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Compensation of Gravity Induced Heliostat Deflections for Improved Optical Performance

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Overview

- **Introduction and Goals**
  - Model the optical performance of gravity-affected heliostats
  - Identify potential improvements
- **Modeling Approach**
  - Modeling the actual heliostat shape
  - Optical verification
- **Methodology for Optical Improvement**
  - Power-Weighted Elevation Angle
  - Metrics and annual efficiency gain
- **Summary**

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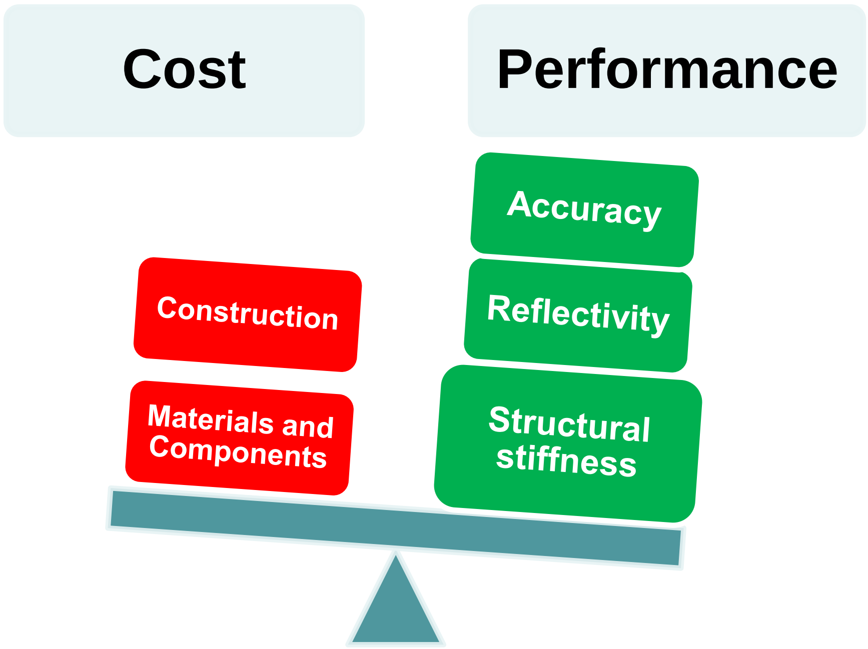
Introduction

- Heliostat designs for commercial CSP installations are a compromise between low cost and optical performance



- A cost-effective heliostat will likely have some degree of gravity-induced structural deflection

Goals of this study

- Characterize the optical performance of gravity-deflected heliostats using finite-element and optical analysis software tools

- Use modeling tools to identify a strategy for countering deflections and improving optical performance

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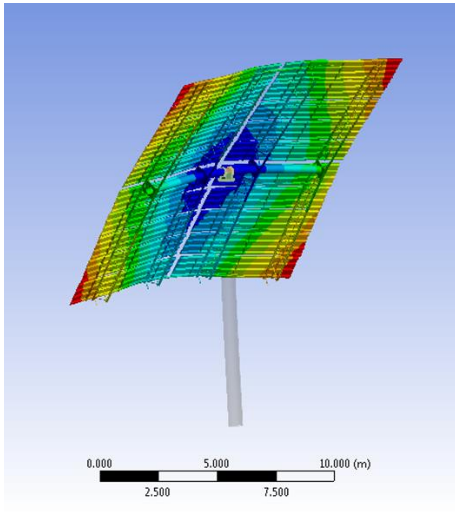
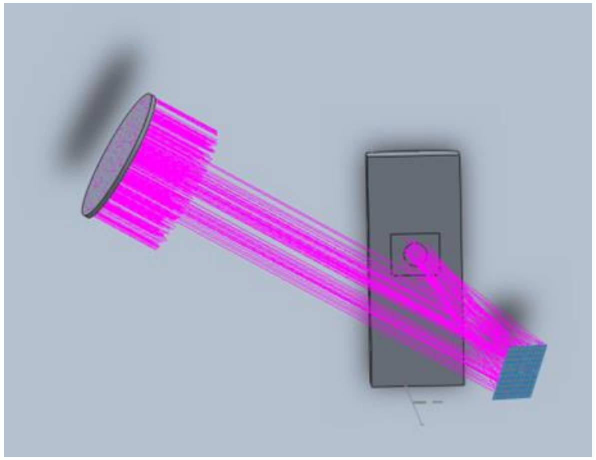
Overall Modeling Approach

ATS Heliostat



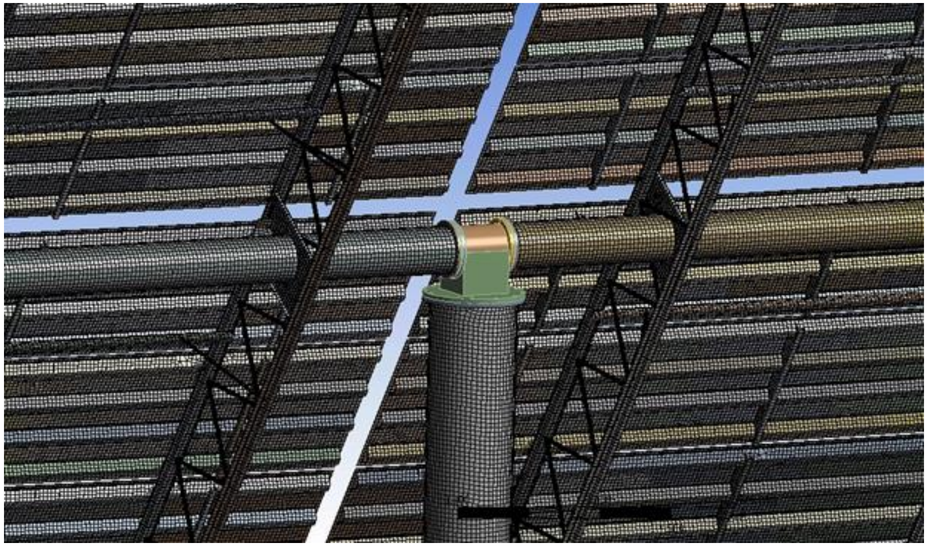
FEA in ANSYS Mechanical

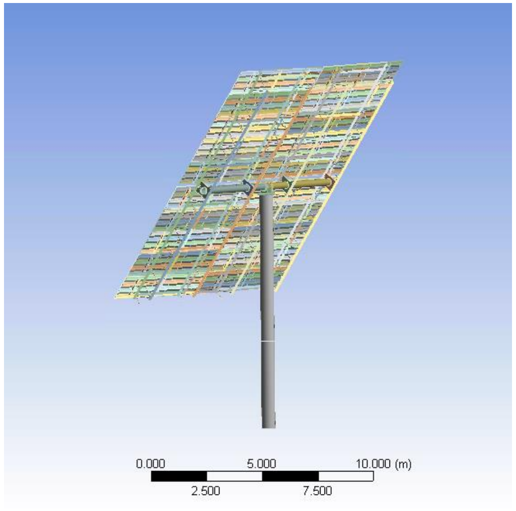


Optical Analysis in Breault APEX

- Heliostat used: Advanced Thermal Systems
  - Typical glass-metal design, ~150 m^2
  - Location: National Solar Thermal Test Facility, Albuquerque, NM

