Phase-Change Thermal Energy Storage to Augment Solar Thermal Propulsion

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Solar Thermal Propulsion (STP) systems, with a unique balance between propulsive efficiency and available thrust, are known to offer significant advantages over chemical and electric propulsion systems for some mission scenarios. However, in a basic STP system, significant thrust cannot be produced during eclipse, and, unlike typical propulsion systems that can utilize the electrical power system already available on a satellite, an STP system requires its own, dedicated solar concentrator for operation. To enable the performance offered by STP, it has been suggested that a means of thermal storage be used to provide thermal energy while the system is eclipsed, and that thermal-electric conversion be used to power the satellite payload and instrumentation, thus obviating the need for a typical photovoltaic-and-battery power system.

Storing the thermal energy via the phase change of an elemental material can provide for relatively constant-temperature, predictable operation. Silicon has been suggested as the phase-change thermal storage material (PC-TSM) for moderate-performance satellites (and for possible terrestrial solar power systems), while boron is suggested as the phase-change medium for a high-performance satellite due to its extremely high heat of fusion and melting point near the ideal temperature for an ammonia-fed STP engine.
With either material, melting via concentrated solar light, containment and insulation in the liquid phase, and thermal energy extraction and conversion have yet to be demonstrated. Additional difficulties in terms of material compatibilities, contamination, and structural fidelity at high temperature also must be solved. An ongoing experimental effort at USC has been working towards the demonstration of a molten silicon based system with the intent of applying the lessons learned to a more technologically challenging molten boron design.

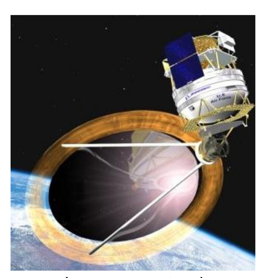
Augmented STP

- **Previous reviews have identified STP as a promising candidate for high performance microsatellite missions. [*Kennedy 2002, Scharfe 2009*]**
  - High ΔV capability with a quick response time
  - Relatively high thrust and efficiency

Chemical	Solar Thermal	Electric
~230s Isp	300-700s Isp	>1000s Isp

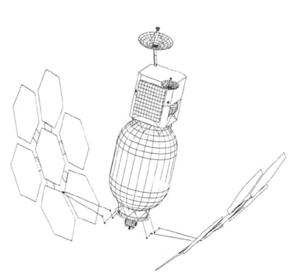
  - Low mass fraction for high capability
    < 50% $m_{propulsion}$ including propellant for ΔV of 1.5 km/s
- **Despite these advantages, no STP system has flown**

Solar Orbit Transfer Vehicle (SOTV)



(Source: Boeing)

Integrated Solar Upper Stage (ISUS)



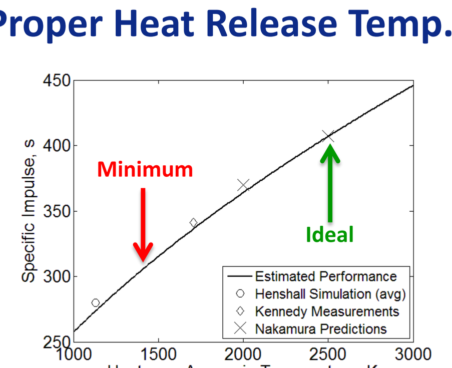
- Without energy storage, output is illumination dependent
- Requires conventional photovoltaic system AND solar collectors

Bi-Modal Solar Thermal With Energy Storage

STP Drawback		Potential Solution
Large propellant storage volume utilizing H_2 to achieve ~700s Isp. *Trade performance for lower volume?*	→	Ammonia Propellant. *400s Isp w/ practical storage*
Solar thermal requires own concentration system. *Additional spacecraft component*	→	Bi-Modal System. *Thermal-Electric Conversion*
Concentrators must be aimed at the sun for propulsion. *De-couple optics from s/c orientation?*	→	Fiber Optics

Thermal Energy Storage Method Design Drivers

Proper Heat Release Temp.

