Silicon Carbide Primary Mirrors for High-Contrast Imaging

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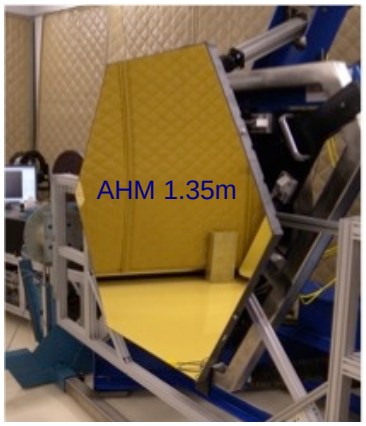
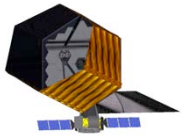
Active Primary Mirrors for Coronagraphy?

- **Active SiC mirrors have the potential to...**
  - Provide diffraction-limited wavefront quality – in the EUV
    - < 1 nm SFE and < 2Å microroughness
    - On orbit, at operating temperature
    - On the ground, for system testing in 1G, at room temperature
  - Remove 1 Deformable Mirror from the coronagraph
    - And any relay mirrors, for fewer aberration sources, less scatter, and higher throughput
  - Provide high actuator density, for a wide dark hole
    - >240x240 actuators across an 8 m aperture, if desired
  - Eliminate the largest WF errors at the source, for segmented or monolithic PMs
- **SiC mirrors are stronger and lighter weight than glass, potentially leading to lower mission cost**
- **But what about thermal stability...?**

Silicon Carbide Primary Mirrors

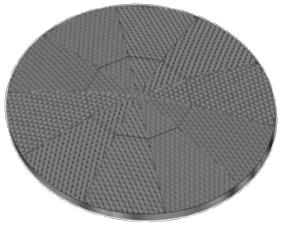
Actuated Hybrid Mirrors (AHMs)

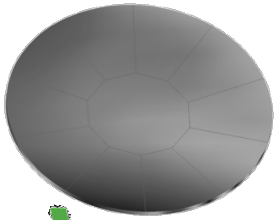


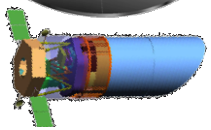


- 0.5 to 1.35 m size demonstrated
- <14 nm rms SFE demonstrated
- <10 Å microroughness (projected)
- 10-15 kg/m^2 substrate
- <25 kg/m^2 total
- Active mirror
  - 37 to 414 actuators
  - Solid state, integrated into SiC substrate
- Testable in 1G to 0G specs
- Made by replication

Superpolished Si/SiC Mirrors (SSMs)







<u>Proposed 4m class mirror</u>

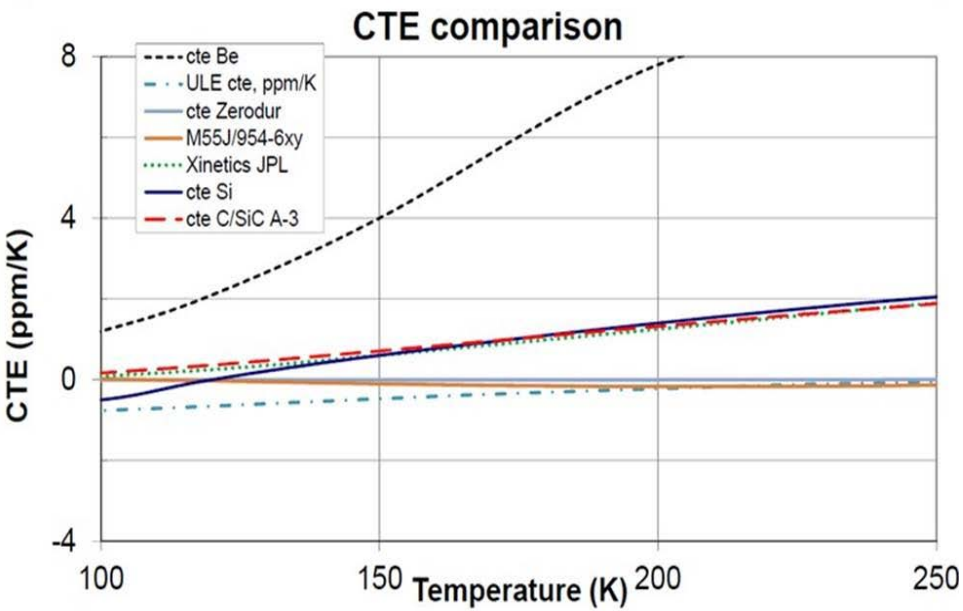
- Passive or active
- Made by casting, joining, cladding and polishing
- Si clad SiC
- <14 nm rms SFE (projected)
- <5 Å microroughness (projected)
- <25 kg/m^2 total
- If active:
  - 0 to 10,000 actuators
  - Solid state, integrated into SiC substrate
- Active version is testable in 1G to 0G specs