FEA Model



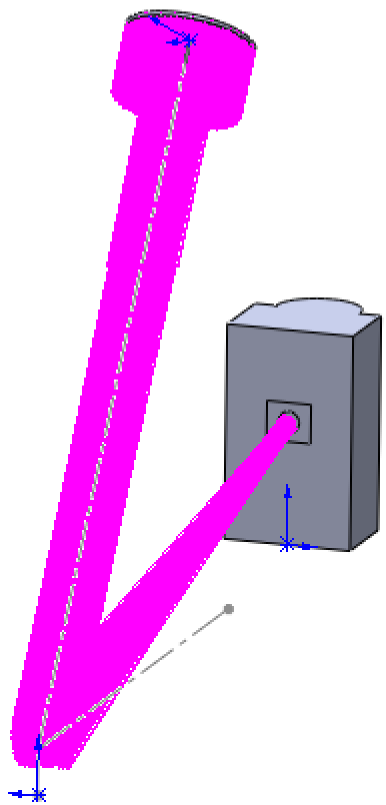


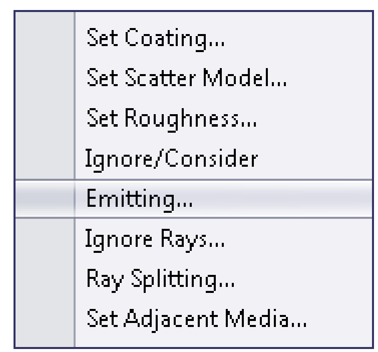
Direct application of ANSYS mechanical

- Contacts chosen to match physical case
- Mesh: ~ 1.5 million elements, deflection based convergence verified at greater resolutions
- Some special loading considerations

Optical Modeling Tool: Breault APEX

- 3D CAD based software
  - Specify sources, target, surface properties
- Post FEA models may be imported, regenerated into surfaces





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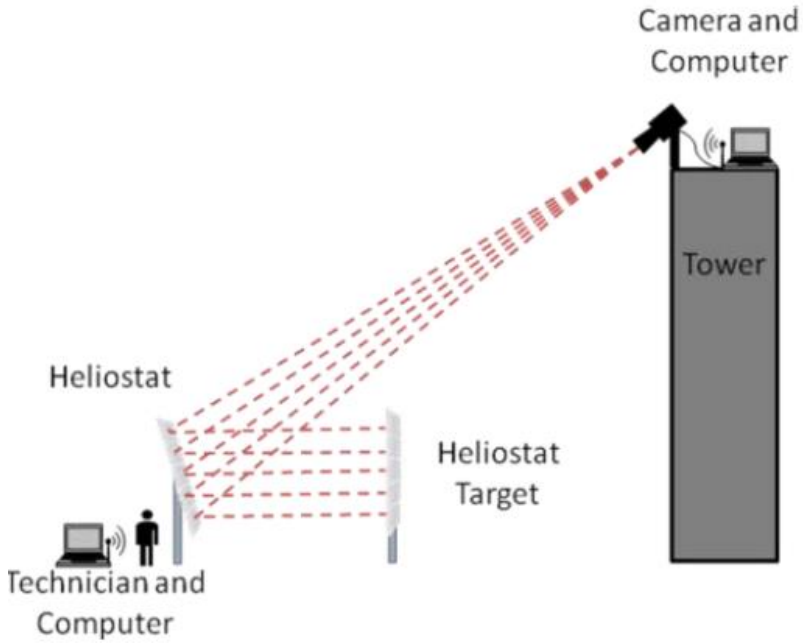
Modeling the Actual Heliostat Shape

- Heliostats may be constructed to counter gravity sag
  - An example is canting by optical verification, or canting on-sun
  - Mirrors are aligned to specifications regardless of deflections in support structure



An Optical Canting Method
[Chavez, Sproul, and Yellowhair]

Modeling the Actual Heliostat Shape

- The fully assembled heliostat cannot always be described by engineering drawings

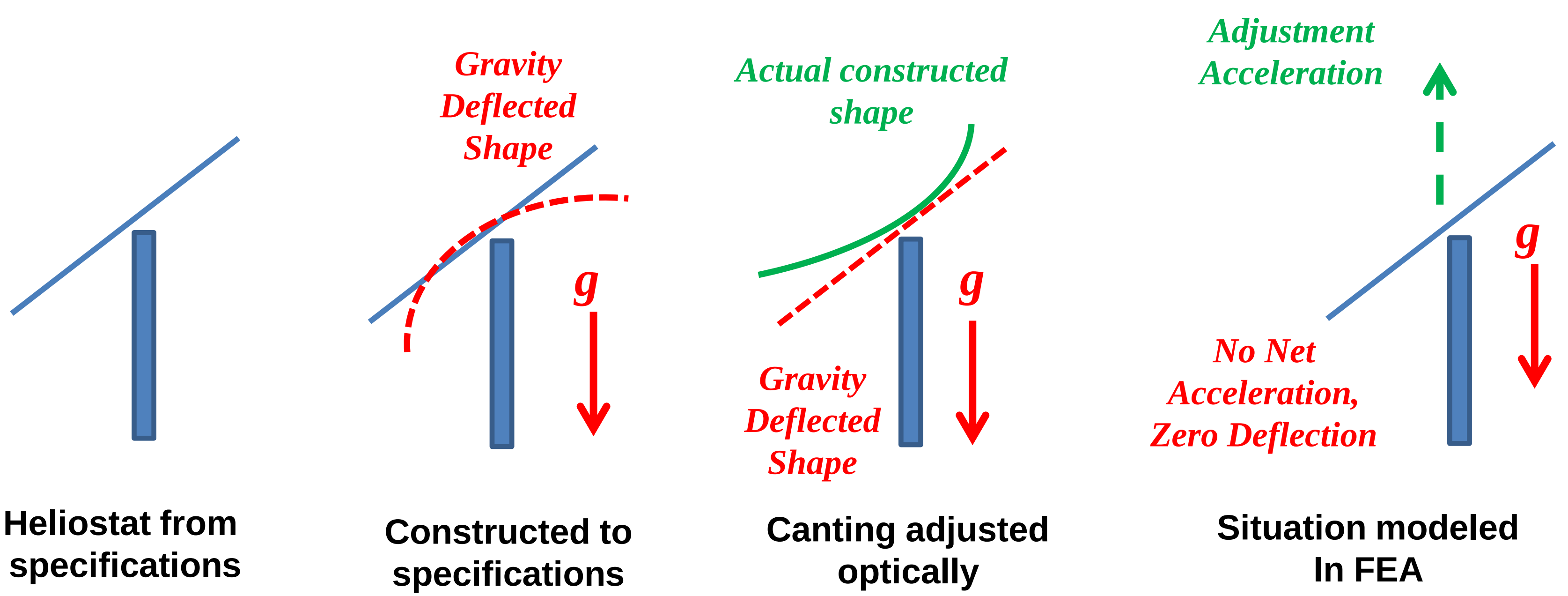
- When moved out of the construction orientation, the direction of gravity shifts relative to the heliostat, and deflections reappear

Modeling the Actual Heliostat Shape

- How to model:
  - A heliostat without rigorous dimensions for mirror positions?
  - Deflections that change with heliostat orientation?