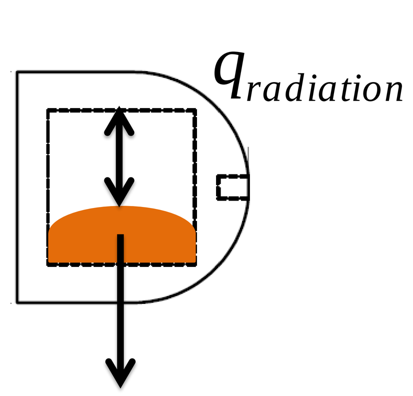


High Energy Density

- Li-Ion batteries achieve 500 kJ/kg
  Needs to be on the order of MJ/kg
- Current PV systems achieve 80 W/kg
  Needs to achieve greater than 100 W/kg

1D Heat Transfer With the PCM

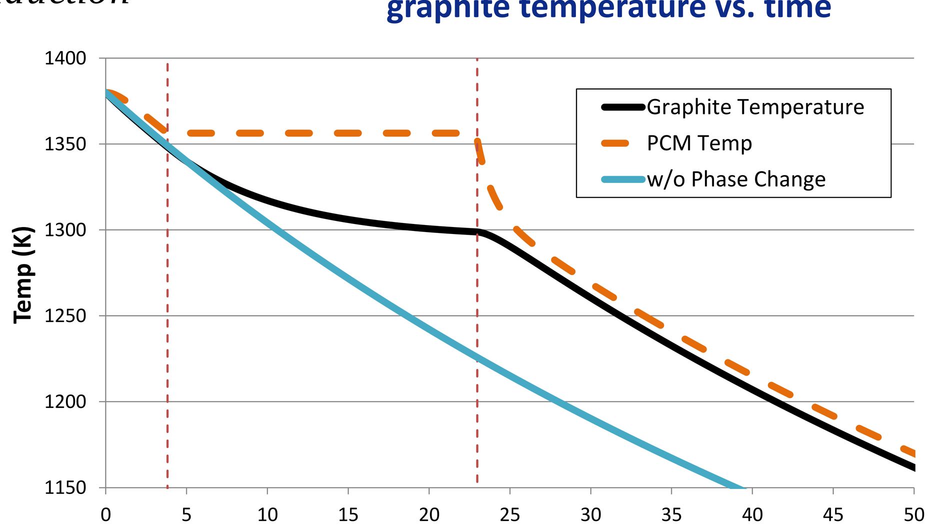
- With current crucible design, the PCM can transfer heat to the graphite crucible in two ways



- The cooling curve becomes

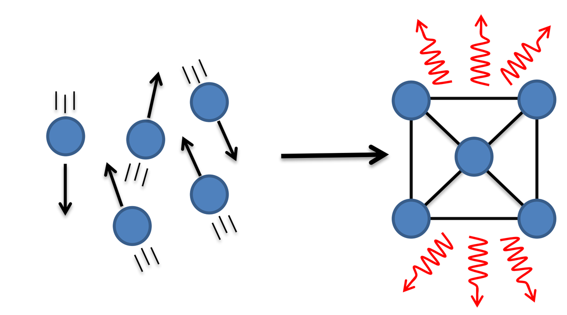
$$mC_p\frac{dT}{dt} = -\varepsilon A\sigma_{SB}\left(T^4_{Crucible} - T^4_{Surr}\right)\left(1-\eta_{Shielding}\right) + q_{conduction} + q_{rad}$$

- Assume infinite $k_{Graphite}$ and k_{Cu} and a known copper-graphite contact resistance
- Assume PCM is isothermal during phase change and that phase change is instant
- Possible to iteratively solve for PCM and graphite temperature vs. time



Advanced Phase Change Materials (PCMS)

- PCMS provide storage by harnessing the heat released during the liquid → solid transition
  - Relatively constant temperature energy delivery
  - Consistent temp. means consistent STP thrust performance



·TRADDITIONAL PCMs can be divided into 3 categories

Class	ΔH_{fus} [MJ/kg]	T_{melt} [K]	k_{th} [W/mK]
Paraffin Wax	0.072 – 0.214	317 – 379	0.19 – 0.75
Fatty Acids	0.045 – 0.210	268 – 344	0.14 – 0.17
Hydrated Salts	0.115 – 0.492	281 – 1170	0.46 – 5.0

Key Problems
1) Energy Density and k_{th} an order of magnitude too low
2) Melt temperatures too low for spacecraft application
3) Decomposition after repeated cycling

·ADVANCED PCMs must meet key requirements

Enabling Parameters	Feasibility Requirements
Properly Matched Melt Temp.	Material Stability
High Energy Density	Material Compatibility
	High k_{th}