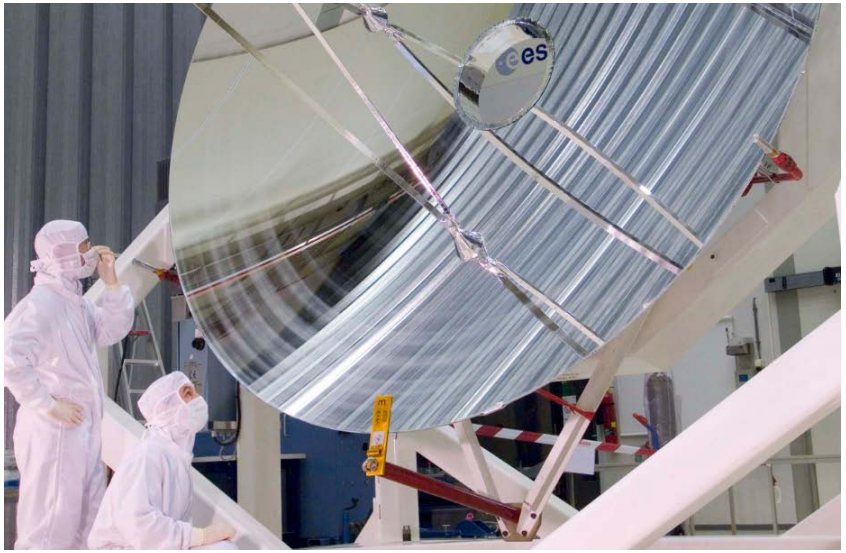
- **Silicon carbide (SiC) has superior stiffness, strength, and thermal properties, making it well suited for space optics**
- **"Actuated Hybrid Mirrors" (AHMs), made by replication using SiC substrates, provide an active option for mirrors up to 1.5 m**
- **"Superpolished Si/SiC Mirrors" (SSMs) use SiC substrates that can be joined, then clad with Silicon, and then polished, for passive or active mirrors**

Silicon Carbide (SiC) for Mirrors

- **SiC has many good properties**
  - Stiff for the weight
  - Robust
  - High thermal conductivity
  - Polishable to <20Å (unclad), and to 2 Å (Si clad)

Property	Units	Aluminum	Beryllium	SiC	ULE	Desire
ρ, Weight	g/cm3	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/°C	22.7	11.4	3.38	±0.03	Low
Δα Homogeneity	ppb/°C	100	100	30	10	Low
K/α, Thermal Gradients	MW/m	6.9	19	51	44	High
K/rCp,Thermal Diffusivity	m2/s	6.55	6.07	8.7	0.08	High
K/αE, Thermal Stress	MW-m/N	101	63	140	646	High

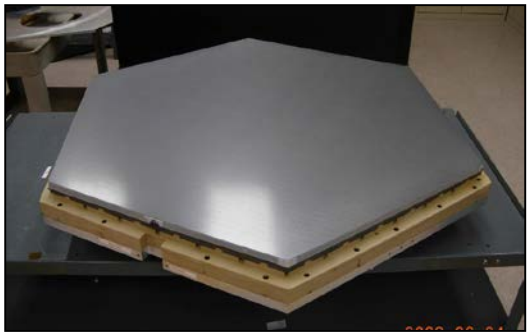




- **The ESA Herschel 3.5 m Primary Mirror (PM)**
  - Multiple segments joined by brazing

