CVC SiC Thermally Insensitive Telescope Development

Fantom Materials, Inc.

Presented by William F. Fischer III, Ph.D.
President

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Outline

- Brief overview of Fantom Materials Technologies
- Thermally Insensitive Telescope Project Review
  - Overall project
  - Goals
  - Status
  - Projections
- Details: Components
- Integration
- Lessons Learned
- Summary and Plan Forward

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Primary Technologies

- CVC SiC® and CVD SiC
  - Capable of processing other materials like TaC, TaB_2, ZrC, ZrB_2, HfC, and HfB_2 etc
- HoneySiC ceramic matrix composite materials
  - Carbon-Carbon & Silicon Carbide Composite
    - Continuous fibers
    - Chopped Fibers
    - Carbon Nanoparticles & Fibers and/or Nanotubes
  - Silicon Carbide & Silicon Carbide Composite
- Radiation & Space hardened reflective coatings

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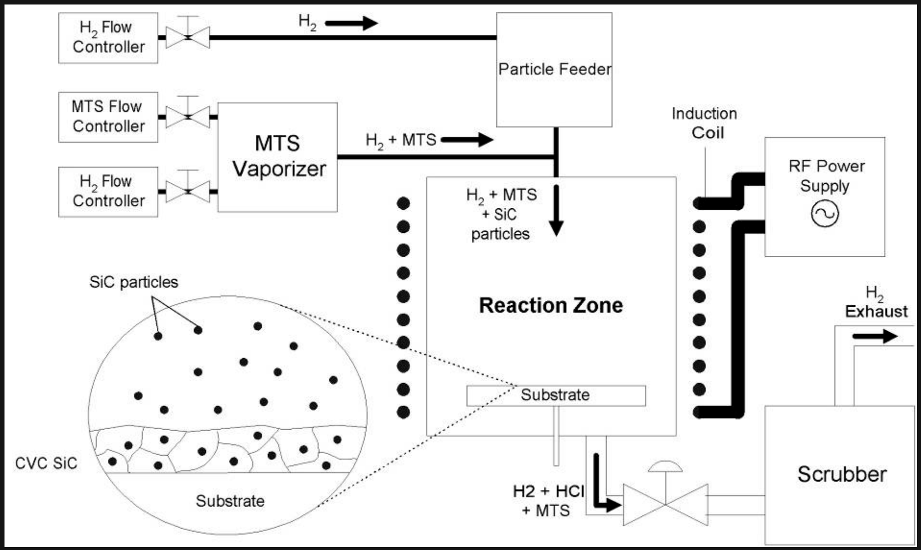
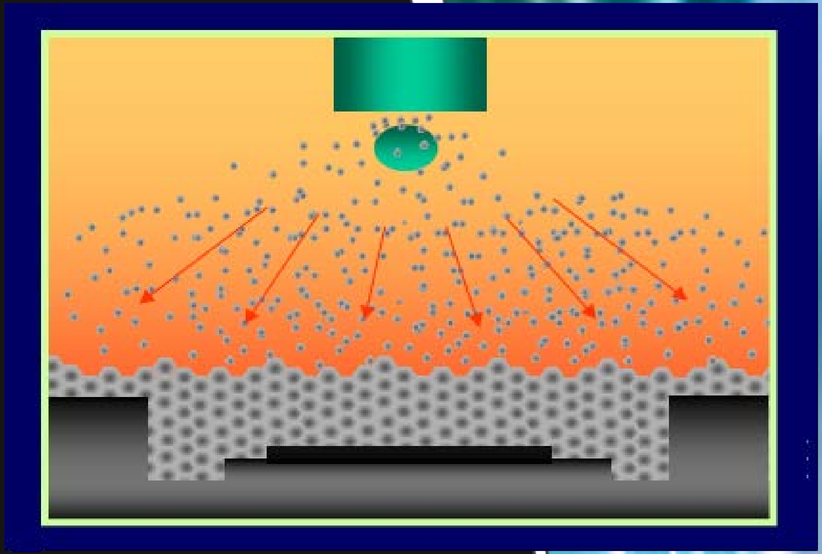
CVC SiC® Process to Grow Ultra High Purity Silicon Carbide





$$CH_3SiCl_{3(g)} \rightarrow SiC_{(s)} + 3HCl_{(g)}$$

Particles added to CVD stream promotes equiaxial grain growth and low intrinsic stress

US Patent No. 5,348,765

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CVD/CVC® Reactor Operations

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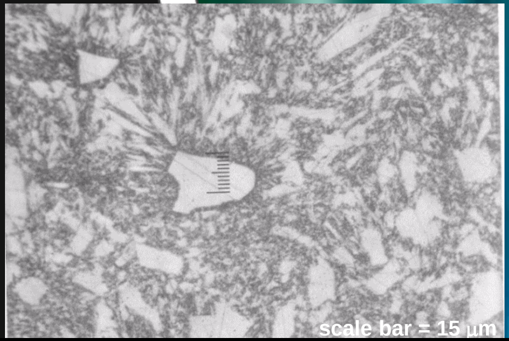
CVC SiC® is a Superior Material

CVD SiC Has *Columnar* Growth

Powder Addition Relieves Intrinsic Stress and Provides Other Advantages



CVC SiC Has ***Equiaxed*** Growth

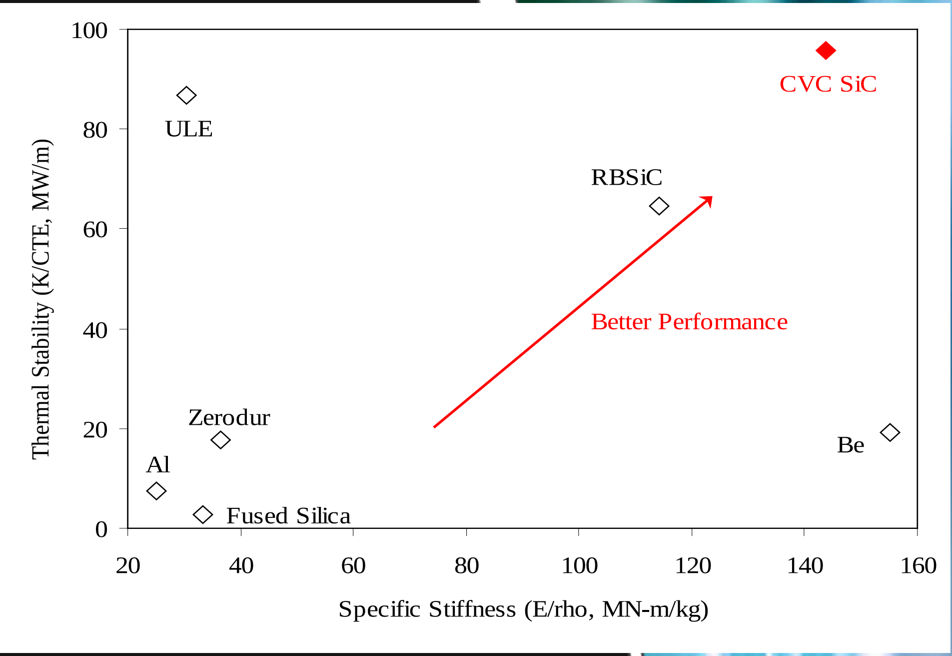
CVC SiC® Has Multiple Advantages

- ✓ Dimensionally stable to temps as low as 4 K
- ✓ Large Size (60-inch) and Thick Parts (>3 inch)
- ✓ High thermal conductivity
- ✓ Temperatures Up To 4500 °F
- ✓ Directly Super-Polishable (w/o Cladding Layer)
- ✓ Faster growth rate (>5x CVD)
- ✓ High Yields (Nearly 100%)
- ✓ Isotropic Microstructure
- ✓ HAENS Survivable
- ✓ Near Net Shape
- ✓ Wear Resistant
- ✓ Corrosion Resistant
- ✓ Machineable (Like Glass)
- ✓ High Aspect Ratio (> 100:1)
- ✓ High Stiffness
- ✓ Lightweight
- ✓ 100% Dense
- ✓ Non-Toxic
- ✓ Low CTE
- ✓ Low Z
- ✓ High Purity

