Thermally Insensitive Silicon Carbide Optical Telescope Payload for High Performance Small Satellite Relevant Space Environments

Trent Newswander[a], Matt Felt[a], Jim Peterson[a], Hugo Vargas[b]; a)Space Dynamics Laboratory, USU Research Foundation, b) POCO Graphite, Entegris

Space Dynamics Laboratory, Utah State University Research Foundation

Entegris | POCO GRAPHITE An Entegris Company

i Abstract

Small satellite buses offer an economical platform for optical payloads. However, the smaller buses struggle to provide the thermal stability that high performance optical payloads typically require. Thermal stability issues can be mitigated through thermal insulating methods and active thermal control requiring additional volume, mass and power; or by decreasing the optical instrument's sensitivity to thermal variations. The goal of the material trades, design, and analysis outlined herein is to develop an optical telescope design for a small satellite that maximizes optical aperture and imaging performance while minimizing thermal variation sensitivity. The material trades evaluated the pros and cons of different optical telescope materials resulting in the selection of graphite converted beta-phase silicon carbide (SiC) due to its high thermal dimensional stability and its advanced shape-making ability. Furthermore, initial optical imaging performance simulation and integrated structural-thermal-optical performance (STOP) analysis were used to predict Earth-viewing visible imaging performance.

A Problem

Small 6U spacecraft

-Struggle to provide the thermal stability that high performance optical payloads require

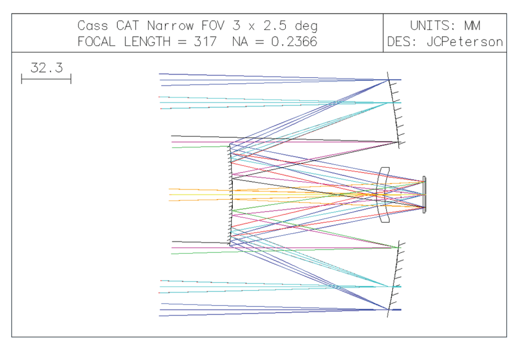
-Are limited by mass, volume, power and cost

Thermal Control Mitigation	6U Implementation	6U Limitation
Material Selection	Yes	Cost
Insulation: MLI, Isolation, Thermal Shields	MLI	Mass, Volume
Passive Thermal Control (e.g. Radiator)	Yes	Mass, Volume
Active Thermal Control (Heaters, TEC, Cryo-Cooler)	Heaters	Power

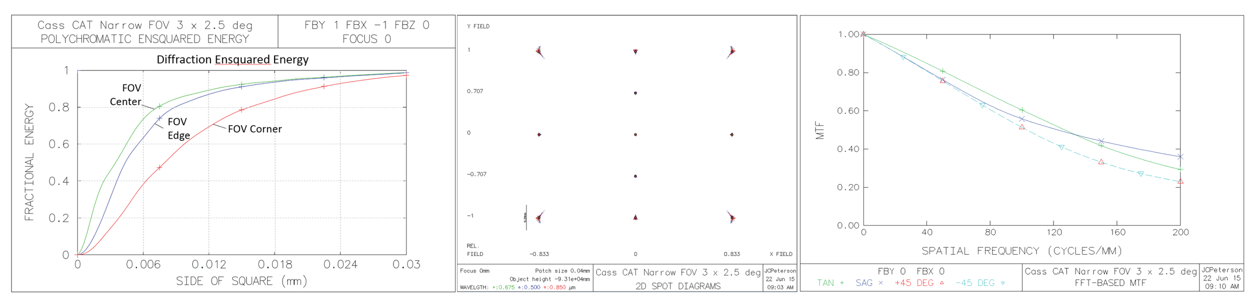
B Optical Design

On-Axis Catadioptric Cassegrain Telescope

- Waveband: 500 – 850nm
- Aperture diameter 15cm
- Focal length: 317mm
- Optical efficiency 80%
- Encircled energy >50%
- Pixel Pitch 6.5μm
- F/# 2.1
- FOV +/- 3° by +/- 2.5°
- Optimized for near diffraction limited performance within 3° radius



