

Advances in Silicon Carbide Manufacturing Enabling Novel Optical Systems

THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

Mirror Tech Days

1-3 November 2016

Ed Seibel

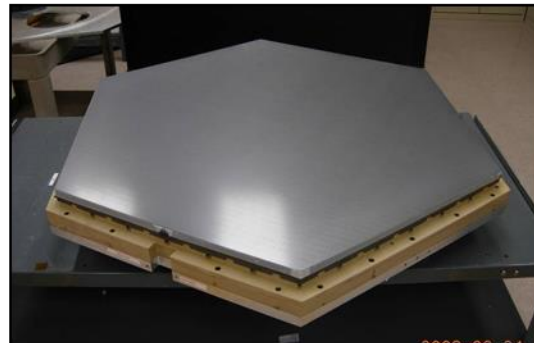
AOA-Xinetics

- **Mature Material & Production Technology Continually Being Advanced**
 - Focused on new manufacturing solutions to improve cost and time-to-market
 - Expanding material catalog offerings that are aligned with new mission areas.
 - Introduced novel telescope architectures.
- **Augmenting Passive Optics with Active Elements**
 - Enabled optical systems that compensate for the external environment
 - Still requires predicable, stable athermal structures.
 - Enables phased development that have aligned production capabilities.
- **Why is this relevant to the NeXt Generation Telescopes**
 - Current activities are accelerating TRL & MRL maturation for SiC Passive and Active Primary Mirrors.
 - Telescope manufacturing processes enables phased optical system development.

Lightweight SiC Mirror Substrates

...SiC production capability in place for 1.35m parts

- AOX SiC fabrication facility capable of producing substrates greater than 2.0 m
- Capable of producing meter class parts on 4 week centers
- Fugitive core casting process enables forming of ultra lightweight substrates
 - Near zero dimensional change from mold to final part
 - Features can be easily machined before final firing
- NGX SiC has polishable microstructure – for advanced passive mirrors
- Low areal density below 10 kg/m² with high stiffness & natural frequency



- Silicon Carbide Furnace Scaled to 2.4 meters
- RS View Based In-Process Production Controls



- Campbell Generator Scaled to 2.4 meters
- 5- μ m Positional Accuracy and On-Board CMM

Silicon Carbide (SiC) for Mirrors

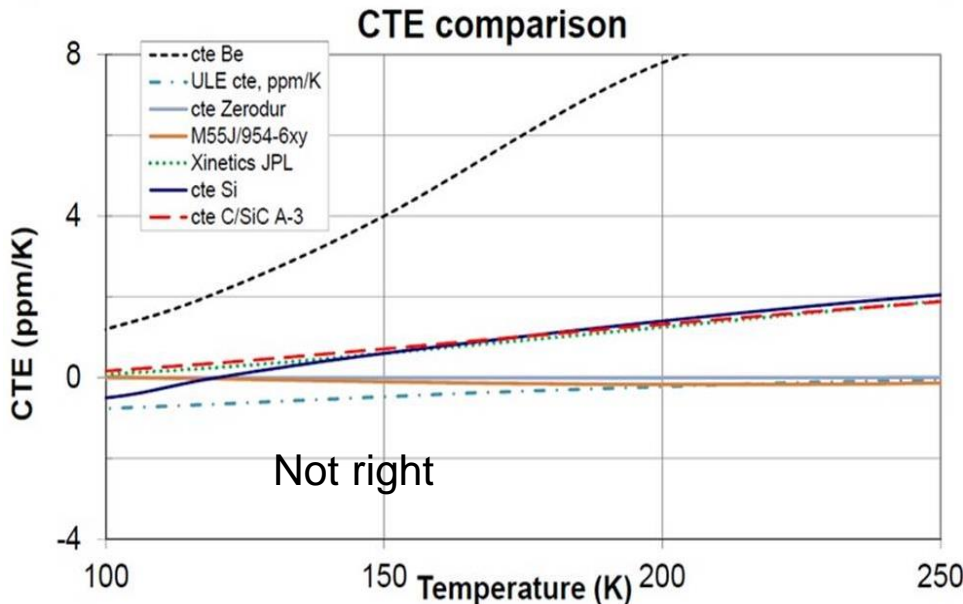
- SiC has many good properties
 - Stiff for the weight
 - Robust
 - High thermal conductivity
 - Polishable to $<20\text{\AA}$ (unclad), and to 2\AA (Si clad)

