Lightweight Optical Systems (LWOS)

SLMS™ and LASIT™ for Be Replacement
AFRL/MLLN F33615-03-M-5222
AFRL/VSSV FA9453-03-C-0223
AFRL/SNJM F33615-03-C-1450

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- Missile Defense Agency (MDA/MP)
  - ⇒ Doug Schaefer, Steve LeClair, Al Lange
- Other Anonymous Individuals

- **THANK YOU!!!**

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Outline

- What is SLMS™?
- Manufacturing Process
- Comparison with Beryllium
- Lightweight Athermal Silicon Innovative Telescope for Airborne Laser Relay Mirrors
- High Structural Efficiency Silicon Lightweight Mirror Systems (SLMS™)
- Common Aperture for EO and RF Communications
- Summary

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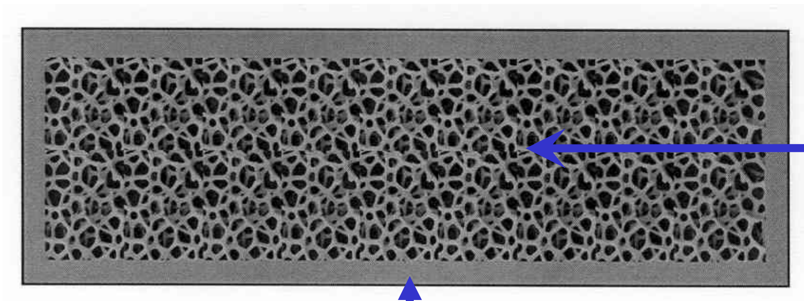
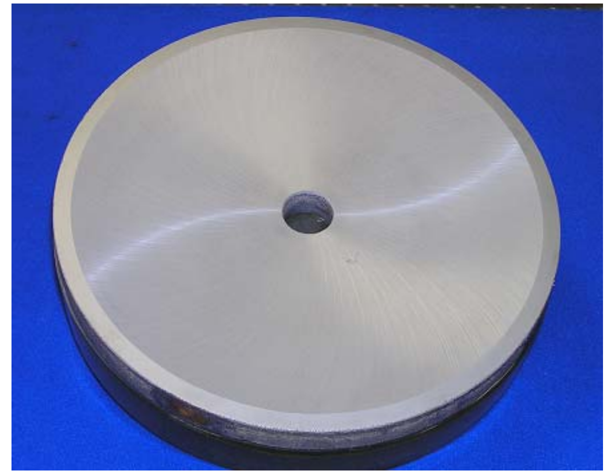
Silicon & Silicon Carbide Lightweight Mirror Systems
SLMS™ & SiC-SLMS™

- Foam Core Optics with a Continuous Shell

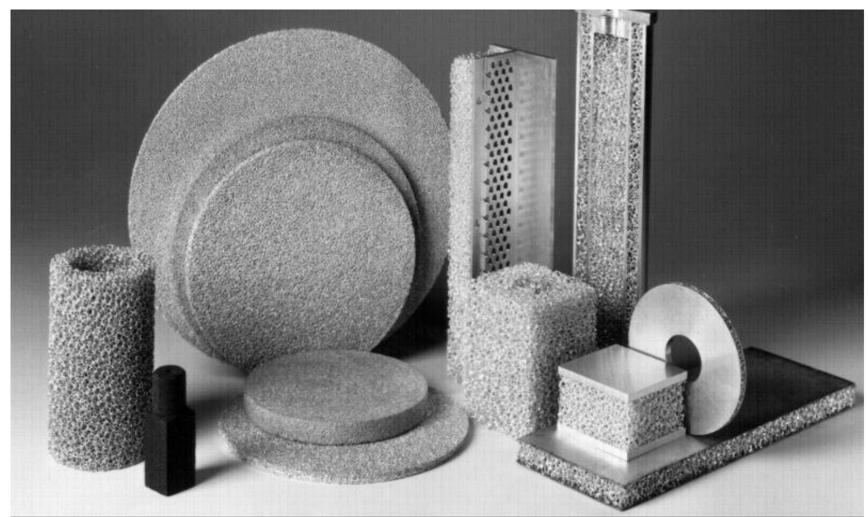


Silicon
or
Silicon Carbide
Foam



Polycrystalline Silicon or Beta-Silicon Carbide
Closeout 0.25-1.27 mm typical (0.01-0.05 inch)

- Foam is Open-Cell, 70-95% Porosity
- Pore Size: 0.40 - 4.0 per mm (10-100 per inch)
- 1500-2000 ft^2 surface area/ft^3
- CNC machined to virtually any shape to ± 50 μm (0.002 inch)