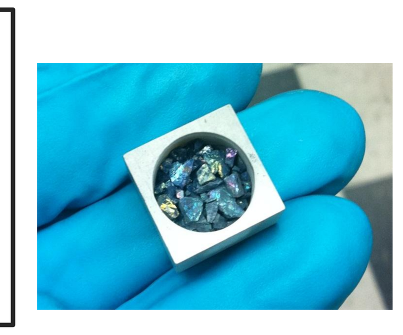
→ High Temperature Elemental Materials

Element	ΔH_{fus} [MJ/kg]	T_{melt} [K]	k_{th} [W/mK]
Beryllium	1312	1560	200
Silicon	1687	1785	149
Nickel	298	1728	100
Iron	274	1811	80.4
Titanium	295	1941	21.9
Chromium	403	2180	93.9
Boron	4600	2570	27.4
Halfnium	152	2506	23.2

Further Advancement Requires Practical Understanding

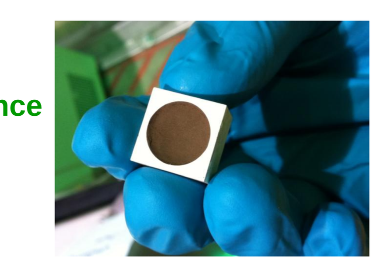
Far Term Goal: Evaluate The Viability of High Temperature Phase Change Energy Storage

Experimental Effort To Address
- High Power Solar Concentration
- Material Compatibilities
- Radiation Shielding
- Power Coupling



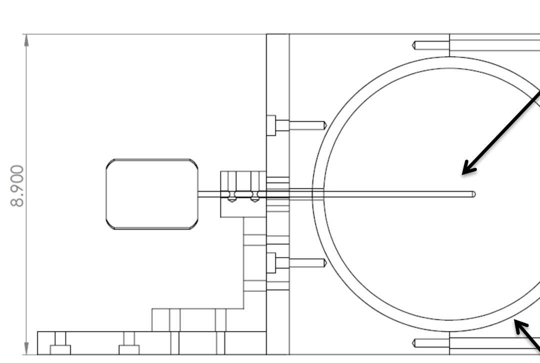
Silicon
Moderate performance
- 300s Isp
- 1.8 MJ/kg

Boron
High performance
- 400s Isp
- 4.6 MJ/kg

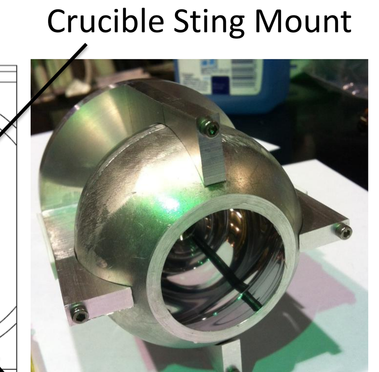


Test Section Design

Spherical Radiation Shielding Cavity based upon the model presented in Steinfeld and Fletcher 1990

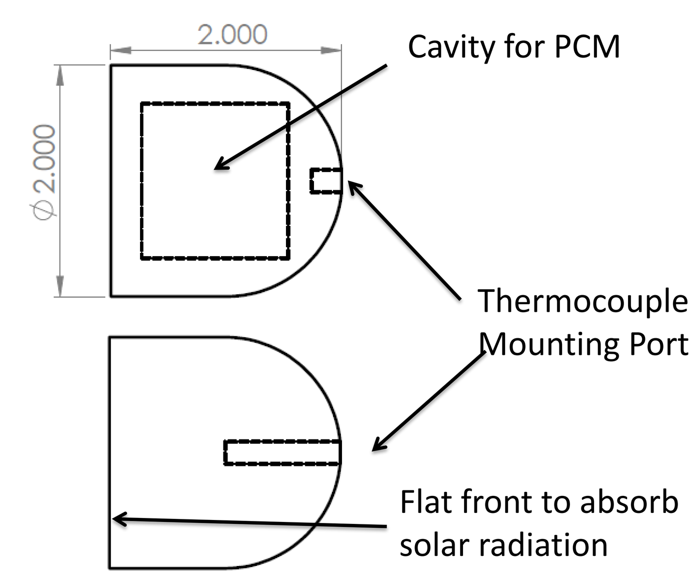


Type C Thermocouple / Crucible Sting Mount



Mirror polished Al Radiation Shields

"Bullet" Style Crucible:
- Graphite: high absorptivity, high working temperature, ease of manufacture

