HDST Mirror Technology Assessment

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Agenda

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- Mirror Materials Assessment for 10+m telescope
  – Telescope will be segmented, but does segment size drive the science?

- Industry Mirror Manufacturing Infrastructure
  – What are the current industry standards?

- General Mirror Quality Assessment
  – What is the current TRL/State-of-the-Art?

Mirror Material Assessment

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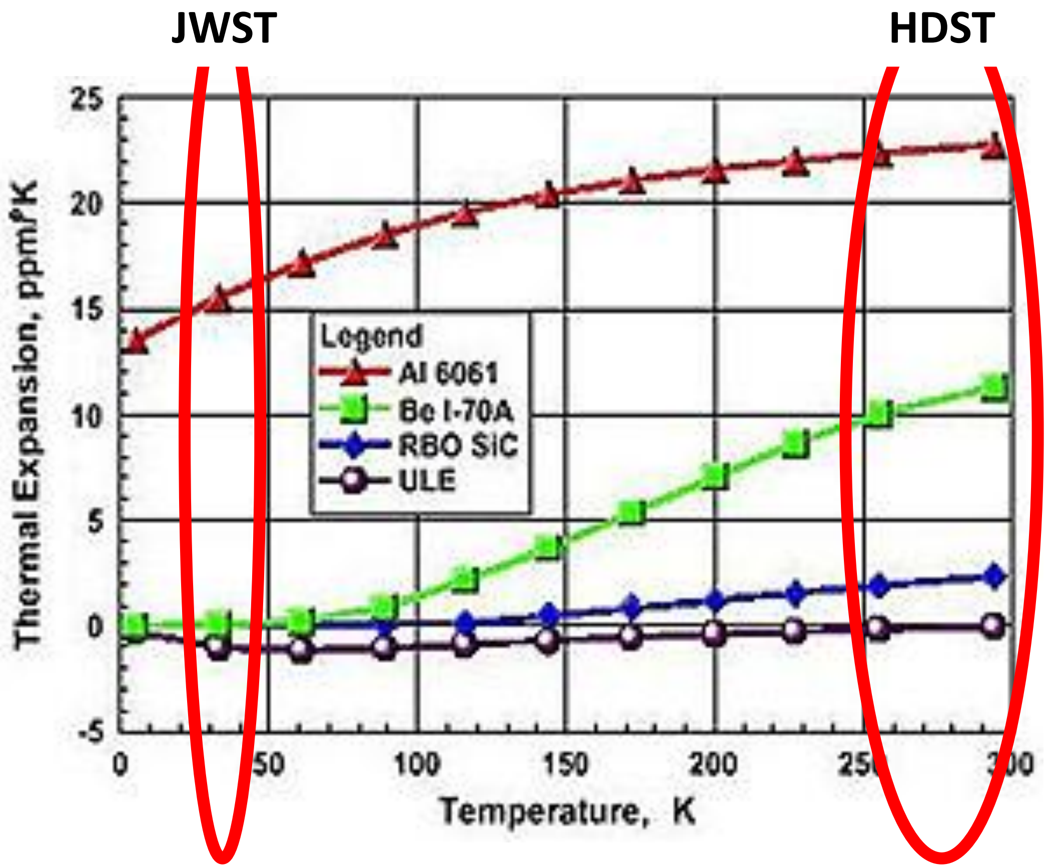
- Current mirror material available for space qualified applications
  - Aluminum
  - Beryllium
  - SiC
  - Glass Ceramics (Zerodur, Astro Sitall, ClearCeram, etc)
  - Glass (Fused Silica, ULE®)

- Aluminum and Beryllium are not applicable to this mission
- The lower CTE materials have advantages and disadvantages



Material Factors

- The glass ceramics will be machined mirrors or thin active face sheets with an open back
  – Stiffness and actuator density will be factors
  – On-orbit simplicity and graceful degradation is important
    • Less things to go wrong
    • Minor failures have small impact performance
- Mirror stability will be critical for mission success
  – 20pm over 10 minutes
  – Comes down to trade between CTE and conductivity
  – Trade likely comes down to ULE® and SiC
- Mirror quality (~5nm RMS surface) and rate of production are key trades