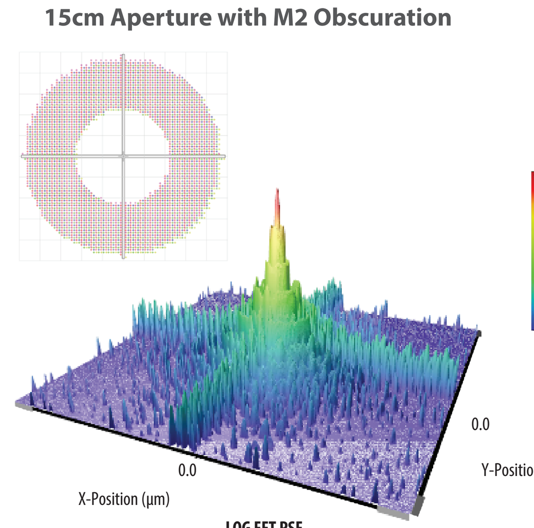
Nominal Optical Performance Predictions



Ensquared Energy | Spot Diagram | MTF

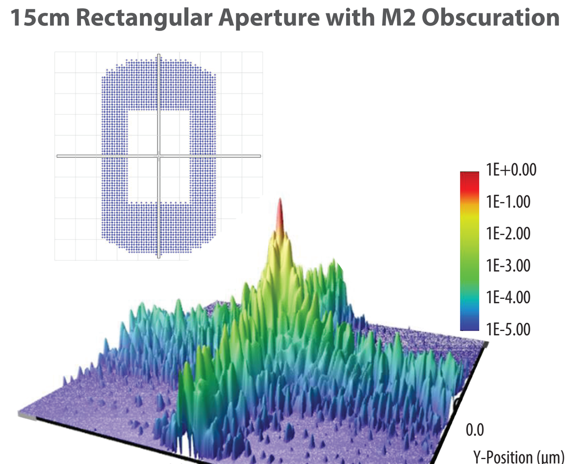
C Simulated Optical Performance

15cm Aperture with M2 Obscuration

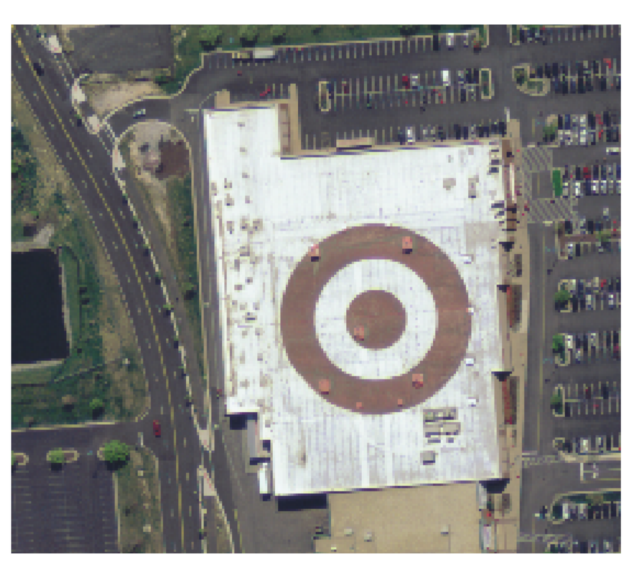


LOG FFT PSF

15cm Rectangular Aperture with M2 Obscuration



Polychromatic LOG FFT PSF



Simulated Image

Simulated Image

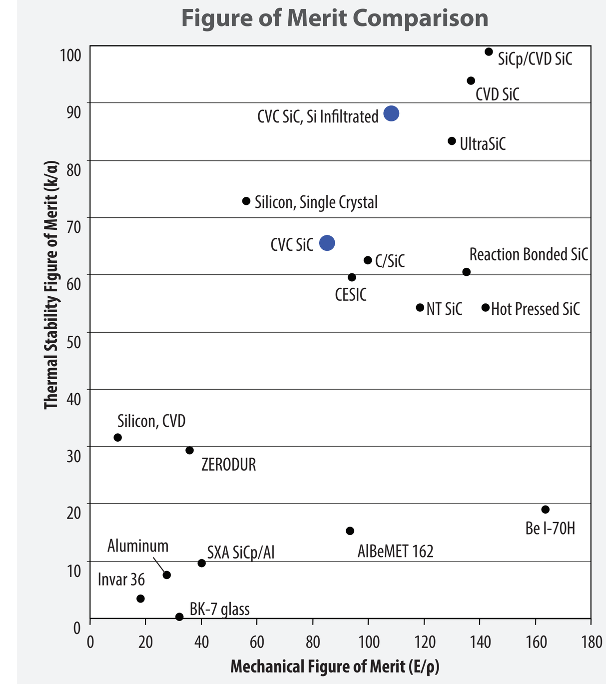
D Material Trades

- Considered metals, glass and ceramics with optical assembly heritage
- Thermal stability figure of merit is the key performance parameter
  - Strong performers: Glass/CFRP, Si, SiC
