MDA and AFRL Silicon Carbide Mirror Applications

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SBIR Activities

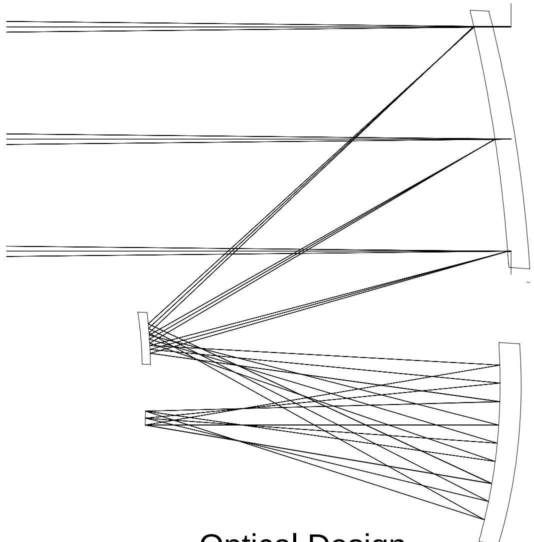
- Silicon Carbide Steering Mirrors for High Energy Laser Applications
  – AFRL Contract#F33615-03-M-5221
  – COTR: Dr. Lawrence Matson AFRL/MLLN
- Advanced Silicon Carbide Seeker
  – MDA Contract #DASG60-03-P-0296
  – COTR: Adam Aberle
- GEO Silicon Carbide Telescope for Full Earth Viewing
  – Contract #F29601-03-M-0288
  – COTR: Dr. Brett deBlonk AFRL/VSSV
- Technologies for Fine Steering Mirror Systems in Space Based Optical Systems
  – AFRLContract #FA9453-04-C-0031
  – COTR: Dr. Brett deBlonk AFRL/VSSV
- SiC All reflective Telescope Supporting Spiral Upgrades for Emerging Kill Vehicle Architectures to Counter Future Ballistic Missile Threats
  – Contract #NOO178-04-C-3079
  – TOPC: Dr. Bob Kessel (NRL)

Advanced Seeker

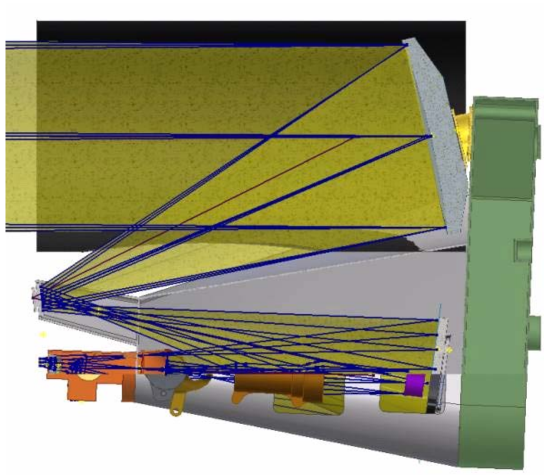
- MDA Contract #DASG60-03-P-0296 (Phase 1)
- COTR: Adam Aberle, U.S. Army Space and Missile Defense Command
- Objective
  - Evaluate technologies such as SiC and advanced fabrication techniques to improve the producibility of next generation exo-atmoshperic seekers
- Process
  - Define requirements for likely next generation seekers
    - Multi-band passive sensors
    - Active LADAR
  - Define a preliminary design concept
    - 3 mirror off axis TMA
    - **Common M1 & M3 optical axis for ease of producibility**
  - Define a opto-mechanical concept
    - Reaction Bonded (cast) SiC mirrors and structures

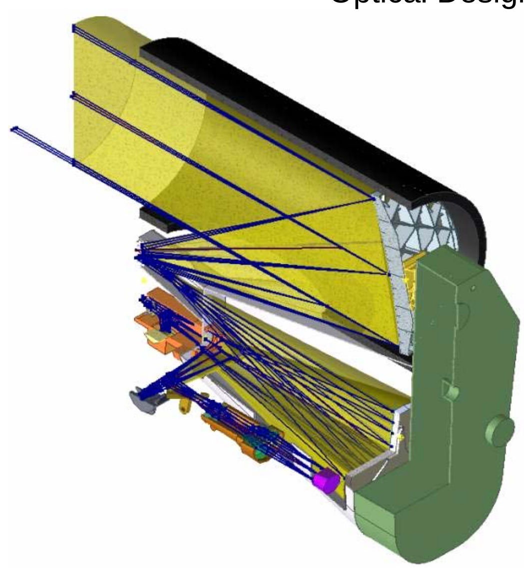
Next Generation SiC Seeker Design Concept

- Design form is a Three Mirror Anastigmat (M1 ellipsoid, M2 hyperboloid, M3 ellipsoid).
- M1 and M3 share the same optical axis (but not same vertex).
- TMA is well corrected over the FOV.
  - LADAR performance requirements drive TMA performance.
  - Final form factor is a balance among design level performance, component sensitivities (wavefront and line of sight), and envelope considerations.