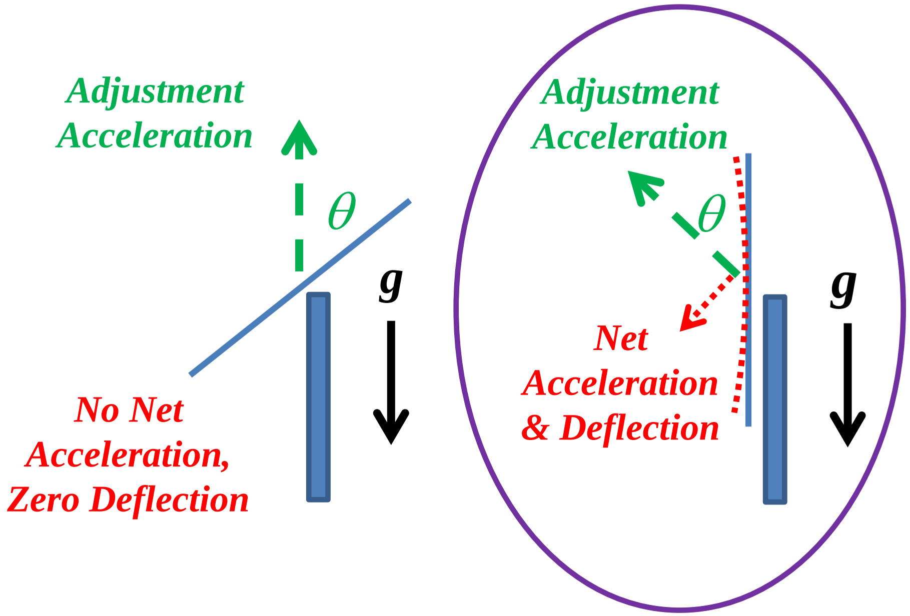
Modeling the Actual Heliostat Shape

- Construct the ideal heliostat configuration in CAD, and implement reversed gravitational acceleration in FEA to approximate canting adjustments



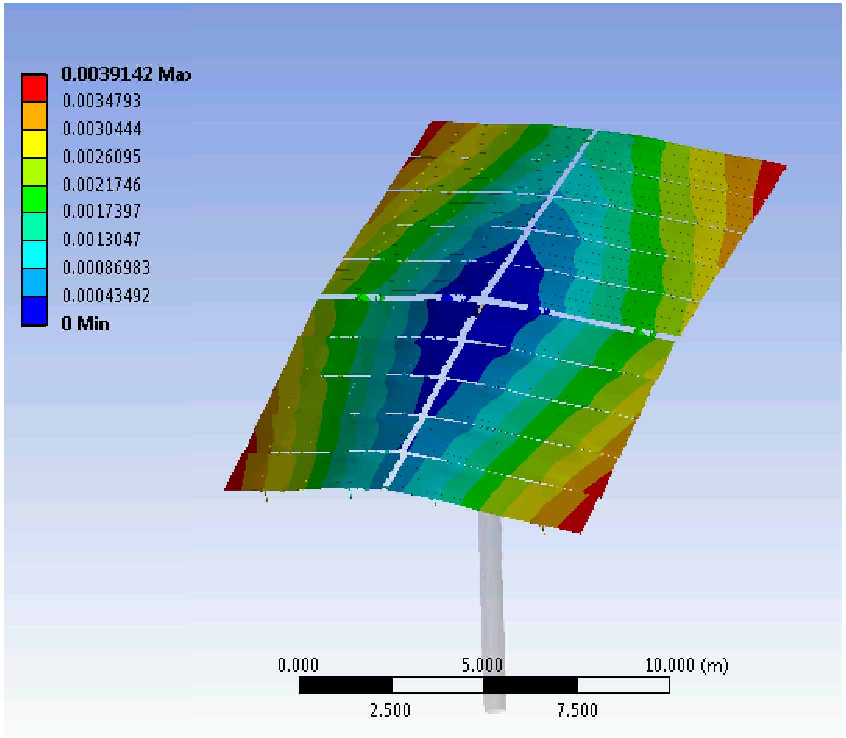
Modeling the Actual Heliostat Shape

- To capture the fixed adjustments made to mirror positions, the adjustment acceleration must be **fixed relative to the mirror surfaces**
  - When the heliostat rotates, accelerations do not align and there is a net deflection

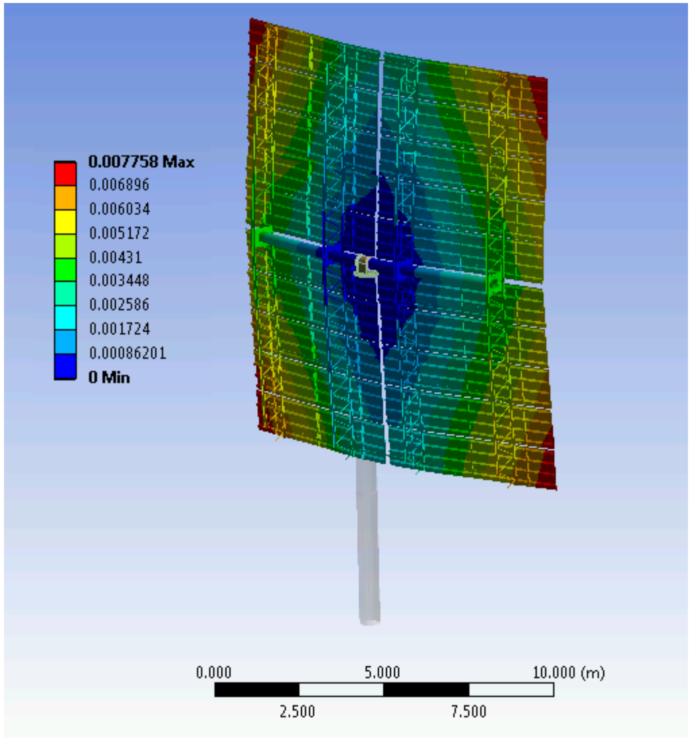


- **Assumptions:**
  - Deflections are small and linear
  - Non-rotating parts (i.e. pedestal) are rigid

FEA Results



Noon, Summer Solstice



Late afternoon, Winter Solstice

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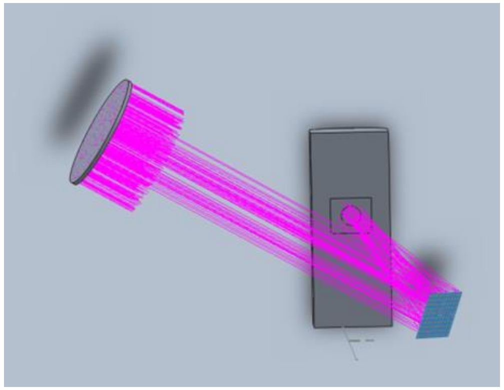
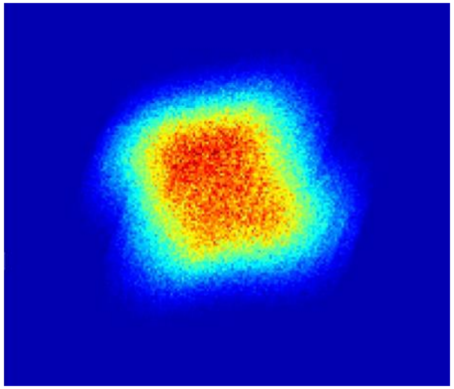
Optical Modeling

- Ray tracing simulation of post-FEA heliostat shape and field geometry produces simulated beams
  - Heliostat and tower orientations match field specifications at National Solar Thermal Test Facility (NSTTF), Albuquerque, NM
  - Rays emitted from a “sun” within 9.3 mrad cone angle
  - Power emitted based on desired DNI for simulated time of day