Ceraform Silicon Carbide

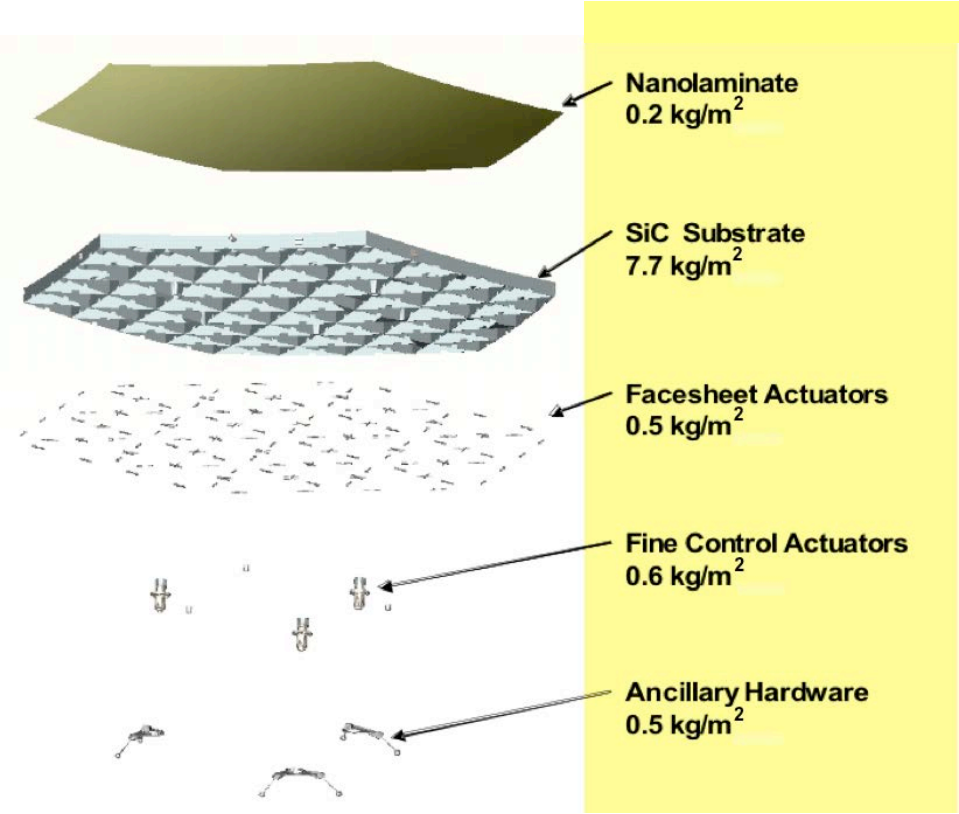
- **AOX Ceraform SiC:**
  - Fugitive core foam mold created by CNC machining
  - SiC nanopowder slip fills mold
  - Part is freeze-dried
  - Mold core is leached out
  - First firing creates green state "prefired" part
  - Part is machined
  - Second firing to full hardness
- **Final rough grind of SiC front surface matches the curvature of the mandrel/nanolaminate to ±5 um**



Typical finished substrate

Actuated Hybrid Mirrors (AHMs)

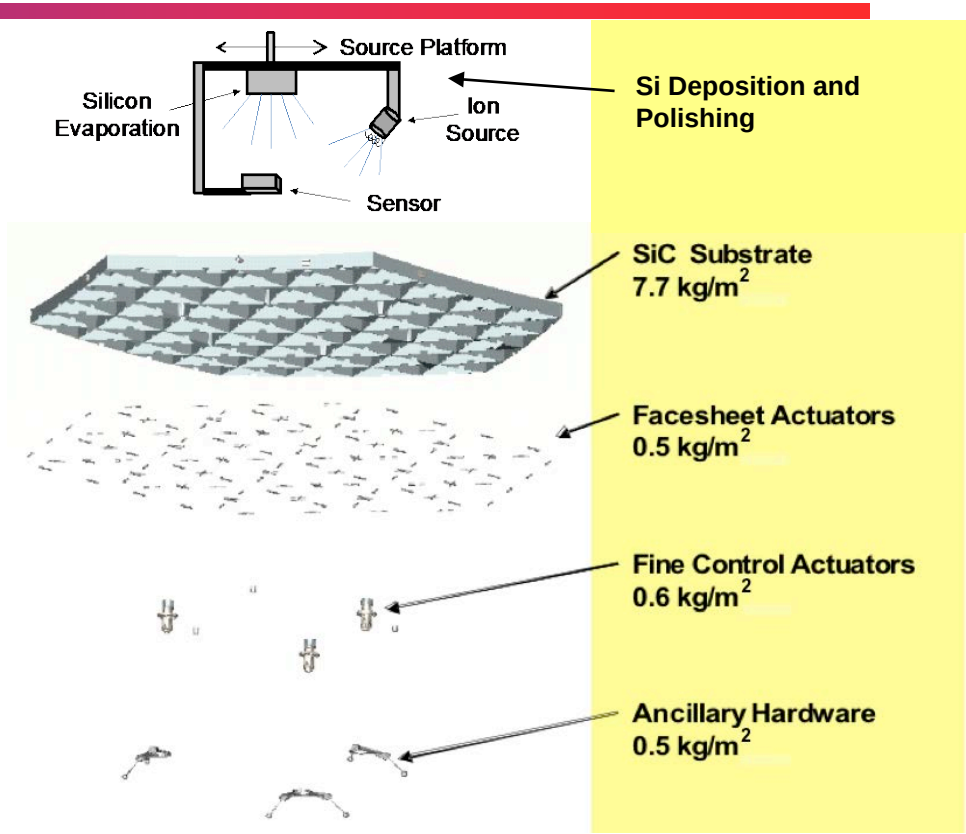
- **AHMs are large mirrors**
  - PMs or PM segments
  - Made by replication
- **Nanolaminate facesheet**
  - Multilayer metal foil, made by sputter deposition on a super-polished mandrel
- **SiC substrate**
  - Reaction-bonded Ceraform SiC is cast in a mold, fired, then bonded to facesheet
- **Electroceramic actuators**
  - Surface-parallel embedded actuators give large stroke and high accuracy, by design



