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Modal Analysis and Dynamic Monitoring of a Concentrating Solar Heliostat

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Outline

- Introduction and Motivation
- Data Acquisition & Instrumentation
- Operational Modal Analysis
- FEA Mode Shape Correlation
- Ray Tracing & Optical Performance
- Conclusion

National Solar Thermal Test Facility

•200 ft. tall tower makes NSTTF one of the "tallest" and "hottest" test facilities in the country

•218 computer controlled heliostats concentrate sunlight producing temperatures up to 5000º K (~8540º F) and 5 MW of power

•Tower applications:
- •CSP R&D
- •Thermal performance testing
- •Space technology testing
- •Radar and Sensor testing
- •Astronomy experiments
- •Nuclear thermal flash simulations

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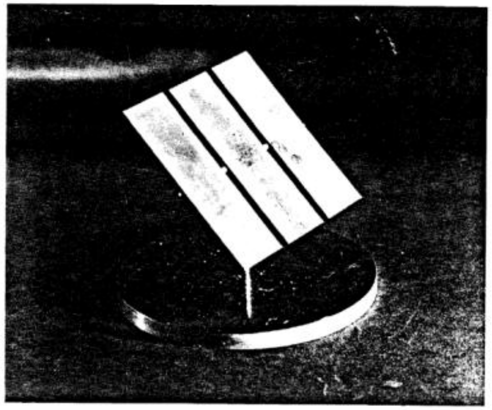
CSP Motivation

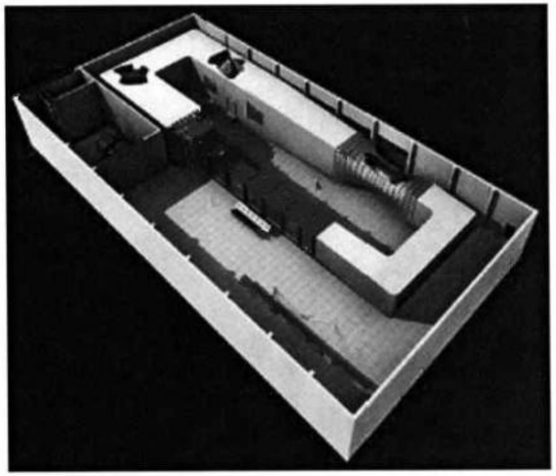
•Heliostat construction costs up to 50% of initial capital required for commercial CSP plant

•There currently exists no optimum heliostat size
- •Large area: ~130 m^2
  - •Larger wind load
  - •Higher cost per area ($/m^2)
  - •Higher electricity requirement
- •Small area: ~1m^2
  - •Requires more heliostats
  - •Higher wiring cost
  - •Low wind load
  - •Lower cost per area $/m^2

•Previous research considered static and dynamic wind loads using isolated scaled models in wind tunnels.
- •Correlation between high wind loads and vibration with turbulence intensity
- •Authors strongly urge full scale testing

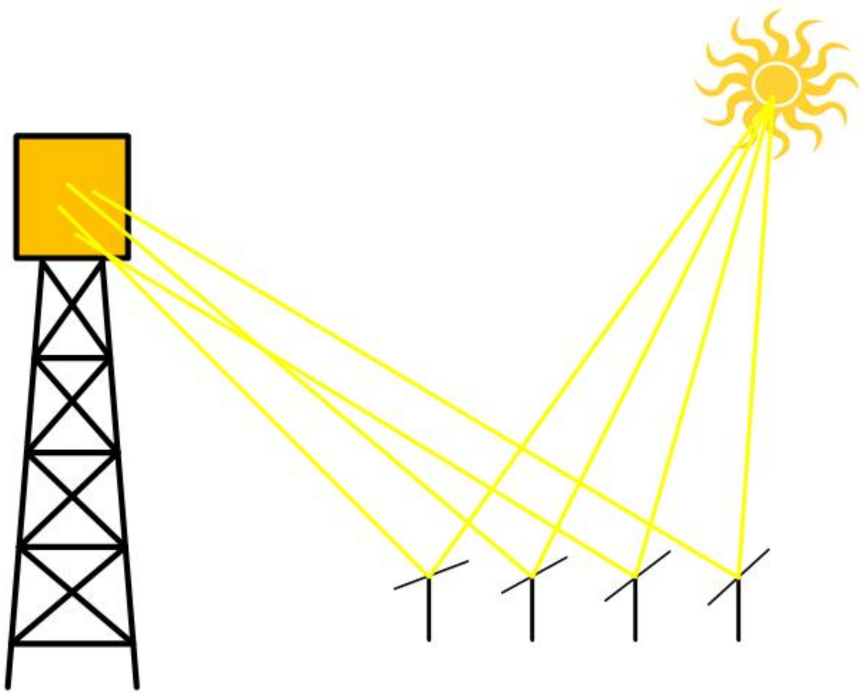


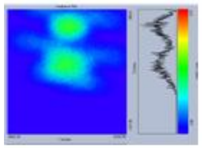
Paterka et al. 1986

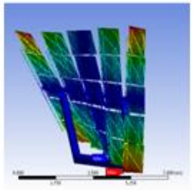


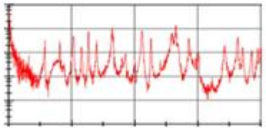
Gong et al. 2011

OMA Motivation









- Wind induced vibration leads to increased fatigue and premature failure
- Operational mode shapes reduce maximum flux contribution per heliostat during wind events
- Experimental validation and optical characterization will lead to further design improvements
- Demonstrate a unique link between structural dynamics and CSP optics engineering fields

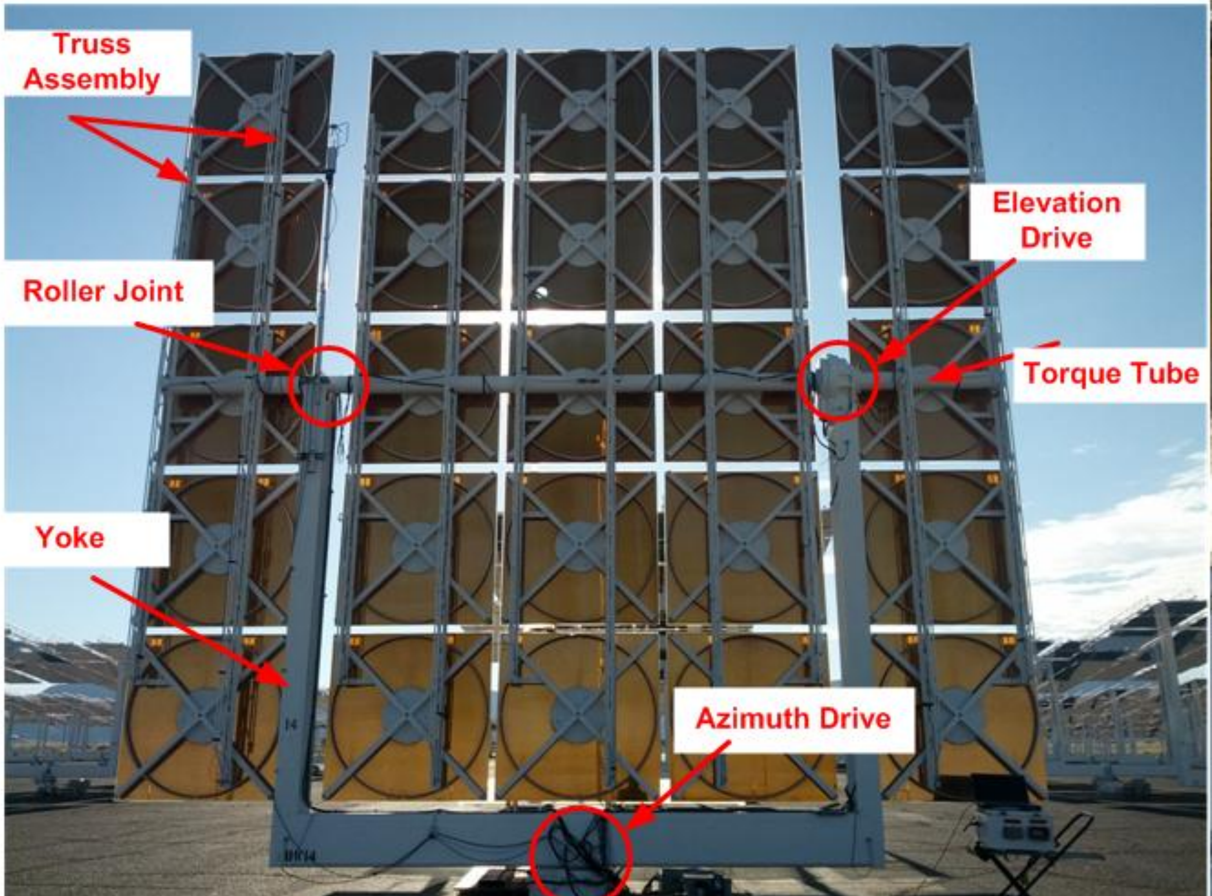
Objective

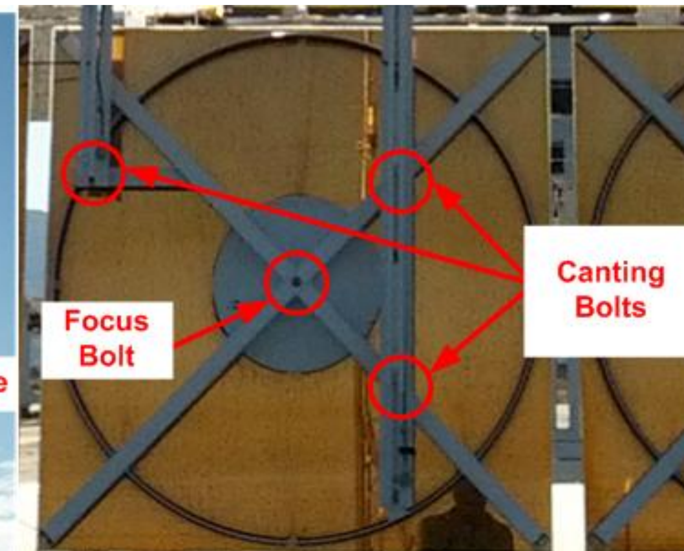
- **Instrument heliostats for dynamic monitoring capability**
  - Perform test and analysis to better characterize heliostat dynamics induced by wind loads
  - Verify FEM produced mode shapes