Segment Size

- JWST segment size is 1.3m flat-flat
- Larger segments are within the trade space to a limit
  - Handling risk
  - Areal density will increase with size
- Likely will want to limit on-orbit correctability to minimize adding new mid and high spatial frequency errors and stability concerns
  - Manufacture a high quality mirror that requires minimal adjustment on-orbit
  - Low order thermally induced figure errors and minor RoC correction
- Segment size will likely want to be between 1.3m and 2.0m
  - For glass segments, ~JWST size would enable two mirror blanks to be manufactured in parallel in existing facilities

ULE® State-of-the-Art and TRL

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- Multi Mirror System Demonstration (MMSD) Program advanced the TRL of ultra-lightweight mirror segments
  - 4 new, 10kg/m^2 segments manufactured
  - AMSD reused and refigured to MMSD specification
- Optical and environmental qualification testing performed

Demonstrations of ULE® Solution

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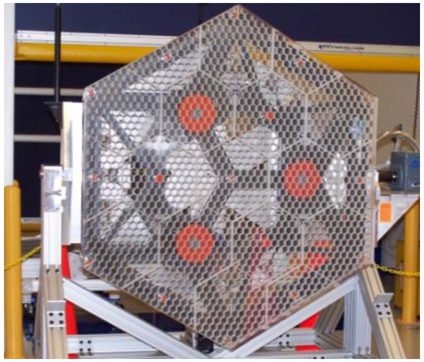
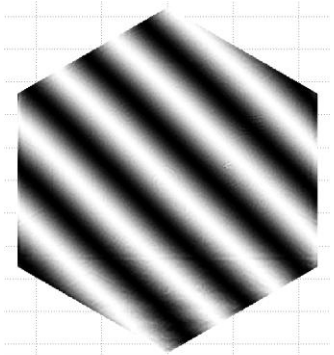
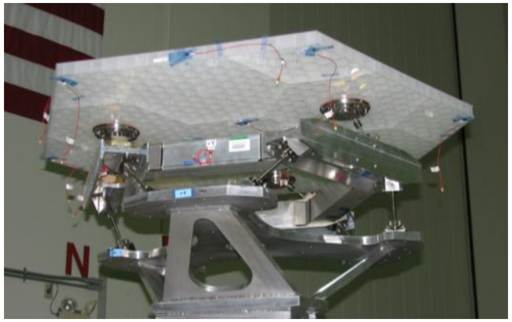
MMSD continued to drive the enhance the TRL level for future missions





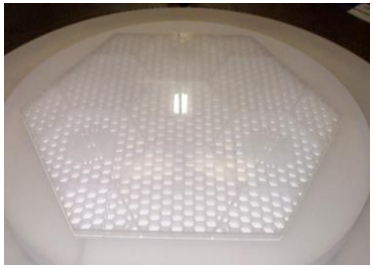


A. OTM PMSA (Optical Test Model)
- Mirror is existing 1.4m AMSD mirror refinished for MMSD
- New MMSD mounts, actuators, reaction structure, elec, controls
- 0-G figure and figure control demonstrated via optical test with both 10 and 16 FCA configurations

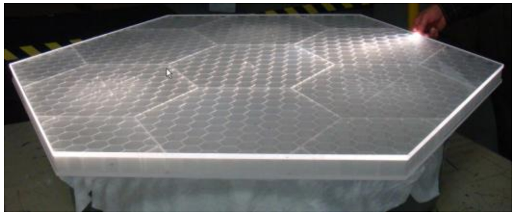
B. Mirror Segment B
- New full size MMSD mirror
- 0-G optical finishing demo
- Finished to 16 nm RMS WFE (no actuation)

C. Mirror Segment C
- New full size MMSD mirror
- Finished thru LTS (100 um PV)
- Mounted & tested to high level random vibe & shock