Silicon Carbide Optics

Advantages

- Specific stiffness
- Thermal stability
- Rad hard
  - Passed several test procedures and environments including HAENS testing



Optical performance:

- Figure: λ/20 P-V typical
- Have achieved λ /40+
- Roughness: 4 Å rms typical
- Have achieved 1 Å

Project Why's and Goals

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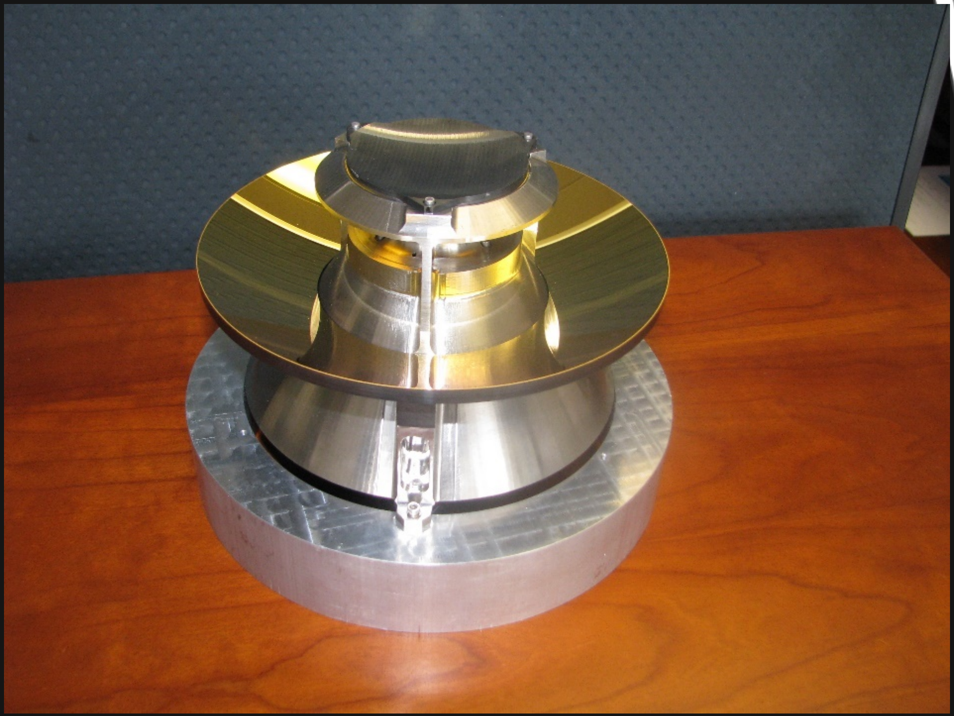
Telescope Description Summary

- Compact Lightweight 4 mirror telescope
- Challenging prescription and requirements
- Rapid movement with stability
- Thermal stability
- Rad hard



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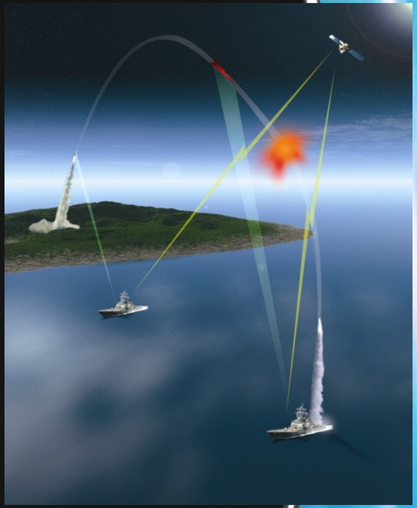
Why "Thermally Insensitive"?

Project Goal: Demonstrate producibility of a thermally insensitive radiation-hard aerospace telescope

- ✓ Extend trajectory and flight path defense capability
- ✓ Perform in space, decoy, and nuclear environment.
- ✓ High HAENS damage threshold
- ✓ Space environment proven



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Telescope Design Ideal Goals

- Reduce lead time and cost
- Meet or Exceed optical performance
- Improve thermal stability and mechanical robustness
- Incorporate radiation hardness
- Maintain weight requirement
- Identify Lessons Learned
- Develop CVC SiC optimized solution

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Primary Mirrors

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Primary Mirror (PM)

- Successfully completed Primary Mirror Development
  - On Schedule and on Budget
- Designed, manufactured, and tested 3 PM units
- Met drawing and requirements
  - Mass, Stiffness, Strength, and Thermal Distortion

Enhanced gold | Enhanced gold | Protected Silver

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Primary Mirror (PM) - Performance

	EU 1	EU 2	EU 3	Be Ref.
Thickness	1.93x	1.42x	0.66x	~1.000
Weight (actual)	2.00x	1.65x	0.75x	1.000
Weight (model)	2.10x	1.63x	0.79x	1.000
Harmonic Frequency	1.31x	1.23x	1.02x	1.000
Harmonic Frequency (model)	1.28x	1.21x	1.04x	1.000

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PM EU1 Optical Surface Figure, Location and Optical Axis Pointing Results

	Requirement	Pre Thermal Cycle
Unrestrained Surface Figure	1.00 1.00 1.00	0.095 ✓ 0.080 ✓ 0.474 ✓
Optical Axis Pointing	1.00	0.633 ✓
Vertex Location	1.00	0.024 ✓
Datum A Surface Profile	1.00	0.000 ✓

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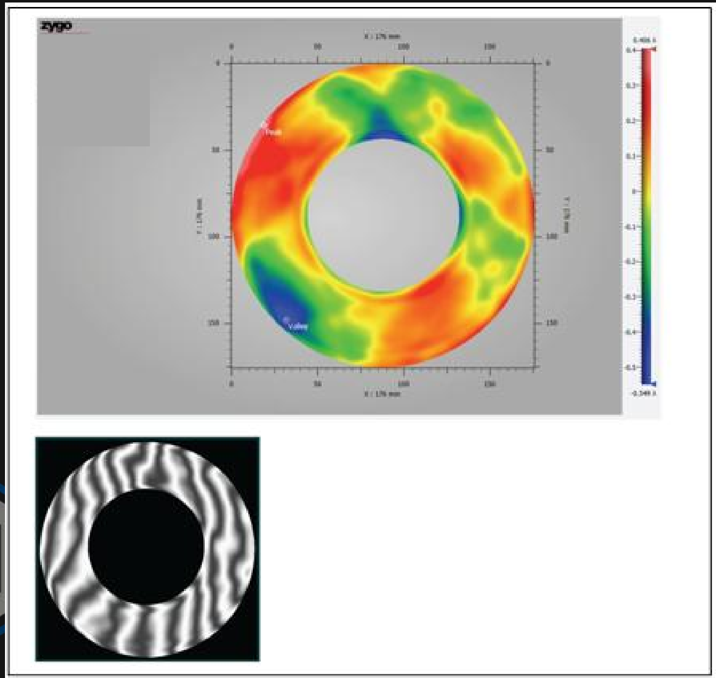
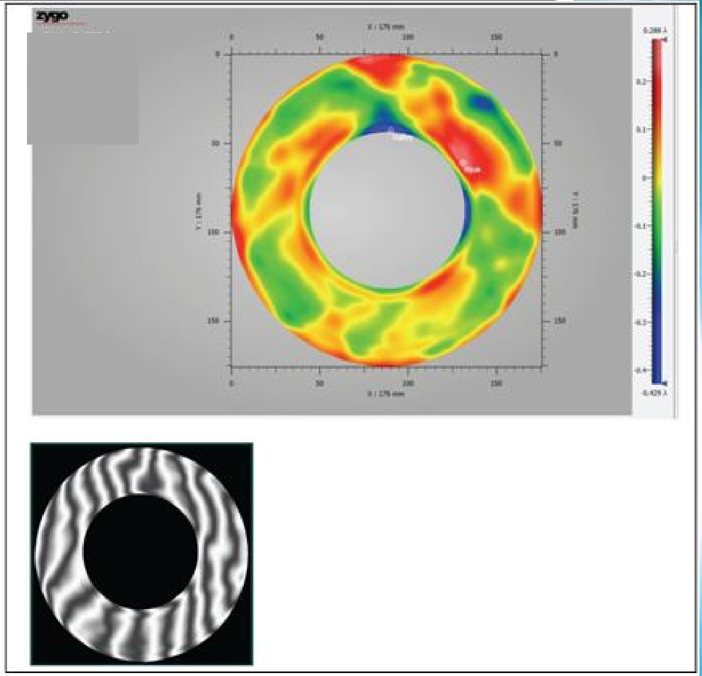
PM EU1 Surface Figure Results