  - Aluminum, Beryllium and AlBeMet provide insufficient thermal stability
- **Costs of viable optical assembly materials:**

Aluminum	$
AlBeMET	$$$
Beryllium	$$$$$
Glass/CFRP	$$$$
CVC SiC	$$$
SiC (general)	$$$$

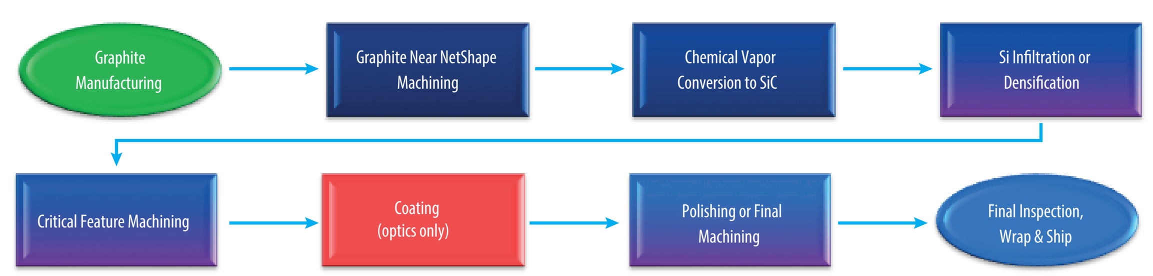
- Single Crystal Si, general SiC and Zerodur metered with CFRP are cost prohibitive for most 6U missions

Figure of Merit Comparison

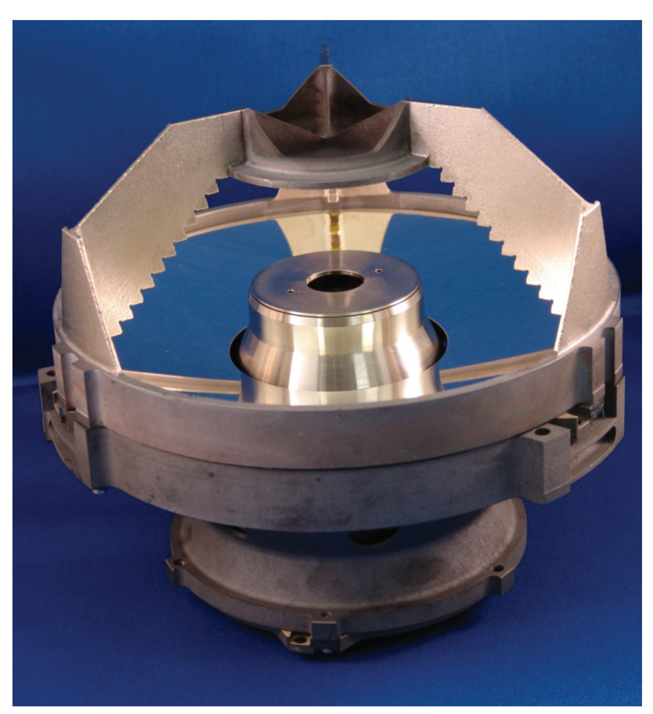


E Graphite Converted Beta-phase SiC

- SiC provides higher thermal stability and stiffness over aluminum and other metals
- CVC SiC (a.k.a SUPERSiC-Si™) provides advanced shape making technology that enables economical fabrication