Optical Design





Opto-mechanical Design Concept

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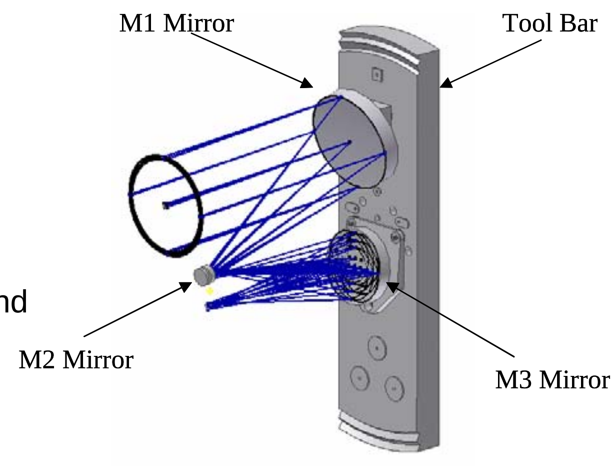
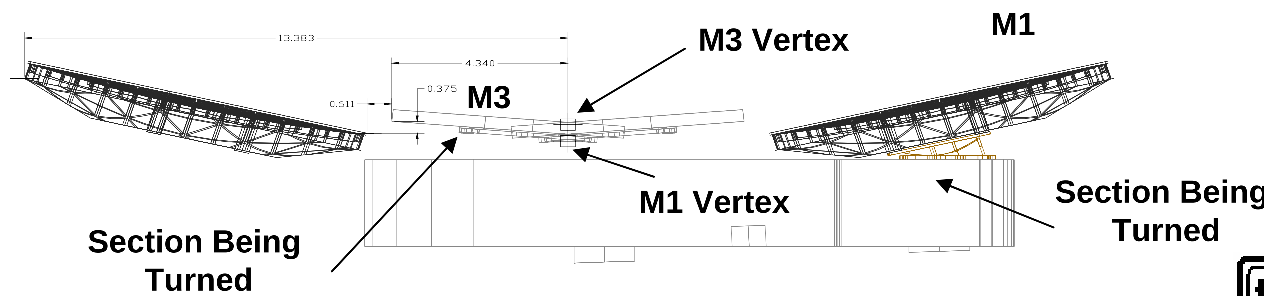
Production Features of the Common Axis Design

- **Common axis optical design**
  - Motivated by desire to minimize alignment time.
  - This goal was driven by schedule needs of a production system.
- **Common axis of M1 and M3**
  - Allows diamond turning of both elements on a single toolbar.
    - The spacing between the elements as well as the difference in the vertex heights is set in a single diamond turning setup.
- **Single mounting plane for M1 and M3**
  - M1 and M3 will be mounted to a single flat plane both on toolbar and bulkhead.
    - Coplanar mounting surfaces of M1 and M3 by straightforward lapping.
    - The usual wedges for M1 and M3 will be incorporated into the elements.
- **Advantages for alignment to bulkhead**
  - Simple transfer of M1 and M3 from planar toolbar to planar bulkhead via a drill template.
  - Additional lapped surfaces normal to the M1/M3 axis





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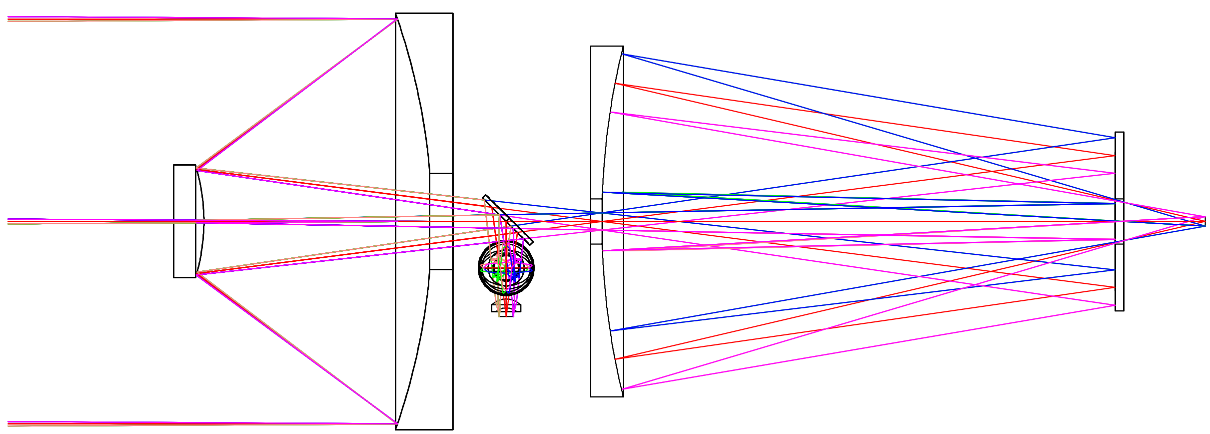
SiC Seekers for Rapid Construction/Upgrade

- SiC All Reflective Telescope Supporting Spiral Upgrades for Emerging Kill Vehicle Architectures to Counter Future Ballistic Missile Threats
  – Contract #NOO178-04-C-3079 (Phase 1)
  – TOPC: Dr. Bob Kessel (NRL)
- Objective: Develop optical architecture for advanced seekers used in kinetic kill vehicles which combines the advantages of SSGPO's low cost cast SiC optical telescope technologies with design forms that allow instrument upgrades and improvements with minimal re-engineering
  – Design of visible space telescope for next generation tactical seekers (EKV, KEI)
    - Symmetric design form
      – Leverages precision machining techniques for ease of manufacture
      – Minimal effort required for applying new capability
  – Investigate manufacturing methods for "snap together" visible quality construction



Baseline Optical Design Concept

Silicon Carbide Optics for UV/EUV Applications

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SSG SiC UV/EUV Optics Activities