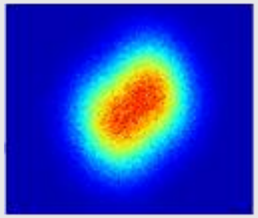
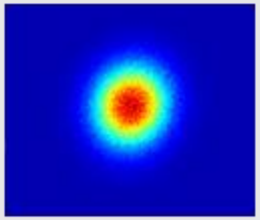
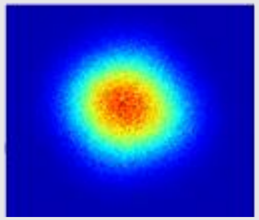
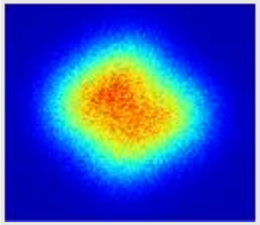
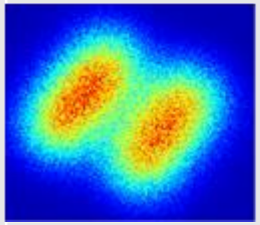




Optical environment constructed to match actual field

Optical Verification

- System-level verification of model performed by comparing measured beams from ATS heliostat at NSTTF site to simulations for a given date: August 23rd
  - Comparison of beams from simulation and contour plots from testing:

Time	10:03 AM	12:30 PM	3:12 PM	4:12 PM	5:45 PM
Actual BCS Contour Plots					
Simulated APEX Irradiance Plots					

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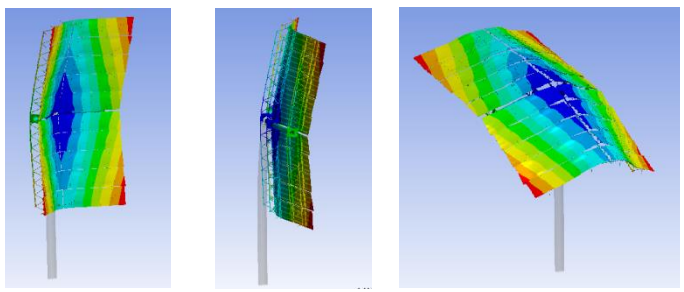
Methodology for Optical Improvement

- Heliostat deflections are a function of elevation angle
  - The further a heliostat rotates from the orientation in which it was canted, the more it deflects
    - The direction of original canting adjustments is no longer opposite to gravity deflections



Heliostat Deflection Modes by Elevation Angle

- The proposed solution: Perform mirror alignment when the heliostat is oriented in the angle in which it will collect the most power during a typical year

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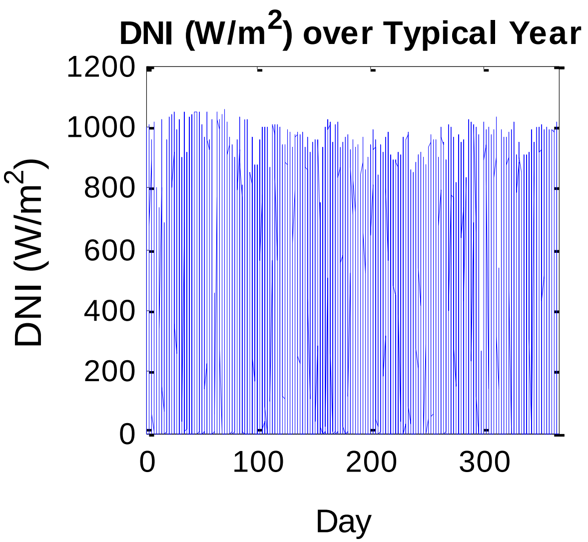
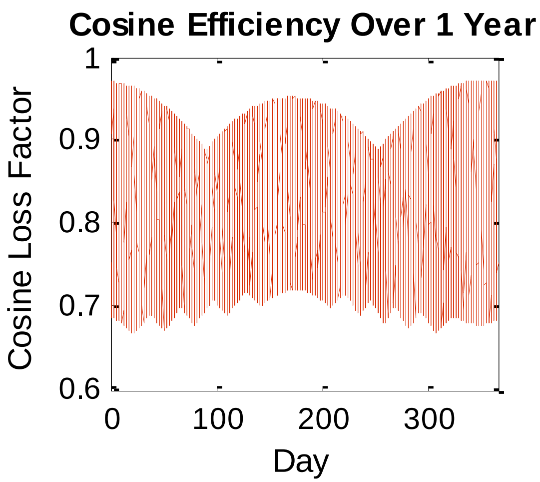
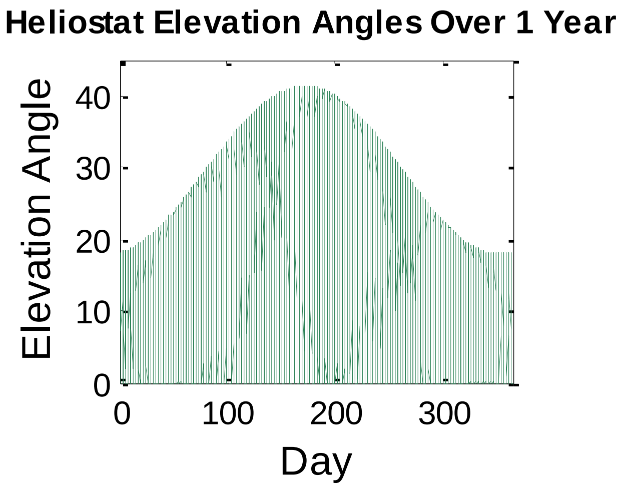
Power Weighted Elevation Angle

- Factoring in seasonal DNI variation and cosine loss what angle is the heliostat in when it is collecting the most power?







- Average over each hour of a year, weighted by power available:

$$\theta_{power\ weighted} = \frac{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i * \theta_{Elevation_i}}{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i}$$

Power Weighted Elevation Angle

$$\theta_{power\ weighted} = \frac{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i * \theta_{Elevation_i}}{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i}$$

- Canting a heliostat in this orientation angle minimizes structural deflections during times of peak power collection potential
  - Canting **strategy** does not change, only the orientation angle in which it is implemented

Key Elevation Angles for ATS Heliostat @ NSTTF Site	Angle
Solar Noon, Equinox	**29.279**
Solar Noon, Summer Solstice	**41.402**
Solar Noon, Winter Solstice	**17.953**
Power-Weighted Elevation Angle	**22.934**

Power Weighted Elevation Angle

$$\theta_{power\ weighted} = \frac{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i * \theta_{Elevation_i}}{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i}$$

- Conceptually, this assumes that:
  1. The heliostat is canted using the strategy desired, with no gravity
  2. The heliostat is rotated to $\theta_{powerweighted}$ and is subjected to gravity
  3. The mirrors are returned to the positions they would have been in if there was no gravity
     - The canting strategy stays the same

- Actual implementation would use same manufacturing and canting methods, but with a different desired shape, obtainable by FEA