- Chemical Vapor Conversion (CVC) of graphite into SiC (Johnson 2002)
- Soft graphite machines similar to aluminum using conventional CNC equipment and tooling for near-net shaping
- Net-shaped graphite is converted into beta-phase SiC with approximately 5% growth
- ONLY critical features are machined in the SiC state for economical manufacture
- SiC optics and structures are highly deterministic for quick assembly and alignment



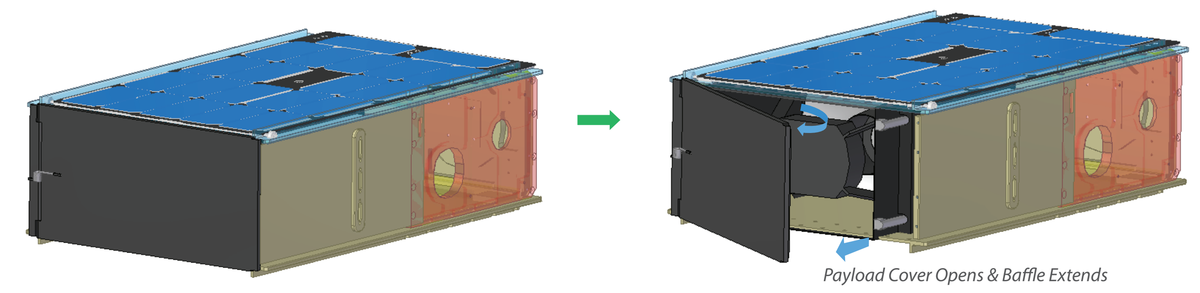
15cm Aperture 4 Mirror Cassegrain CVC SiC Telescope

Typical Material Properties

Property	CVC SiC (Silicon Infiltrated)
Apparent density	3.01 g/cm³
Bulk density	2.93 g/cm³
Total porosity % of volume	4%
Total porosity % of total	0.5%
Total impurity level	<10 ppm
Flexural strength	223 MPa
Tensile strength	124 MPa
Elastic modulus	338 GPa
Poisson's ratio	0.17
Dynamic shear modulus	138 GPa
Fracture toughness	2.63 MPa·m$^{0.5}$
Hardness, knoop	1643 kg/mm^2
Thermal diffusivity	115 mm^2/s
Thermal conductivity	220 W/m·K
Electrical resistivity	4000 μΩ·cm
Instantaneous coefficient of thermal expansion at RT	2.4 ppm/K