| Property | Units | Aluminum | Beryllium | SiC | ULE | Desire |
|---------------------------------|-------------------------|----------|-----------|------|------------|--------|
| ρ , Weight | g/cm ³ | 2.71 | 1.85 | 2.95 | 2.21 | Low |
| E, Stiffness | GPa | 68.3 | 303 | 364 | 67.6 | High |
| E/ ρ , Specific Stiffness | KN-m/g | 25 | 164 | 123 | 31 | High |
| σ/ρ , Stress Loading | N-m/g | 46 | 11 | 24 | 3.2 | High |
| α , Thermal Soaks | ppm/ $^{\circ}\text{C}$ | 22.7 | 11.4 | 3.38 | ± 0.03 | Low |
| $\Delta\alpha$ Homogeneity | ppb/ $^{\circ}\text{C}$ | 100 | 100 | 30 | 10 | Low |
| K/ α , Thermal Gradients | MW/m | 6.9 | 19 | 51 | 44 | High |
| K/rCp, Thermal Diffusivity | m ² /s | 6.55 | 6.07 | 8.7 | 0.08 | High |
| K/ α E, Thermal Stress | MW-m/N | 101 | 63 | 140 | 646 | High |

Note :Some values not right

| Property | Unit | Aluminum 6061-T6 | Beryllium I-70 | CERAFORM SIC | Silicon | ULE | Desired Value |
|-----------------------------------|-----------------------------------|------------------|----------------|--------------|---------|------------|---------------|
| Structural FOM E/ $\rho(1-\nu^2)$ | (s ² /m ²) | 0.16 | 0.56 | 0.87 | 0.28 | 0.15 | High |
| Thermal FOM k/ α | (W/m x10 ⁶) | 6.9 | 18.9 | 64.3 | 51.5 | 43.7 | High |
| ρ , Density | g/cm ³ | 2.71 | 1.85 | 2.92 | 2.33 | 2.21 | Low |
| E, Young's Modulus | GPa | 68.3 | 303 | 310 | 130 | 67.6 | High |
| ν , Poisson's Ratio | --- | 0.33 | 0.07 | 0.19 | 0.26 | 0.17 | Low |
| α , Thermal Expansion | ppm/ $^{\circ}\text{C}$ | 22.7 | 11.4 | 2.44 | 2.62 | ± 0.03 | Low |
| $\Delta\alpha$, CTE Uniformity | ppb/ $^{\circ}\text{C}$ | 100 | 100 | 30 | 10 | 10 | Low |
| k, Thermal Conductivity | W/m $^{\circ}\text{C}$ | 156 | 216 | 157 | 135 | 1.31 | High |
| C _p , Specific Heat | J/Kg $^{\circ}\text{C}$ | 879 | 1820 | 670 | 713 | 766 | Low |
| σ , Design Stress | MPa | 124 | 17 | 70 | 62 | 7 | High |

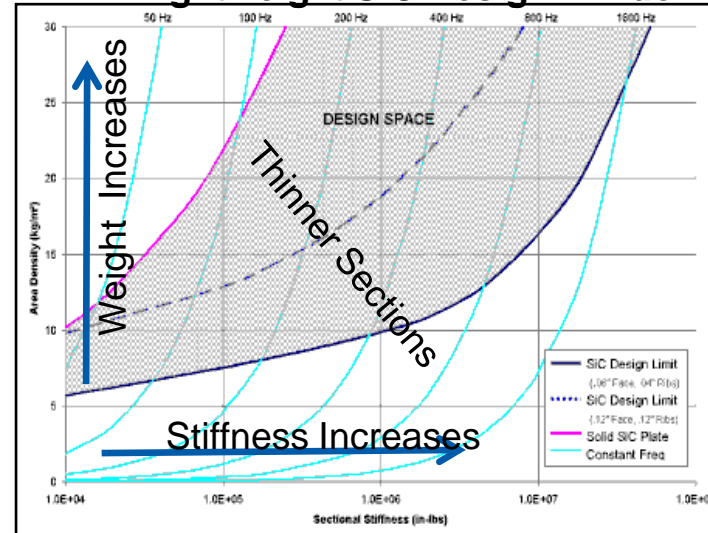
FOM = Figure of Merit



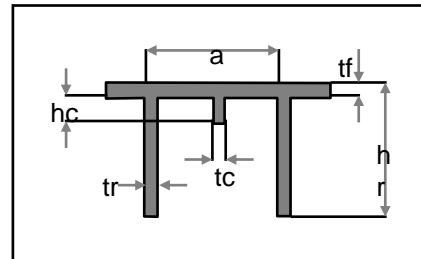
Technology – Why SiC?