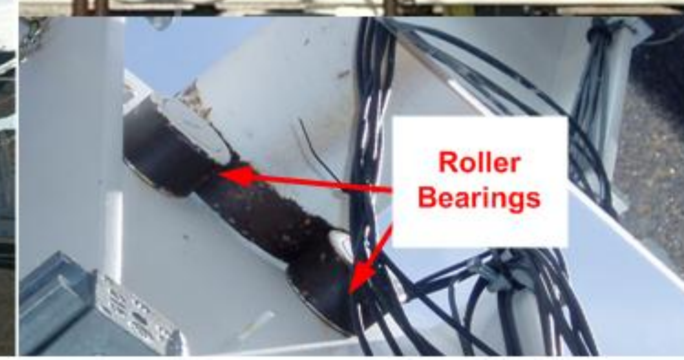
- **Characterize optical degradation via ray tracing methods**
  - Use scaled deformed FEM mode shapes as deformed heliostat surface

- **Mitigate wind induced fatigue and increase optical performance of next generation heliostats**
  - Improve existing heliostat design criteria which currently only considers wind induced fatigue and static loads

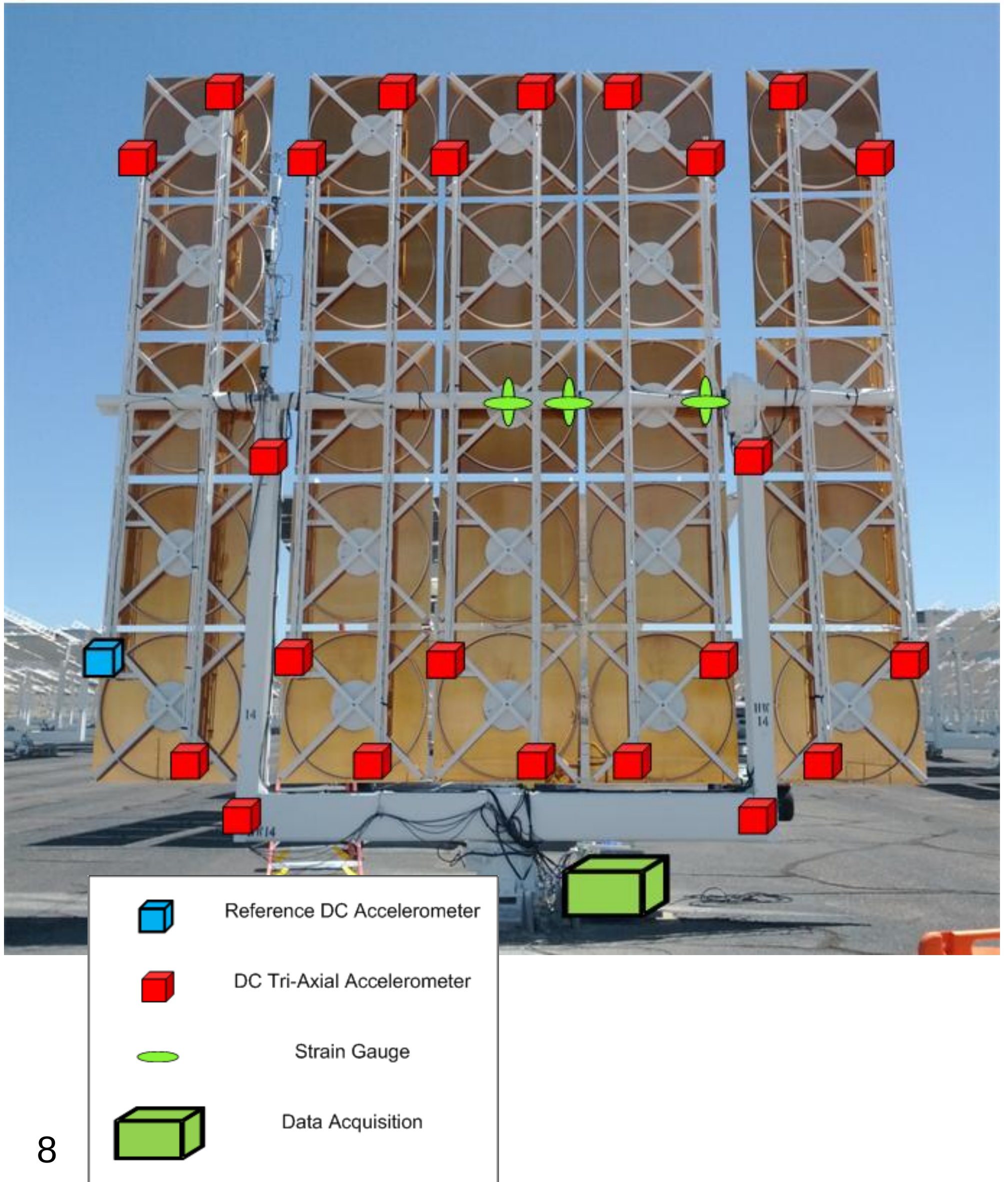
NSTTF Heliostat Geometry





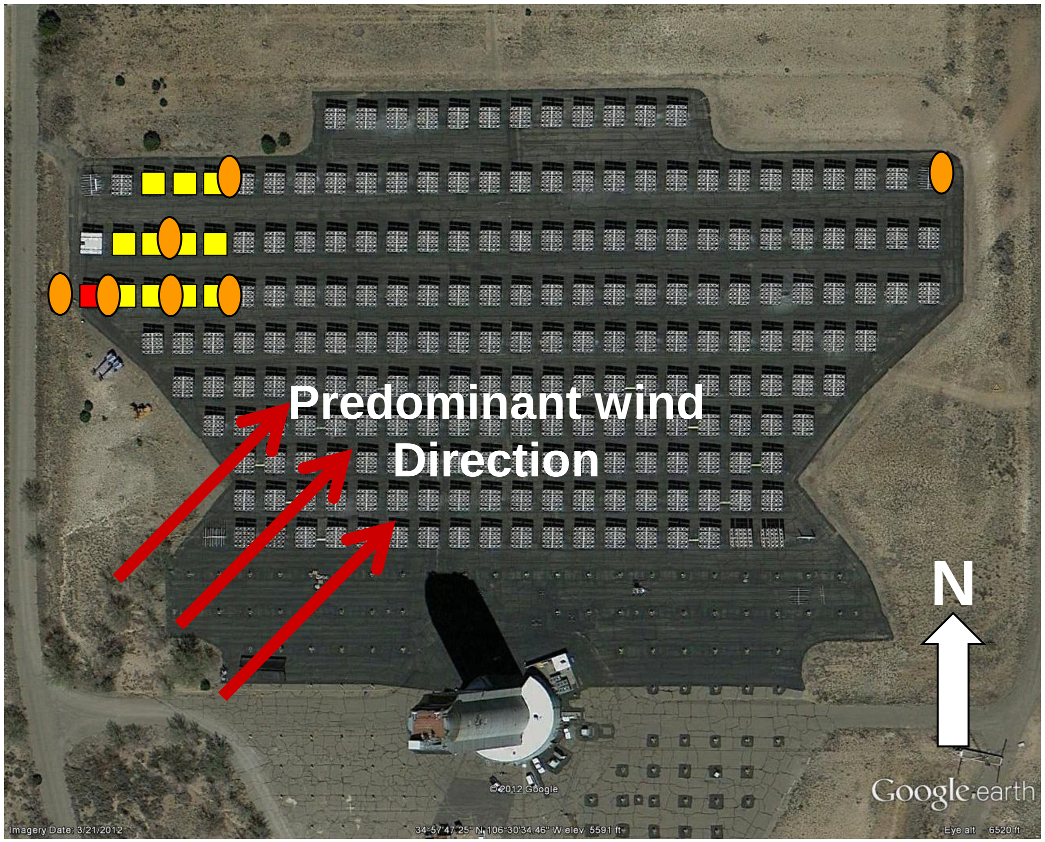


Well Instrumented Heliostat



- Heliostat 11W-14 Instrumented
    - 6 3D Wind Anemometers
    - 24 Tri-axial Accelerometers
    - 6 Strain Gauges
- Data communication between field and control tower established via fiber optic comm.
- Data acquisition system installed and verified
- Six wind sensors at various heights surround heliostat on anemometer towers
- Accelerometer sensitivity: 1000 mV/G

Instrumentation and DAQ



Wind Anemometer

Nominal Heliostat

Well Inst. Heliostat

- 13 total heliostats instrumented
- One single well instrumented heliostat used for full modal testing
- 11 Nominal heliostats monitor vibration magnitudes, strain, and wind data at select locations
- 1 Wind Anemometer located on western corner
- Data acquisition developed to stream data in real time to control tower