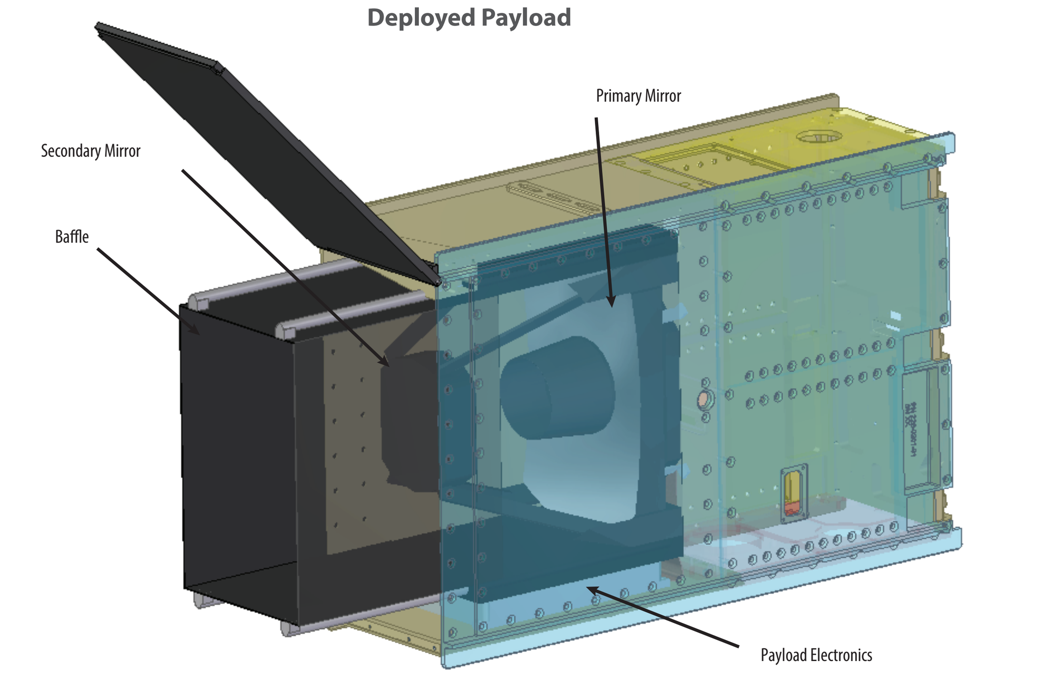
Reference: J. Johnson et al; Rapid fabrication of lightweight silicon carbide mirrors; SPIE Vol. 4771; 2002

F Layout



6U CubeSat Stowed Payload | *Payload Cover Opens & Baffle Extends*

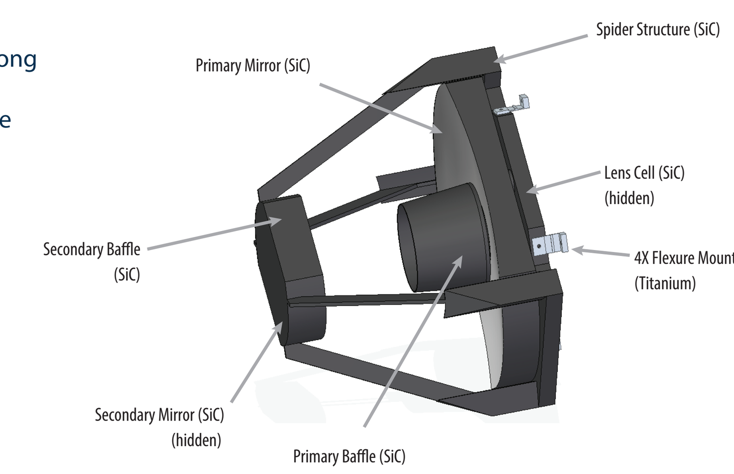
Deployed Payload



Deployed Solar Arrays not shown for clarity

G OTA Layout

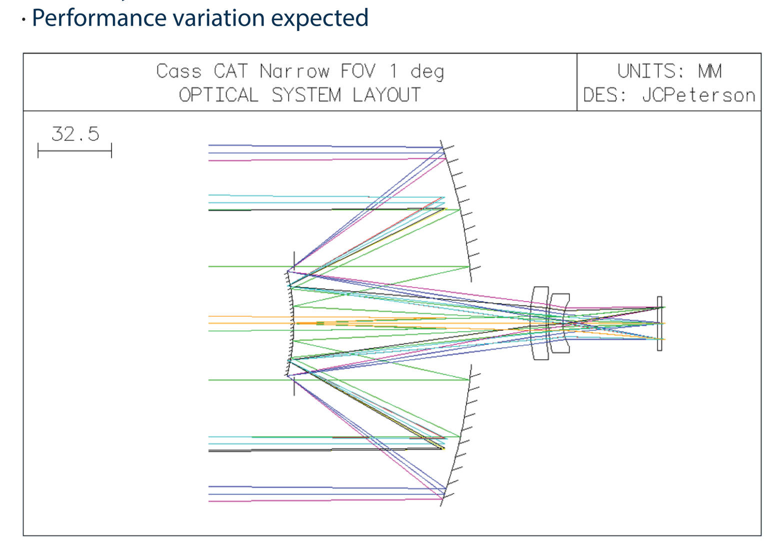
- OTA is constructed primarily of SiC
- Mono-material construction provides strong athermal performance
- Titanium flexure interface absorbs relative thermal strain of aluminum spacecraft