- AOX SiC material properties provide high stiffness to weight performance
- Sectional stiffness may be tailored to meet both weight and stiffness requirements
 - Open back & partial closed back configurations
- Typical SiC thickness dimensions:
 - SiC rib thickness ~1mm
 - Facesheet thickness ~1.2mm
 - Section geometry outperforms the capabilities of many other substrate materials, including other SiC forming techniques
- Cathedral rib structure provides additional stiffness to reduce facesheet quilting
- Areal densities ~8 kg/m² maintained even as mirror size increases

Lightweight SiC Design Window

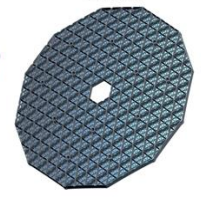
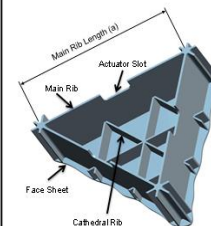
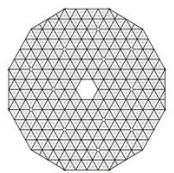
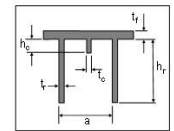


Sectional Stiffness Parameters



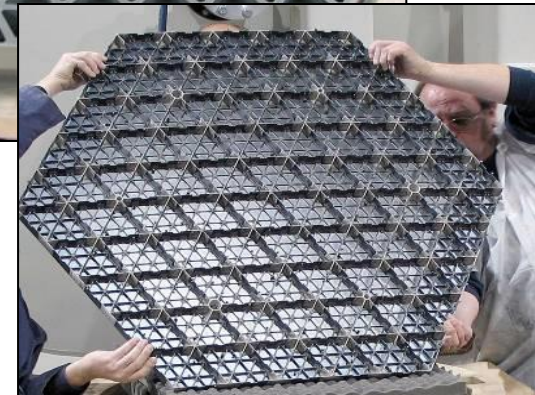
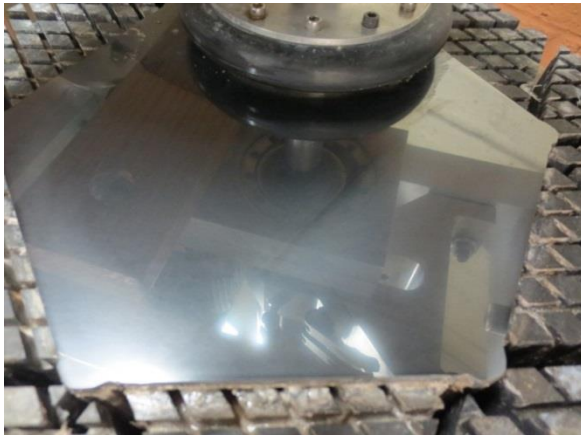
AOX Typical Manufacturing Capabilities and Design Criteria for CeraForm Optical Grade Silicon Carbide Mirror Components

| Feature | Typical values |
|--|-----------------------------------|
| Main Rib Height (mm) | h_r < 200 |
| Cathedral Rib Height (mm) | h_c < 20 |
| Main Rib Length (mm) | a 35-125 |
| Main Rib Thickness (mm) | t_r 0.5-8.0 |
| Cathedral Rib Thickness (mm) | t_c 0.5-3.5 |
| Face Sheet thickness (mm) | t_f 1.0-8.0 |
| Areal Density (kg/m ²) | ≥ 7 |
| Stiffness, First Mode (Hz) | > 100 |
| Generated surface Roughness, Ra (μ m) | > 0.15 |
| Generated SFE, (μ m) | 20 |
| Main Rib Height:thickness | $< 32:1$ |
| Functionality | Active/Passive |
| Optical Surface Shapes: | Sphere, asphere, off-axis asphere |



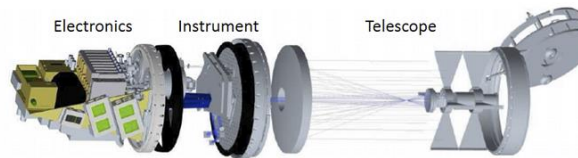
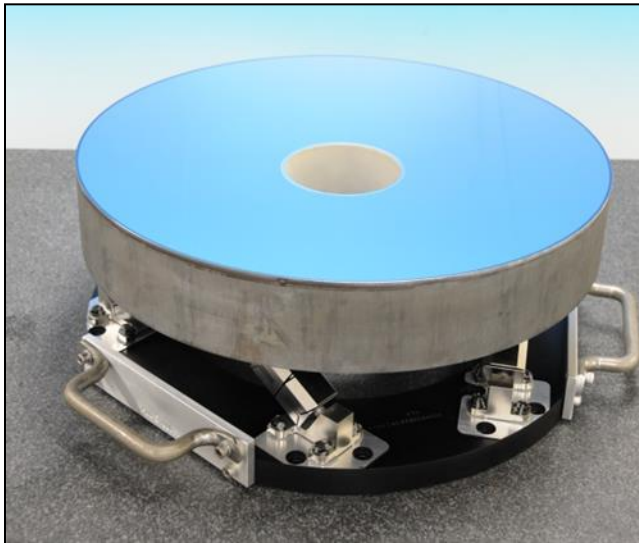
The criteria above should only be used as an initial starting point and does not define the actual limits of manufacturing capability.