Design Flexibility with Large Manufacturing Basis

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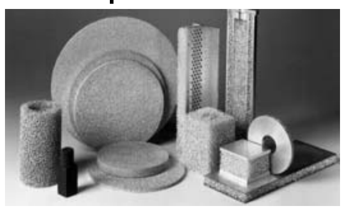
SLMS™ Manufacturing Process

Task: Optical and Mechanical Design

Task: Generate RVC Raw Material – Visual Inspect
Net Shape Machine – Visual Inspect
Infiltrate Foam – Confirm density
Close-Out Foam – Visual and Weight

RVC Foam

Net Shape Si or SiC Foam



SiC clad SiC Foam

Silicon Encapsulated

Task: Visual, Dimensional, Hermetic Inspections

Task: Rough Grind to Near Net

Task: Fine Grind or SPDT

Task: Addition of Cladding for Specific Applications

Optional

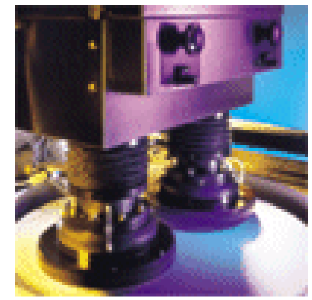
Task: Hermetic, Acoustic Inspect

Task: Polish

Task: Coat

Task: Metrology

Deliver



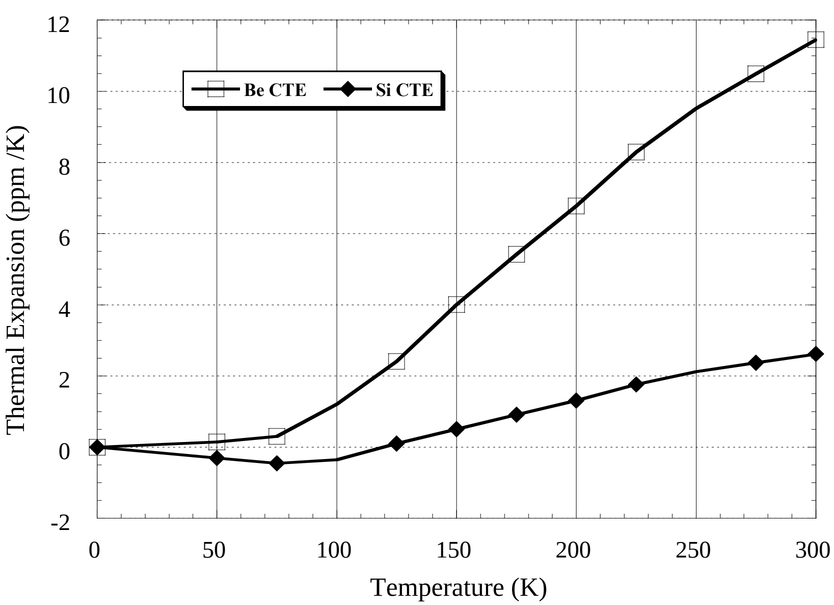
Silicon Lightweight Mirrors
SLMS
Athermal Technology for Cryogenic and HEL Applications

Cost Less Than Beryllium – Polishes Like Glass – ISO9001 Processes

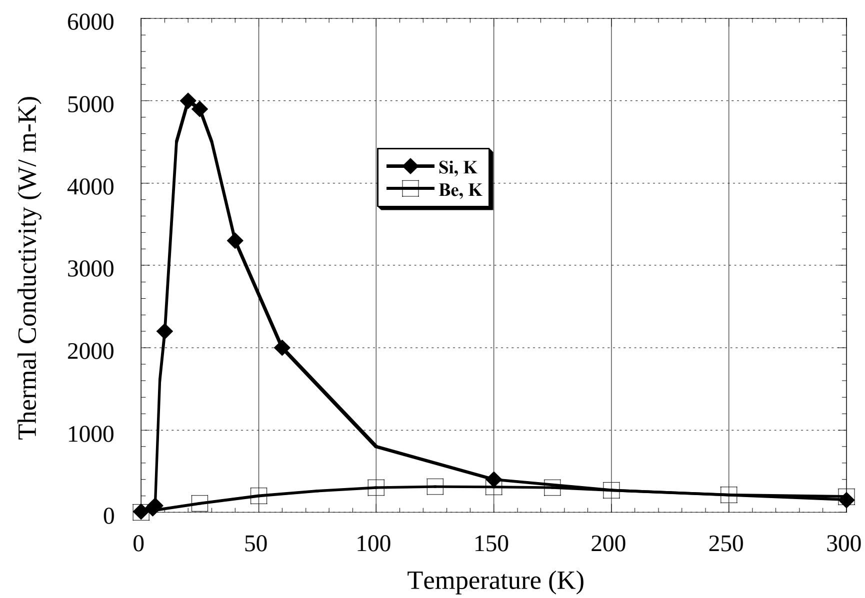
Silicon vs Beryllium – Thermal Comparison