H Interchangeability: Rapid Mission Flexibility

- Identical mirror system supports multiple configurations
  - Use identical mirrors and spider structure
    - » Long lead costly components
  - Provides flexibility for rapid response to many possible missions
- Change out lens cell and detector spacing
- Flexibility: Medium FOV / narrow FOV
- Flexibility: Visible / infrared
- Performance variation expected

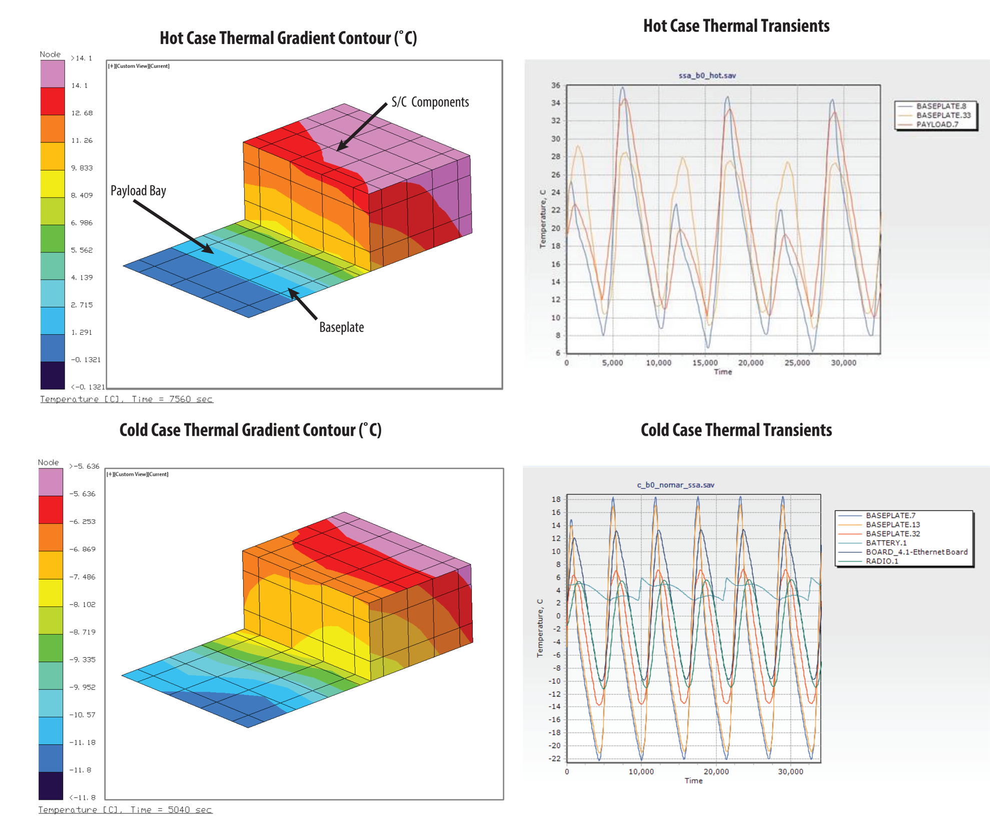
Parameter	Fast	Slow
F/#	2	6
Aperture	15 cm	15 cm
Focal Length	30 cm	90 cm
Field of View	3°	1°
Angular Resolution	2.2 μrad	0.7 μrad