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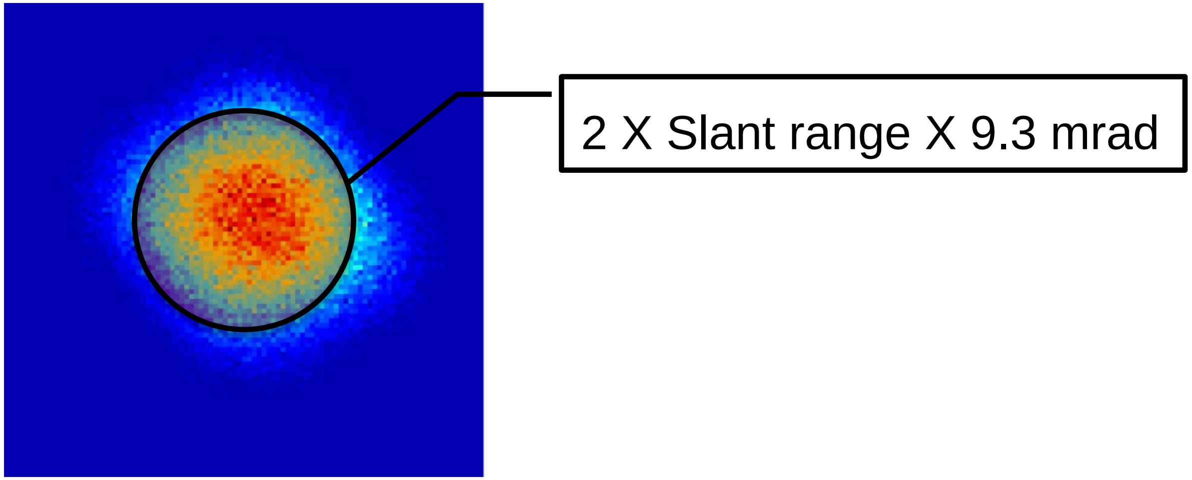
Metrics

- Performance for each canting orientation was quantified based on *the amount of power incident on a target* ***twice the diameter*** *of the* ***ideally focused beam*** (slant range x sun subtended angle)

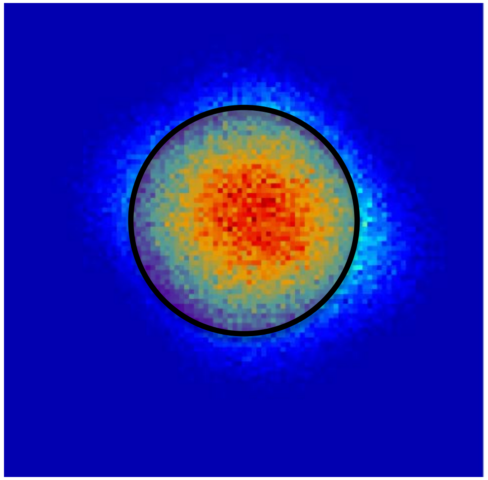


- Simulations were performed to obtain comparisons of:
  1. Instantaneous intercept factor
  2. Daily intercept factor
  3. Annual intercept factor ← **This is the key performance metric**

Metrics: Instantaneous Intercept

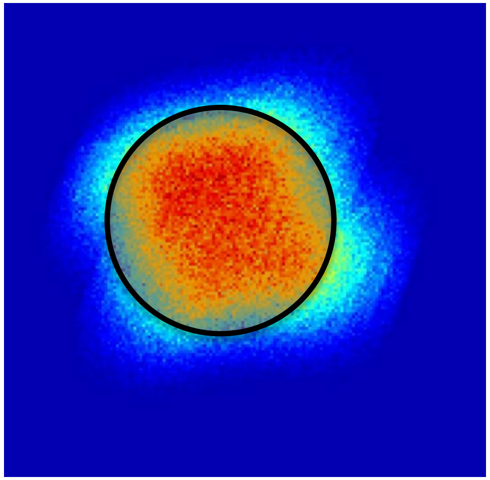
- Step 1: Compare instantaneous intercept factors for each method

3:12 PM (NOON +2.07 HRS), SUMMER SOLSTICE



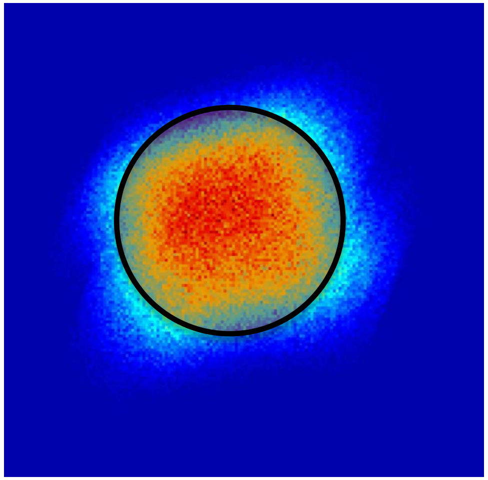
NO DEFORMATION

Total Power: 128 kW
Power on target: 117 kW
Intercept Factor: 91.4%



CANTED AT 29.279 DEG (NOON EQUINOX θ)