- High Quality, Low Scatter, SiC Optics Suitable for Space-based UV and EUV Applications-Phase 2 SBIR
  - NASA Contract #NNG04CA15C
  - COTR: Dr. Dave Content NASA-GSFC
- Superpolished Silicon Coated SiC Optics for Rapid Manufacture of Large Aperture UV and EUV Telescopes-Phase 1 SBIR
  - NASA Contract #NNG04CA64C
  - COTR: Dr. Dave Content/Dr. Peter Blake NASA-GSFC
- Single Crystal Silicon Asphere for Argonne National Labs Synchrotron Source

High Quality, Low Scatter, SiC Optics Suitable for Space-based UV and EUV Applications

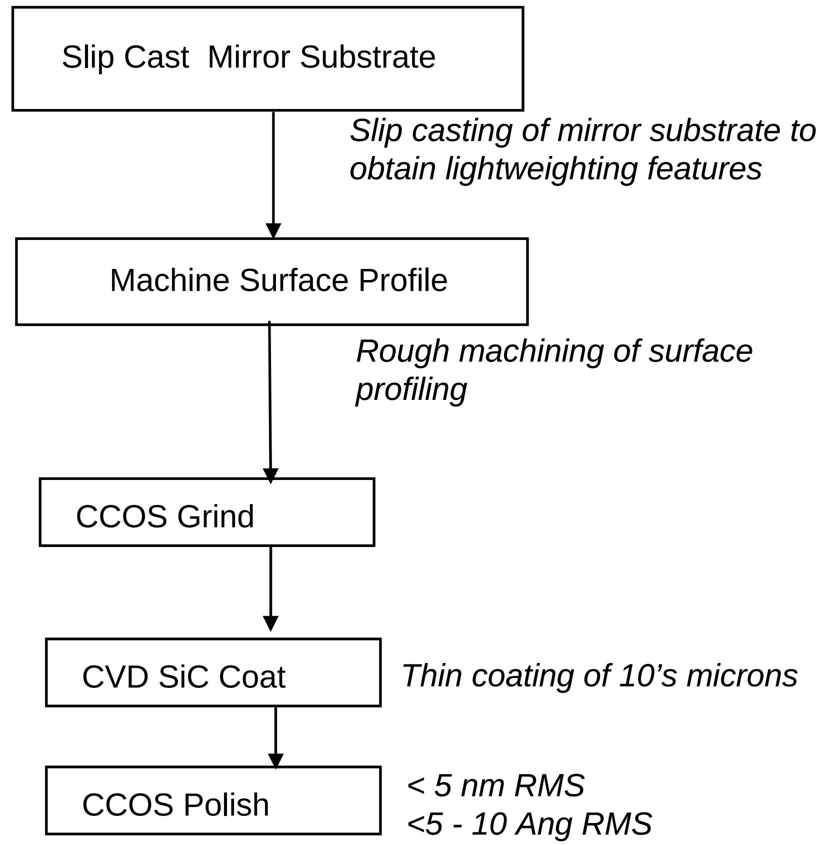
- Phase 1 Objective: Develop Computer Controlled Optical Surfacing techniques for creating CVD SiC coated RB SiC EUV quality optics
  - Two 4.5" diameter RB SiC concave spheres coated with thin layer of sputtered CVD SiC
  - 10 angstrom RMS micro-roughness achieved using CCOS process.

- Phase 2 Objective: Apply CCOS process to CVD SiC coated RB SiC lightweight mirror for coronographic mission
  - CCOS optimization underway
    - Goal of micro-roughness < 5 angstroms RMS using CCOS
    - Sample demonstration on CVD SiC flats
    - 3.5 angstroms RMS achieved thus far

  - Mirror design underway for SHARPI secondary
    - Baseline Material: RB SiC with thin CVD SiC coating
    - Construction: Open back, rib supported
    - Areal Density: 15.9 kg/m^2
    - Optical Surface Requirements
      - Figure: 3 nm RMS
      - Mid-frequency: 1.7 nm RMS
      - Micro-roughness: 1.0 nm RMS

Manufacturing Process Flow for CVD clad SiC EUV Aspheric Optics

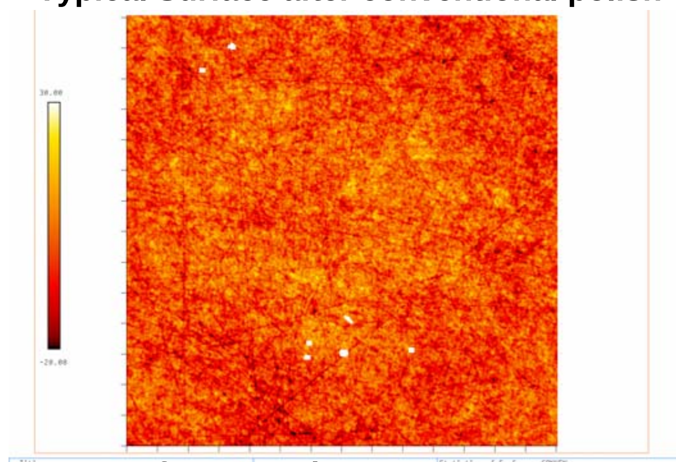
- Novel, manufacturing process for SiC optics for EUV applications
  - CVD clad RB SiC optics have been demonstrated to provide surface finishes suitable for EUV applications
  - CVD SiC materials have been demonstrated to provide excellent EUV reflectivities
  - Tinsley's CCOS process has demonstrated to provide surface figures/finishes which are consistent with stressing EUV optical requirements
    - CCOS process suitable for SiC materials