In waves (P-V) after removal of piston, tilt and power	Spec	In waves (RMS) after removal of piston, tilt and power	Spec	In waves (RMS) after removal of piston, tilt, power, astigmatism, coma, and trefoil	Spec
0.95 ✓	1.00	0.80 ✓	1.00	0.70 ✓	1.00





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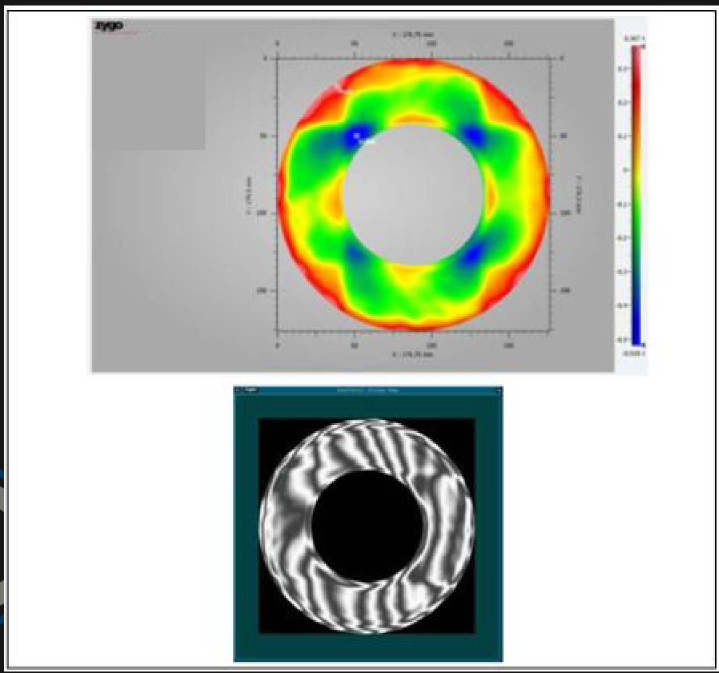
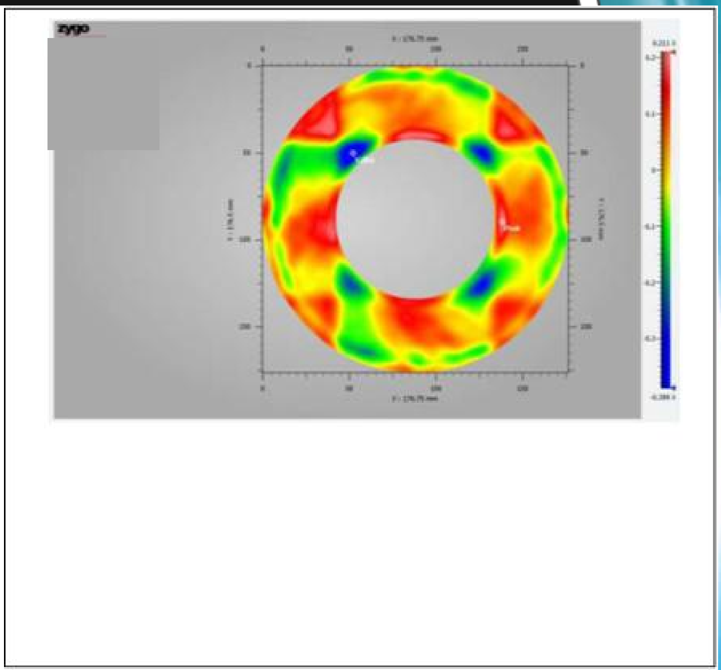
PM EU2 Surface Figure Results

In waves (P-V) after removal of piston, tilt and power	Spec	In waves (RMS) after removal of piston, tilt and power	Spec	In waves (RMS) after removal of piston, tilt, power, astigmatism, coma, and trefoil	Spec
0.89 ✓	1.00	0.85 ✓	1.00	1.00 ✓	1.00





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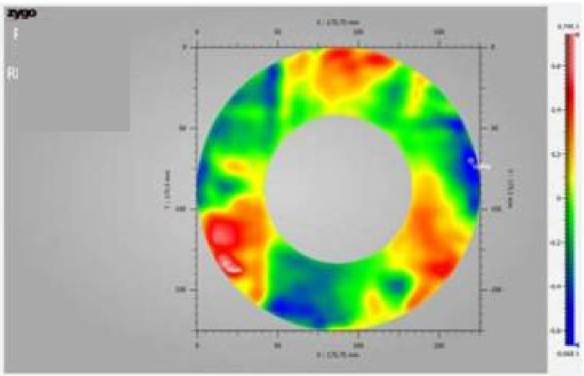
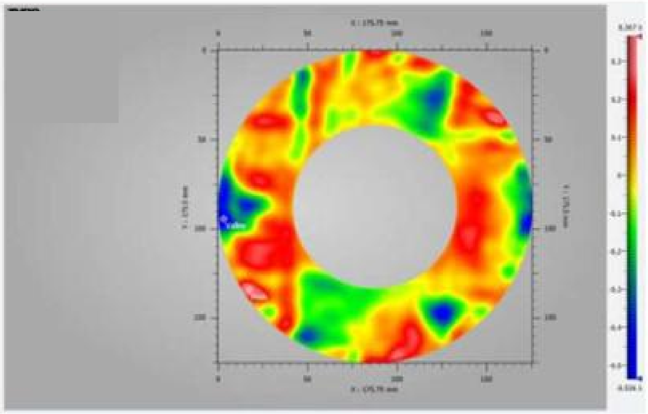
PM EU4 Surface Figure Results

In waves (P-V) after removal of piston, tilt and power	Spec	In waves (RMS) after removal of piston, tilt and power	Spec	In waves (RMS) after removal of piston, tilt, power, astigmatism, coma, and trefoil	Spec
1.41 ✓	1.00	1.20 ✓	1.00	1.47 ✓	1.00