Key validations achieved on each of these 10kg/m^2 mirrors



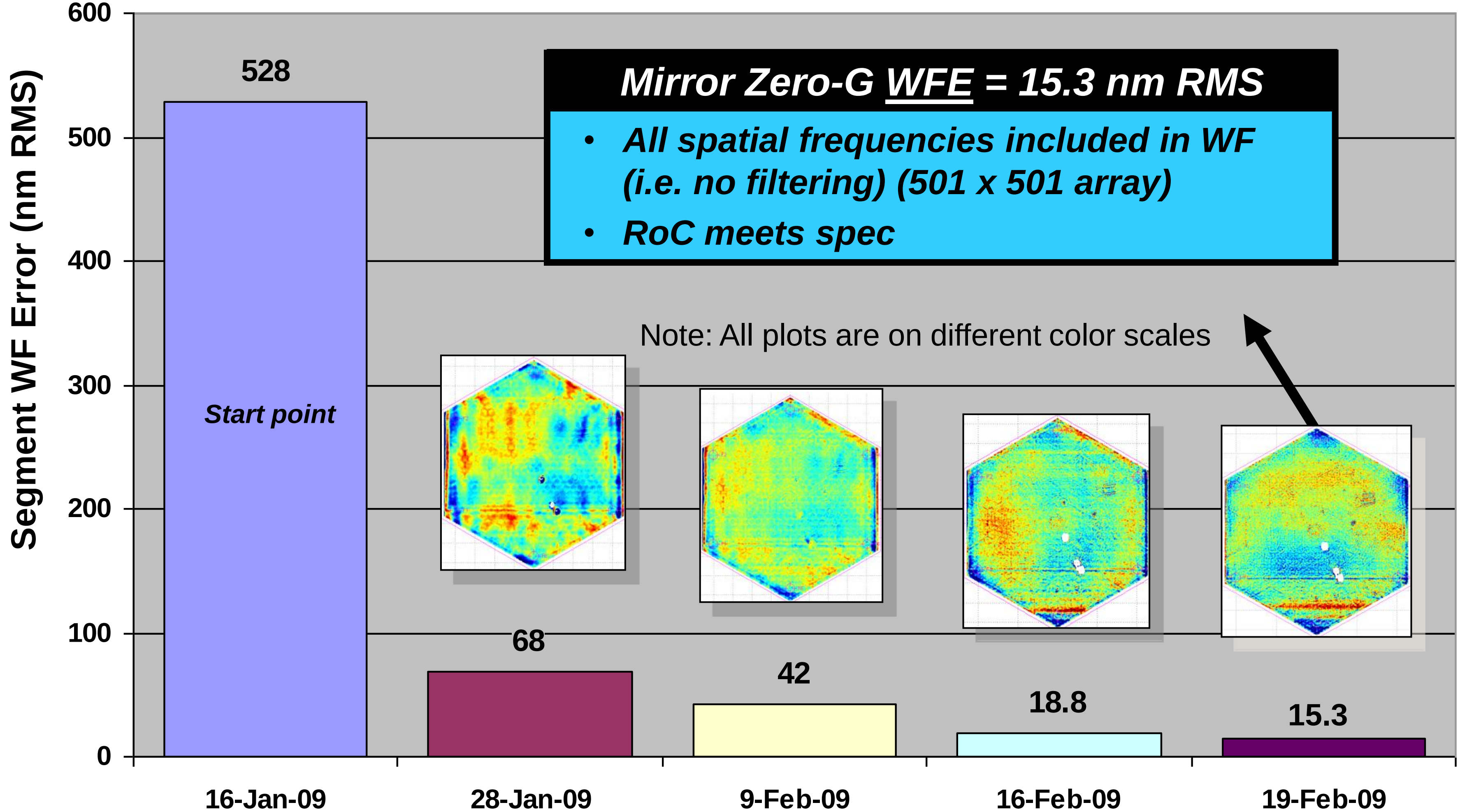
Production rate on 3.5 week centers



D. Mirror Segment D
- New full size MMSD mirror
- Completed thru plano fusion

E. Mirror Segment E
- New full size MMSD mirror
- Completed thru plano fusion

Predictable figure convergence builds schedule confidence



Recent advances in manufacturing will enhance HDST

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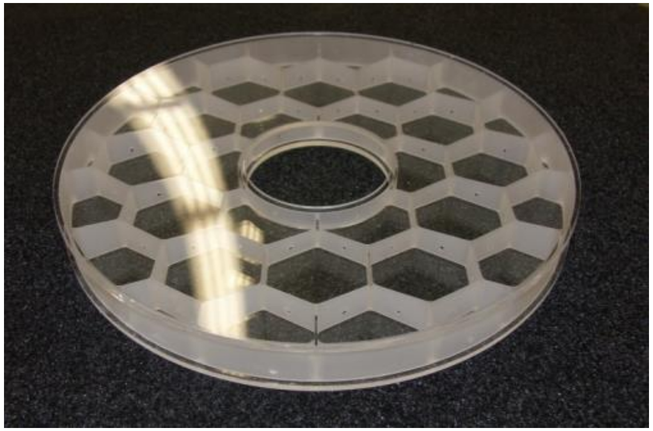
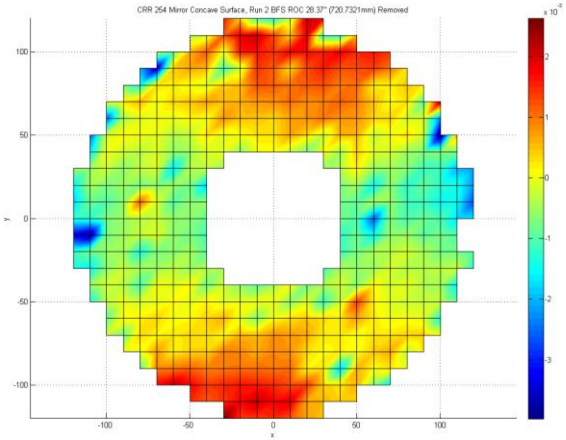
- TMT will add industrial capability to test and finish off-axis parabolic segments
  - 574 segments will start production soon
  - Harris has plans to be able to ion figure up to 5 segments simultaneously
- Harris Capture Range Replication (CRR) IR&D has potential to dramatically reduce processing time of ultra-lightweight mirror segments
  - Reduces processing time by ~50%

CRR results

- Designed and built mandrel to demonstrate replication of a 250mm spherical mirror with a center hole.
