Lightweight and High-resolution Astronomical X-ray Optics Using Single Crystal Silicon

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Next Generation X-ray Optics Team

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Mirror Fabrication Requirements

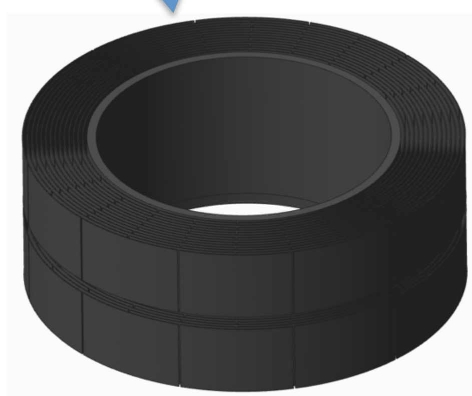
Parameter	Requirement
Angular resolution	Precise Figure: < 0.1” RMS slope
	Good micro-roughness: < 2 Å RMS
Collecting Area	Lightweight: < 1 kg/m^2 areal density
	Thickness: < 1 mm
Production Cost	Production cost: < \$0.5M/m^2 < \$5000/mirror
Production Schedule	Production rate: > 200 m^2/year

Mirror Alignment & Bonding Requirements

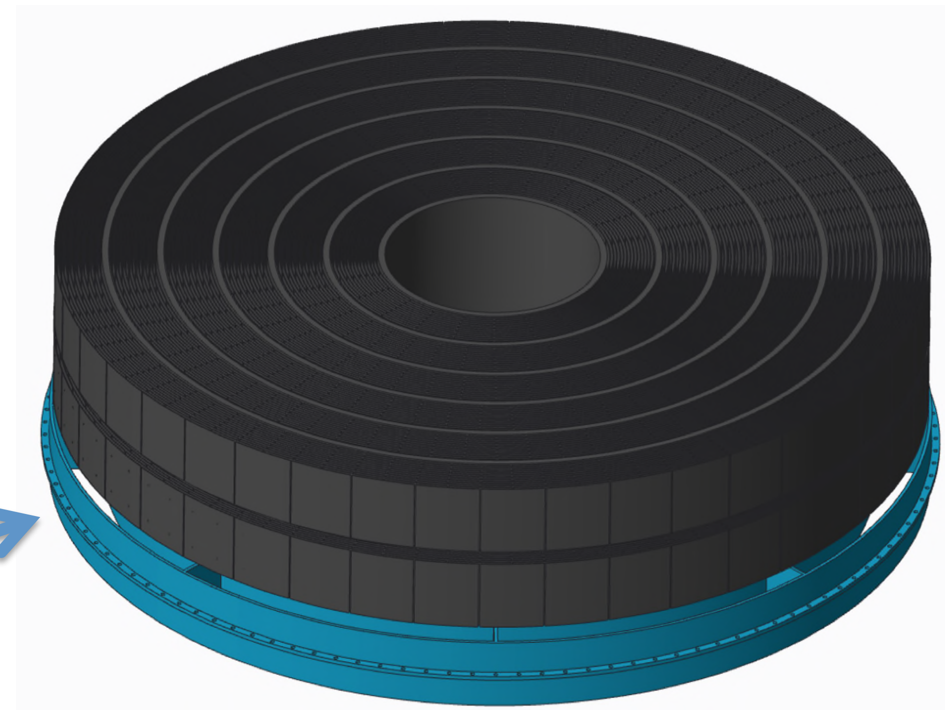
Procedure	Practical Requirements
Alignment	Setting mirror in right location and orientation
Bonding	1. Figure preservation
	2. Alignment preservation
	3. Survival of spaceflight environment
	4. Long term stability in vacuum
Gravity Release	PSF preservation/restoration in microgravity environment
Cost	Production cost: <$5,000/mirror
Schedule	Production rate: ~hours/mirror