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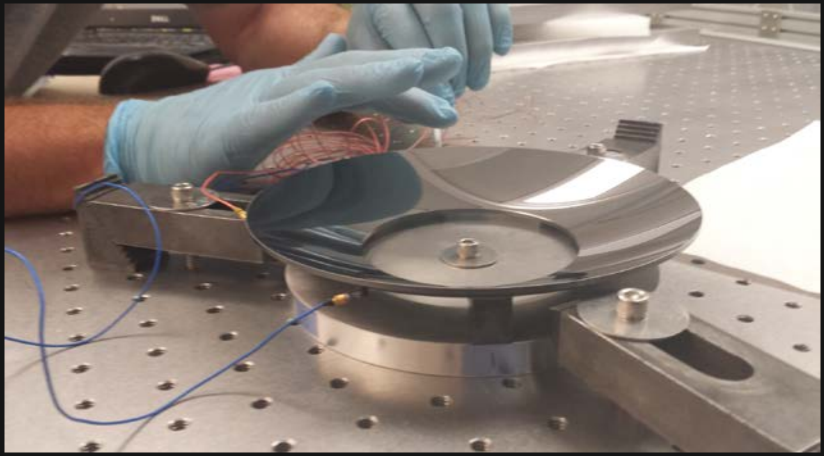
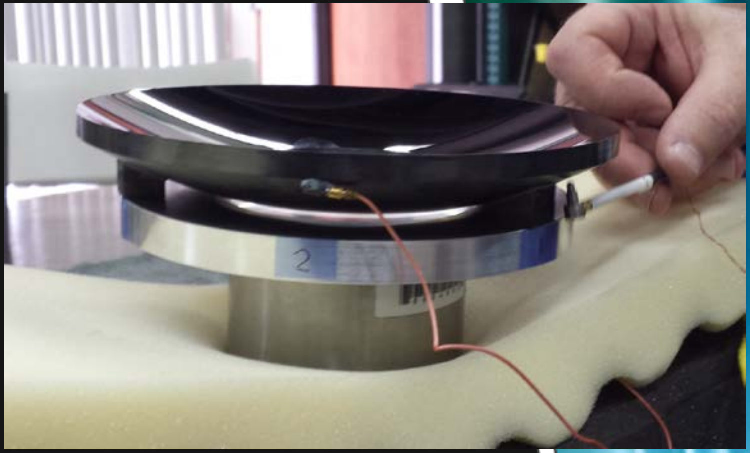
CVC-SiC Primary Mirror Modal Survey





Modal Tap Test Surveys were performed on all Units, before and after thermal cycle

Free-Free and Constrained

- Attached to a Warm Stop Interface Simulator

Modes correlated well with analysis predictions

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Secondary Mirror

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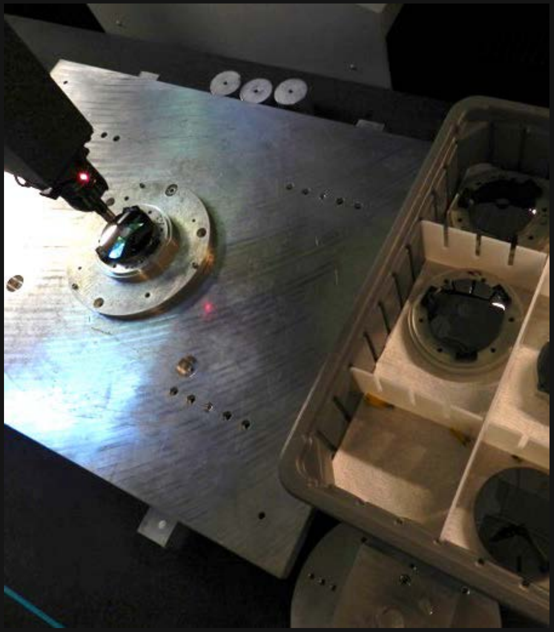
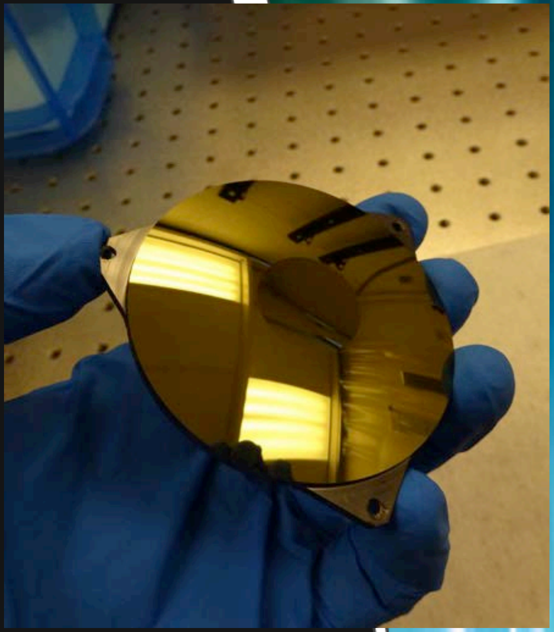
S1 to S2 Transition

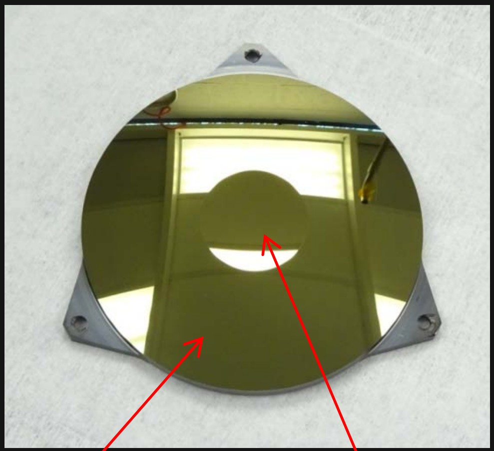




- Developed S2 processing on top of S1 to optimize / minimize the transition zone.
- A “grinding study” established & calibrated the process for production of SM mirrors.
- Radius and tilt were tightly maintained while controlling transition.

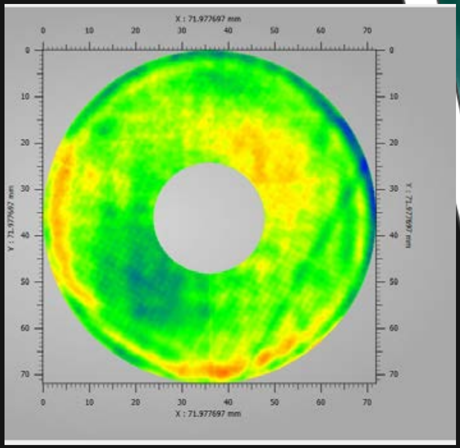
Secondary Mirror

Polishing out critical S1/S2 transition



S1 S2

SM EU1 after gold coating



SM EU1 Optical Figure & Surface Roughness	S1	S2	Reqmt
(P-V) after removal of piston, tilt and power:	0.58	0.64	1.000
(RMS) after removal of piston, tilt and power:	0.05		1.000
(RMS) after removal of piston, tilt, power, astigmatism, coma, and trefoil:	0.50		1.000
Optical surface roughness:	0.91	0.09	1.000 RMS

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Secondary Mirror Analysis

Mirror	Mass	Stiffness (Hz)			S1 Surface Gravity Sag			S2 Surface Gravity Sag		
		f1	f2	f3	1gx	1gy	1gz	1gx	1gy	1gz
Baseline Be	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
EU 1	1.683	1.200	1.120	1.120	0.059	0.373	0.693	0.407	0.410	0.665
EU2	1.417	1.168	1.019	1.019	0.053	0.340	0.738	0.372	0.375	0.681
EU3	1.150	1.223	1.031	1.032	0.045	0.284	0.564	0.319	0.318	0.631
Fixed a 3 interface holes for modal analysis and gravitational sag										

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Tertiary Mirror

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Manufacturing – Tertiary Mirror