	ρ	E	E/ρ	σ_t	σ_t/ρ	α	k	C_p	$D=k/\rho C_p$	α/k	α/D	ν
Room Temperature Property:	**Density**	**Young's Modulus**	**Specific Stiffness**	**Tensile Strength**	**Specific Strength**	**Thermal Expansion**	**Thermal Conductivity**	**Specific Heat**	**Thermal Diffusivity**	**Steady State Distortion**	**Transient Distortion**	**Poisson's Ratio**
Units:	kg/m^3	GPa	$MPa\text{-}m^3/kg$	Mpa	$MPa\text{-}m^3/kg$	$10^{-6}/K$	W/m-K	j/kg-K	$10^{-6}/m^2/s$	μm/W	$s/m^2\text{-}K$	arbitrary
Preferred Value:	**Small**	**Large**	**Large**	**Large**	**Large**	**Small**	**Large**	**Large**	**Large**	**Small**	**Small**	
Beryllium:I-70	1850	287	155	237	0.13	11.3	216	1920	60.81	0.05	0.19	0.25
Silicon SLMS™ Skin	2330	130	56	120	0.05	2.5	148	750	84.69	0.02	0.03	0.24
Beta-SiC-SLMS™ Skin	3210	465	145	470	0.15	2.2	300	640	146.03	0.01	0.02	0.21

Linear Coefficient of Thermal Expansion for Silicon and Beryllium

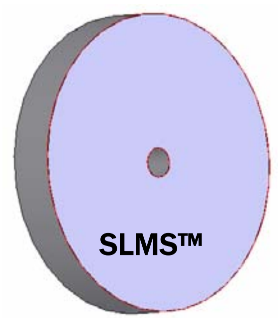


Thermal Conductivity of Silicon and Beryllium



Si has superior thermal performance than Be with similar Structural Properties

Structural Efficiency Comparison



Mirror	1st frequency (kHz)	Mass (kg)	Areal Density (kg/m^2)
ULE	1.76	0.98	16.1
Zerodur	1.93	1.12	18.4
Beryllium	3.98	0.81	13.3
SLMS, design A	3.98	0.75	12.3
SLMS, design B	4.29	0.81	13.3
SiCSLMS	5.24	0.81	13.3

- **SLMS™ same 1st Frequency as Be, at 93% the weight of Be**
- **SLMS™ same weight as Be, at 108% 1st Frequency**
- **SiC-SLMS™ same weight as Be at 131% 1st Frequency**

Stiffer than Be at Same Mass; Lighter at Same Stiffness

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Lightweight Athermal SLMS Innovative Telescope (LASIT™) for Airborne Laser Relay Mirrors

AFRL/MLLN F33615-03-M-5222

Dr. Larry Matson

Phase I Accomplishments

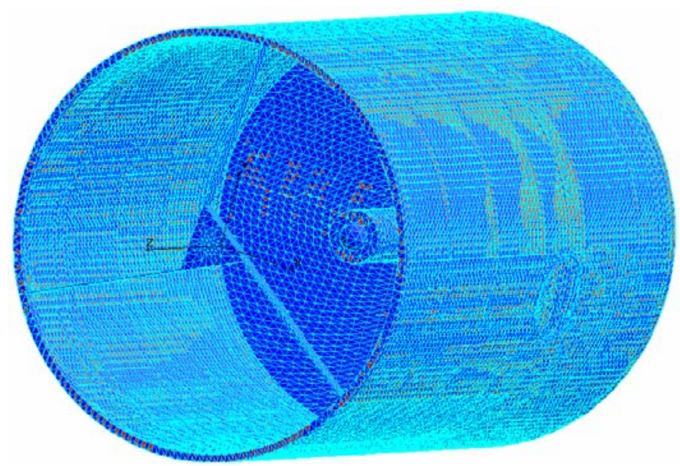
- Air Force Interest: Optical Systems with high strength, high stiffness, capable of operating with geometric stability under varying thermal conditions
- Used Boeing supplied 75 cm aperture relay mirror telescope PDR Design
  - ⇒ Design and Requirements are Boeing Proprietary
  - ⇒ Incorporated gimbal interface for ARMS Test bed
  - ⇒ Interface allows Receiver or Transmitter modes
- Performed confirming optical engineering analysis using Zemax
- Generated lightweight, dimensionally stable design
  - ⇒ Schafer's Silicon Lightweight Mirror Systems (SLMS™) Technology
  - ⇒ Vanguard's OptiGraf™ for Structures
  - ⇒ Frequency, gravity sag, random vibration, ring-down and wave-front error analysis were performed
  - ⇒ Specification Control Drawings
- Phase II – BUILD IT!