Hierarchical Approach: Mirrors → Meta-Shells → Assembly

Single Crystal Silicon Mirrors

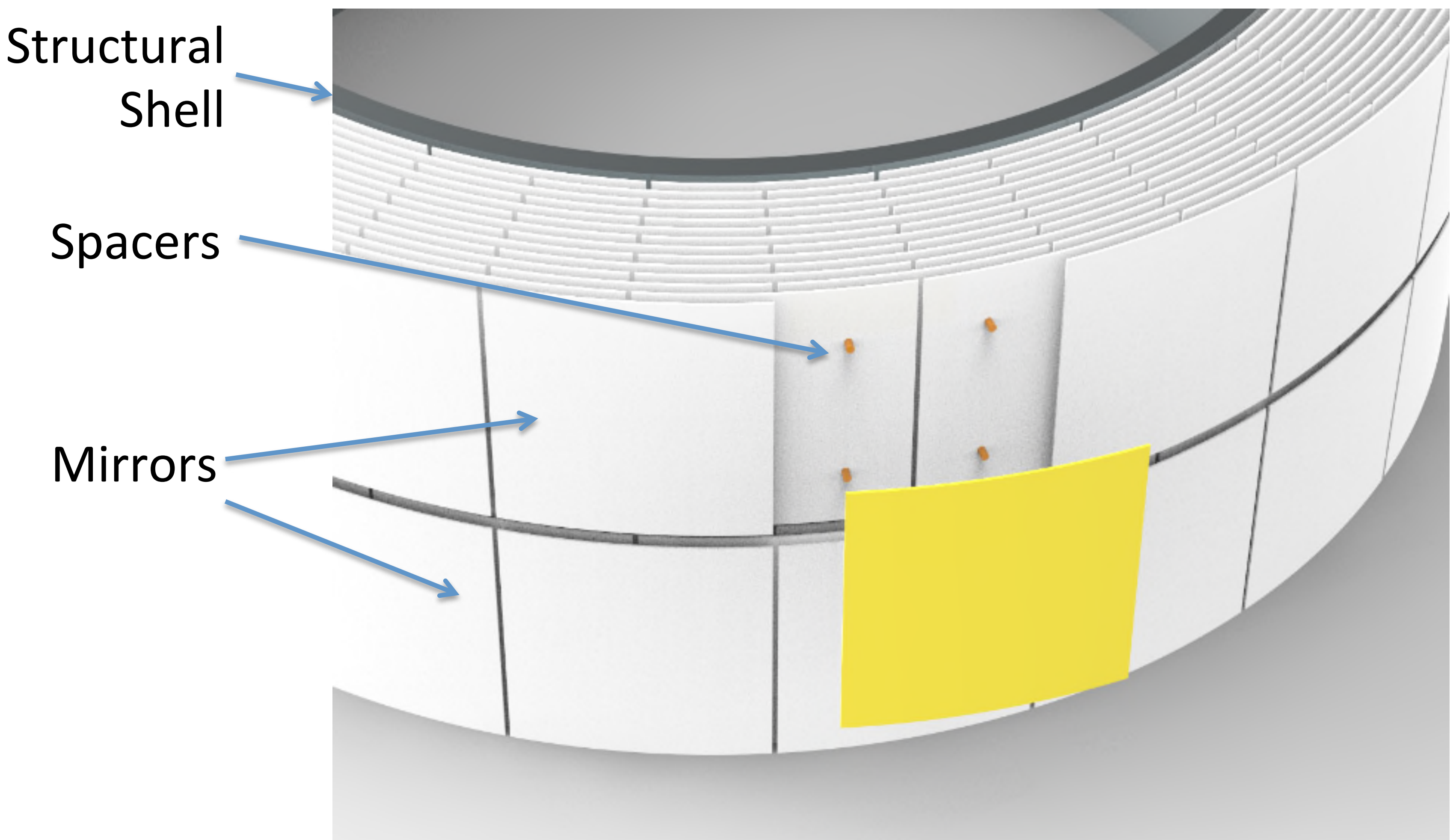


Meta-shell: ~$10^{2\text{-}3}$ mirrors bonded onto a silicon structural shell using silicon spacers and epoxy



Assembly: Many meta-shells aligned and flexure-mounted onto an aluminum or composite spider web