- Successful replication with a resulting figure error of ~6.5µm P-V (~1µm RMS), and <3µm P-V from mandrel shape.





Note low order errors which are easy to remove

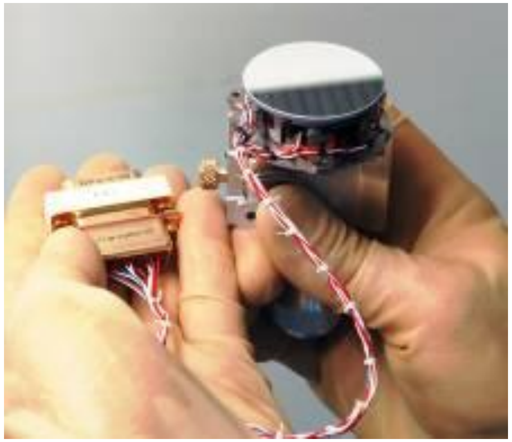
- Demonstrated potential to eliminate early processing steps (generation, rough shaping, grind) and go directly to minor MRF polish and then to final ion figuring

Proven Actuator Technology Ready for HDST

NORTHROP GRUMMAN AOX

Delivered Deformable/Active Mirrors:

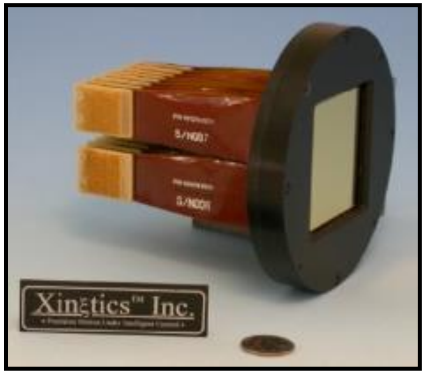
- WFPC2 Articulating Fold Mirrors – helped restore HST, on-orbit for 15+ years
- Keck 10m - 2x349ch deformable mirrors
- Gemini 8m - 177ch deformable mirror
- Palomar 5m – PALM 3000: Extreme Adaptive Optics including 4300+ channel deformable mirror enabling Hale to image exoplanets
- MPIA 3m – 349ch
- Mt. Wilson 2.5m – 349ch
- Big Bear Solar Observatory 1.6m – 3x349ch (example image below right)
- DKIST 4m – 1600 ch thermally managed