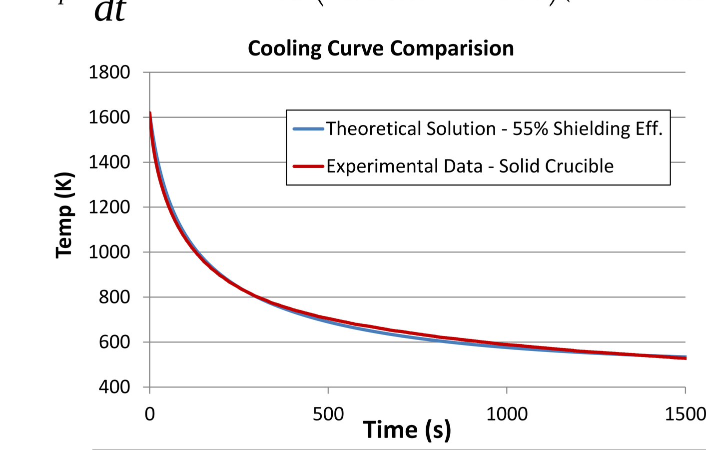


Solid graphite version for Cooling Curve Analysis

Shielding Efficacy:
- Theoretical model predicts 65% reduction in radiation losses (65% efficiency)
- Can determine actual reduction by cooling curve analysis
- With a solid graphite crucible, the cooling curve is defined by

$$mC_p\frac{dT}{dt} = -\varepsilon A\sigma_{SB}\left(T^4_{Crucible} - T^4_{Surr}\right)\left(1-\eta_{Shielding}\right)$$

Cooling Curve Comparison



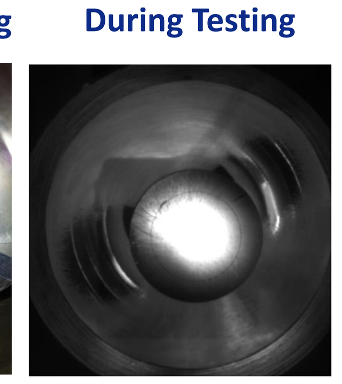
Radiation Loss Cut by Approx. 55%

Current Tests

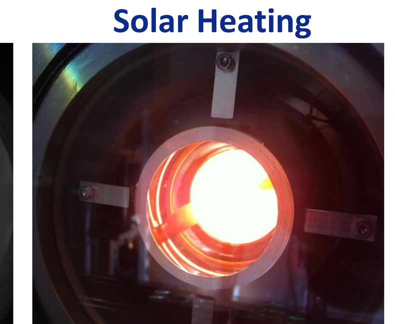
- Testing with copper as a PCM to see if latent heat release will be visible
- Loaded with 5g Copper (50% total mass)

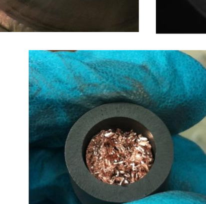
Before Heating

During Testing



Immediately After Solar Heating





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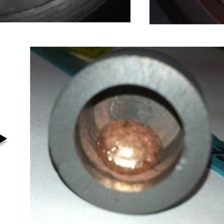
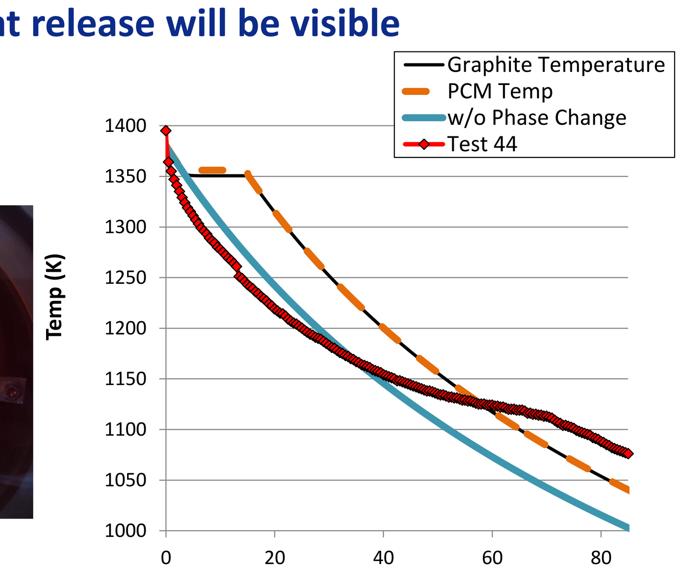
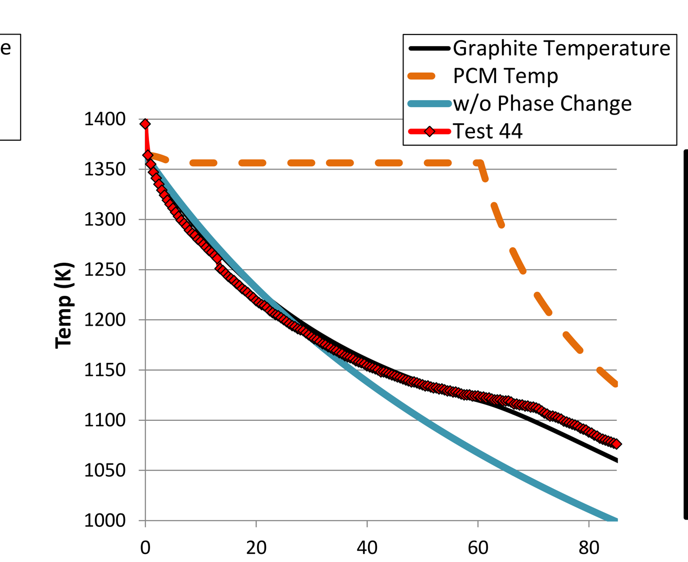