Phase 2 Process Development Results

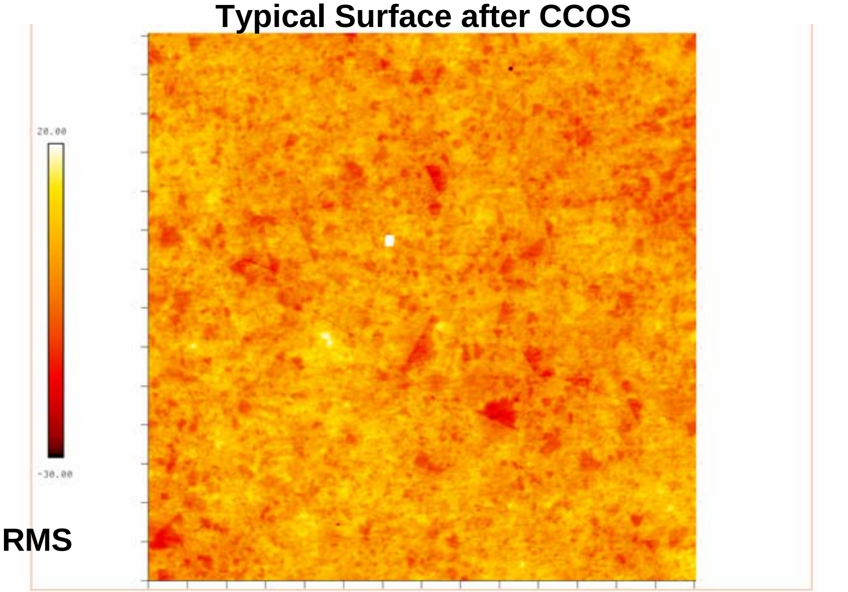
- Series of 6” x 6” CVD SiC flats processed using CCOS sub-aperture tools.
  - RMS measurements taken with Phase Measuring Microscope with 10x objective over 1.41x 1.41 mm^2 area.
  - Average of 5 locations on mirror, with 4 interferograms averaged at each location.
  - The abberations from the microscope cavity were removed.
- 3.38 angstroms RMS achieved
- CCOS shown effective at removing pits and scratches

Typical Surface after conventional polish



Surface Roughness = 6.1A RMS

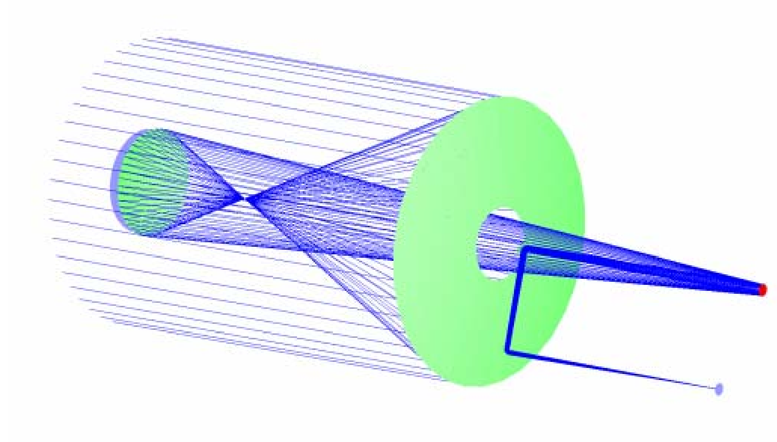
Typical Surface after CCOS



Surface Roughness = 4.5A RMS

Phase 2 Demonstration Mirror
SHARPI Secondary Mirror

Material	RB SiC, thin sputtered CVD SiC coating
Construction	Rib supported lightweight design
Clear aperture	200 mm
Edge thickness	~ 20 mm
Faceplate thickness	~2.0 mm –3.0 mm
Vertex Radius	437.1959 mm
Conic Constant	-0.5445 (ellipsoid)
Global surface figure	3 nm RMS
Micro-roughness (spatial periods 1 μm 1mm)	1.0 nm RMS
Mid-frequency roughness (spatial periods 1 10 mm)	1.7 nm RMS
Areal density	10 – 20 kg m ^{2}



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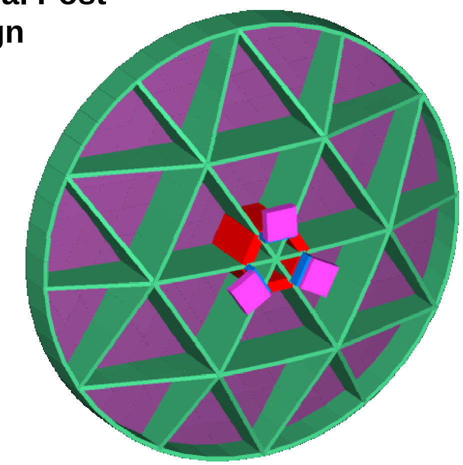
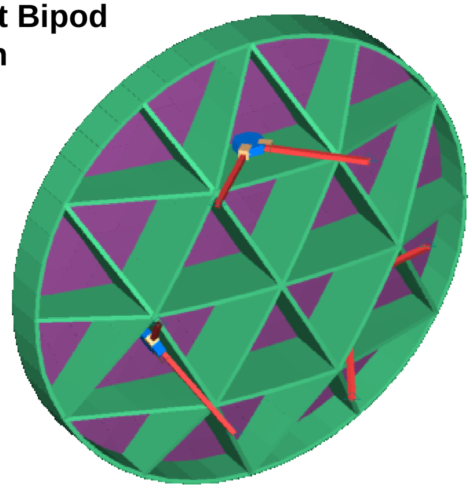
SiC Secondary Mirror Design Study