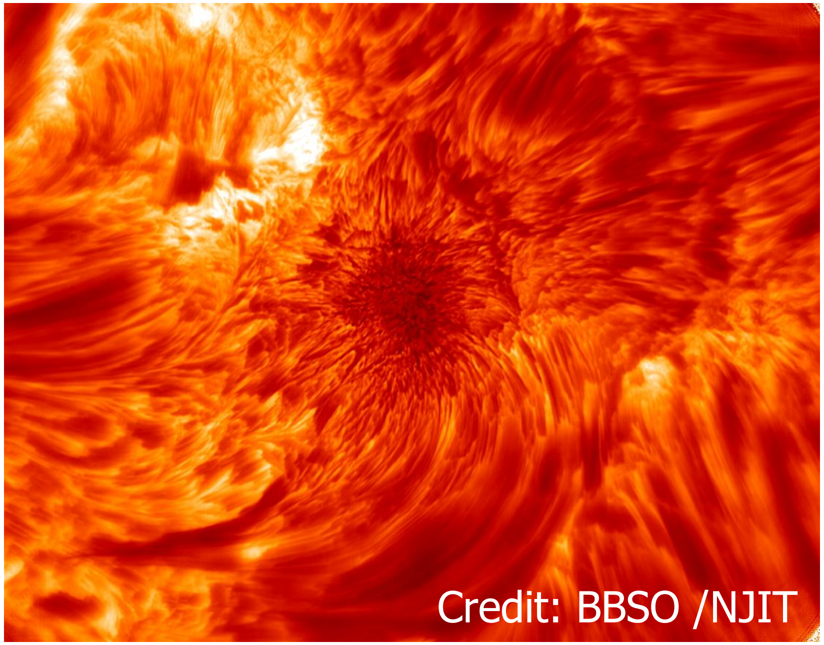
Articulating Fold Mirror

In Development

- Thirty Meter Telescope – cold temp DMs
- WFIRST Coronagraph – 2300 ch space qualified
    - Enabled JPL-HCIT to reach contrast goal of 10E-10



WFIRST Prototype DM



Ground-based image of Sunspot Chromosphere
Image created using AOX deformable mirrors

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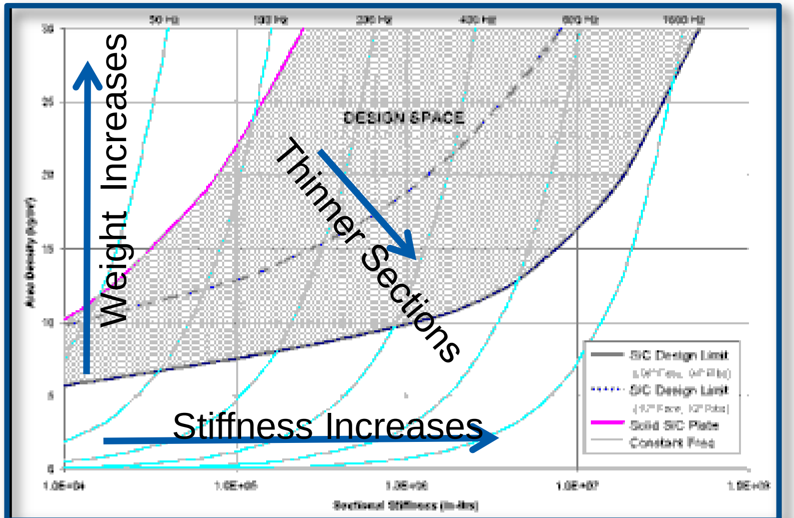
AOX Silicon Carbide Material Properties

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 κ/α	$(W/m\ x10^6)$	6.9	18.9	64.3	51.5	43.7	High
ρ, Density	g/cm3	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/°C	22.7	11.4	2.44	2.62	±0.03	Low
Δα, CTE Uniformity	ppb/°C	100	100	30	10	10	Low
k, Thermal Conductivity	W/m°C	156	216	157	135	1.31	High
C_p, Specific Heat	J/Kg°C	879	1820	670	713	766	Low
σ, Design Stress	MPa	124	17	70	62	7	High