Large, Lightweight Mirror Manufacturing at AOX



High Strength SiC Passive Primary – PICTURE-B Sounding Rocket Mission

- Mission was designed to measure light reflected by dust in debris disks around nearby stars.
- 58 cm diameter silicon carbide mirror successfully withstood launch and impact on landing, and will be used for future missions
- *Mirror survived an estimated 100g's during landing – well above design criteria*

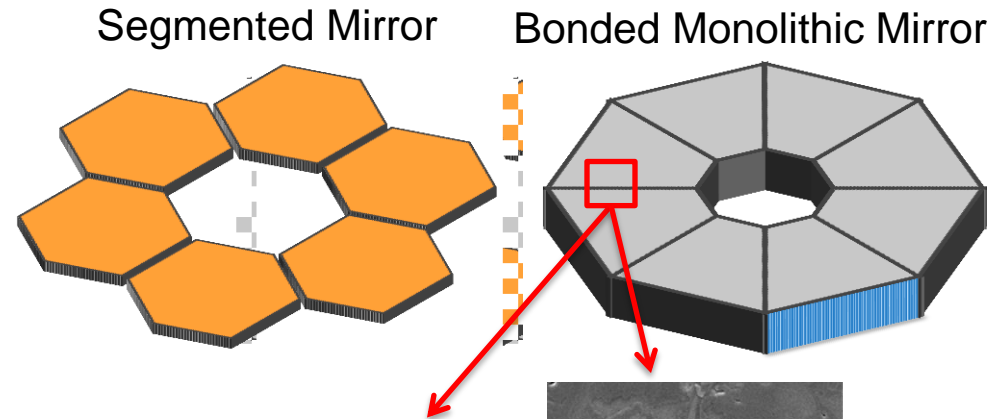


PICTURE-B (Planet Imaging Coronagraphic Technology Using a Reconfigurable Experimental Base) mission of the Lowell Center for Space Science and Technology at the University of Massachusetts Lowell successfully launched and returned to Earth on Nov. 25, 2015 from NASA's White Sands, New Mexico Test Facility.

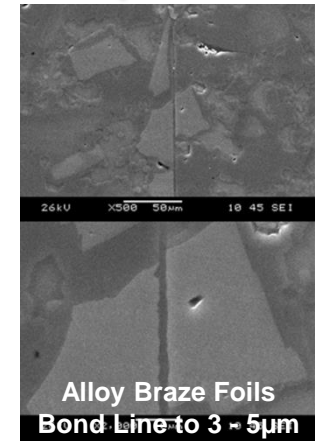
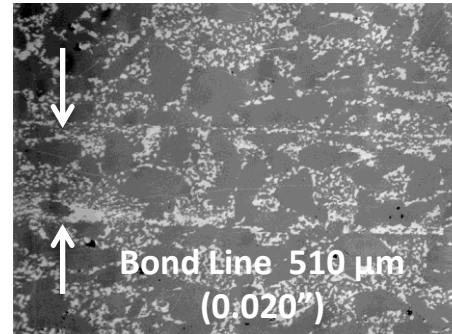
Scaling SiC Mirrors for Large Apertures

Segmented vs Bonded Monolith Mirrors

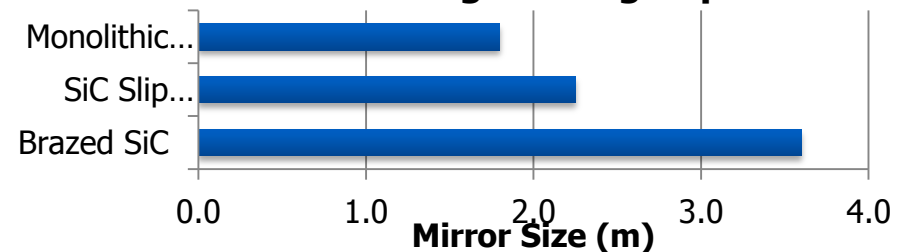
- **AOX SiC manufacturing capability limited to 1.8-2.0m based on size of current infrastructure**
- **Large apertures with segmented mirrors**
 - Segmented mirrors enable scaling to much larger apertures than monolithic mirrors with existing production capabilities by increasing the number of segments
 - Have to deal with phasing segments
- **Large bonded monolithic mirrors**
 - SiC parts can be joined together to form larger monolithic substrates reducing cost and risk of scaling infrastructure
 - Leverages SiC strength, stiffness and production manufacturability to enable ultra-lightweight substrates
 - Large 1 – 2m SiC substrates to be joined using either established brazing or SiC slip bonding techniques
- **SiC Slip Bonding**
 - Parts bonded with SiC slip in prefired state before final firing
 - Bonded substrate is polishable across bond joint
 - SiC bonding can be scaled to ~2m using existing furnaces
- **Brazing SiC**
 - Brazing occurs at a lower temperature than final SiC firing
 - Enables the bonding of siliconized components
 - Active fugitive braze materials enable multi-step braze assembly
 - Large braze ovens much less expensive to scale than large high temp SiC furnaces