- Two Open Back Designs being investigated for UV/EUV M2 Design
  - Material: mirror: SiC, mount: Invar
  - Mirror Height = 30.48mm (center); 20.32mm (edge)
  - Face Sheet Thickness = 2.03mm
  - Rib Thickness = 2.03mm
  - Diameter of Inscribed Circle = 33.73mm
  - Bipods: 44.45mm x 2.286mm x 2.286mm; 45 deg angle
  - Areal Density: 15.9 kg/m^2 (segment only)

Central Post Design



3 Point Bipod Design



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UV/EUV M2 Trade Study

UV/EUV M2 Surface Errors for Two Different Mirror Mount Types		
Load Case	Fit Tilt, nm rms	
	Central Post	Bipods
1G-X, Lateral	1.3	0.7
1G-Y, Lateral	1.3	0.7
1G-Z, Vertical	4.2	1.2
One Bipod Leg 0.001" Up	0.06	2.6
One Bipod Leg 0.001" Outward	144.8	1.5

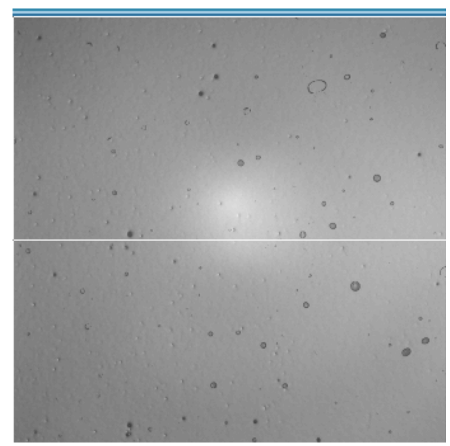
Significant Surface Error from movement of Central Post.

Bipod Mounting appears to be the best design solution

Superpolishing Silicon Coated SiC Optics for Rapid manufacture of Large Aperture UV and EUV Telescopes

- Objective: Develop CCOS superpolishing techniques for Si coated SiC UV and EUV Optics with a micro-roughness goal of <5 Angstroms RMS.

- Status
  - Series of SiC samples were generated and coated with a thin layer of amorphous Si (nominal thickness 50 microns).
    - 10 cm On-axis parabola
    - Various 2” and 3” flat samples
    - 5.9” diameter flat samples (pre-coat surface grind/polish and coated, but not polished)
  - Best local results between 5 and 7 angstroms RMS
    - Results were limited by defects in the Si layer
    - Improved uniformity in coating and substrate prep will be explored to address defects
  - Phase 2 submitted 7/19/04

