300 Hz**
  - **10.0 m = 30 Hz**

Structural Dynamics
Analytical Fundamental Behavior



Structural Dynamics
Edge and Boundary Effects





- **Effects of Edge Discretization on Fundamental Dynamics Can be Readily Alleviated Through More Mounts or Increased Flange Thickness/Stiffness**