SiC Slip Bonding



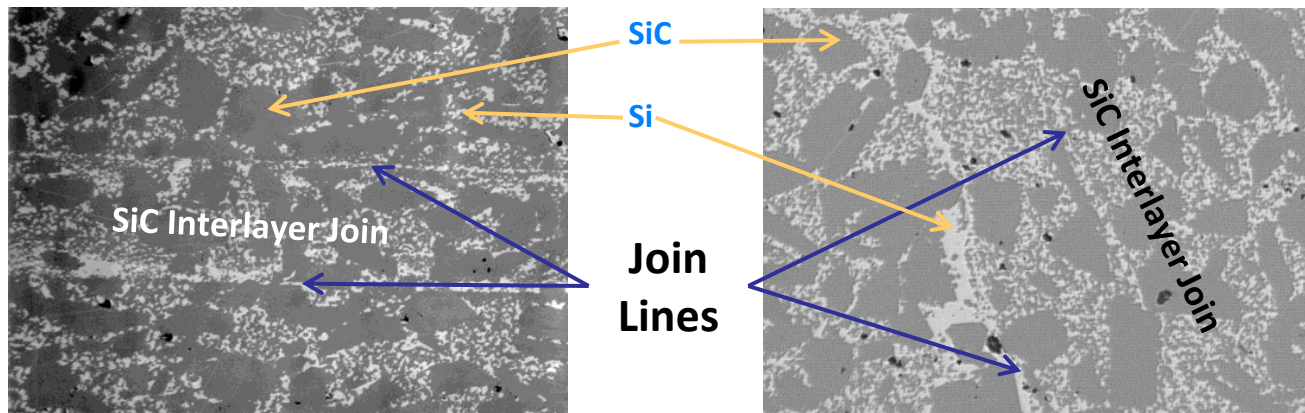
AOX SiC Scaling for Large Apertures



SiC Substrate Interlayer Joining Allows Creation of Large SiC Mirrors

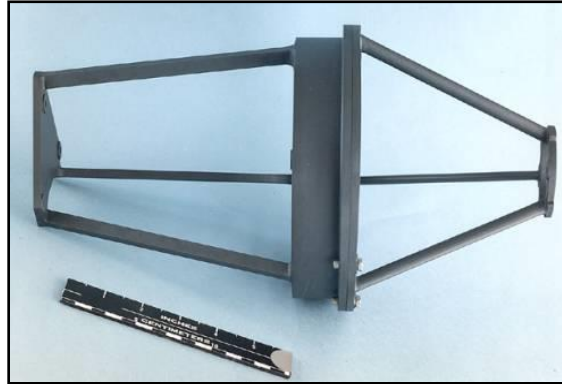
| Metric | Value | Comments |
|---------------------------------|-------------------------|--|
| Joint Thickness | 5-600 microns | Released to Production. |
| Joint Bending Strength | 80% of monolithic SiC | Released to Production. |
| Joint Shear Strength | 80% of monolithic SiC | Released to Production. |
| Joint Surface Quality | No voids | Assured by filling and refiring before siliconization. |
| Joint Surface Continuity | <30Å step discontinuity | Measured after surface generation. |
| Joint Length | 30 cm scalable to 4 m | To be scaled to 2m. |

Photomicrographs of SiC Interlayer Joins



- Unpolished, as-cast surfaces following siliconization firing
- Joint width \cong 0.5 mm