Actual Parameters

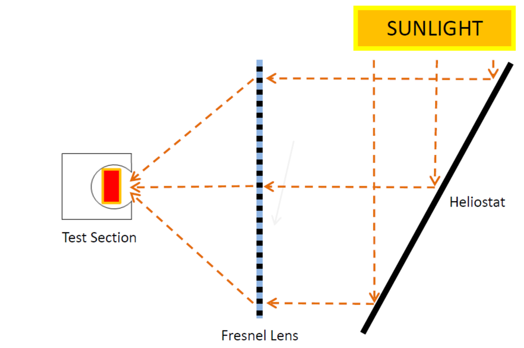


Greatly Reduced PCM-Graphite Heat Transfer

1D assumptions and instant phase transition assumptions are insufficient to describe behavior

USC Solar Furnace

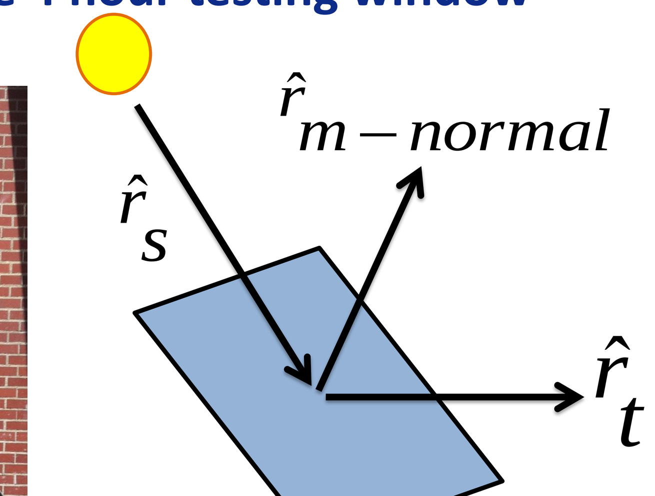
- Programed and built at USC
- Two stage design
- 6 m^2 heliostat mirror
- 1 m^2 Fresnel lens concentrator



>200 W in a 2 cm Spot

Heliostat

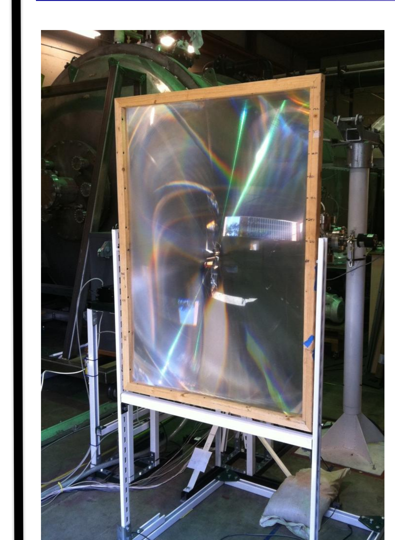
Provides continuous direct normal sunlight to the Fresnel lens during the 4 hour testing window



$$\hat{r}_{m-normal} = \frac{\hat{r}_s + \hat{r}_t}{\left|\hat{r}_s + \hat{r}_t\right|}$$