Total Power: 128 kW
Power on target: 109kW
Intercept Factor: 85.2%

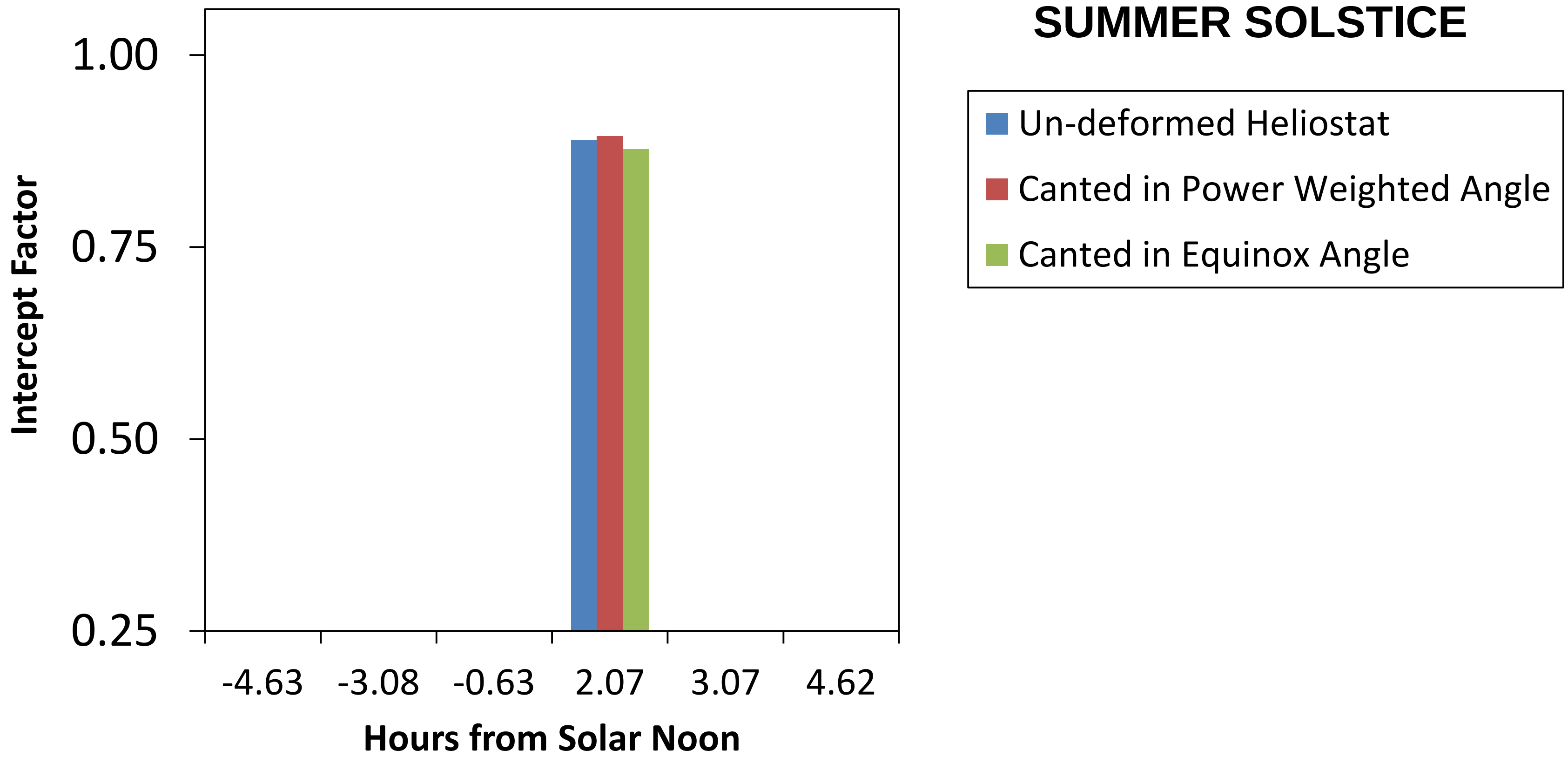


CANTED AT 22.934 DEG (POWER WEIGHTED θ)

Total Power: 128 kW
Power on target: 113 kW
Intercept Factor: 88.3%

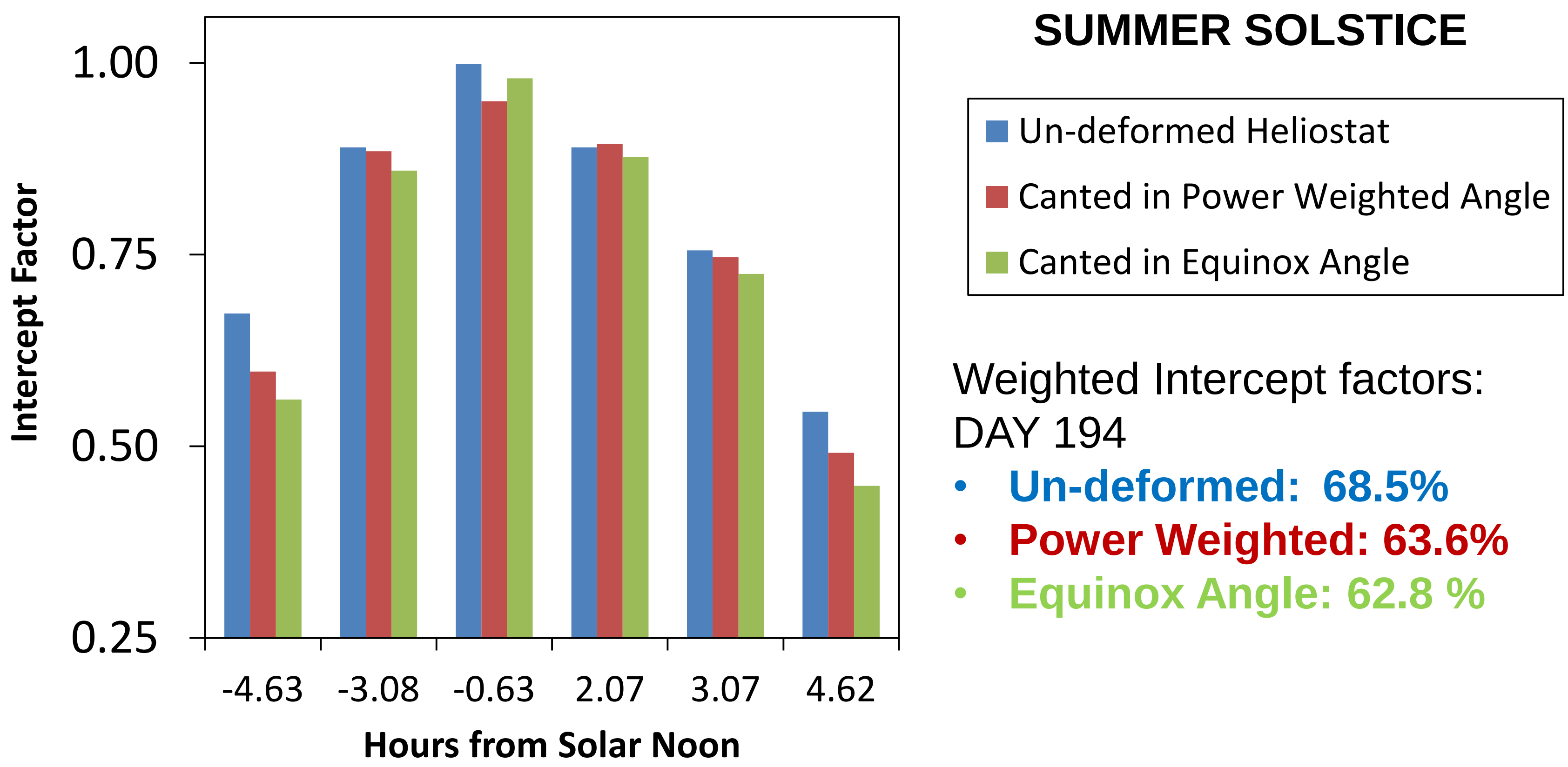
Metrics: Instantaneous Intercept

- Place instantaneous results in the context of a full day. Repeat the analysis for remaining times of day.



Metrics: Daily Intercept Factor

- Step 2: Compile instantaneous results for one day to obtain a weighted, interpolated daily intercept factor