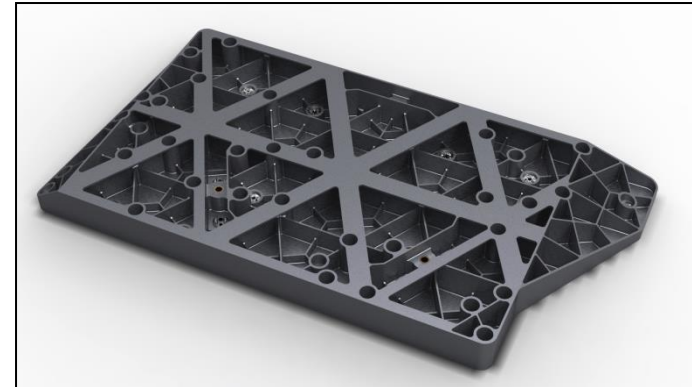
Bonded Structures & Components



**15-cm All Silicon Carbide
Telescope Structure**



**Monolithic Metering Structure Strut
0.9m length**



0.55m x 0.27m Optical Bench



**0.55m Diameter
Optical bench structure**

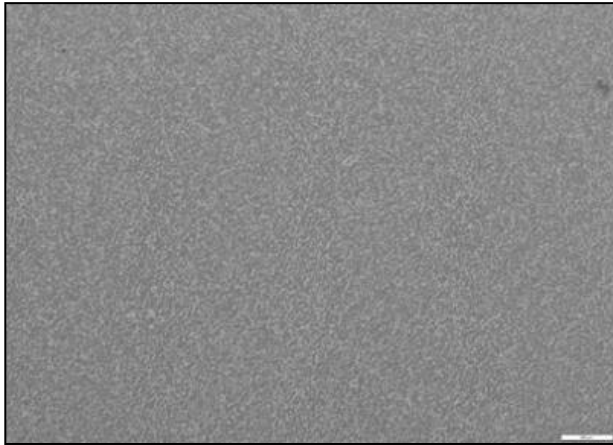


**3D Printed Components
100mm SiC TMA**

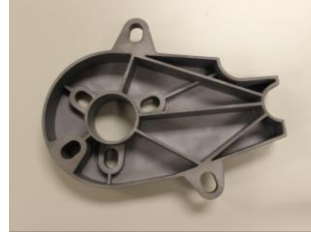


**0.9m Diameter
Optical bench structure**

'Printed' SiC Components + Advanced Bonding Processes = Novel Cost-Effective Athermal Optical Structures



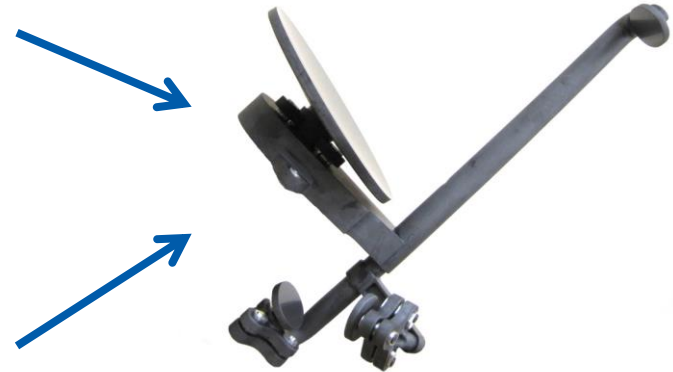
**'3D Printed' Material Siliconized
High Density Microstructure**
*(fully densified microstructures achieved
with near 0% internal porosity)*



**Fugitive Core Cast
Optical Bench**



3D Printed Optical Bench



**SiC Cast/Assembled Telescope
with 4" Primary Mirror**
(weight <1kg)

Benefits

- **Optical Bench printed using SiC grain: Bi-modal distribution of particles allows for minimal shrinkage; <0.7% linear shrinkage**
- **Load-path optimized telescope design using high strength to weight material enables extremely light telescopes.**
- **Minimal mass + thermal conductivity minimized thermal management requirements.**

Active Hybrid Mirrors Offer System & Manufacturing Benefits Through All Development Phases

- Nanolaminate facesheet or Si-Cladded Surface

- Multilayer metal foil, made by sputter deposition on a super-polished mandrel

OR

- Low-stress Si deposited provides amorphous surface layer
- Polishable to 1 Å microroughness

- SiC Substrate

- Reaction-bonded Ceraform SiC is cast in a mold, fired, then bonded to facesheet or cladded