Phase I Results
Exceeded All Requirements

- Total Weight = 105 pounds, >3X lighter than ARMS design
- First Fundamental Frequency = 115 Hz, Significantly Exceeds Requirement
- Wavefront Error Requirement
  - ⇒ We predict gravity sag of 4 microns for PM and SM – better than requirement
  - ⇒ Coude needs to be oversized by 27 microns to meet requirement
- +/- 1 micron position tolerance and +/- 1 arcsecond tilt capability
  - ⇒ Analysis shows 5 micron de-center of the primary and secondary mirrors allowable
  - ⇒ Analysis shows Primary-Secondary Mirror tilts of 0.003 degrees (10 arcsec) allowable

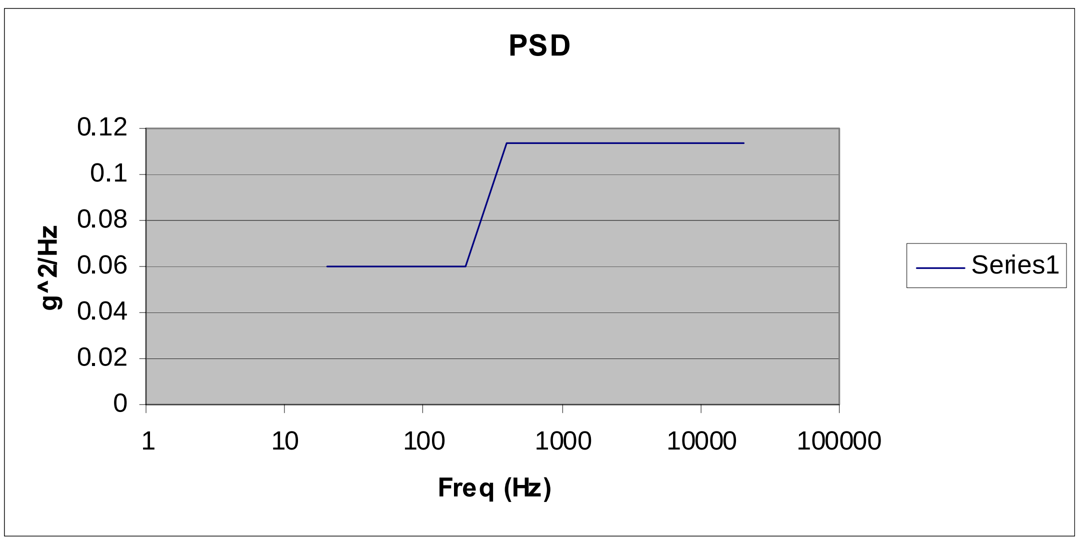
Random Vibration Results

- **Telescope Remains Stable for Specified PSD**



Model details

- **Four parts**
  - Primary SLMS™ closeout
  - Primary SLMS™ foam
  - Simulated secondary
  - OptiGraf structure
    -
    -
    - **2nd and 3rd mirror mounts**
    - **Simulated tertiary**
- **Elements:**
  - TETRA10
  - 270797 used
- **Nodes:**
  - 480076 used



Excitation Axis	Axis	Max(in)
Y-axis	X	1.412e-05
	Y	1.023e-04
	Z	1.047e-05
X-axis	X	1.273e-04
	Y	6.583e-05
	Z	1.302e-05
Z-axis	X	2.358e-05
	Y	3.347e-05
	Z	5.327e-05