Meta-Shell:
Optically precise and structurally stiff



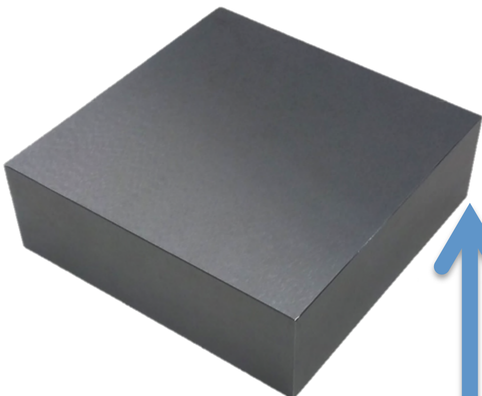
Mirror Fabrication

- **So far the only way to fabricate mirrors that meet requirements is precision polishing**
- **Two problems**
  - It has only made thick mirrors
    - Typical aspect ratio (size/thickness): **~6 to 10**
    - Future mission requirement (size/thickness): **~200**
  - It is slow and expensive
- **Solutions to address these two problems**
  - Use single crystal silicon to make **thin mirrors**
  - Perfect a mass production process to **drive down cost**

Why Single Crystal Silicon?

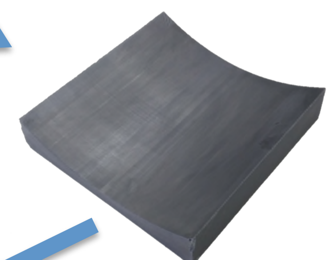
- **It has no internal stress**
  - Damage-free removal of material from the surface does not lead to unpredictable figure change, in contrast to thin sheet of glass or any other ordinary material.
- **It has excellent properties**
  - Low density
  - High thermal conductivity
  - Low thermal expansion
  - High elastic modulus
- **It is commercially available**

Mirror Fabrication



Fabrication Process:

~15 hours of labor
~4 days of calendar time



Mirror Fabrication Process

1. **Generation:** setting radius and cone angle
2. **Light-weighting:** removing the extra pounds
3. **Acid etch:** removing damage and stress
4. **Stress-polishing:** making precise optics
5. **Trimming:** making it fit
6. **Edge treatment:** preventing breakage
7. **Metrology:** verifying figure & finish

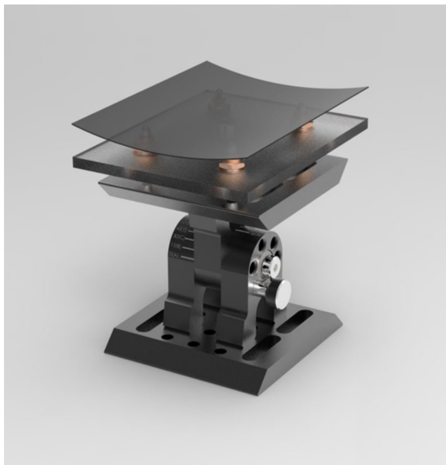
Mirror Fabrication Status

- **Making the best lightweight X-ray mirrors**
  - ~2" half-power diameter (2 reflections equivalent)
  - 3X better than the best glass mirrors we made 2 yrs ago
- **Going forward**
  - Will understand, engineer, and perfect current process
  - Establish the technology at 2" HPD resolution
  - Seek to improve it by another factor 5
    - Improve our current process and/or
    - Work with industry to use existing commercial technology to improve the mirror

Mirror Alignment & Bonding:
Basic Principle (in a gravity environment)