- **AHMs are low mass and high strength**
  - Areal density < 25 kg/m^2 including electronics for meter-class AHMs
- **AHMs are made by replication for high optical quality and low cost**

Polished Active SiC Mirrors

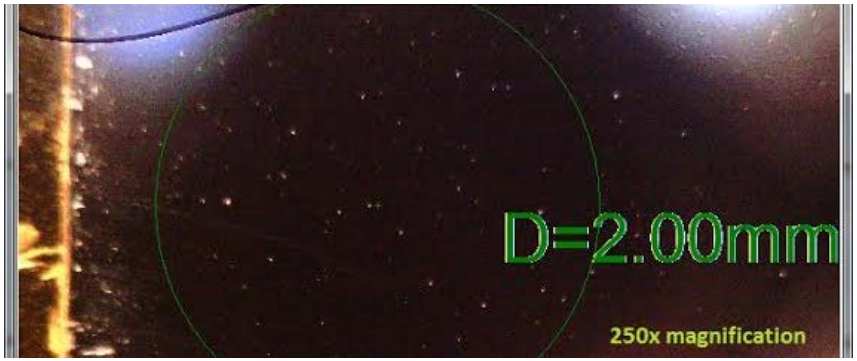
- **Same SiC substrate**
  - Cast to near-net shape, then rough ground
  - Large mirrors made by joining (brazing, e.g.) multiple segments
- **Nanolaminate replaced by Silicon cladding**
  - Low-stress Si deposited provides amorphous surface layer
  - Polishable to 1 Å microroughness
- **Same facesheet actuators, mounts, and thermal control subsystems**



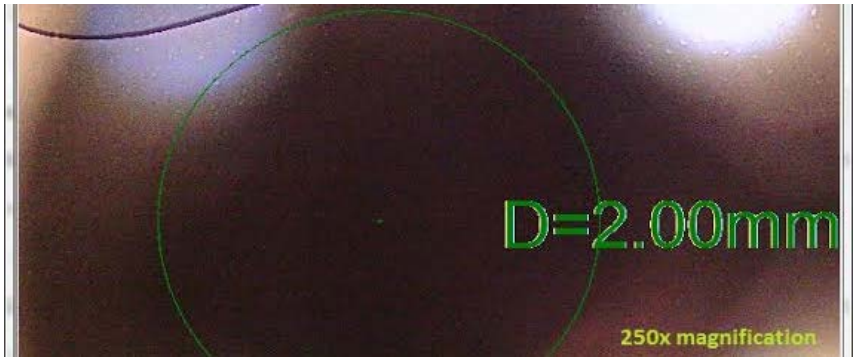
- **Polished SiC mirrors are also low mass and high strength**
  - Areal density < 25 kg/m^2 including electronics for meter-class mirrorss
- **Large SiC mirror**

ZeCoat Si Cladding Performance

Before polish:



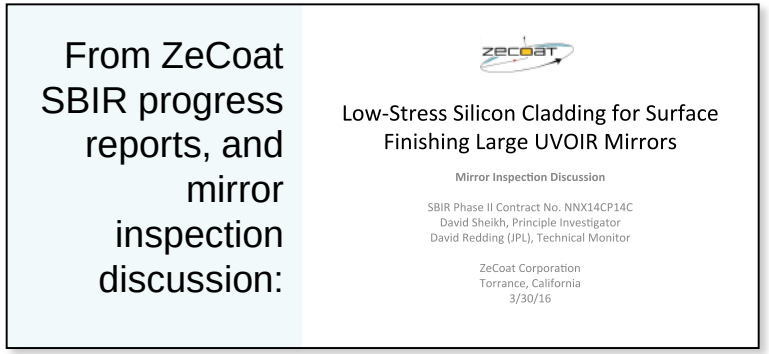
After polish:



Surface Quality		Before Polish		After Polish	
		RMS (A)	PTV (A)	RMS (A)	PTV (A)
6 months ago	high rate	17	302.4	0.86	7.13
	low rate	11.5	142.5	1.45	8.9
recent	high rate	4.2	80.1	1.46	8.63

Stress	thickness (microns)	Stress (Mpa)	rate (A/sec)
run 3	25	18	50
run 4	27	53	50
run 6	28	51	50

From ZeCoat SBIR progress reports, and mirror inspection discussion:

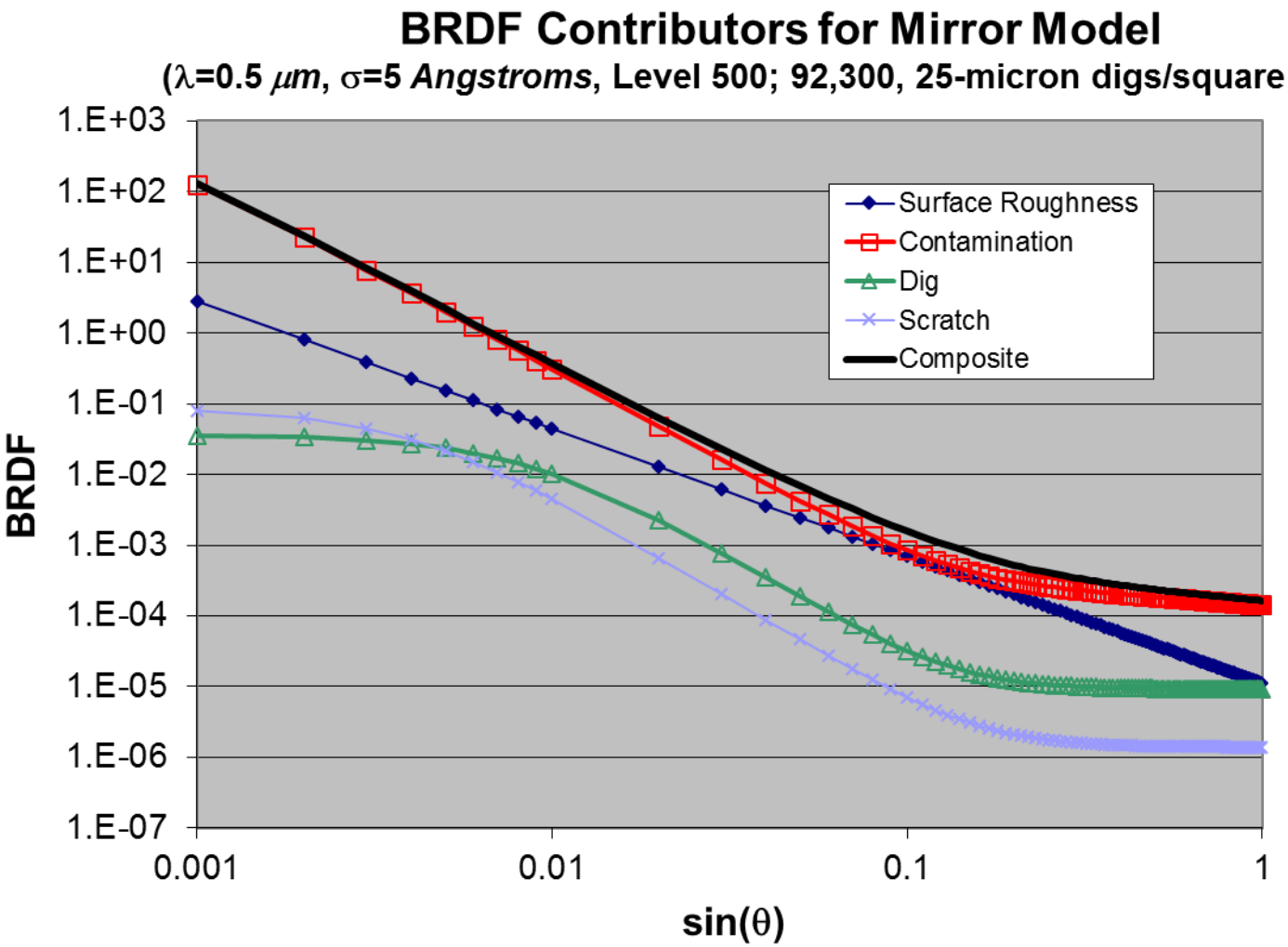

Low-Stress Silicon Cladding for Surface Finishing Large UVOIR Mirrors

Mirror Inspection Discussion

SBIR Phase II Contract No. NNX14CP14C
David Sheikh, Principle Investigator
David Redding (JPL), Technical Monitor