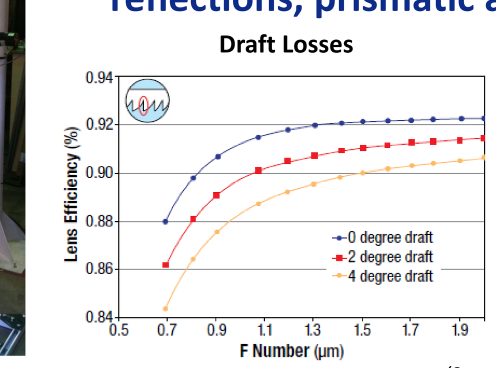
- Completely rebuilt and programed from surplus AFRL components
- Discretized Alt - Az tracking accurate to 0.1 degrees
- Custom LabView software with variable speed motor control

Fresnel Lens

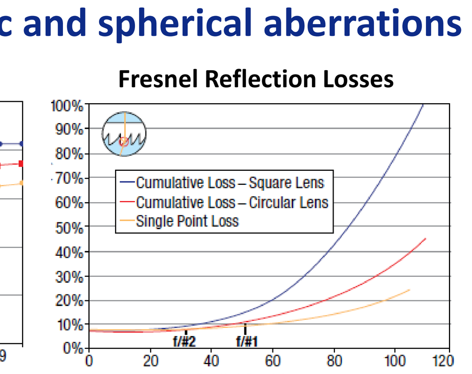


- Repurposed from a rear projection television
- Only 40% efficient due to draft loss, reflections, prismatic and spherical aberrations

Draft Losses



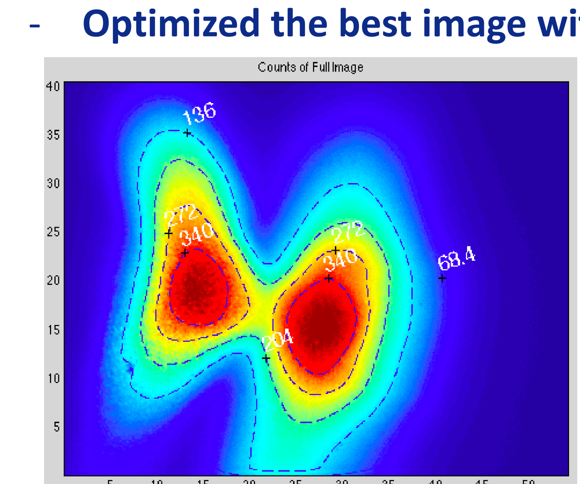
Fresnel Reflection Losses



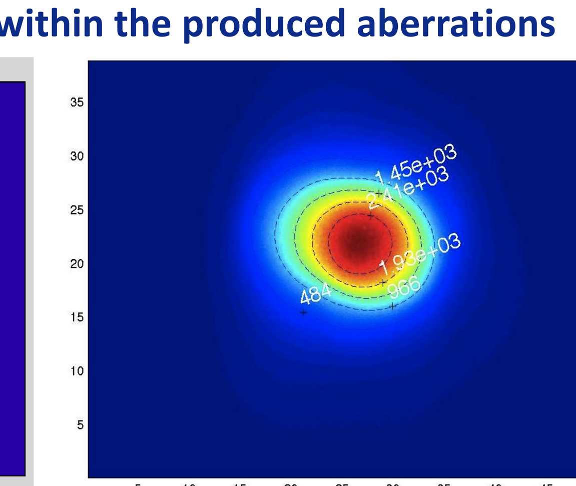
(Source: 3M)

CCD Characterization

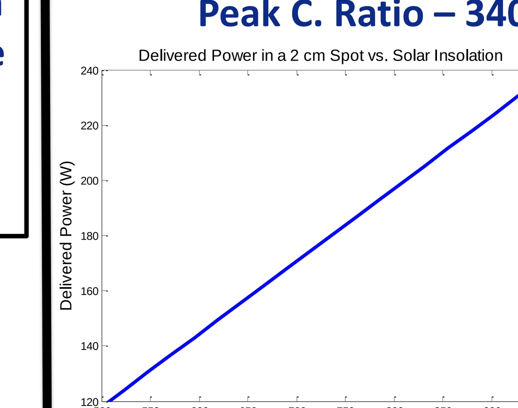
- Measured the intensity of the resulting image on a Lambertian surface with a black body calibrated CCD camera
- Optimized the best image within the produced aberrations



"Visual" Focus
Peak C. Ratio – 340:1



3cm back from "Visual" Focus
Peak C. Ratio – 2400:1



- Data taken at "optimized" focus for maximum solar concentration ratio
- Output is linearly dependent on solar insolation
- Insolation measured with a NIST calibrated pyroheliometer

Total System Efficiency: $\eta_{Heliostat}\eta_{Fresnel}\eta_{Quartz} \approx 25\%$