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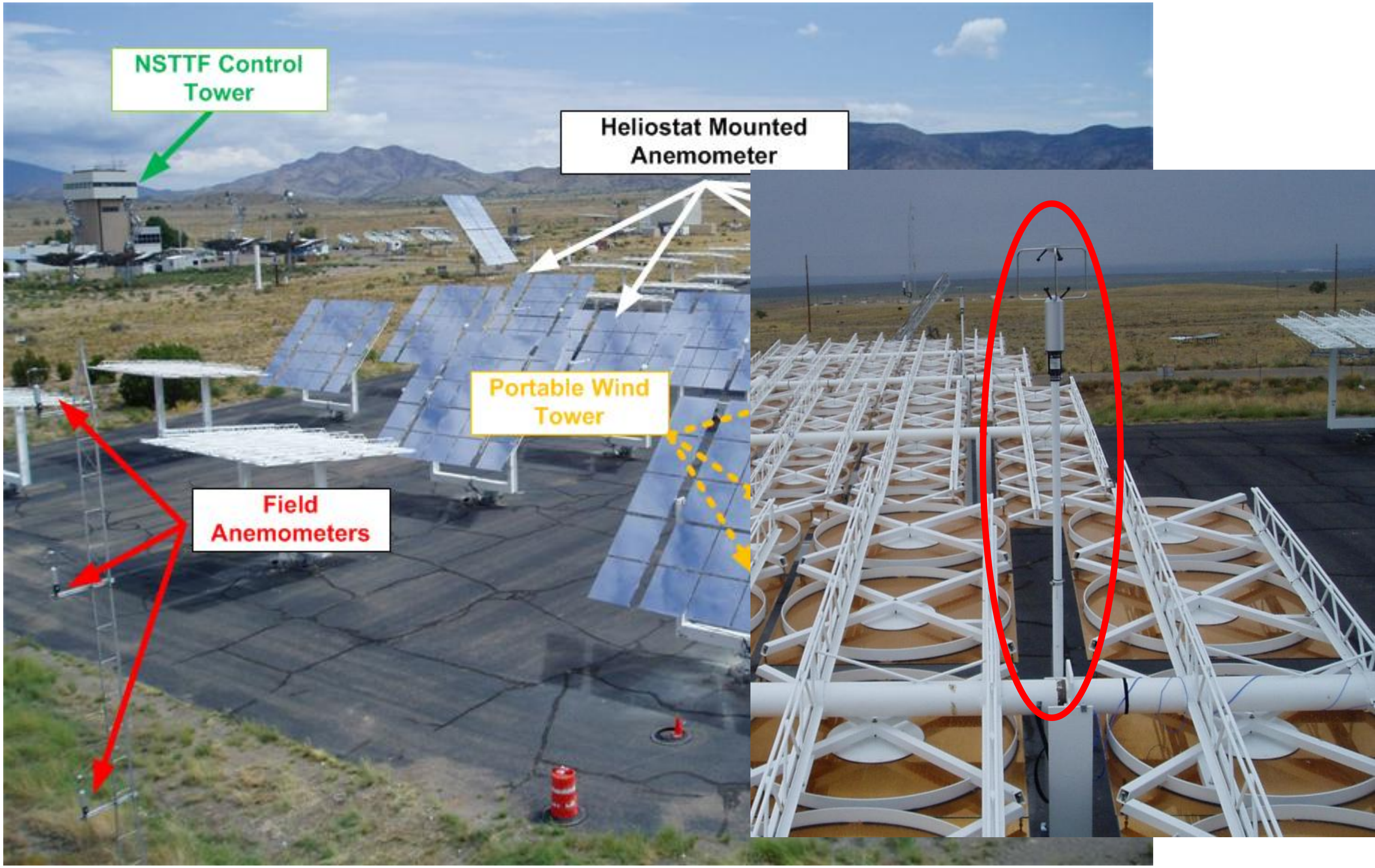
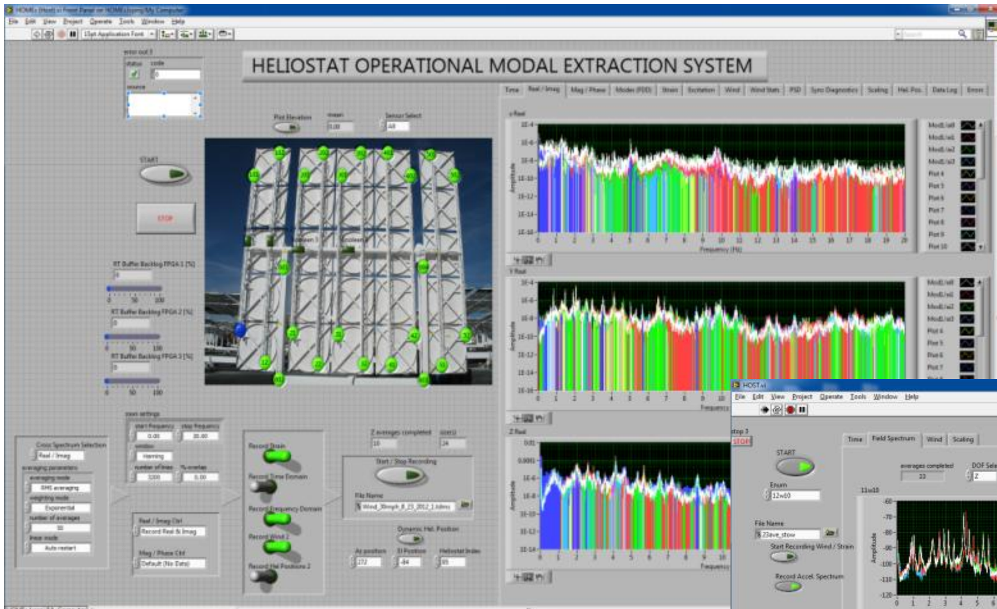
Instrumentation and DAQ

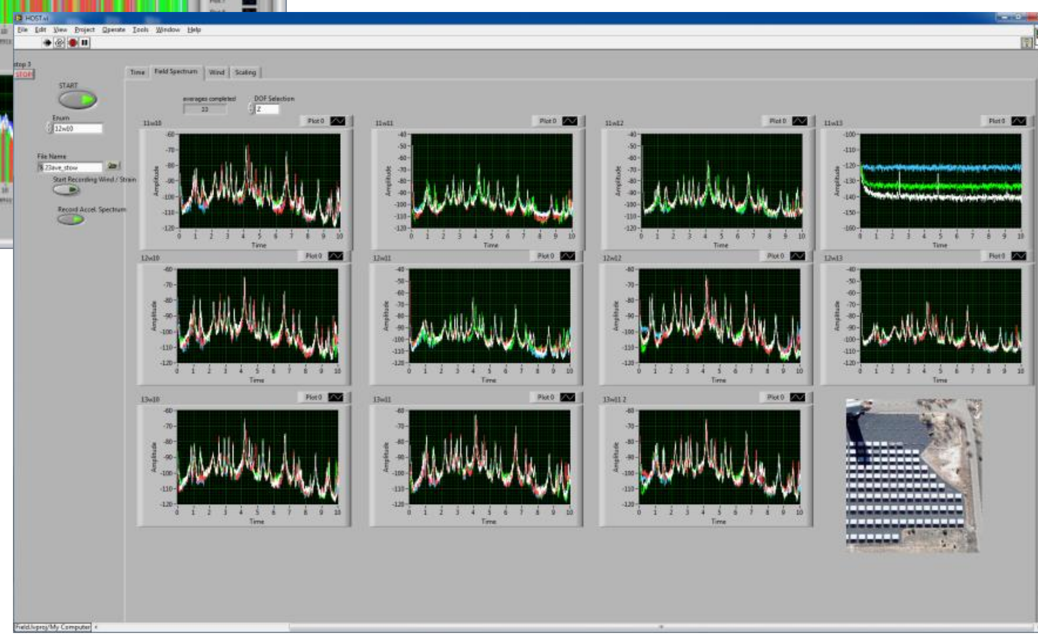


Instrumentation and DAQ



Well Instrumented Heliostat

•Monitors 24 tri-axial accelerometers, 6 strain, and 6 3D anemometers (~102 total channels on one heliostat)