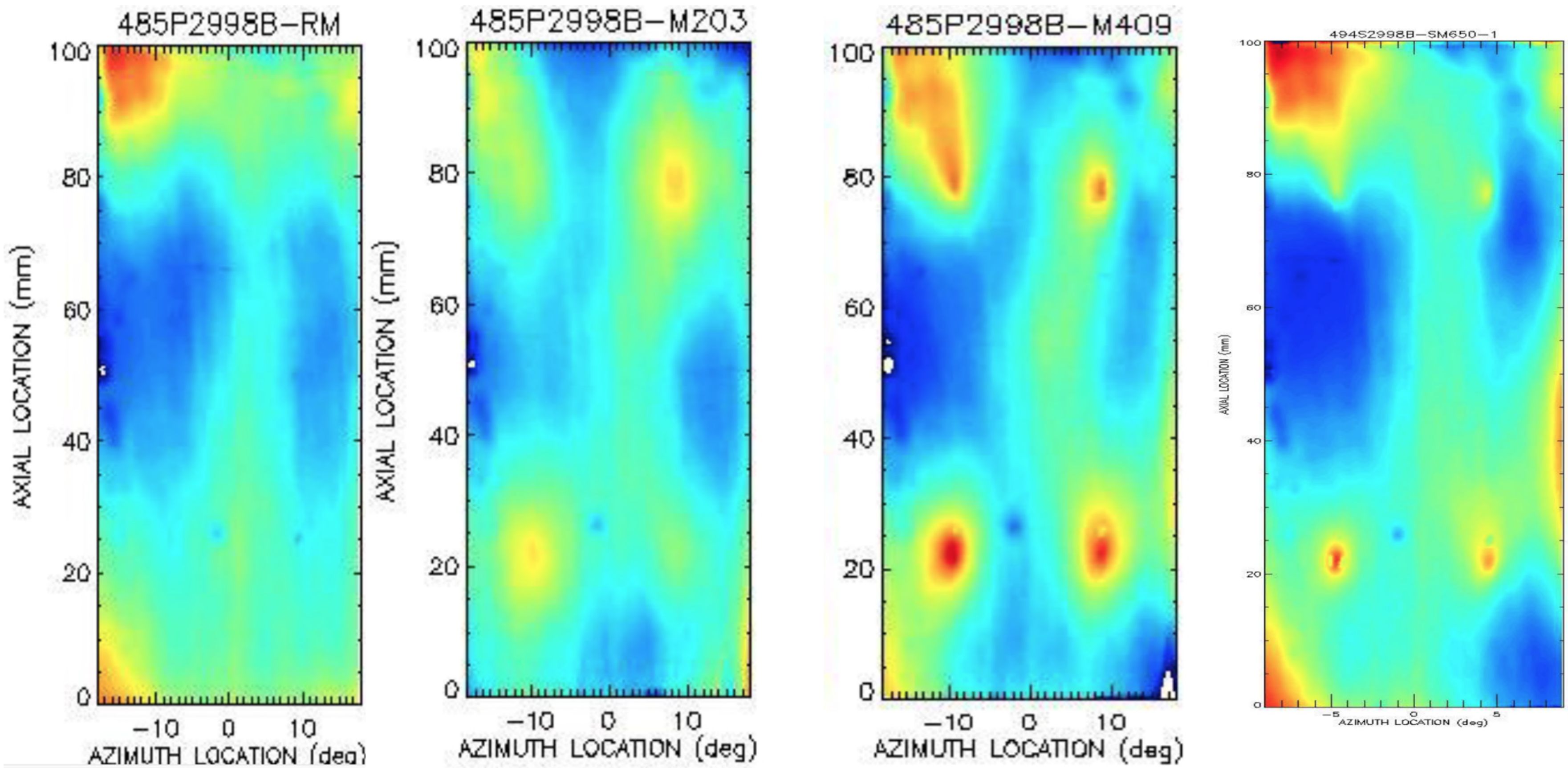
- **A Flat mirror (x, y, z, pitch, yaw, roll)**
  - **Three** supports uniquely constrain a flat mirror
  - Pitch, yaw, and z completely fixed
  - x, y, & roll fixed by friction
- **An X-ray mirror (or cylindrical mirror) (dx, dy, dspace, pitch, yaw, roll)**
  - **Four** supports uniquely constrain a cylindrical mirror
  - dx, dy, pitch, and yaw completely fixed
  - dspace and roll fixed by friction