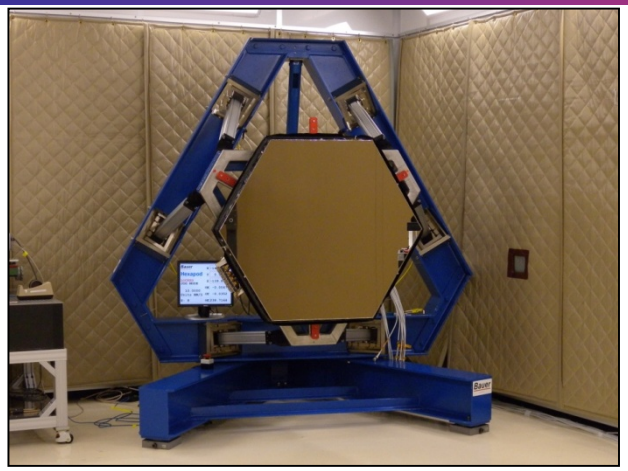
ZeCoat Corporation
Torrance, California
3/30/16

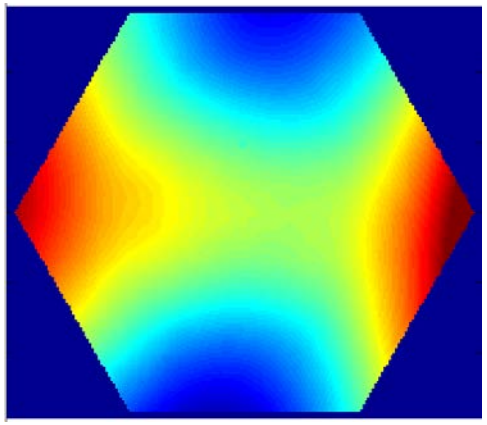
Preliminary BRDF for Si-clad SiC



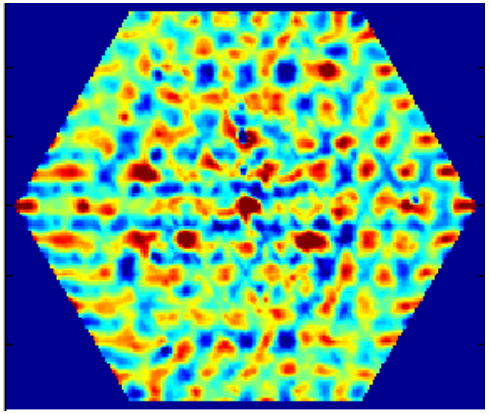
- **For a 10 m primary mirror**
- **Based on ZeCoat measurements**
  - Scratch = #1 (10 micron width)
  - Dig density observed: 92,300 20-um defects per square meter
- **No reflective coating**