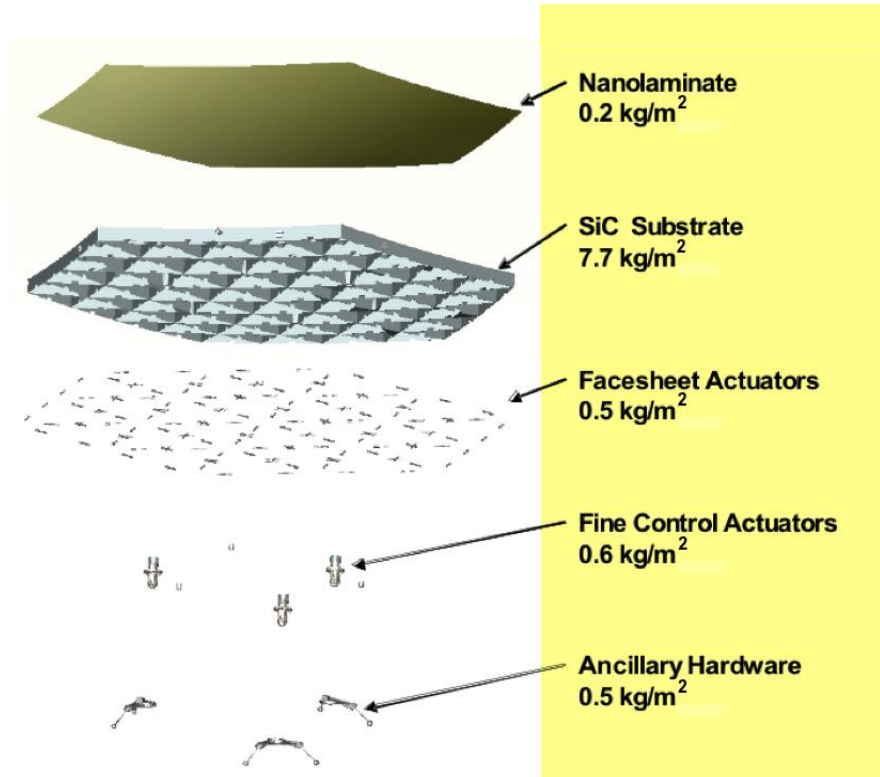
- Electroceramic actuators

- Surface-parallel embedded actuators give large stroke and high accuracy, by design

- AHMs are low mass and high strength

- Areal density < 25 kg/m² including electronics for meter-class AHMs

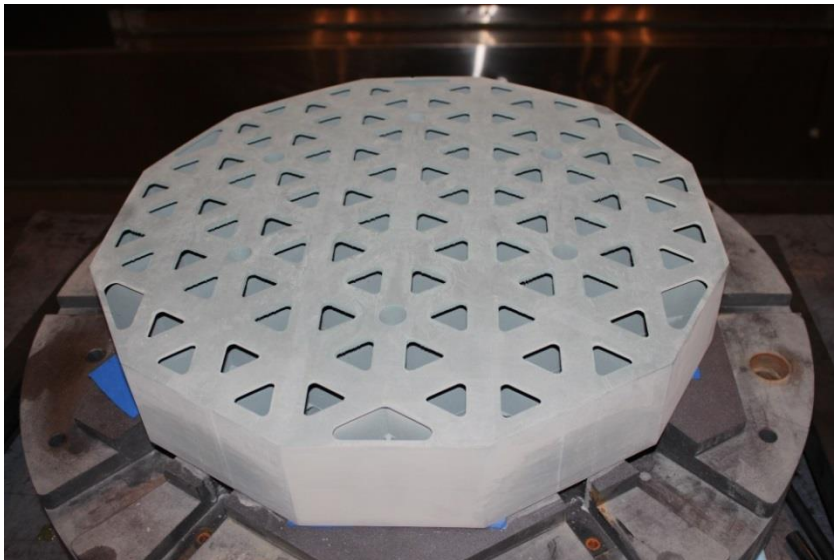
- AHMs can be made by replication to achieve high volume production cost targets that can be initiated with ‘production-of-one’ Si-cladded systems that are finished with available polishing processes.



Light Weight Beam Director Example – Passive/Active Versions of Same Primary Mirror

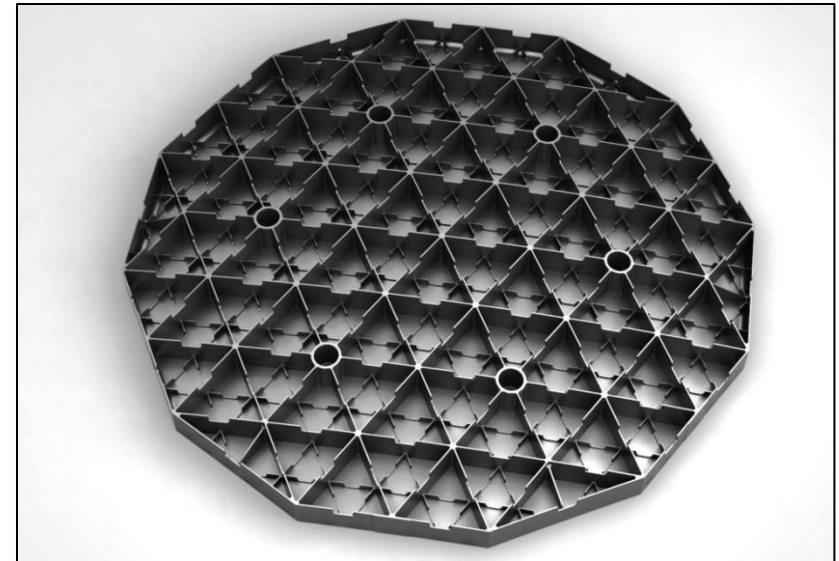
Opportunities Offered

- Two different capabilities, one production process.
- Allows for concurrent SIL testbed development while continuing with flight telescope integration.