Mirror Alignment & Bonding: Illustration with a Single Mirror



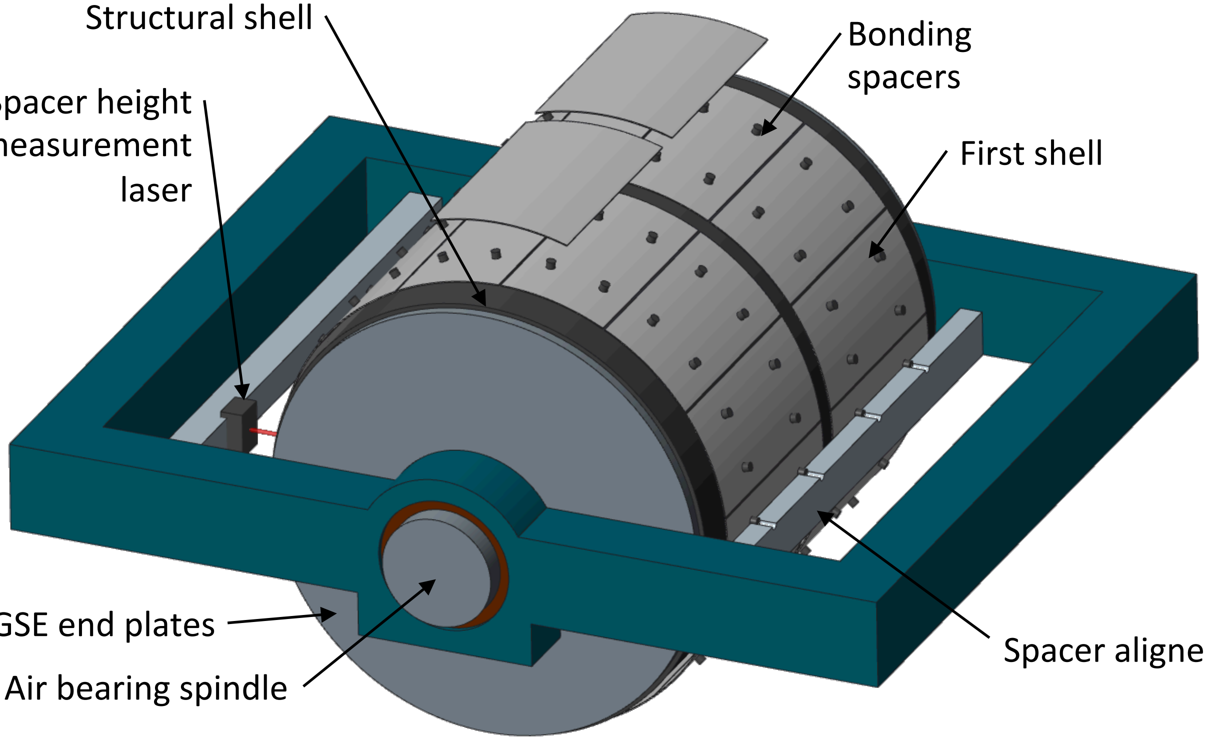
- **Horizontal Configuration**
  - Mirror supported at 4 optimal locations
  - Mirror distorted by gravity
  - Distortion precisely and accurately predictable by FEM
- **Vertical Configuration**
  - Gravity “removed” or minimized
  - Mirror figure restored/recovered