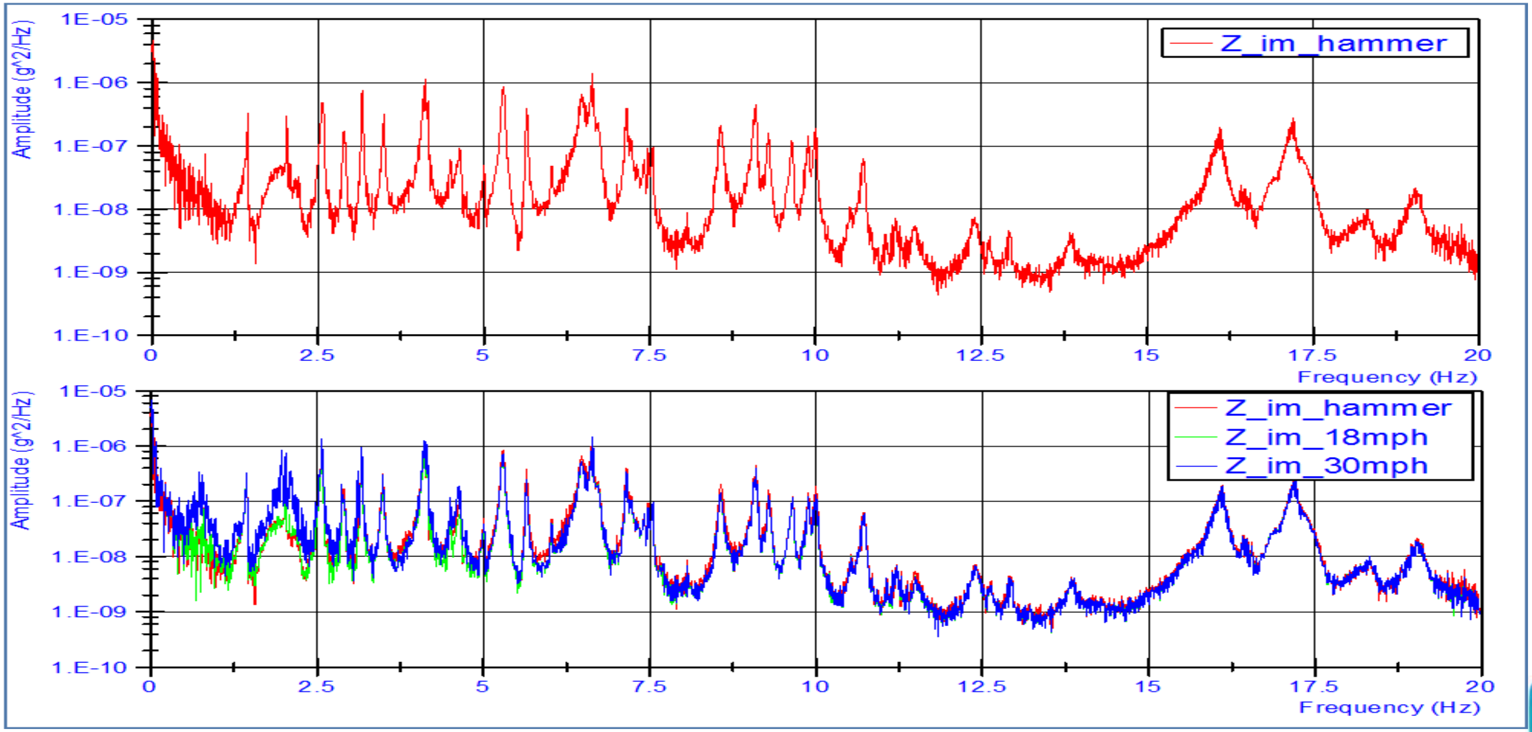


Nominally Instrumented Heliostats

•Monitors 4 tri-axial accelerometers per heliostat, strain, and wind sensors across 11 nominally instrumented heliostats

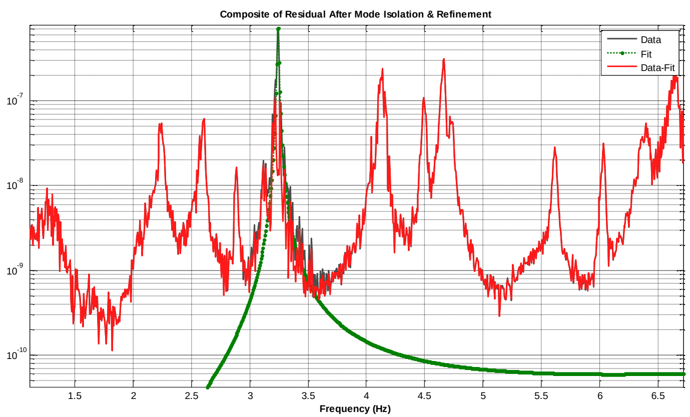
OMA (Random Excitation)

- Random excitation was shown to duplicate wind excited modes
  - Random excitation introduced via hammer input at various locations (red)
  - Power Spectra of 18-30 mph wind averages taken for comparison (blue / green)
- Random excitation technique was found replicate wind conditions and accelerate data collection
- Future monitoring of wind events will verify this method and / or provide a wind excitation profile for different wind speeds

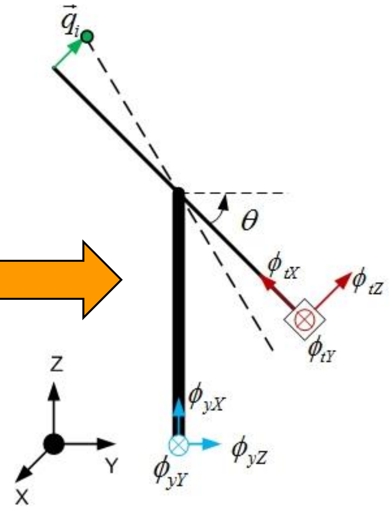


Mode Shapes

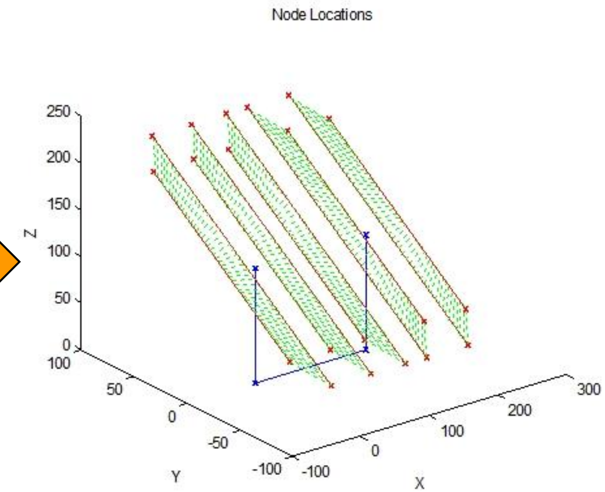
Mode Isolation (Curve Fitting)



Coordinate Transformation



Operational Mode Shapes



$$\vec{q_i} = \begin{Bmatrix} q_{i,x} \\ q_{i,y} \\ q_{i,z} \end{Bmatrix} = \begin{Bmatrix} q_{x0} \\ q_{y0} \\ q_{z0} \end{Bmatrix} + \begin{bmatrix} \phi_{tY} \\ \phi_{tZ}\cos(90-\theta) - \phi_{tX}\cos(\theta) \\ \phi_{tZ}\sin(90-\theta) + \phi_{tX}\sin(\theta) \end{bmatrix} \begin{Bmatrix} M_X \\ M_Y \\ M_Z \end{Bmatrix}$$

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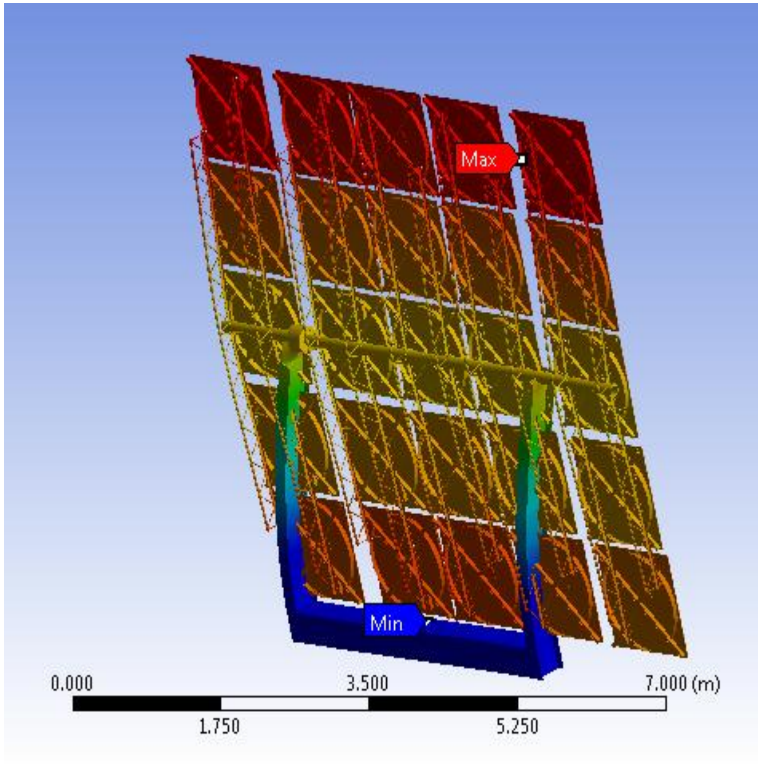
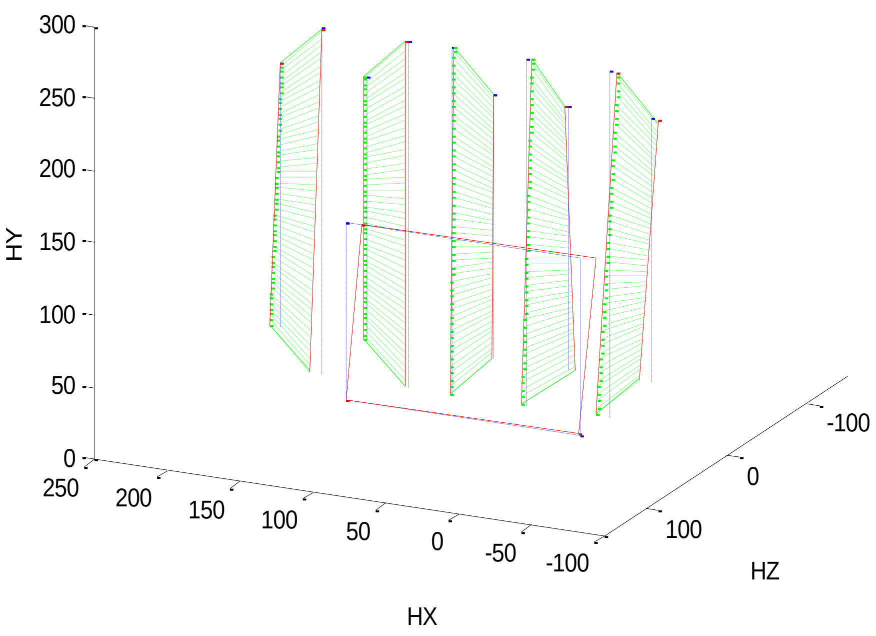
Yoke Bending Modes