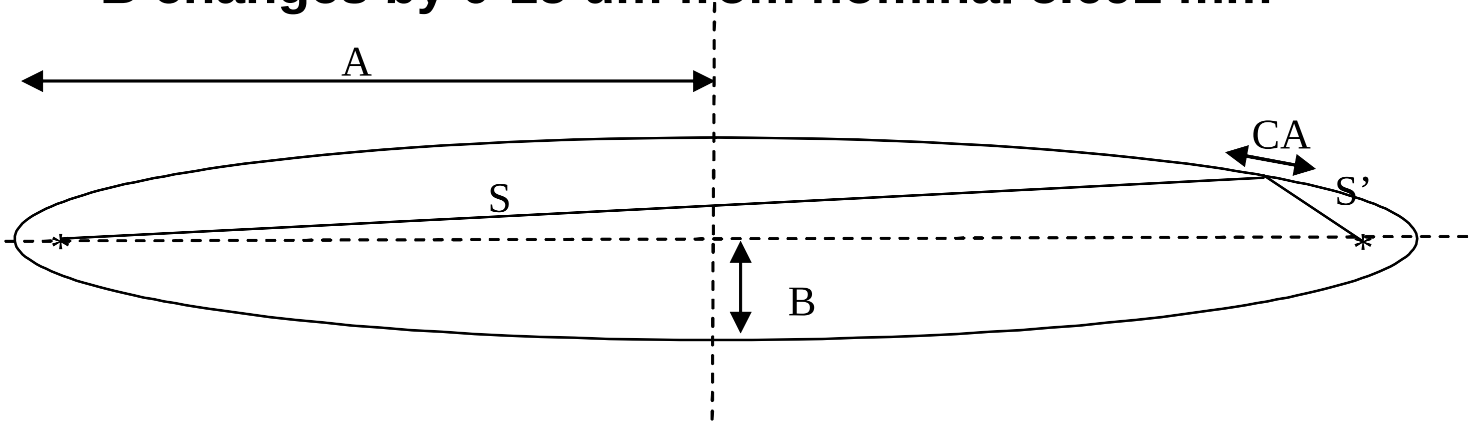


Typical Defects Observed in Si layer

Single Crystal Silicon Asphere for Argonne National Labs Synchrotron Source

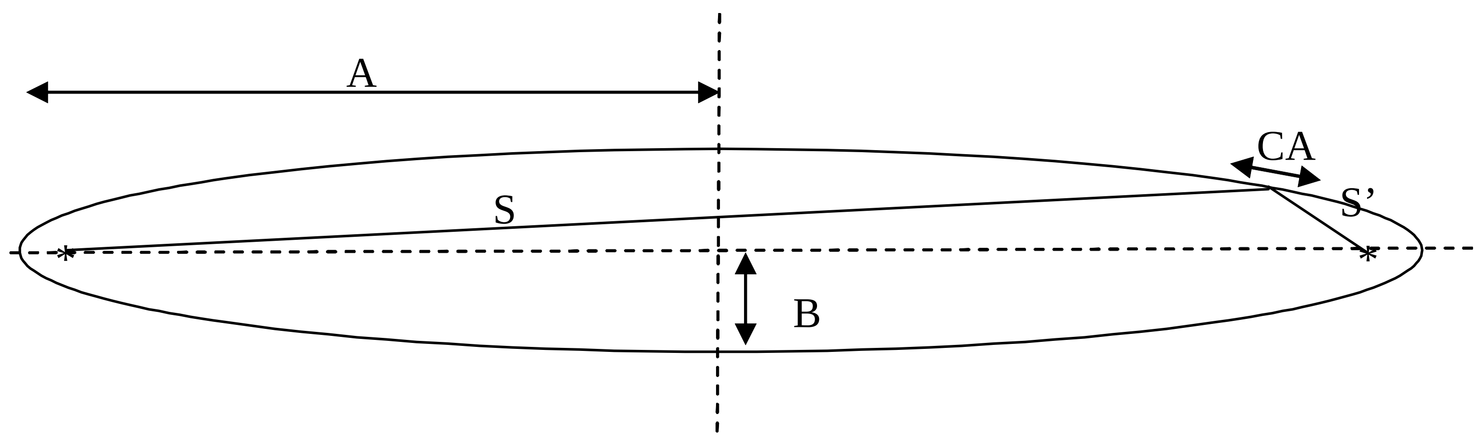
Argonne Test Method Description

- Test component as high quality spherical map
  - Use rotational shearing and high quality reference optic at same nominal radius as part to obtain very high accuracy in the test
- Remove S/W null map from spherical data
- Clip out sub-apertures (line scan of data at four heights)
- Optimize asphere to best value of “B” (A isn’t floated)
  - B changes by 0-15 um from nominal 5.692 mm



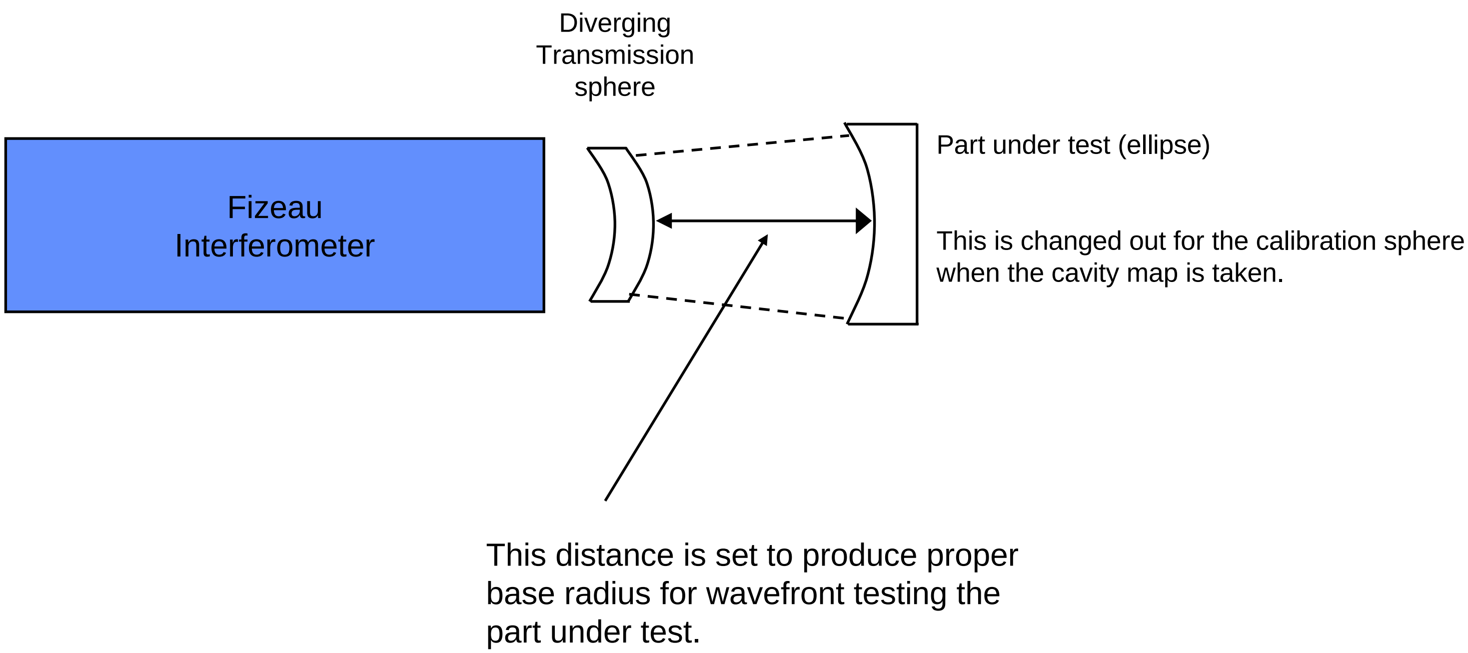
Ellipse Constraints

- Ellipse is polished as a sphere in the cross axis direction and as an ellipse in the long axis direction
- Aspect ratio of the ellipse must be long enough that aspheric departure is kept relatively low (few um)