FOM = Figure of Merit

- SiC ranks highest on structural and thermal figures of merit for common substrate materials



- Sectional stiffness tailored to meet both weight, stability, and stiffness requirements
- Areal densities ~8 kg/m² maintained even as mirror size increases
- Mirrors can be fully active, partially active or fully passive; polished or replicated optics
- High stiffness-to-weight ratios and excellent long-term dimensional stability for substrate, optical bench, and metering structure use

SiC manufacturing maturity opens up new design space for telescope and optic design, manufacturing, and operation

Monolithic SiC Structures

Monolithic Optical Bench

AOX fabricated this all-SiC optical bench as a single-cast part to maximize stiffness to weight ratio and minimize alignment complexity.

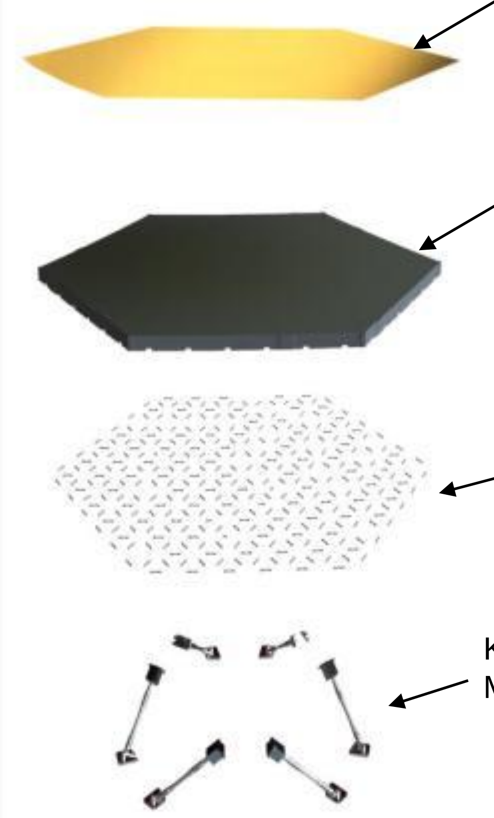
- Pathfinder optical bench supporting potential space-based coronagraph missions
- Cast using a single graphite mold and our proprietary fugitive core process
- Bench is just over 1 meter long and approximately 30 centimeters tall and 50 cm wide
- Weighs just over 8 kilograms
- Dimensionally stable, lightweight, and stiff

Advanced Active Hybrid Mirror (AAHM) Overview

NORTHROP GRUMMAN AOX

Replicated Optics Enable Affordable Segmented Telescopes

- Advanced Active Hybrid Mirror (AAHM) technology: a new paradigm for large optical systems
  - Nanolaminate optical replicated surface eliminates the need for polishing : demonstrated production on 6 week centers
  - Lightweight SiC substrates provide high stiffness and dimensional stability at remarkably low areal densities with apertures up to 2.4m.
  - Surface Parallel Actuation with discrete PMN actuators integrated into SiC rib structure eliminates need for reaction structure
  - Full environmental qualification completed
- Advantages of AAHM
  - Reduced fabrication times result in reduced segment, system and programmatic costs
  - Active control enables correction for gravity and thermal errors reducing complexity of system performance verification
  - SiC high stiffness and strength enables scaling of lightweight substrate designs that can survive launch loads
  - Achieve lighter area density enabling scaling to larger apertures
  - SiC "fugitive core" casting and nanolaminate optical replication processes enable production fabrication



Replication = Faster builds, less $$. Active = more capabilities, less $$

Technology Development

- Basic concepts have been demonstrated in ULE® to achieve better than 20nm RMS WFE in a short period of time
  - The mirror requirement may require 5nm RMS surface quality
- Further leverage will be gained from near-term ground based observatories production
  - Additional metrology development required to produce a repeatable test set capable of sub-3nm RMS surface measurements
- Technology development still needed
  - Process harden CRR for size and production to achieve a 5nm RMS surface mirror at production size and rate
  - Edges are always a worry with any mirror
  - Force and sub-nm displacement actuators have been built but robust qualification program required