Ansys: 1.604 Hz



OMA: 1.63Hz



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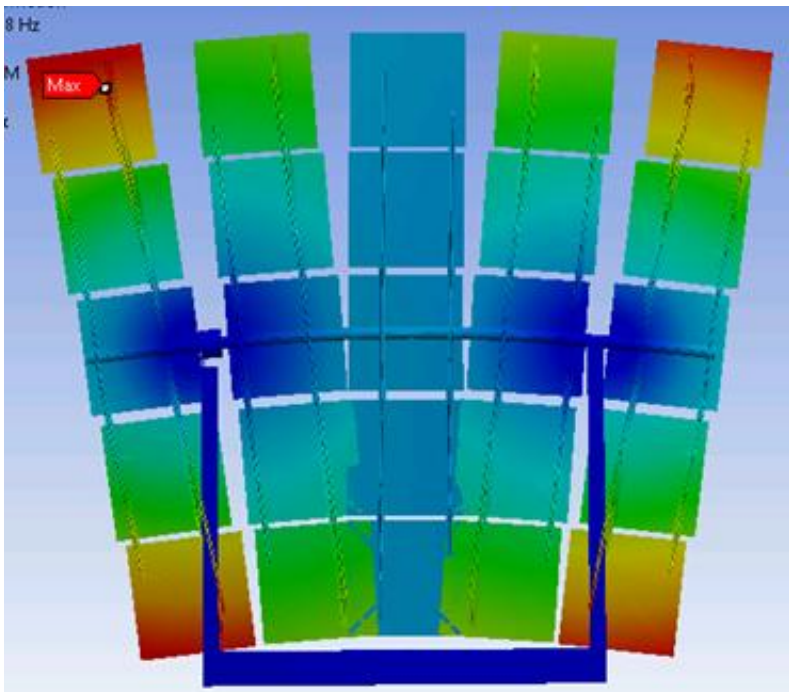
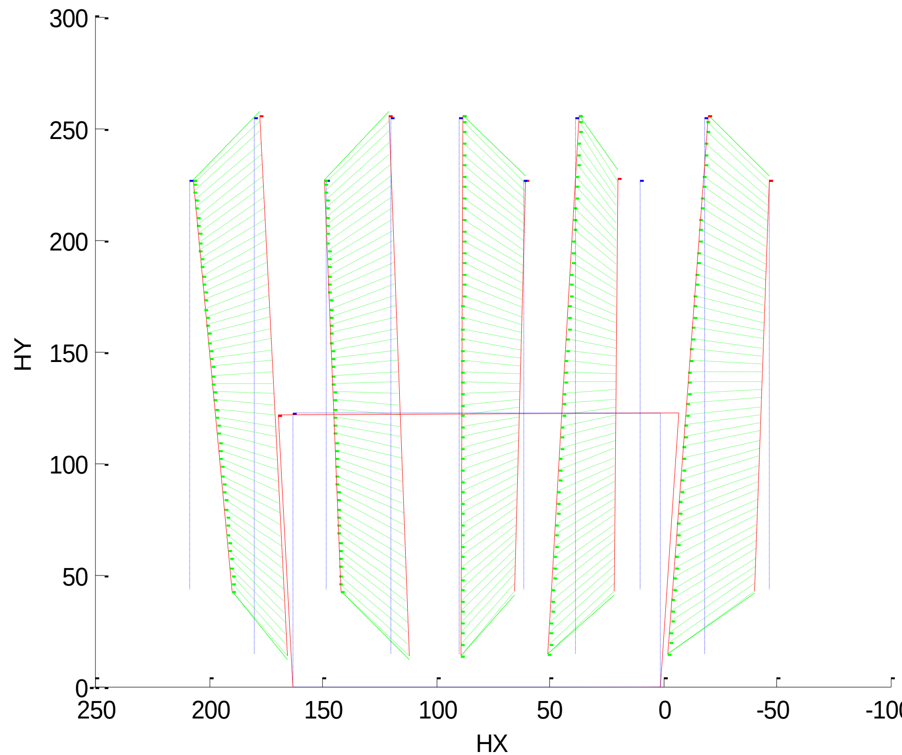
In-Plane Modes

Ansys: 3.0 Hz



OMA: 3.24Hz



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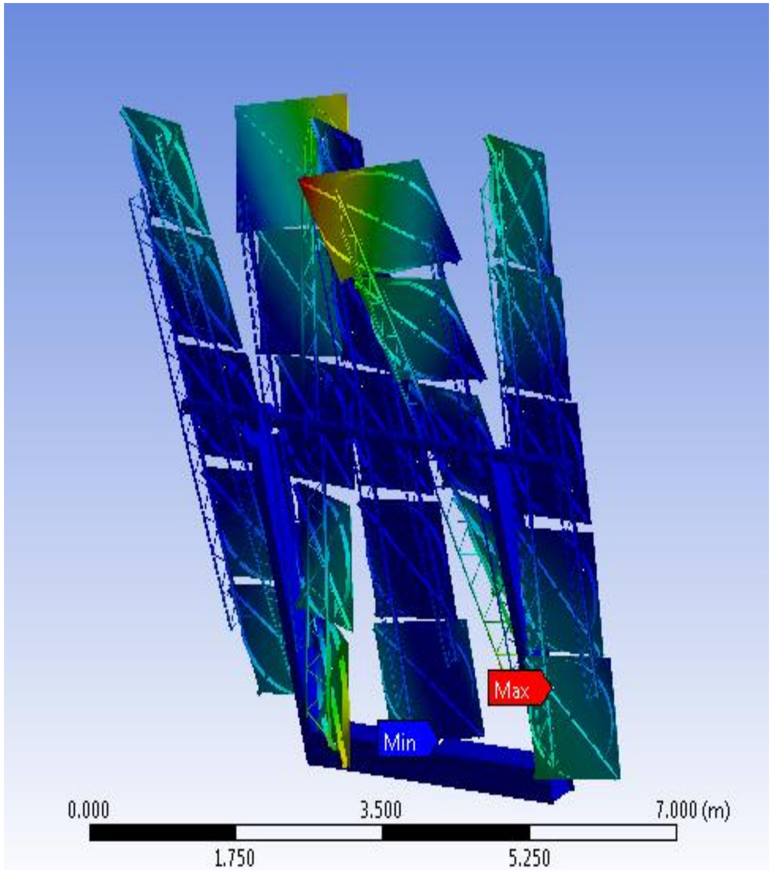
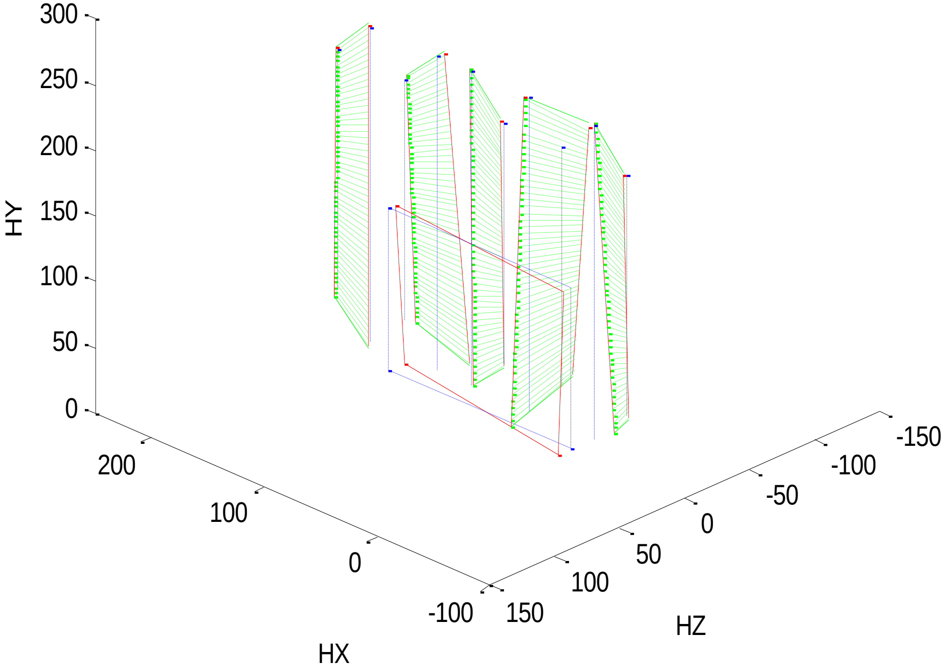
Out-of-Plane Modes