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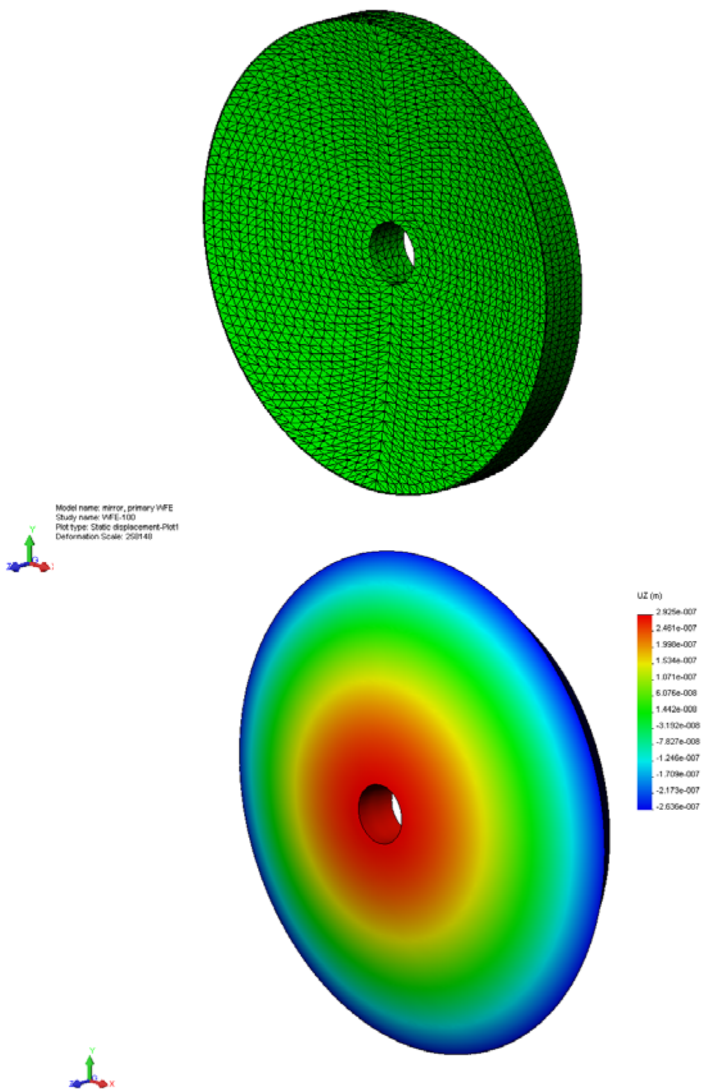
Thermal Distortion

- **50 W Absorbed Power for 10 seconds – Almost Negligible WFE**



Units of cm

Coefficient	
6.8E-08	Piston
-4.21E-09	x-tilt
1.8E-09	y-tilt
6.46E-10	x-astigmatism
-2.73E-07	focus
-6.5E-11	y-astigmatism
3.32E-11	trefoil x
1.78E-11	coma x
-4.91E-11	coma y
-4.99E-11	trefoil y
3.12E-09	trefoil x
-5.3E-10	secondary x-astigmatism
-1.94E-09	primary spherical
-3.63E-11	secondary y-astigmatism

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High Structural Efficiency Silicon Lightweight Mirror Systems (SLMS™)

AFRL/VSSV FA9453-03-C-0223

Phase II Objectives

- Air Force Interest: Lightweight Telescopes for Be Replacement
- Silicon Lightweight Mirror Systems (SLMS™) provides the enabling technology for manufacturing lightweight, dimensionally stable optical subs-assemblies and instruments, such as a telescope
- Revised SOW: Off Axis Lightweight Athermal SLMS™ Innovative Telescope (LASIT™)

- **Technical Requirements**
  - ⇒ 30 cm clear aperture
  - ⇒ 2 degree full field of view
  - ⇒ Wavelength range of 1.3 microns – 1.7 microns
  - ⇒ Unobscured system
  - ⇒ Wavefront quality better than 0.07 waves at 1.3 micron wavelength
    - → Equivalent to Strehl ratio of 0.8
  - ⇒ Afocal, 6X-10X magnification
  - ⇒ Thermally stable
  - ⇒ Stray light suppression - point one degree from the sun while in geostationary orbit
  - ⇒ Instrument footprint less than 750mm X 750mm X 750mm