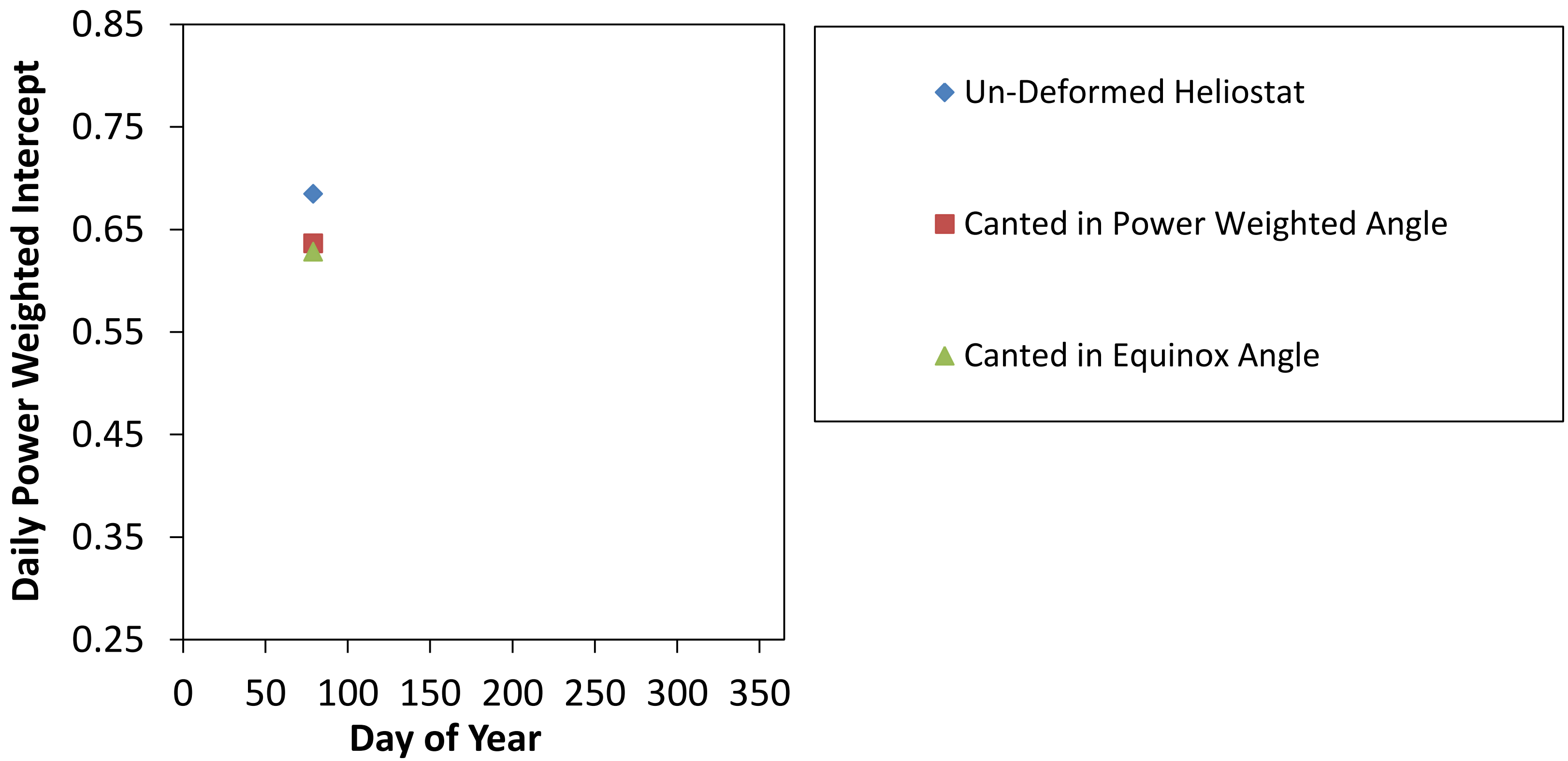


Weighted Intercept factors:
DAY 194

- **Un-deformed: 68.5%**
- **Power Weighted: 63.6%**
- **Equinox Angle: 62.8 %**

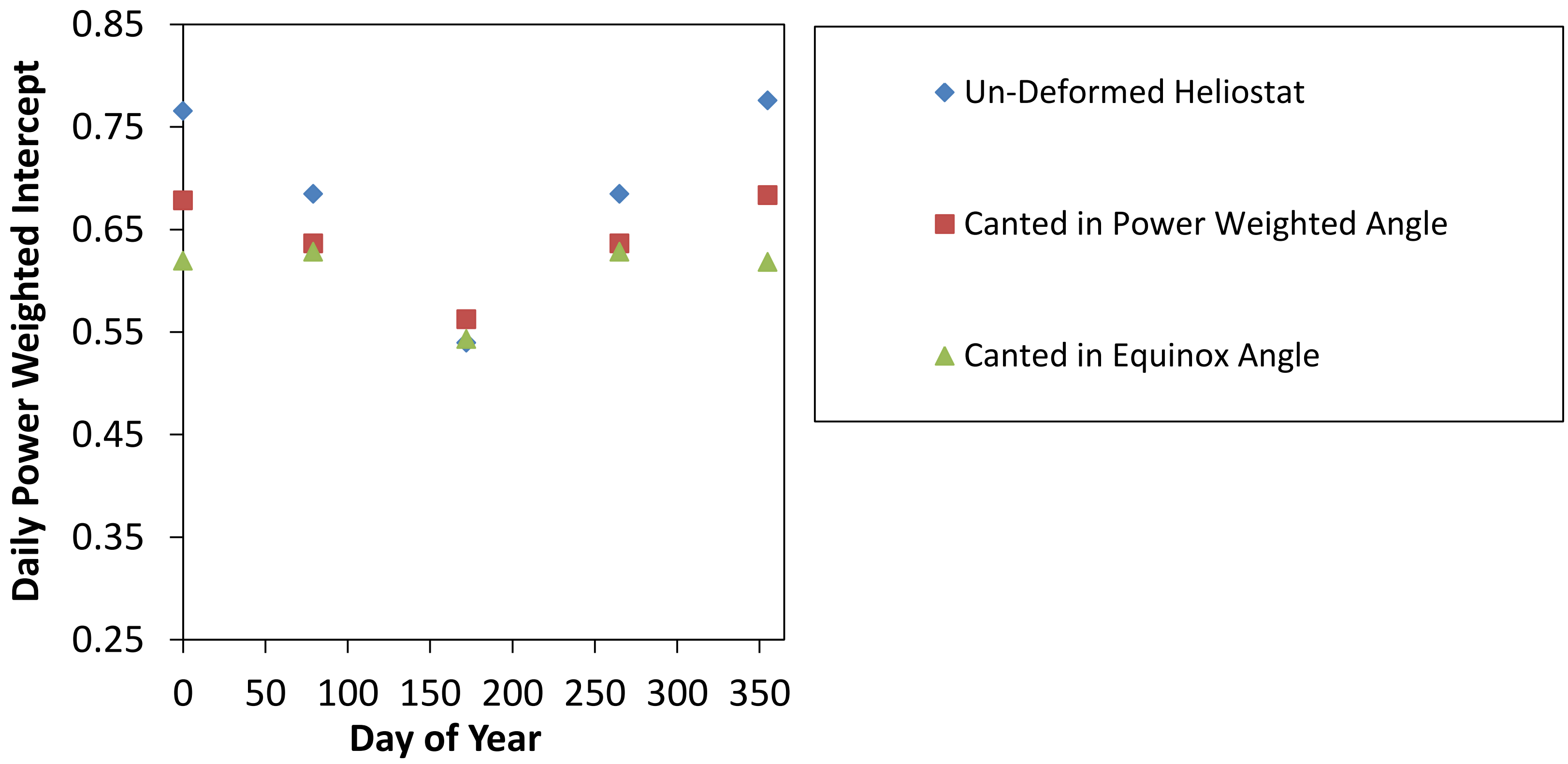
Metrics: Daily Intercept Factor

- Place results from one day in the context of a full year. Repeat the analysis for additional days.