Deposition

Mirror blank slice separation

CNC mirror tab formation routines

CNC optical S1 surfacing routines

Pre-polished TM mirror blank (S1)

Pre-polished TM mirror blank

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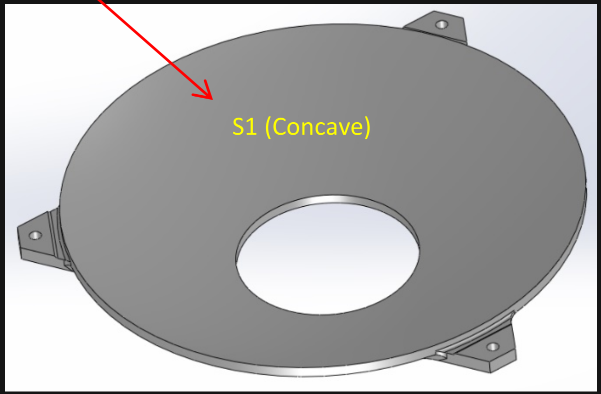
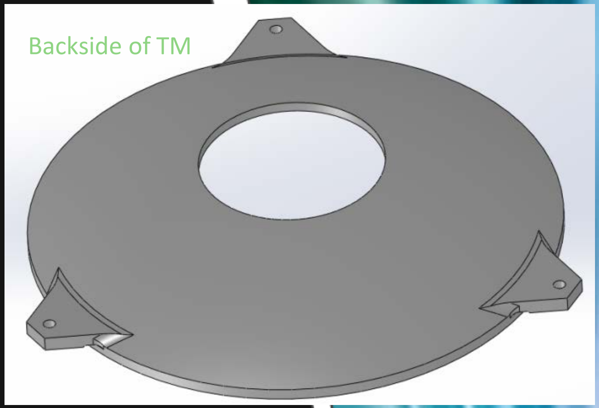
Tertiary Mirror

Optical Surface





Finite Element Analysis – TM

Mirror	Mass	Stiffness (Hz)			S1 Surface Gravity Sag		
		f1	f2	f3	1gx	1gy	1gz
Baseline Be	1.00	1.00	1.00	1.00	1.00	1.00	1.00
EU 1	1.161	20.515	1.728	1.727	0.417	0.415	0.205
EU2	0.967	1.841	1.573	1.572	0.455	0.452	0.202
EU3	0.773	1.633	1.391	1.391	0.547	0.544	0.203
Fixed a 3 interface holes for modal analysis and gravitational sag							

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Quaternary Mirror

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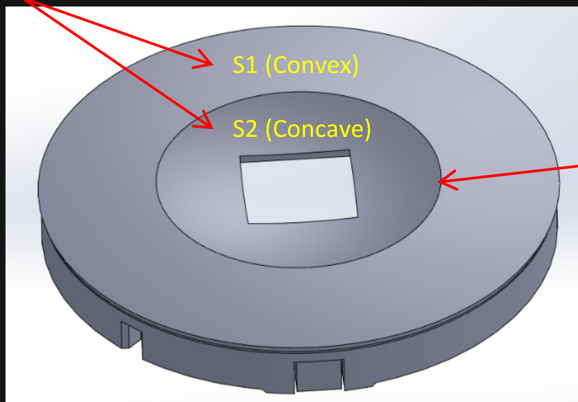
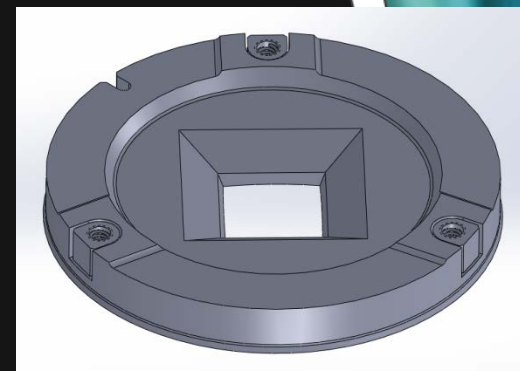
Quaternary Mirror

Optical Surfaces



Sharp edge S1/S2
transition required



Finite Element Analysis – QM

			Stiffness (Hz)		
Mirror	ID	Mass	f1	f2	f3
Berrylium	Reference Design	1.000	1.000	1.000	1.000
EU1	CVC SiC	2.000	2.171	2.170	1.849
EU2	Conductive CVC SiC	2.000	2.180	2.177	1.865
EU3	SuperSic-Si-4S	1.833	1.952	1.949	1.666

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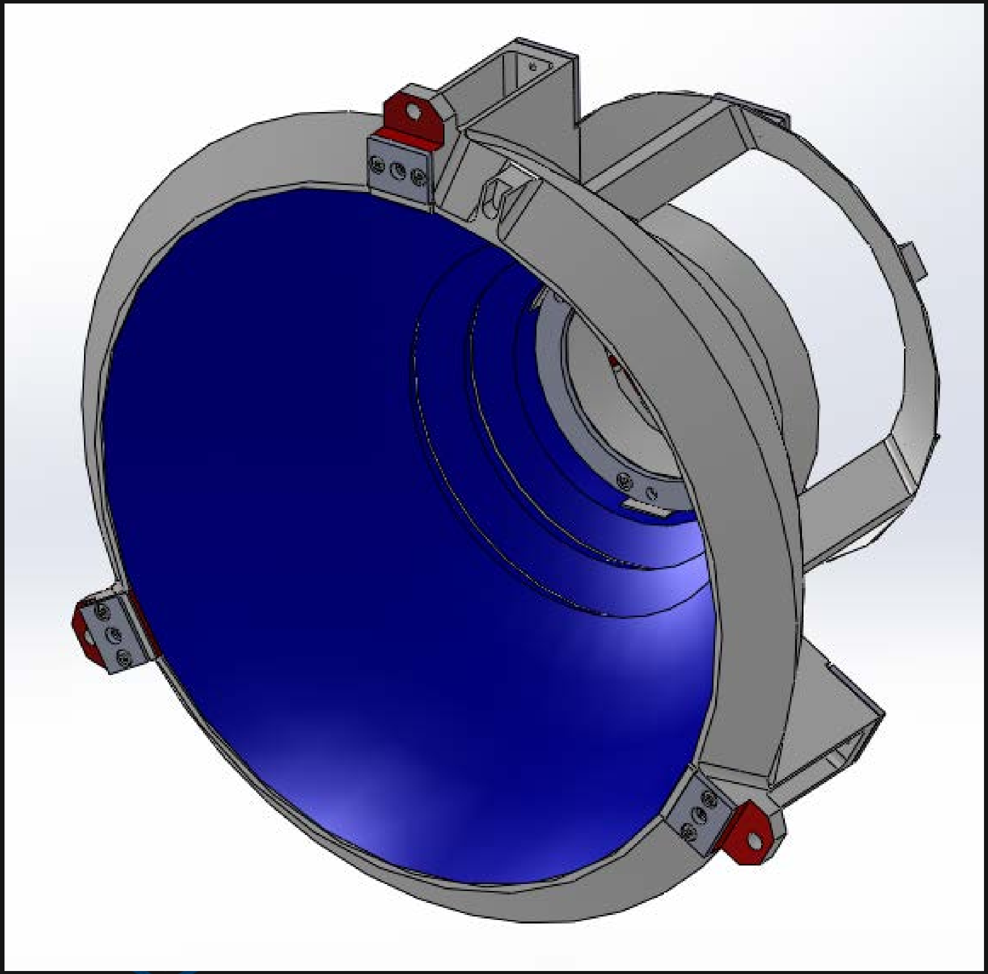
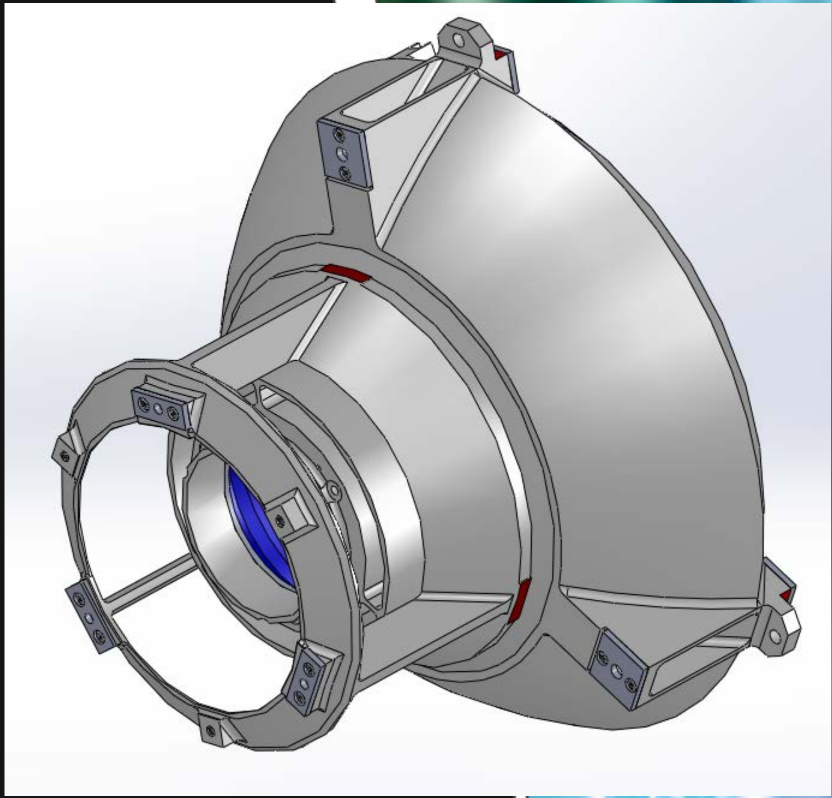
Integrated Telescope