I 6U Thermal Analysis

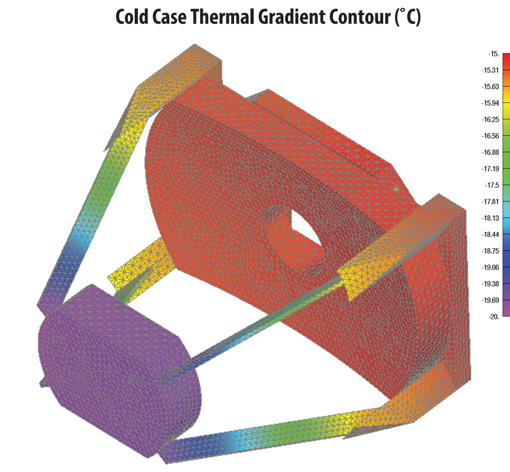
- Modeled a 6U CubeSat in various representative orbital environments
- Predicted payload baseplate temperature excursions of 25K and gradients of 5K

Spacecraft Thermal Analysis Results

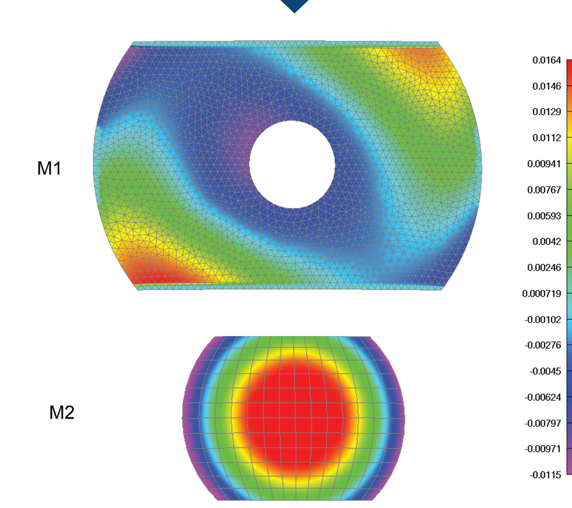


J STOP Analysis: Thermal Elastic Deformation

Cold Case Thermal Gradient Contour (°C)



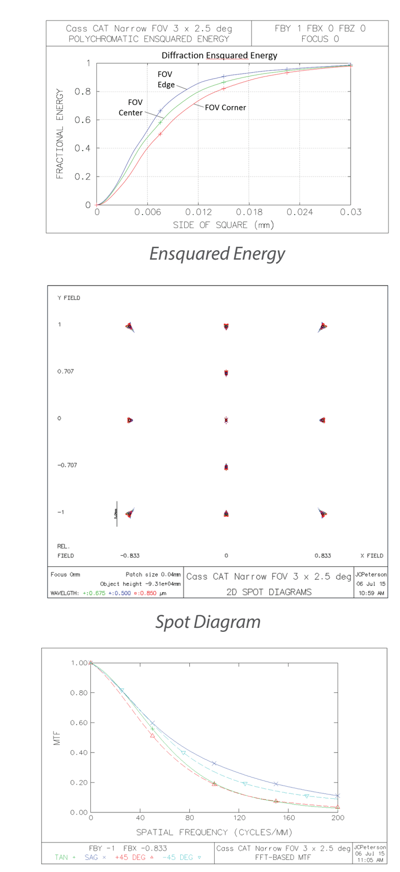
Optical Surface Error (PV λ_{HeNe})



Thermal Elastic Optical Performance Predictions Without Focus Mechanism

Error	M1	M2
PV Surface Error λ_{HeNe}	0.03	0.04
Relative Decenter (μm)	0.03	-0.03
Relative Tilt (μrad)	0.5	-0.5
Defocus (μm)	12*	

*Alignment and thermal contributors



Ensquared Energy

Spot Diagram

MTF

K Conclusions

- Small satellites experience stressing thermal environments
- Size, weight and power limit thermal control options
- STOP analysis shows that high-performance optical payloads require high thermal stability
- CVC SiC-Si provides high stability and economical fabrication
- A 6U optical payload is predicted to provide high performance with interchangeable flexibility for rapid support of multiple missions