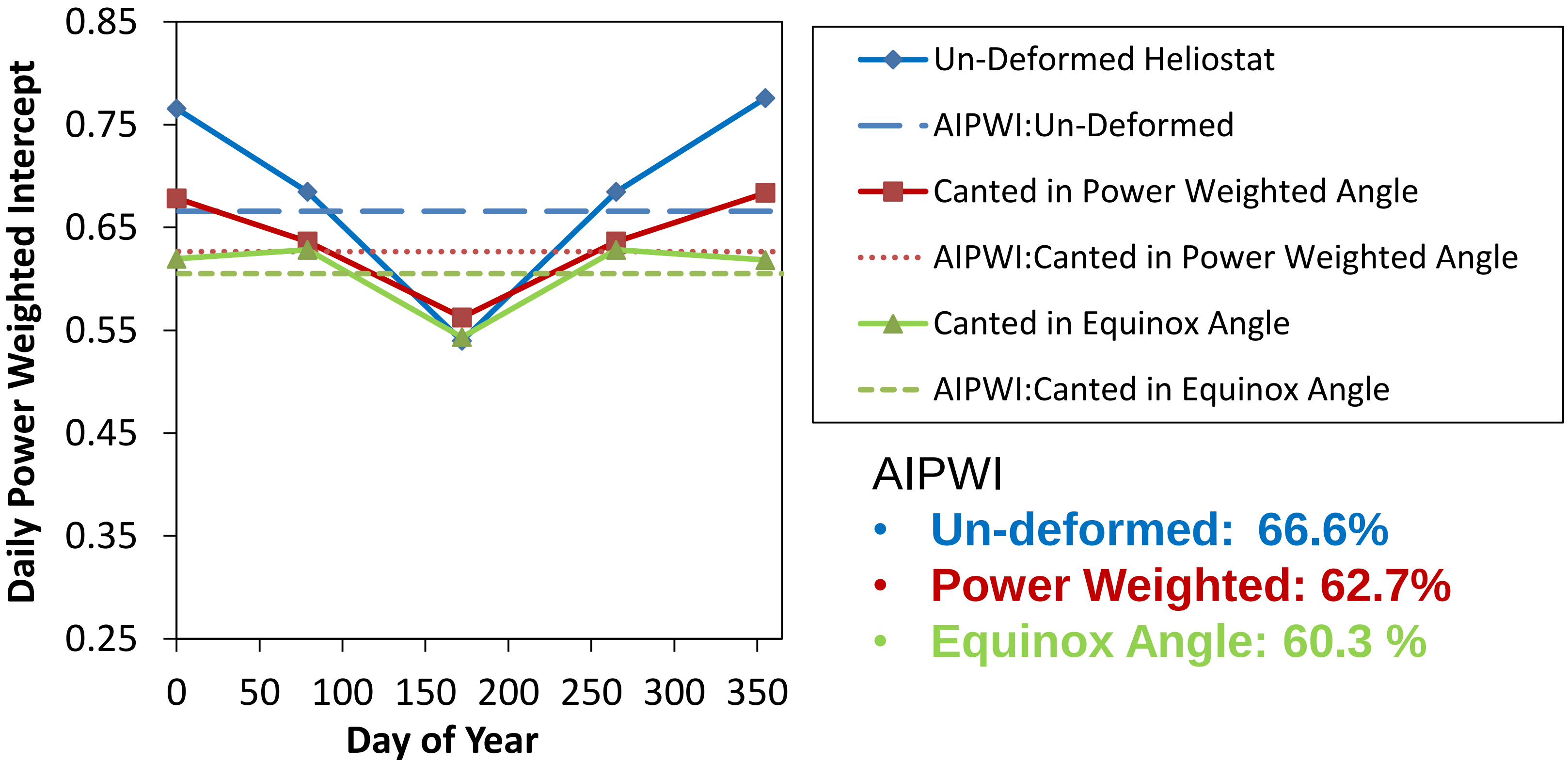
Metrics: Annual Intercept Factor

- Step 3: Compile results from several days throughout the year to obtain a weighted, interpolated estimate of annual performance



Metrics: Annual Intercept Factor

- Step 3: Compile results from several days throughout the year to obtain a weighted, interpolated estimate of annual performance



AIPWI

- **Un-deformed: 66.6%**
- **Power Weighted: 62.7%**
- **Equinox Angle: 60.3 %**

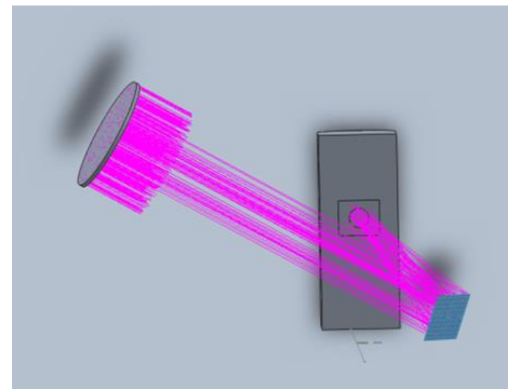
Notes on Improvement Metrics

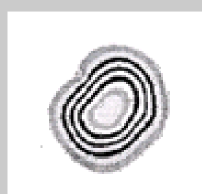
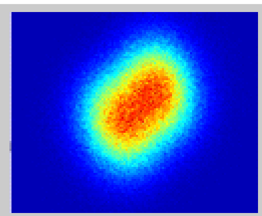
- An even greater gain could be realized with a change in canting strategy
  - Base case was taken as canted **TO** and **ON** solar noon during the equinox
  - Other canting strategies may yield further improvement
- Analyses were performed with no slope error
  - Actual improvement would be less apparent

-> This analysis presents a generalizable, implementable method for improving heliostat optical performance using existing manufacturing techniques

Summary

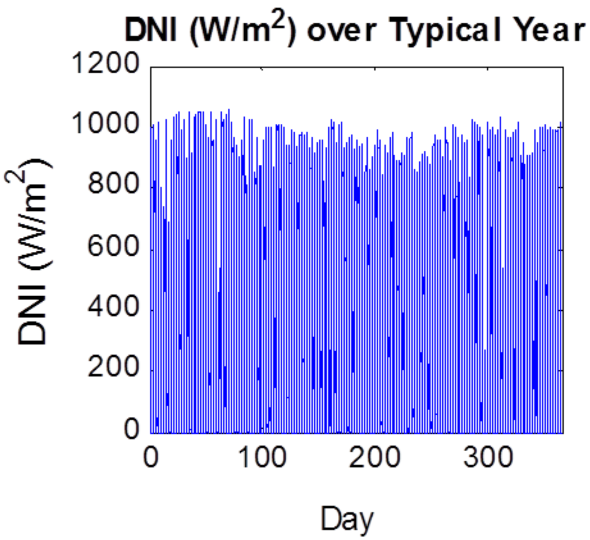
- A coupled FEA to optical modeling method to rigorously simulate heliostat beams was developed and verified against an beams produced from testing

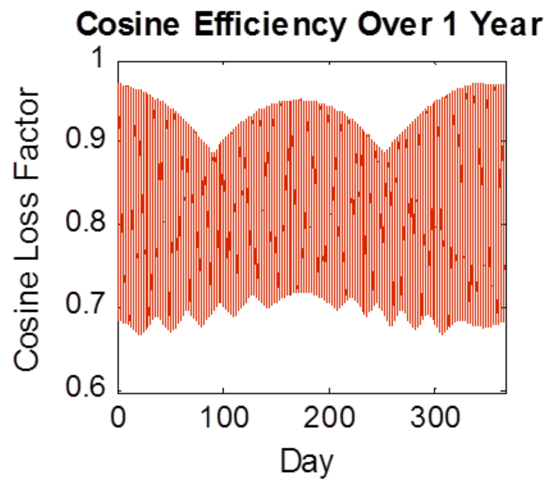


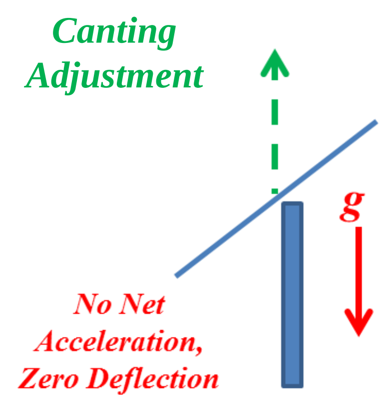
Contour from testing	Simulated irradiance
	

Summary

- A new method for performing canting was investigated
  - Consists of performing adjustments at the orientation the heliostat will be placed in when collecting the most power
  - **Shown to provide up to a 4.1% improvement**







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Questions

The National Solar Thermal Test Facility in Albuquerque, NM