Warm Shield Design





HoneySiC Warm Stop Fabrication Process

- High temperature Fiber Treatment
- Wet Layup and Pre-Pregging
- Infiltration
- Pyrolysis
- Infiltration
- Machining
- Pyrolysis
- PIP Iterations to achieve <1% weight change

Currently working on 3D printing techniques

HoneySiC Technology allows for

- Tailoring CTE

and

- Elimination of any layering effects

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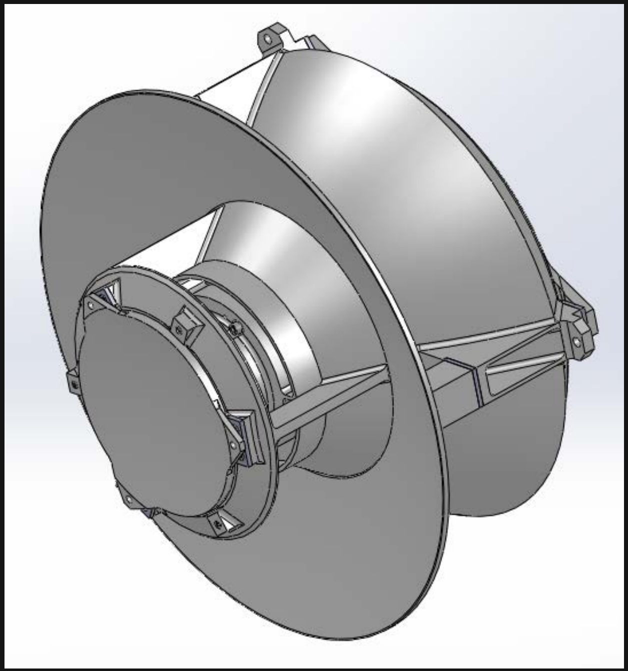
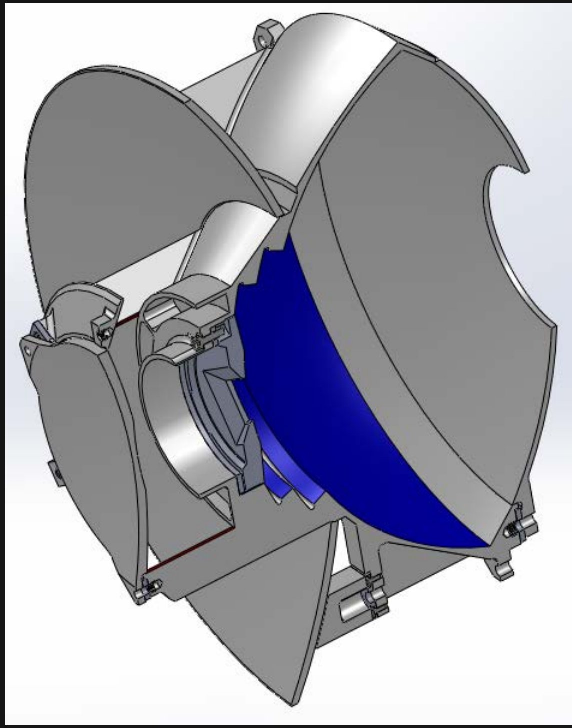
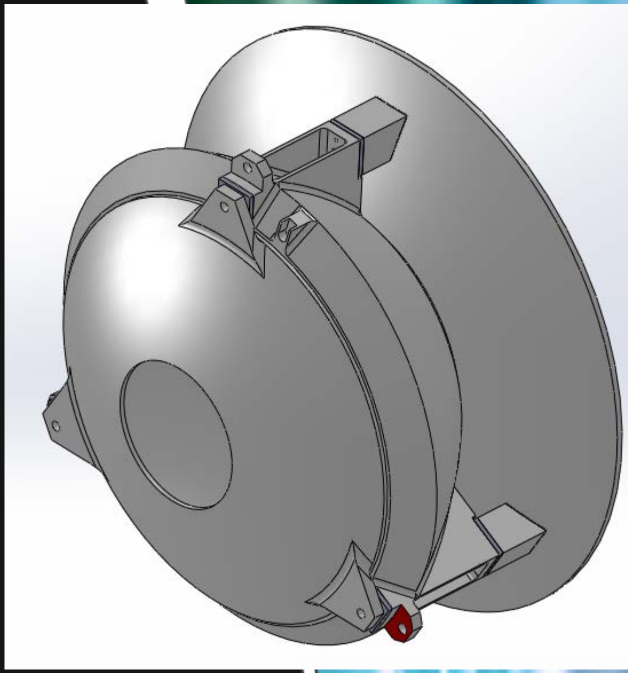
Telescope Assembly Design