Test Setup

- A reference sphere is used to map the transmission sphere cavity
- The ellipse is spaced relative to the transmission sphere to produce the proper base radius for the asphere



Data Results: Clear Aperture 1

- Tilt and focus are removed from this map
- Aperture is 16x38mm

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       y = mm
       z = nm
xspac: 0.2921
yspac: 0.2921
ngx  : 131
ngy  : 55
gxcen: 0
gycen: 37.97

z ptv: 4.119
z rms: 0.5916

x-apr: 37.97
y-apr: 15.77

z min:-2.417
  @ (131, 43)
z max: 1.703
  @ (122, 10)
z avg:-2.311e-005

ndata: 7205

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theta: 90.0000
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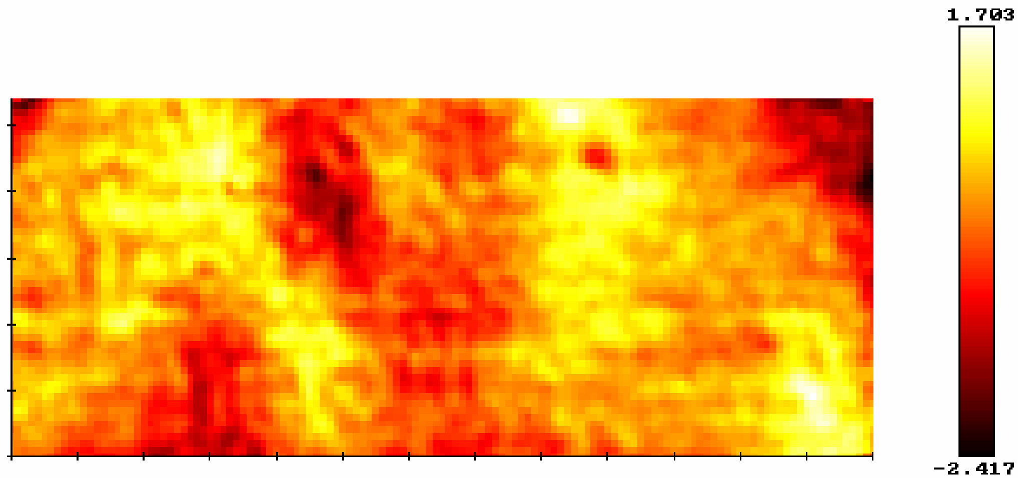

Surface accuracy: 0.59 nm RMS

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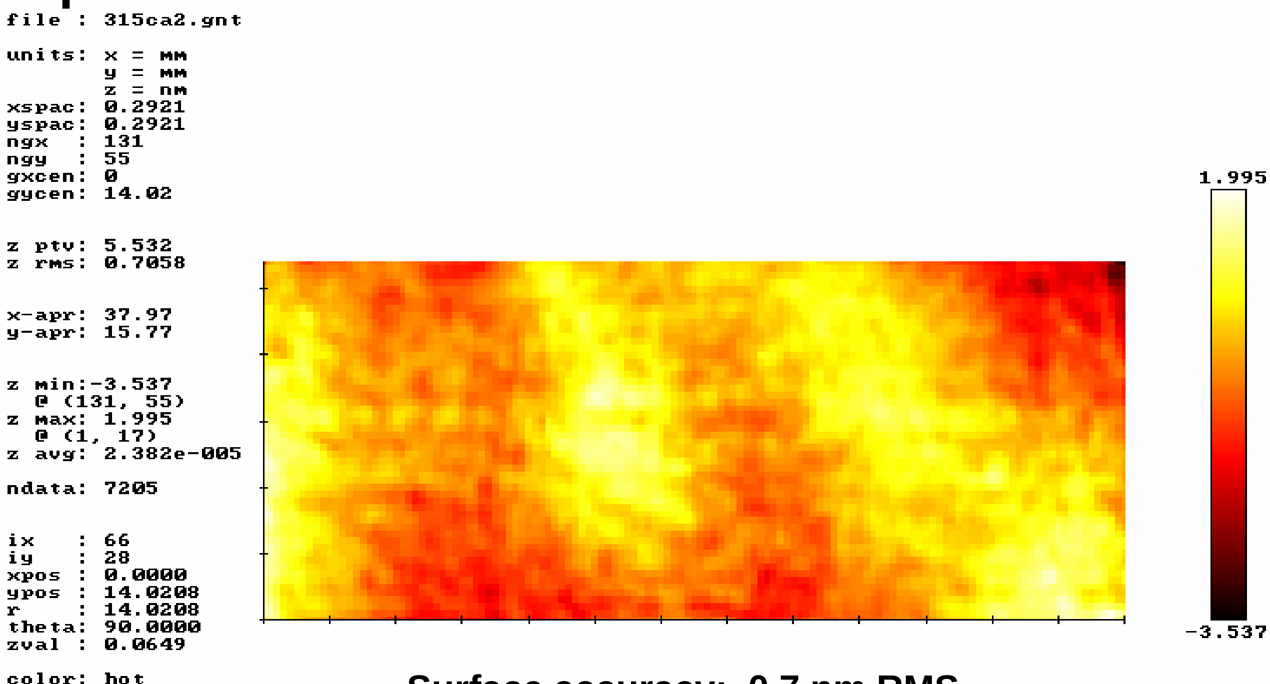
Data Results: Clear Aperture 2