Ansys: 5.2 Hz



OMA: 5.61Hz



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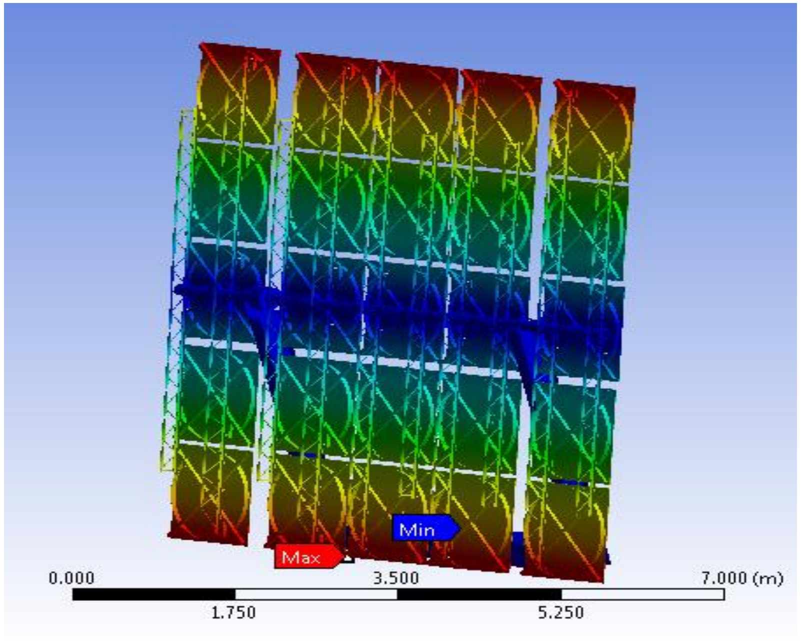
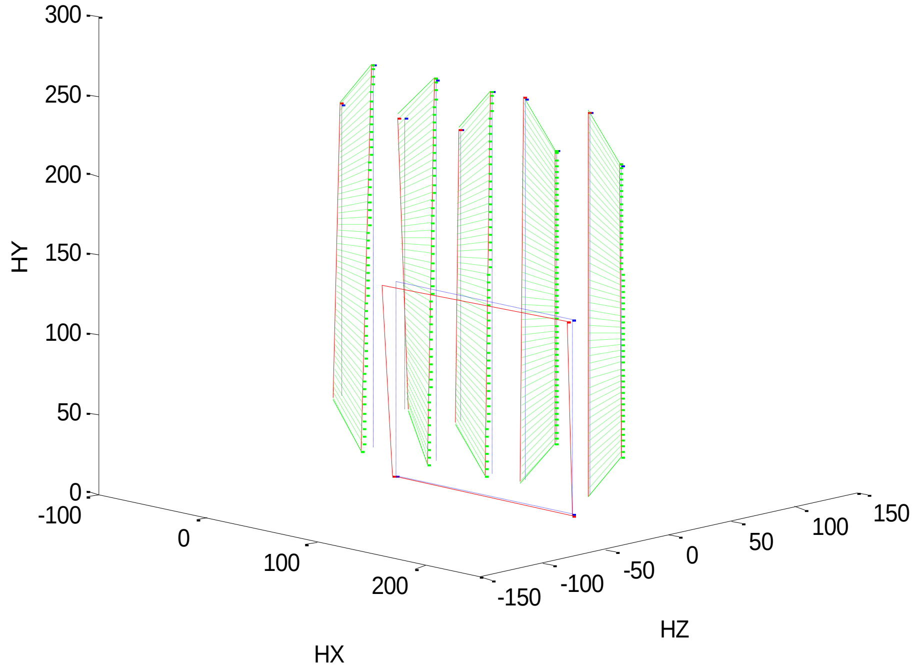
Rigid Body Modes

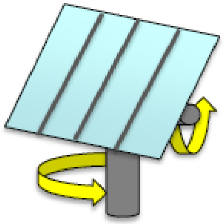
Ansys: 1.1 Hz



OMA: 0.9Hz

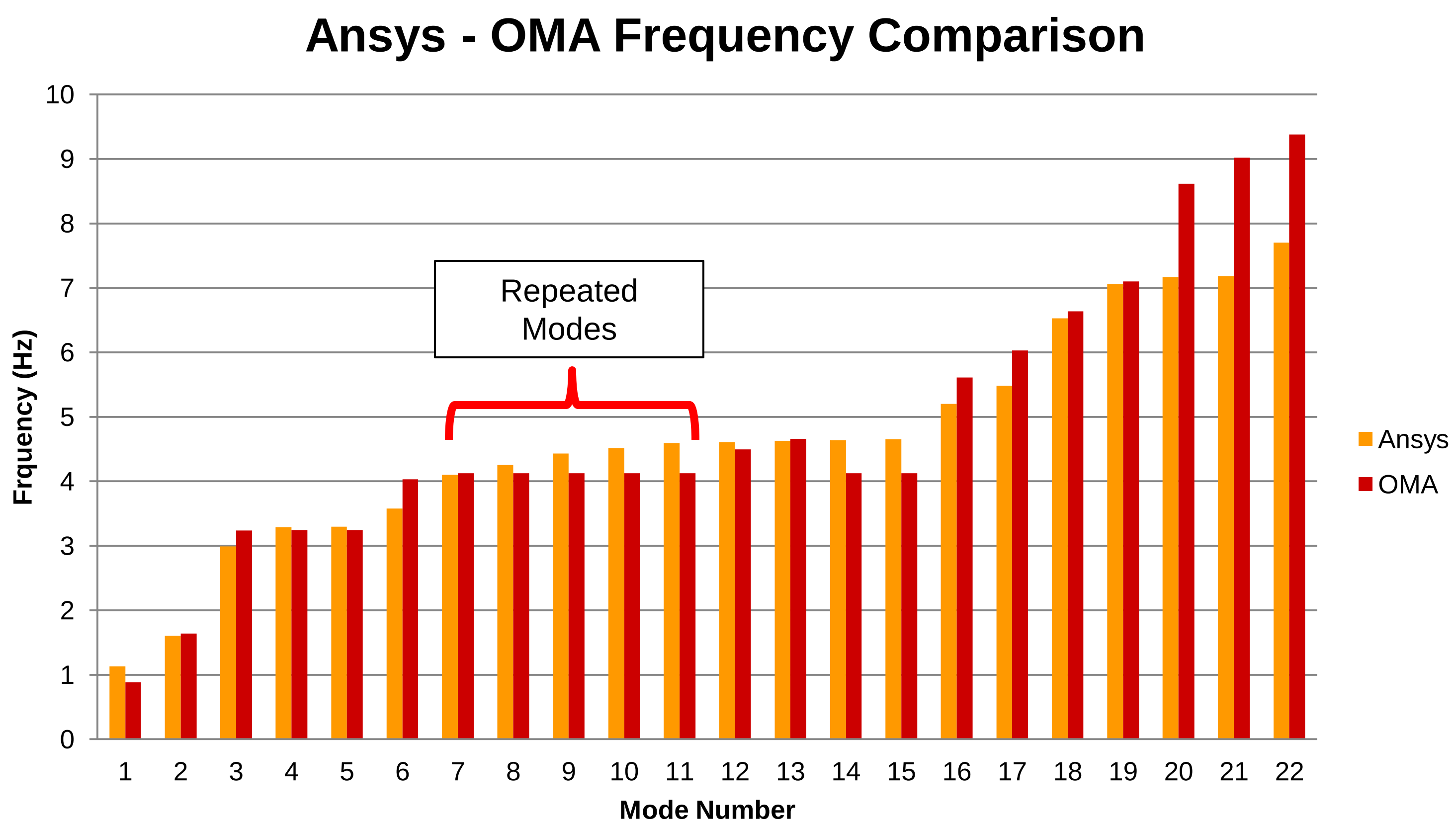


$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_\theta}{I_\theta}}$$



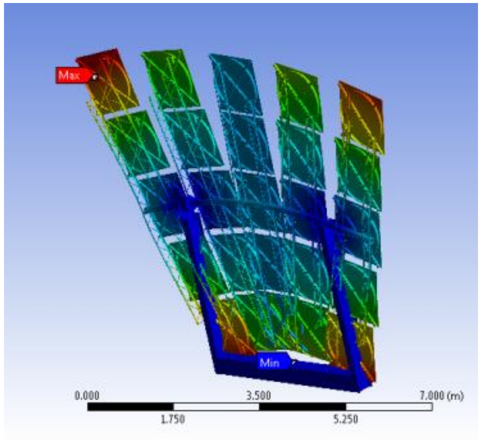
Rigid Body Modes ~0.8-1.25 Hz

FEA Comparison

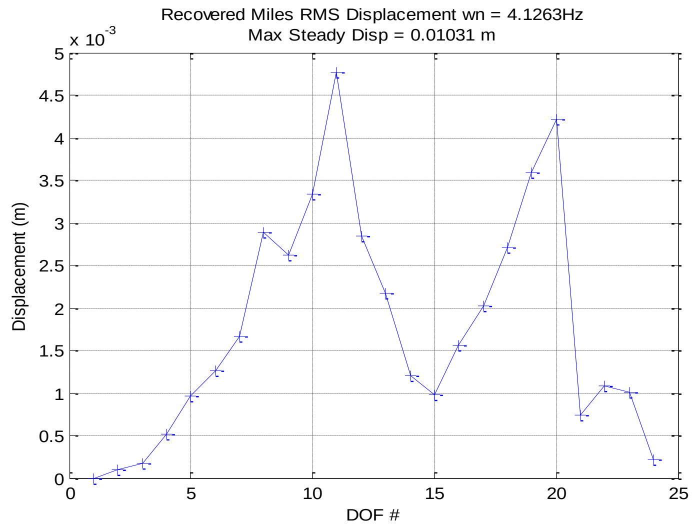


Displacement Model

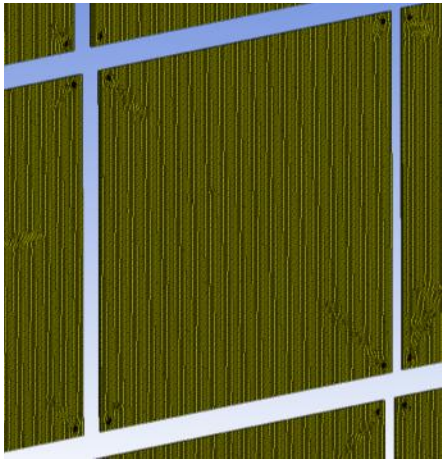
Arbitrary Displacement Result



Approximate DOF Displacements



Scale Output Mesh Surface



Miles Equation

- Assumes 1 DOF model
- Assumes "white noise" random vibration
- Q = Transmissibility factor
- D = Approximate Displacement (rms)