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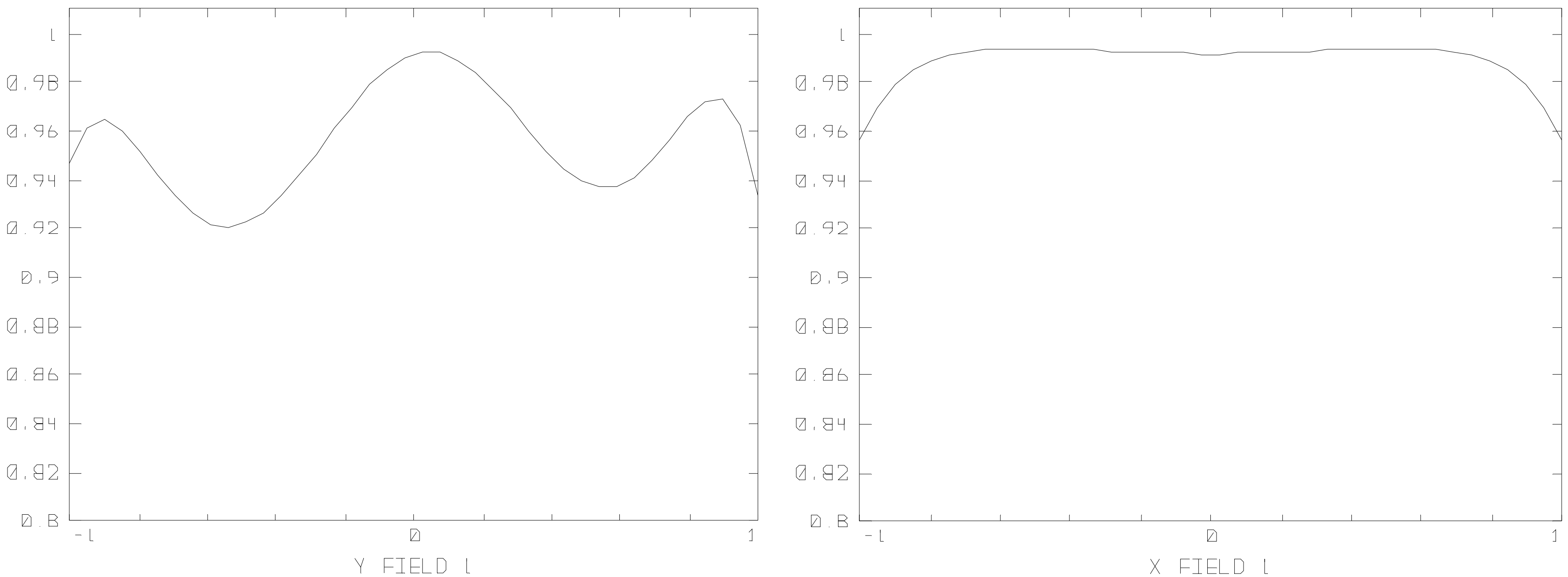
Design Tasks Performed

- Most Results are Proprietary and Competition Sensitive, Tell What We Can

- Optical Design – Proprietary - Reduced Physical Envelope by Factor of 4
- Coating Design – Designed Broadband MLDC, Commercial Off-The-Shelf Design Meets Requirements
- Mechanical Design – Proprietary - Mechanical Alignment Procedure
- Telescope Alignment – Proprietary Procedure

Optical Design

- 10X magnification
- All mirrors are off-axis sections of aspheric parent shapes
- Design capable of meeting stray light suppression requirement



Strehl ratio vs. Y field of view, in degrees

Strehl ratio vs. X field of view, in degrees

Exceeds Strehl Ratio Requirement of 0.8 by 20%

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Mechanical Design Tolerances

- Performed Monte Carlo Analysis
- Used Tight, But Achievable Tolerances
  - +/- 1 micron position and +/- 1 arcsecond tilt

Comment	Nominal	Min	Max
Axial position, secondary mirror, in mm	-527.034	-0.001	0.001
x tilt, secondary mirror, in degrees	-3.47082	-0.0003	0.0003
y tilt, secondary mirror, in degrees	0	-0.0003	0.0003
y decenter, secondary mirror, in mm	6.479925	-0.001	0.001
x decenter, secondary mirror, in mm	0	-0.001	0.001
Axial position, tertiary mirror, in mm	365.7966	-0.001	0.001
x tilt, tertiary mirror, in degrees	-11.3302	-0.0003	0.0003
y tilt, tertiary mirror, in degrees	0	-0.0003	0.0003
y decenter, tertiary mirror, in mm	2.454083	-0.001	0.001
x decenter, tertiary mirror, in mm	0	-0.001	0.001
Surface figure error, primary mirror, in RMS waves HeNe	0	λ / 20	λ / 20
Surface figure error, secondary mirror, in RMS waves HeNe	0	λ / 20	λ / 20
Surface figure error, tertiary mirror, in RMS waves HeNe	0	λ / 20	λ / 20

Monte Carlo Analysis Results

- **We have 98% Confidence the As-Built Telescope will Exceed the Wavefront Error Requirement**

Number of systems simulated	1000
Nominal RMS wavefront @ 1.3 micron wavelength	0.04
Maximum RMS wavefront allowable	0.07
Best	0.043
Worst	0.068
Mean	0.049
Std. Dev.	0.00062
98% <=	0.063
90% <=	0.059
50% <=	0.048
10% <=	0.042
2% <=	0.041

98% confidence level wavefront error still well within spec

Schafer Manufacturing Considerations

- All three mirrors are moderate F# conics. No complicated surface prescriptions.
- Alignment and surface figure tolerances are well within current manufacturing limits.
- Schafer has successfully single point diamond turned (SPDT) on-axis aspheric SLMS™.
- First time for SPDT of off-axis SLMS™.
  - ⇒ Buying down risk with 1/2 –scale Pathfinder mirror

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CDR Completed, Telescope In Fabrication

- **Design is complete**

Technical Requirements

Requirement	Optical	Mechanical
⇒ 30 cm clear aperture	√	
⇒ 2 degree field of view	√	
⇒ Unobscured system	√	√
⇒ Wavefront quality better than 0.07 waves RMS at 1.3 microns wavelength **(exceeded)**	√	
⇒ Afocal, 6X - 10X magnification **(10X)**	√	
⇒ Thermally stable		√
⇒ Stray light suppression	√	
⇒ Instrument footprint less than 750 mm x 750 mm x 750 mm **(4X smaller volume)**	√	√

Telescope Weighs Only 8-15 Pounds!