Closed-Loop Performance



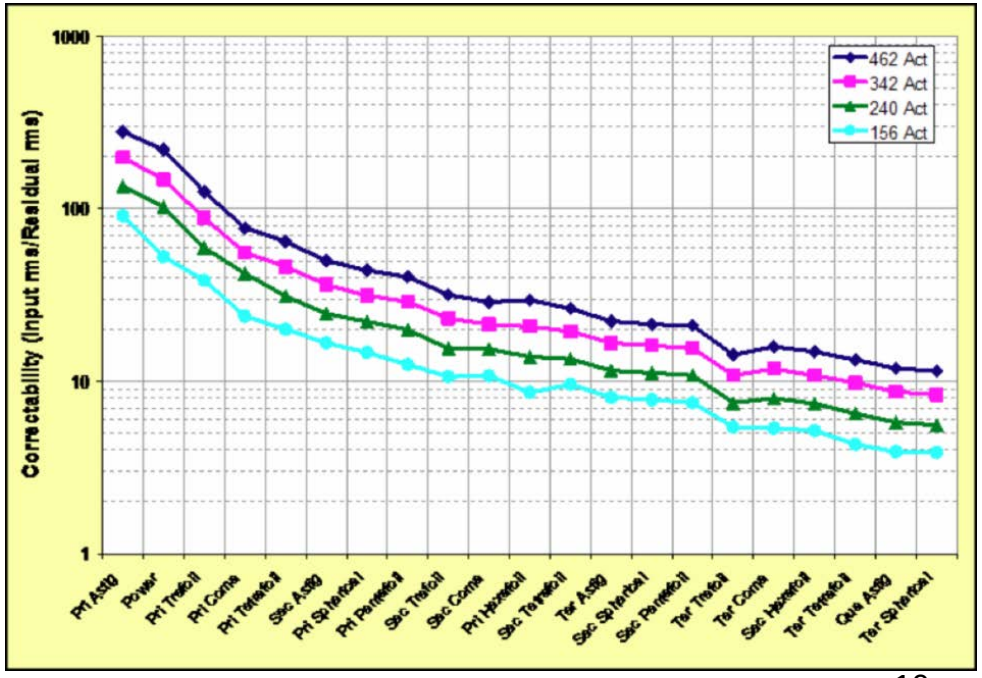


SFE = 1.88 µm RMS



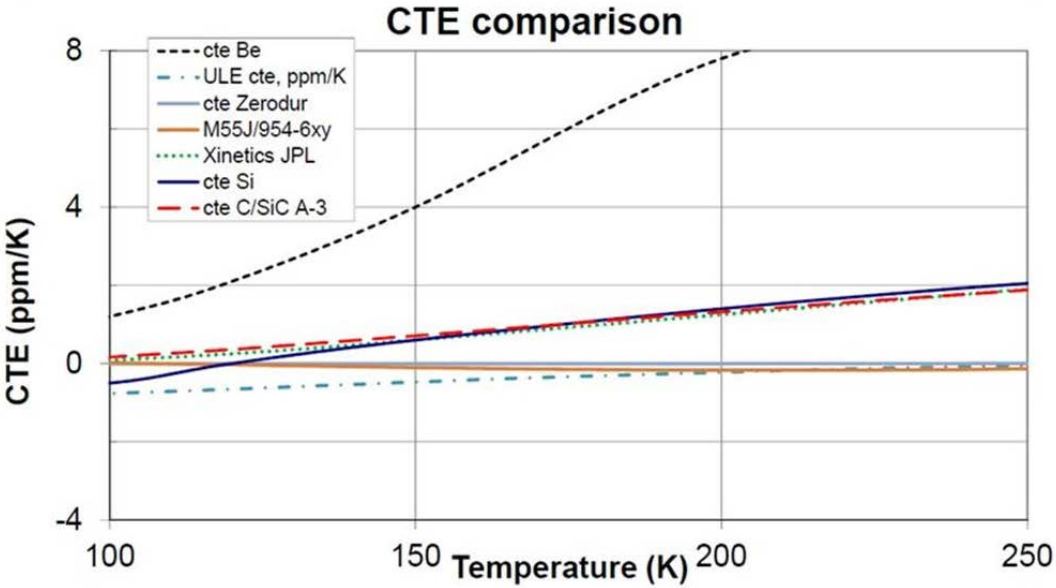
SFE = 0.014 µm RMS

- **AHMs routinely demonstrated > 100x reduction in Surface Figure Error (SFE), after WF sensing and control**
  - For 1.35 m segments with 342 actuators, SFE of ~2 um was repeatedly reduced to < 15 nm
  - High dynamic range
- **This provides several advantages**
  - Relaxed tolerances for AI&T
  - Testing to spec even in 1 G
  - On-orbit correction of system errors
- **Active SiC mirrors polished to a relaxed 100 nm could achieve < 1 nm SFE, if this correction factor holds**



What About Thermal Stability?