Section View



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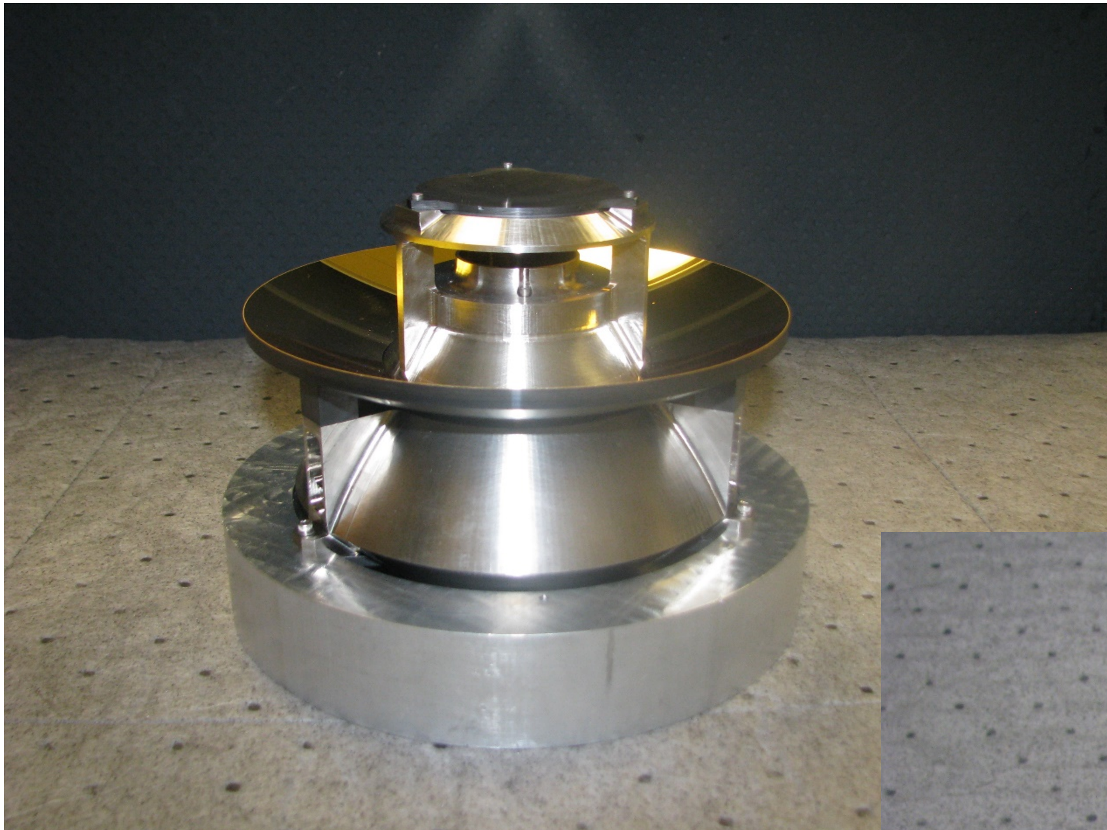

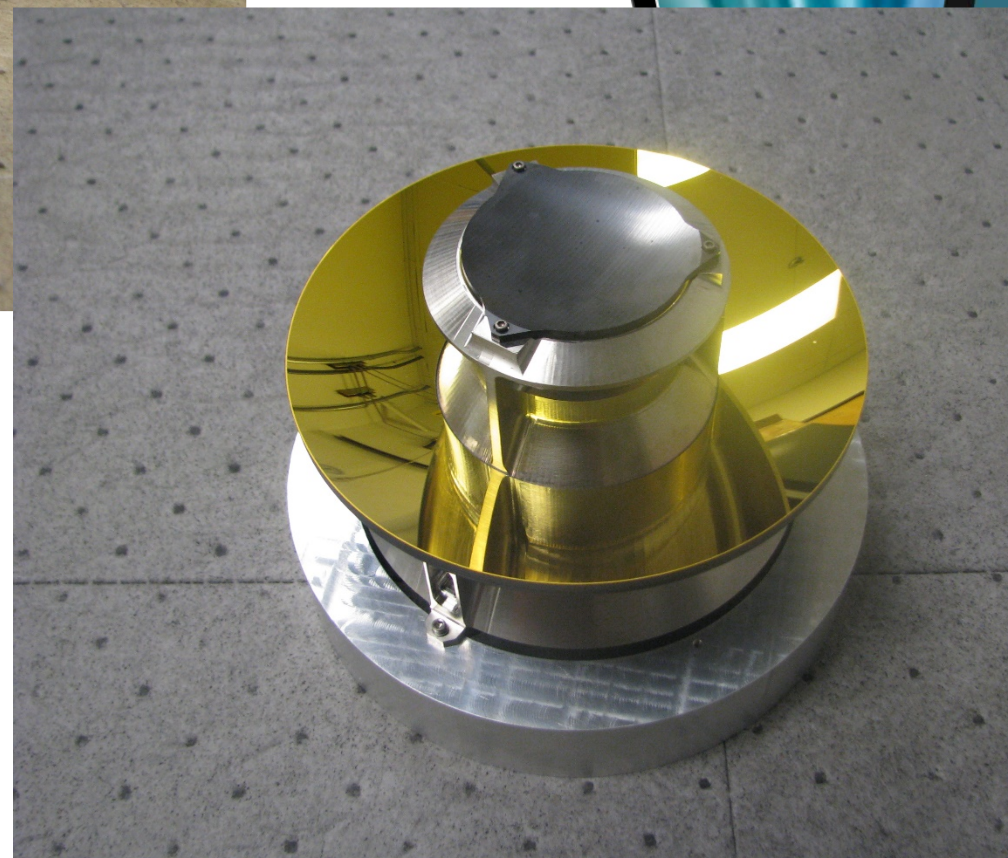

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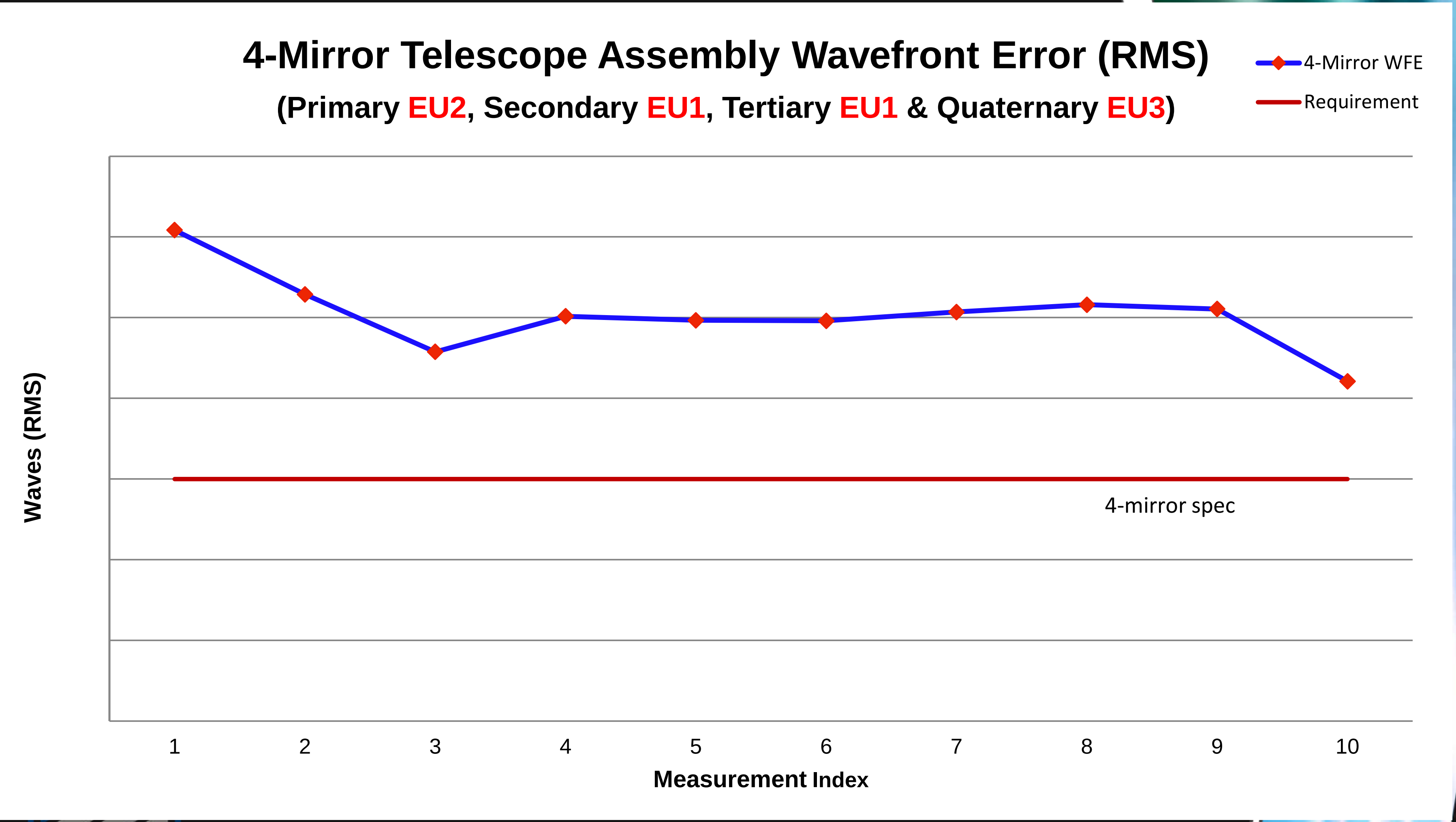
4-Mirror Assembly – Optical Test