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Common Aperture for EO and RF Communications

A Communications Hybrid Optical/RF Dish (CHORD™)

AFRL/SNJM F33615-03-C-1450

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Phase II Description

- Air Force Interest: investigate the feasibility of combining collection of radio frequency (RF) and electro-optic (EO) communications signals onto a single lightweight antenna
- Technical Requirements
  - ⇒ Deliver 50 cm diameter (5/12 scale model) RF/optical aperture antenna
  - ⇒ Antenna architecture feasibility analysis and trade studies
    - → Aperture subsystem
      - – Provide high precision surface for the laser link
      - – Provide low noise temperature and suppress sidelobes for the microwave link
    - → Up- and down-converter subsystems
    - → Digital processing requirements
    - → Beam control for tracking the satellite

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Phase II Accomplishments

- Performed Trade Study to Determine Optimal Antenna Architecture
  - ⇒ Antenna Architecture includes aperture subsystem, up- and down-converter subsystems, and digital processing requirements
- Identified critical design issues for broadband
- Designed Prototype Communications Hybrid Optical RF Dish (CHORD™)
  - ⇒ 5/12 scale of L3 Communications Satcom antenna on Global Hawk
  - ⇒ Dish has high precision surface for IR and low sidelobes for RF
  - ⇒ Optical and Coatings Design and Analysis
  - ⇒ RF Antenna Design
  - ⇒ Feed Horn Design
- CHORD™ can perform Ku- or Ka-band (18-36 GHz) RF communications simultaneously with 1.55 micron lasercom

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Antenna Architecture Study

- Key Parameters for Broadband Operation
  - Data rate
  - Aperture sizes
  - Laser power
  - Link range
  - Link margins
  - On-board power/weight/volume
    - ⇒ Airborne platform
    - ⇒ Lasercom Satellite Package
  - Acquisition time
  - On-orbit lifetime
  - Bit Error Rate (BER)
  - Tracking envelope (jitter, slew)
  - Atmospheric path length
  - Atmospheric absorption, scattering, scintillation and fade
  - Number of terminals per platform
  - Number of aircraft serviced
  - Quality of service
    - ⇒ Timeliness
    - ⇒ Applicability
    - ⇒ Availability

CHORD™ Design Compatible With Broadband Architecture

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Global Hawk Satcom Antenna

- Global Hawk has wide band satellite data links and line of sight data links developed by L3 Communications. Data is transferred by Ku-band satellite communications, X-band line-of-sight links and both satcom and line of sight links at UHF-band.

SATCOM Antenna

L"	W"	H"	Weight (lbs)	Power (Watts)
54.6	48.4	48.8	46	35

- Temp: -54C to +60C, liquid -10C to +43C
- Altitude: Sea level to 70,000 ft
- Vibration: 1.3 grms

Ku-BAND SATCOM LINK Features
- Ku-band
- 1.544-47.85 Mb/s return link data rates (selectable)
- Compatible with INTELSAT & PANAMSAT
- COMSEC compatible
- Modular design (SEM E)
- Three axis steerable antenna

Performance Specifications
- Forward link
  - 200 Kb/s composite data rate
  - FEC - R=1/2; K=7 concatenated with Reed Solomon R=192/208
  - Interleaved
  - QPSK/BPSK modulation
  - RF tuneability in 20 kHz steps across all three ITV bands
  - BER < 1 X 10 -8 w/o encryption
- Return link
  - 1.544 to 50 Mb/s data rate
  - FEC - R=1/2 or 3/4 K=7 concatenated with Reed Solomon - R=192/208
  - Interleaved
  - QPSK/BPSK modulation
  - RF tuneability in 20 Khz steps
  - 400 Watt TWTA
  - BER < 1 X 10 -8 w/o encryption
- Antenna
  - 48", three axis parabolic
  - Automatic acquisition
  - Open loop pointing or open loop assisted self scan