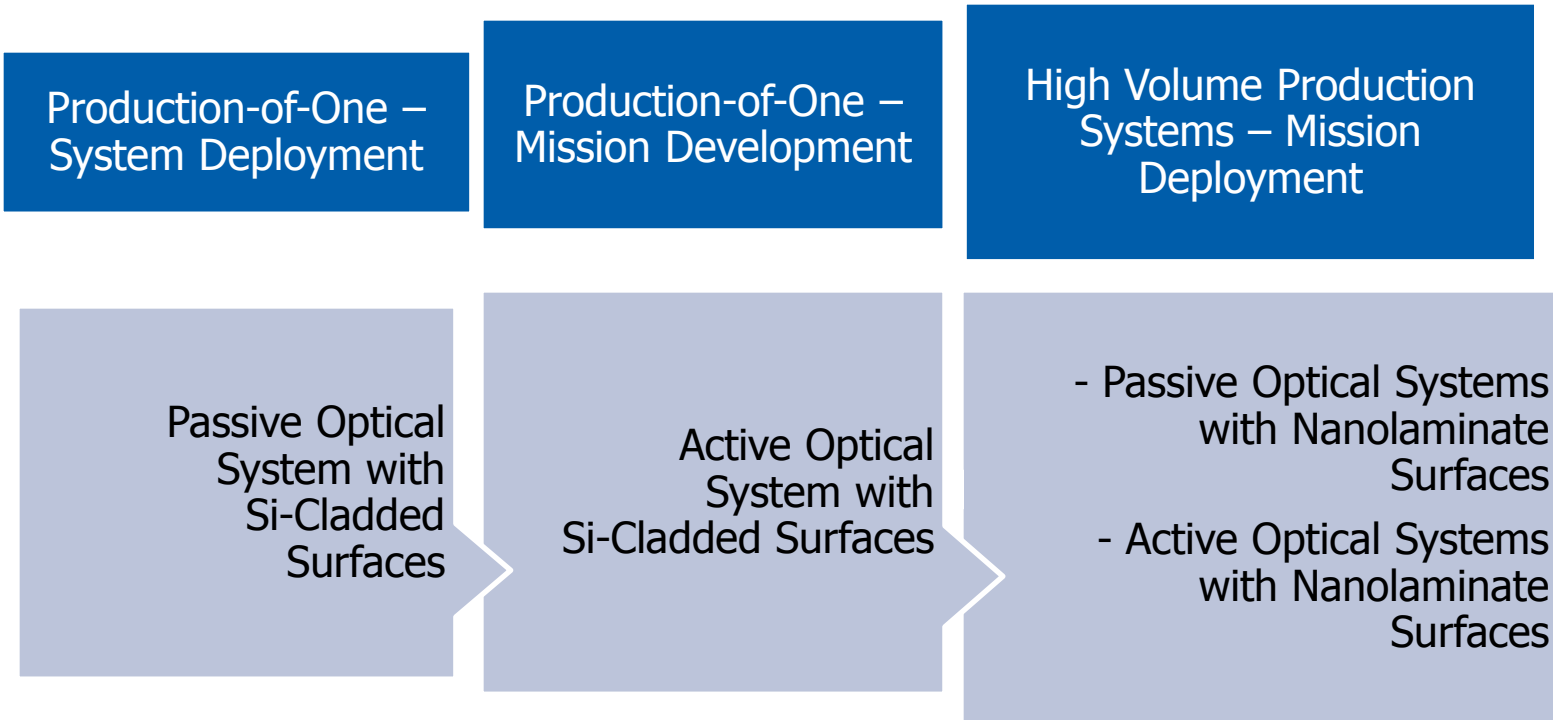
Partial Closed Back Passive Version (*in process*)

- 0.5m
- ROC 2.1m
- CC -1.000
- 18.4 lbs
- Free-free first mode resonance – 2565Hz



**Active Version of Similar Primary Mirror
- Woofer/Tweeter Active Design**

Resulting Production Strategy Directly Supports Phased Program Needs



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 - Expanding material catalog offerings that are aligned with new mission areas.
 - Introduced novel telescope architectures.
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