Mirror Alignment & Bonding:
Basic Principle/Procedure Proven

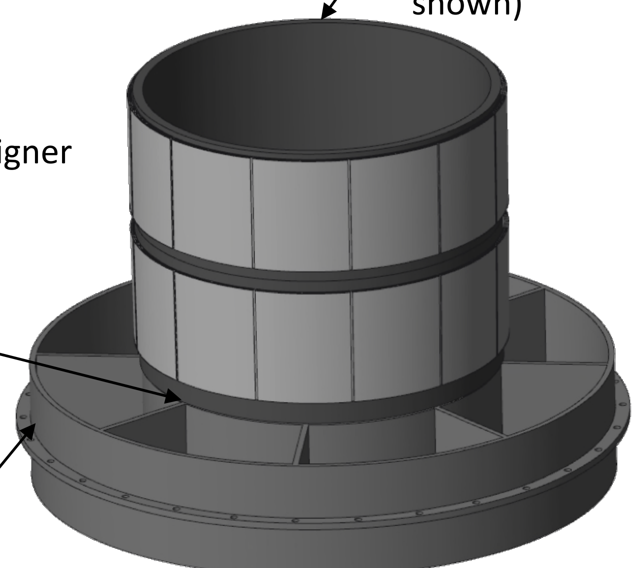


Un-bonded	Un-bonded	Bonded	Bonded
Vertical	Horizontal	Horizontal	Vertical

Concept for Building a Meta-shell

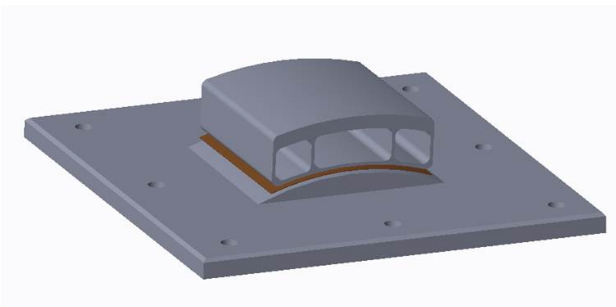


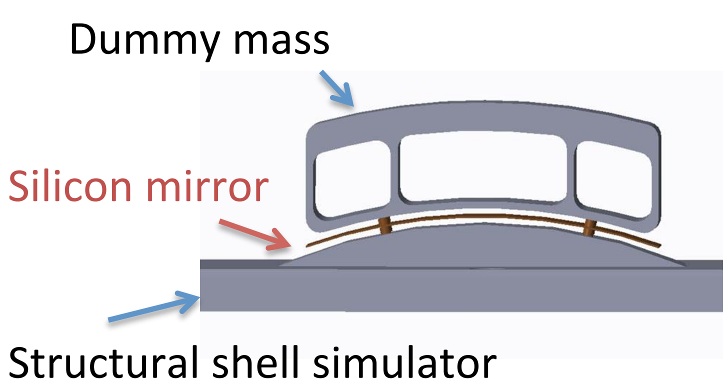
Meta-shell Makeup: Silicon mirrors, Silicon spacers, and trace amounts of iridium and epoxy



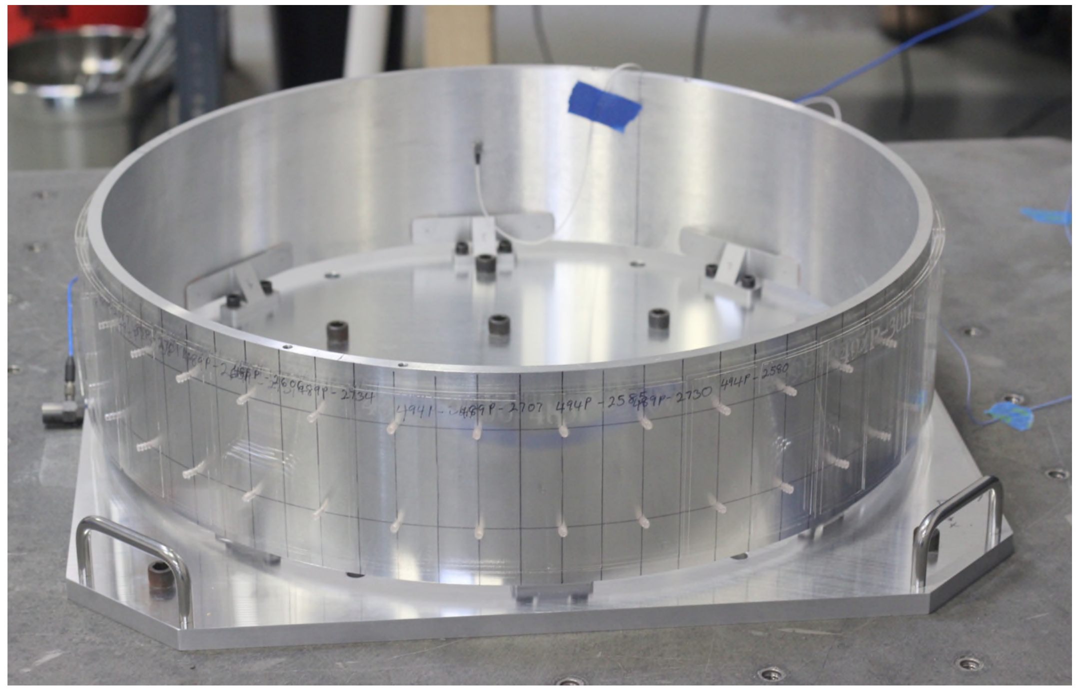
- **Spindle defines the optical axis.**
- **Each mirror is bonded at 4 locations.**

Meta-Shell Concept:
Validated by Engineering Tests





Single Mirror Vibration and Shock Tests



Mechanical Engineering Meta-Shell Test:

Aluminum structural shell

54 glass mirrors (each 100X100X0.4 mm^3)

216 spacers

432 epoxy bonds

Areas of Development

- **Mirror Fabrication**
  - Figure quality improvement (currently at ~2" HPD)
  - Process refinement & complexity reduction
- Coating
  - Atomic layer deposition or magnetron sputter
  - Reduction/elimination of figure distortion
- **Alignment and Bonding**
  - Precision machining of spacers
  - Fast application and cure of epoxy
  - Better control of thermal environment
- **System level studies**
  - Complete end-to-end structural, thermal, and optical performance (STOP) analysis
  - Construction and test of meta-shells: performance and environmental tests

Acknowledgement

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