- **What about thermal stability?**
- **For a "cold" telescope, SiC provides superior thermal stability below ~140 K**
  - Ambient at L2 < 50K
- **For a "warm" telescope, SiC provides superior thermal controllability**
  - ULE has 100x better CTE, but 100x worse thermal diffusivity; the ratio indicates the thermal controllability of a material through conduction
  - SiC mirrors are strong enough to use open-back structure, for better thermal controllability through radiation, compared to closed-back mirrors
    - SiC mirrors are 100s of times faster to respond to thermal inputs, but need more precise control for the same level of stability

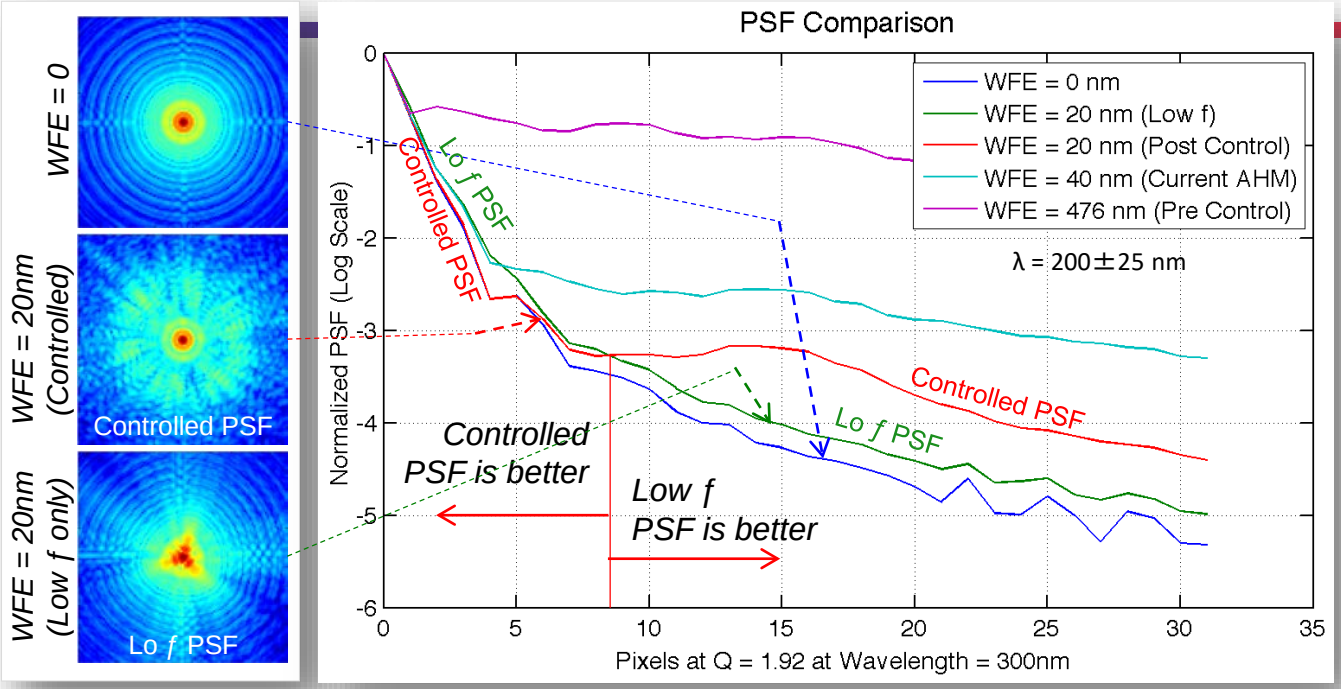


SiC Development Status

- **SiC manufacturing**
  - Substrate manufacturing by AOA Xinetics (AOX), and others
  - SiC substrate joining using brazing or other techniques
    - 3.5 m Herschel primary mirror (BoosTek)
- **Actuators are mature products from AOX**
  - Wide temperature range (300-10 K) actuators also demonstrated by AOX; further development underway at JPL/Caltech and AOX
- **Low-stress Si cladding**
  - ZeCoat process appears to meet objectives, scalable to sizes > 1.2 m
    - Testing is ongoing
- **Space qualification**
  - AHMs have been qualified at 1.35 m size for VIS performance, with lien on mount-point print-through due to epoxy creep
    - Active mirror with flight-like mounts, thermal control, and metrology hardware
- **Thermal control to achieve nm per hour stability has been demonstrated**
  - Picometer per minute stability not yet shown

Backup

Active Mirror PSFs



Simulated narrow-band PSFs at 200nm wavelength, for a UV telescope optimized for 300nm wavelength

- Nominal WFE = 20nm
- Detector is critically sampled at λ = 300nm
- 400 actuators for control case

- **AHMs and active SSMs, like Deformable Mirrors generally, have a different distribution of WFE vs. *f* than conventional optics**
  - Lower error in the low spatial frequencies
  - Higher error at and beyond the actuator spatial frequency
- **This results in a tighter PSF core, but a raised "halo" in the sidebands**
- **Post-control PSF quality is a function of actuator density and initial WFE, and can be engineered to meet science requirements**