- Tilt and focus are removed from this map
- Aperture is 16x38mm



Surface accuracy: 0.7 nm RMS

Data Results: Typical Surface Roughness
Single Crystal Silicon

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       y = mm
       z = nm
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yspac: 0.001381
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ngy  : 1022
gxcen: 0
gycen: 0

z ptv: 5.775
z rms: 0.2879

x-apr: 1.41
y-apr: 1.41

z min:-3.016
  @ (3, 334)
z max: 2.759
  @ (761, 601)
z avg: 0.0003548

ndata: 1041416

ix   : 511
iy   : 512
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r    : 0.0010
theta: 44.9995
zval : -0.0342

color: hot
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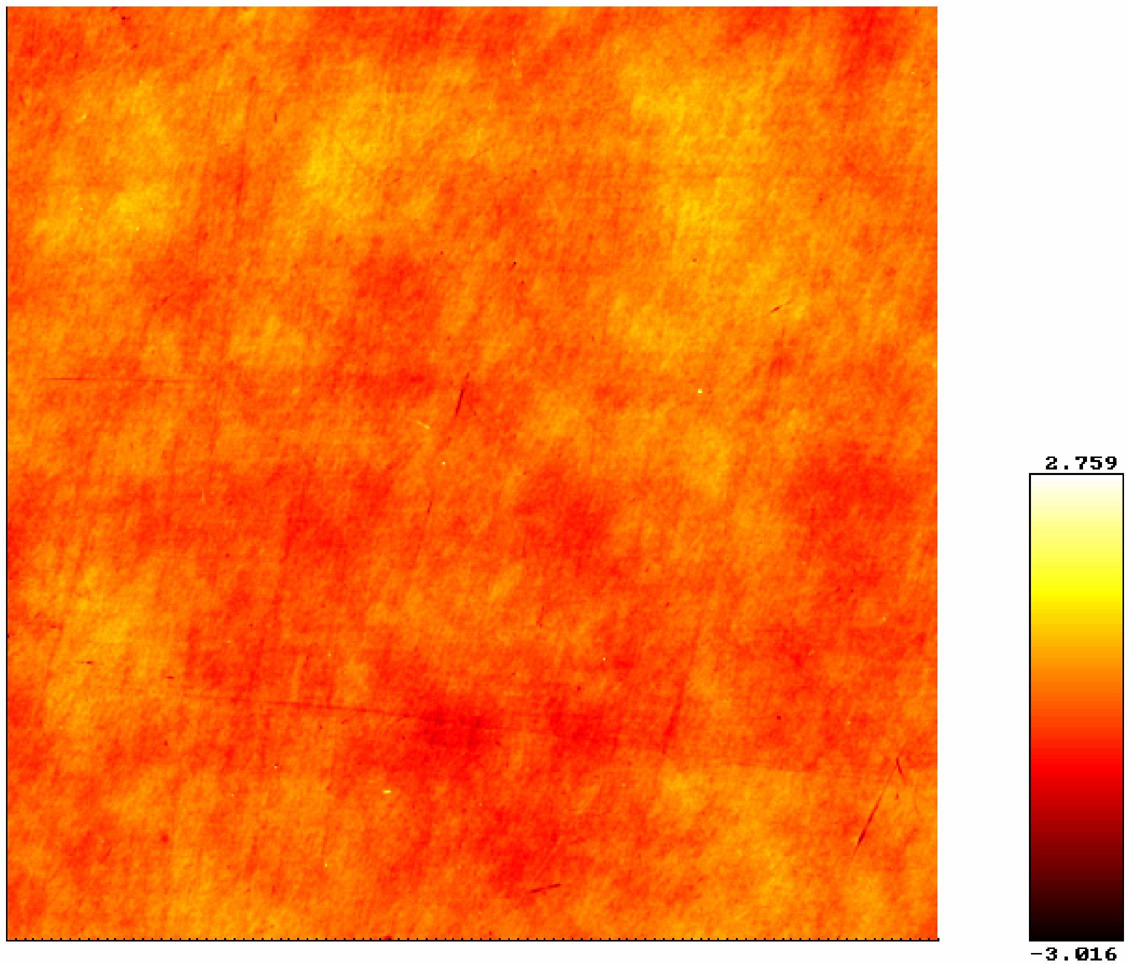

Micro-roughness: 2.88 angstroms RMS

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JRS Phase 1 ABL FSM 040213

Summary

- Combination of SiC bulk material properties, and near net shape forming techniques make SSG's SiC an excellent optical material for lightweight, stiff space-based optical systems
- Application of Tinsley's CCOS process to SiC and single crystal Silicon optics enables EUV level aspheric optics
- CCOS results have been demonstrated in a number of different forms
  - CVD SiC (3.38 angstroms RMS micro-roughness)
    - Use of CVD SiC thin coating on SSG SiC demonstrated on flat with 1.5 nm RMS surface error
  - Si coated SiC (5 to 7 angstroms RMS demonstrated in Phase 1 SBIR)
    - Results limited by coating defects
      - Improved coating uniformity and surface prep avenues to <5 angstroms
  - Single crystal Silicon
    - <0.7 nm RMS surface error
    - 2.88 angstroms RMS micro-roughness
- Successful completion of SBIR efforts will lead to demonstration of lightweight (~16 kg/m^2) SiC aspheres for space-based EUV telescopes