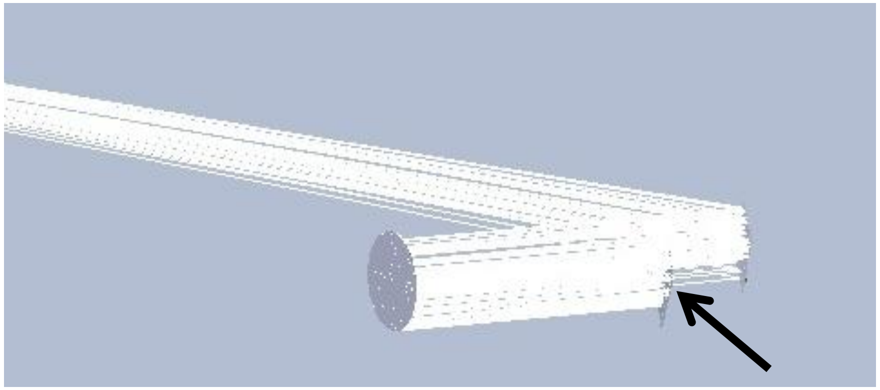
$$D_{rms} = \sqrt{\frac{\pi}{2} f_n Q \frac{\ddot{X}_{PSD}}{-\omega^2}}$$

$$\ddot{X}(f) = -\omega^2 X(f)$$

$$Q = \frac{1}{2\zeta}$$

Ray Tracing (CAD Model)

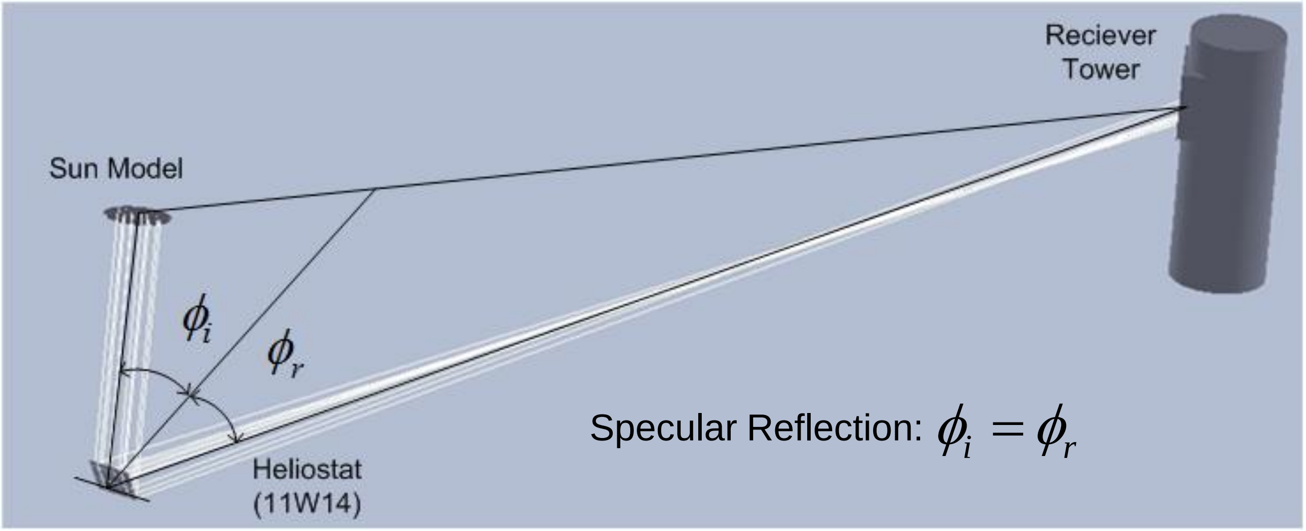
Reconfigurable model automatically updates by re-aiming heliostat for desired inputs



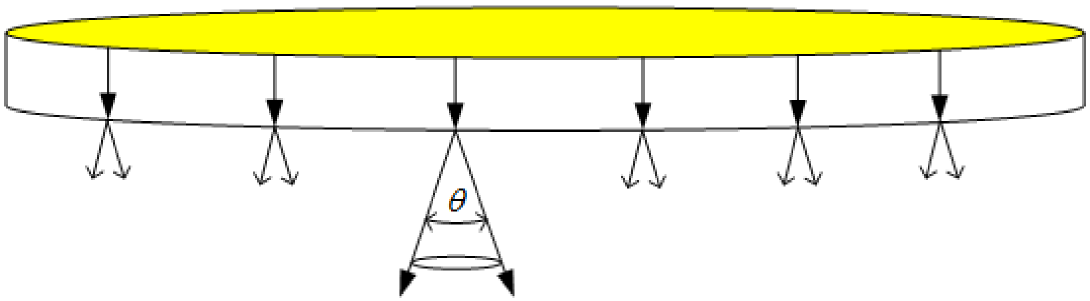
Adjacent Heliostat Added for Blockage Effects in Evening

<u>Inputs</u>

- Time of Day
- Day of Year
- Longitude & Latitude
- Solar Insolation



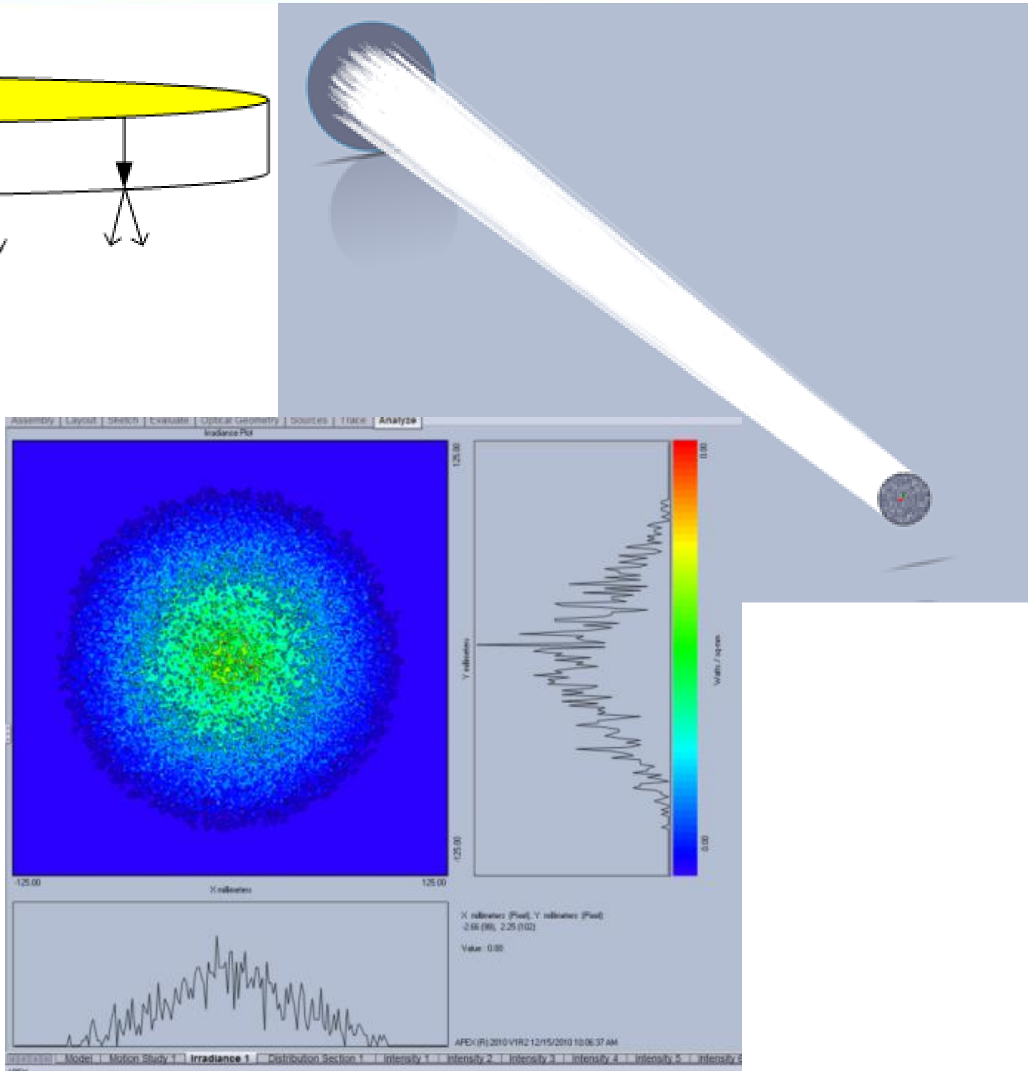
Ray Tracing (Sun Model)



$$Power = DNI * A_{Emmiting} * \frac{4}{\theta^2}$$

Rays Traced = 5.5 million
DNI = 1000 (W/m^2)
Wave Length = 550 nm
θ = Sun Cone Angle (0.57º)