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IR Optical Design

- Optical Design and Layout – Proprietary
- Coating Design and Analysis
  - ⇒ Developed coating designs for primary and secondary mirrors
  - ⇒ All analysis performed using Schafer THINFILM code
    - → THINFILM used on many programs, e.g. SBL, THEL, ABL
  - ⇒ Conductors considered included gold, silver, copper and aluminum
  - ⇒ Dielectrics considered included niobia, silica, tantula
  - ⇒ Substrates considered were PROPRIETARY
- Mechanical Design - Proprietary

Design is Frequency Agile - Can Support C, X, Ku, Ka and V-Bands with Little or No RF Performance Degradation

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Rationale for RF Design and Analysis

- Prototype Design – No formal system requirements
- Goal to demonstrate Signal Separation in the Laboratory
- Feedhorn parameters form a trade space
  - ⇒ RF bandwidth, beamwidth to achieve desired illumination on the primary, aperture diameter, length, gain and voltage standing wave ratio (VSWR)
  - ⇒ Signal strength = f(illumination pattern vs gain)
- Selected RF Design Space to generate strong signal
  - ⇒ RF bandwidth: 18-36 GHz
    - → Candidate AF ranges can support 9-18 GHz, demonstrate Ku band
  - ⇒ Beamwidth: 60 – 90 degrees
  - ⇒ Gain can be increased to military performance
  - ⇒ VSWR: <1.5
  - ⇒ Polarization: Circular or Dual-Linear

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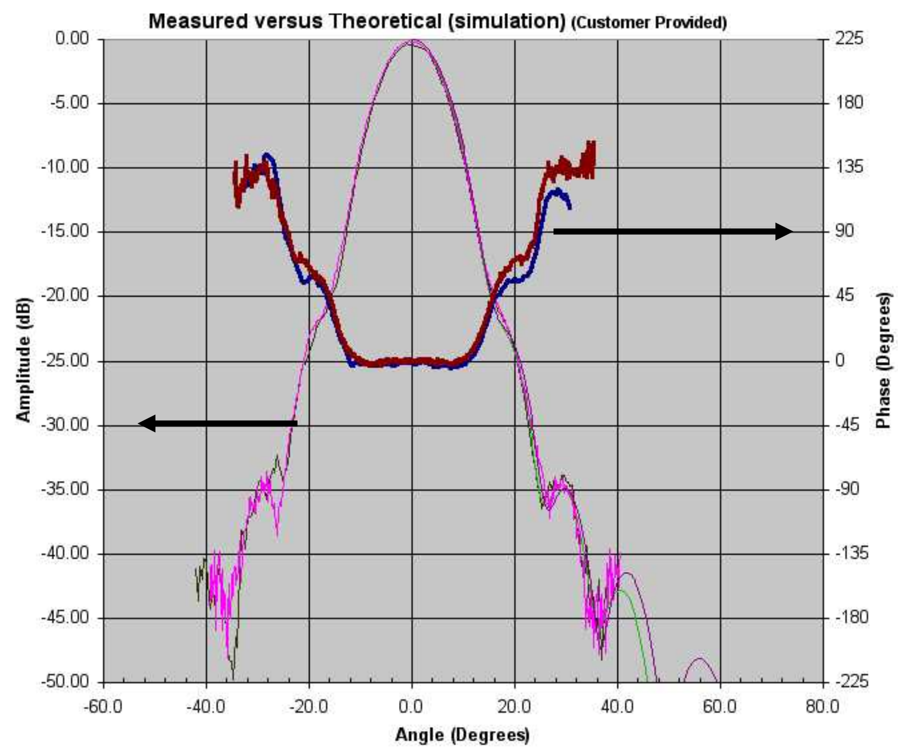
RF Feed Horn Point Design

- Baseline Feed horn:
  - 1 octave bandwidth for 18-36 GHz operation (point or continuous)
    - Matches AF indoor range capabilities
  - Beamwidth of 60 degrees
  - Aperture Diameter is Proprietary
  - Length is Proprietary
  - Side lobe suppression
  - Low VWSR, Gain is Proprietary
  - Circular polarization
  - Excellent illumination characteristics



RF Horn Design Interfaces Well With Optical Design

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Summary

- Schafer Has Designed Mirrors, Telescopes and Instruments which Exceed Our Customers Requirements
- Product Lines are SLMS™, LASIT™ and CHORD™
- SLMS™ and LASIT™ are Beryllium Replacement Technologies
  - ⇒ Same Frequency at Equal or Lower Weight
  - ⇒ Better Thermal Performance
  - ⇒ Better Schedule
  - ⇒ Lower Cost
  - ⇒ Non-Toxic
- We are Beyond CDR and are Fabricating Ahead of Schedule on Off-Axis LASIT™ and CHORD™ projects
- Schafer is working closely with Government and System Houses towards Phase III Programs
- ISO9001:2000 Certification Expected in 2005