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Lessons Learned

Primary Mirror Lessons Learned

- Tight tolerances dictate integrated fine grinding and optical polishing in lieu of the traditional sequential approach
- Some print tolerancing exceeded metrological capabilities of most fabricators
- EU 4 is high aspect ratio CVC SiC mirror
- Bonding surface preparation/cleanliness is more critical than our previous studies have shown
- Design rules (component level and mounting/assembly) used for Be do not necessarily apply to CVC SiC™
- Development of custom CVC SiC design rules developed and would greatly improve performance
- FEA Models fit measured data very well

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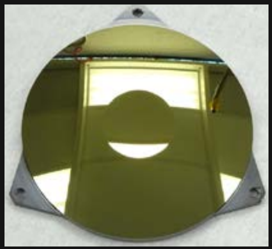
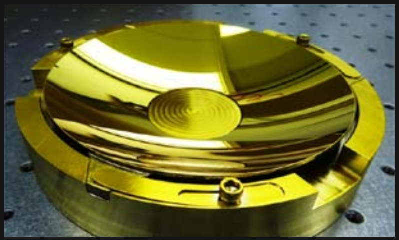
Milestone Summary

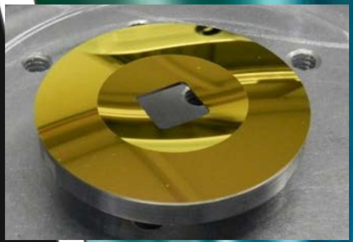
Primary Mirror
Met optical specifications
Superior thermal stability
Superior stiffness
Potential 25% wt reduction



Secondary Mirror
Met optical spec.
Superior Thermal
Superior Stiffness

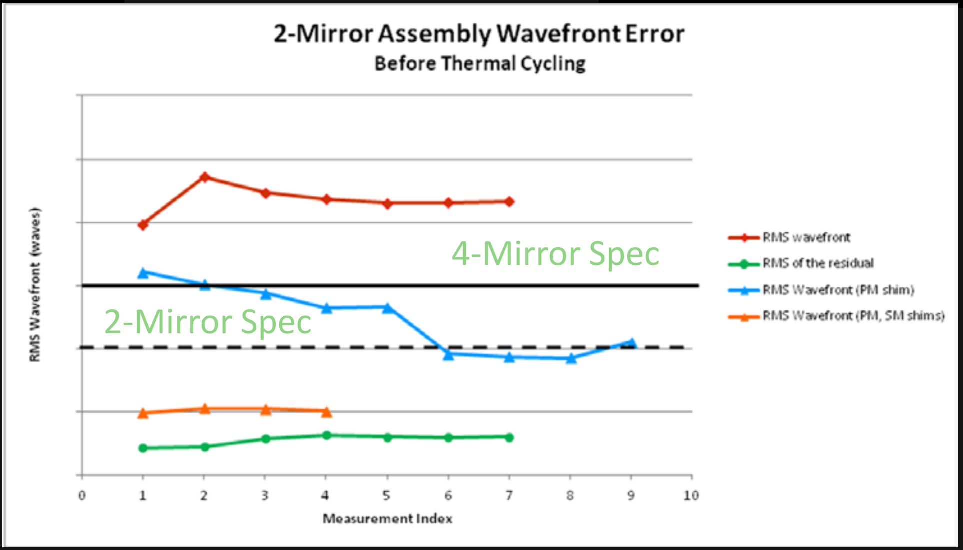


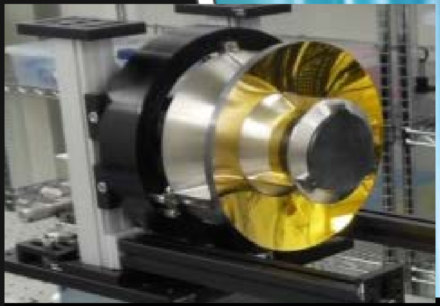
Tertiary Mirror
Slightly Off-specification
Superior Thermal
Superior Stiffness
Potential 23% Wt Reduction



Quaternary Mirror
Met Optical Specs.
Superior Thermal
Superior Stiffness

Invar Warm Stop
Meets drawing





2-Mirror Telescope
With minor adjustments
exceeds projected 2-mirror
Wave-front requirement.

Substantially Along the Learning Curve. Optimization Will Achieve a Superior Telescope and Capability.

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Summary and Path Forward

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Mirrors Optimized after Lessons Learned

Mirror	Mass	Surface Figure (λ)	Surface Figure (λ)	Surface Figure (λ)	Surface Roughness (Å rms)	f1	f2	f3
Primary Be	0.964 1.000	~0.95 1.00	~0.15 0.20	~0.07 0.10	< 50 N/A	2267 1953		
Secondary Be	~1.333 1.000	~0.6 1.00	~0.10 0.20	~0.05 0.10	< 50 55	6051 5094	7519 6716	7522 6719
Tertiary Be	~0.947 1.000	~1.00 1.00	~0.15 0.20	~0.10 0.10	< 40 55	5181 2526	5270 3050	5271 3052
Quaternary Be	~1.000 1.000	0.80 1.00	0.15 0.20	0.05 0.10	< 40 55	38505 17737	38683 17826	42720 23106
Total Be	~0.989 1.000	All in spec	All in spec	All in spec	All in spec	All in spec	All in spec	All in spec

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Path Forward & Next Steps

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Next Steps

- Modify mirror designs slightly for optimized CVC SiC and our production process
  - Goal hard mounted, bolt together design
  - Tertiary mirror especially
- Determine Optimum Warm Shield Structure
  - CVC SiC, SiC, HoneySiC, Other or composite design
  - Stray light control task especially
- Build and test insertable design prototype using manufacturing process and supply chain
- Review results
- Build XXXX units as needed
- Apply processing and design lessons learned to other DoD and Commercial telescopes

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Seeker Telescope Program Analysis

	Beryllium	CVC SiC®
Cost for 1x w/o detector	???	Target Price: ~0.9x or less
Lead Time for 1x	???	16-20 weeks typical
Cost for 100x w/o detector	???	TBD, but less
Lead time for 100x	???	Incremental 1-2 weeks
Weight of Telescope	1.00	1.00 or lower (~0.8)
Rad Hard	No	Yes
Optical Specs	All Met	All Met
Mechanical Integrity		Improved
Harmonic Resonances		Increased
Current Capacity (#/yr)	??????	>1,700
Total Capacity	??????	Virtually unlimited

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