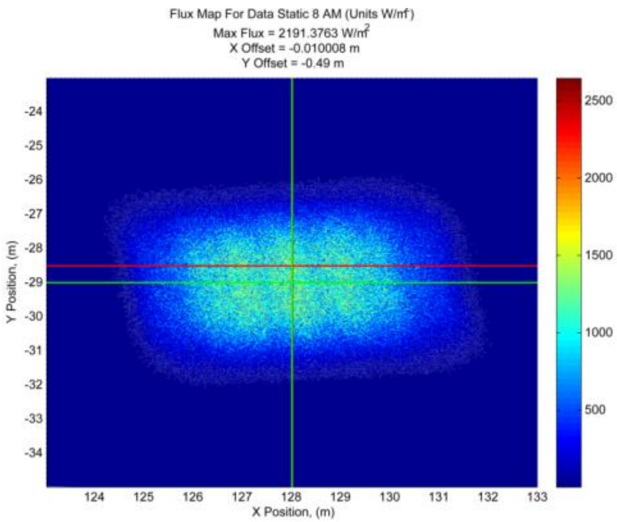
Simulations performed for March 21 at 8 AM, Solar Noon (~1 PM), and 6 PM



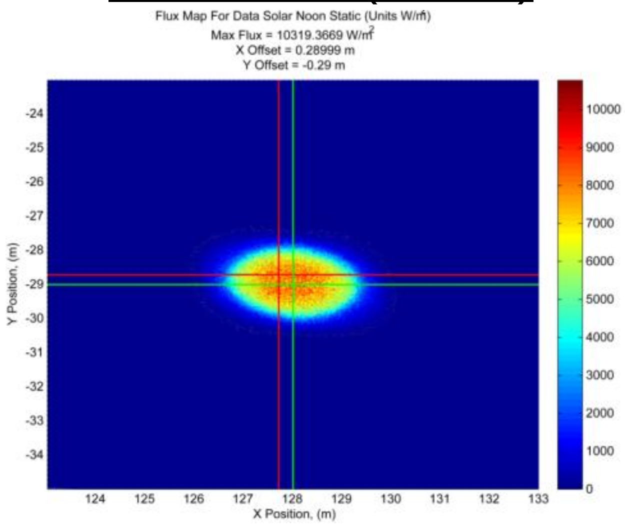
*Courtesy Joshua Christian, SNL

Ray Tracing: Static (Gravity)

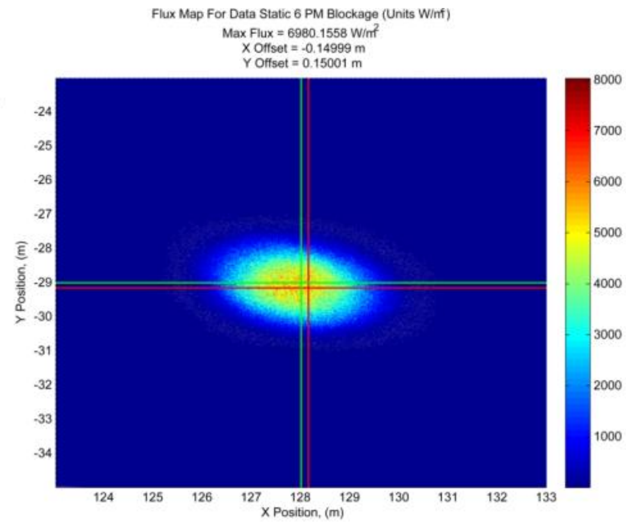
8 AM

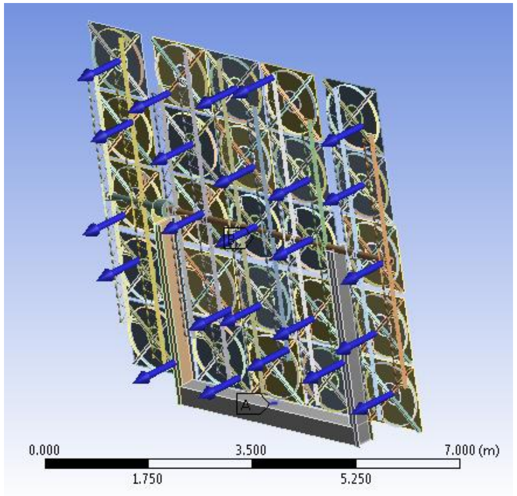


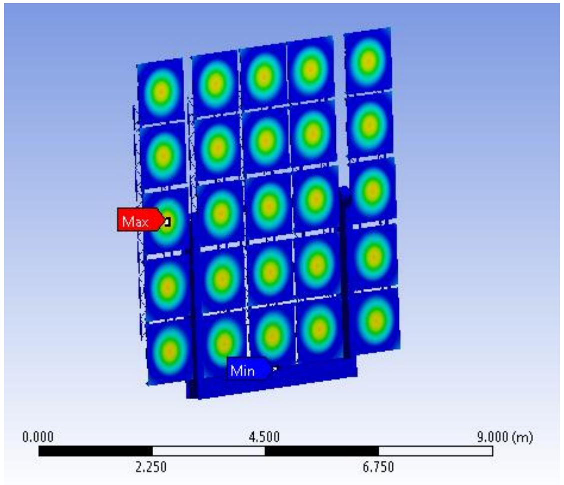
Solar Noon (~1 PM)



6 PM

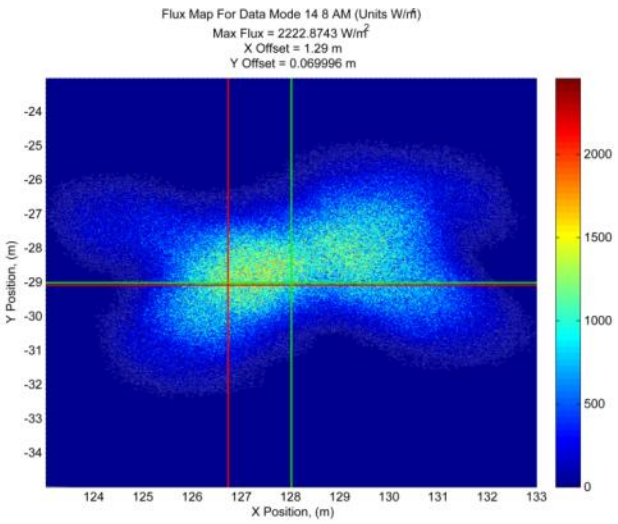




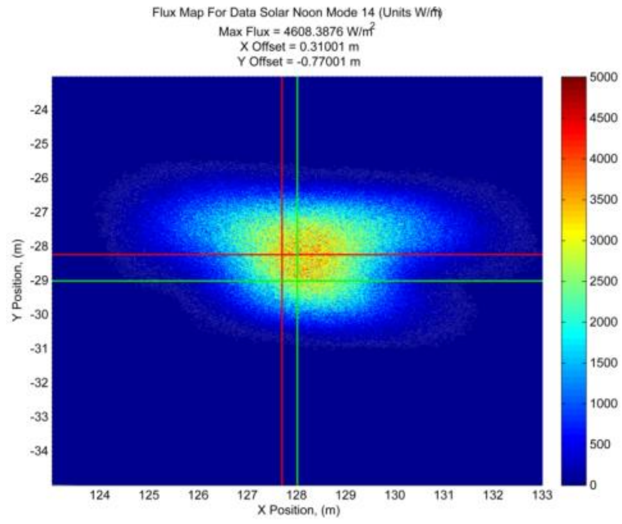


Ray Tracing: Mode 14

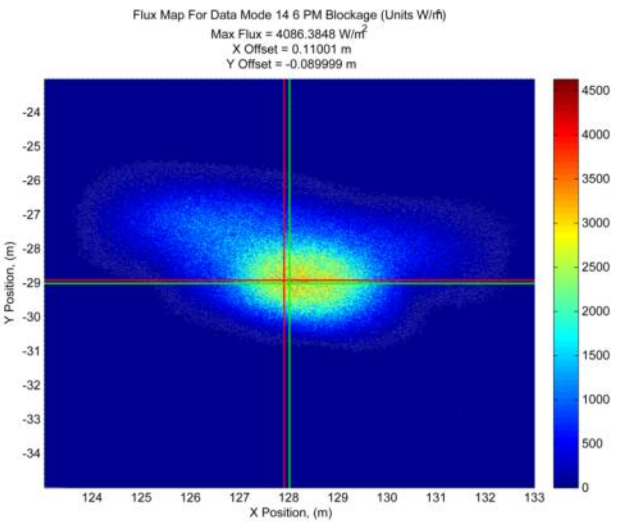
<u>8 AM</u>



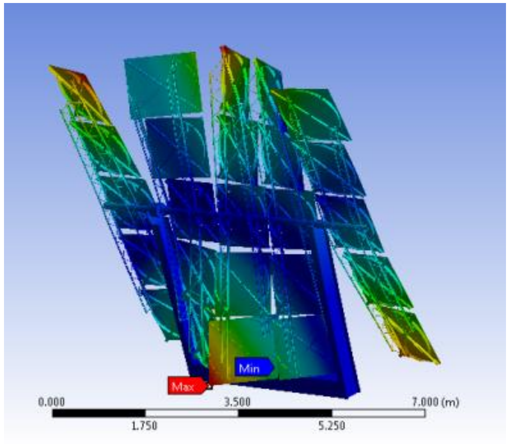
<u>Solar Noon (~1 PM)</u>



<u>6 PM</u>



<u>Mode #14</u>
Fn = 4.126 Hz
Max Disp. ~ 10.3 mm



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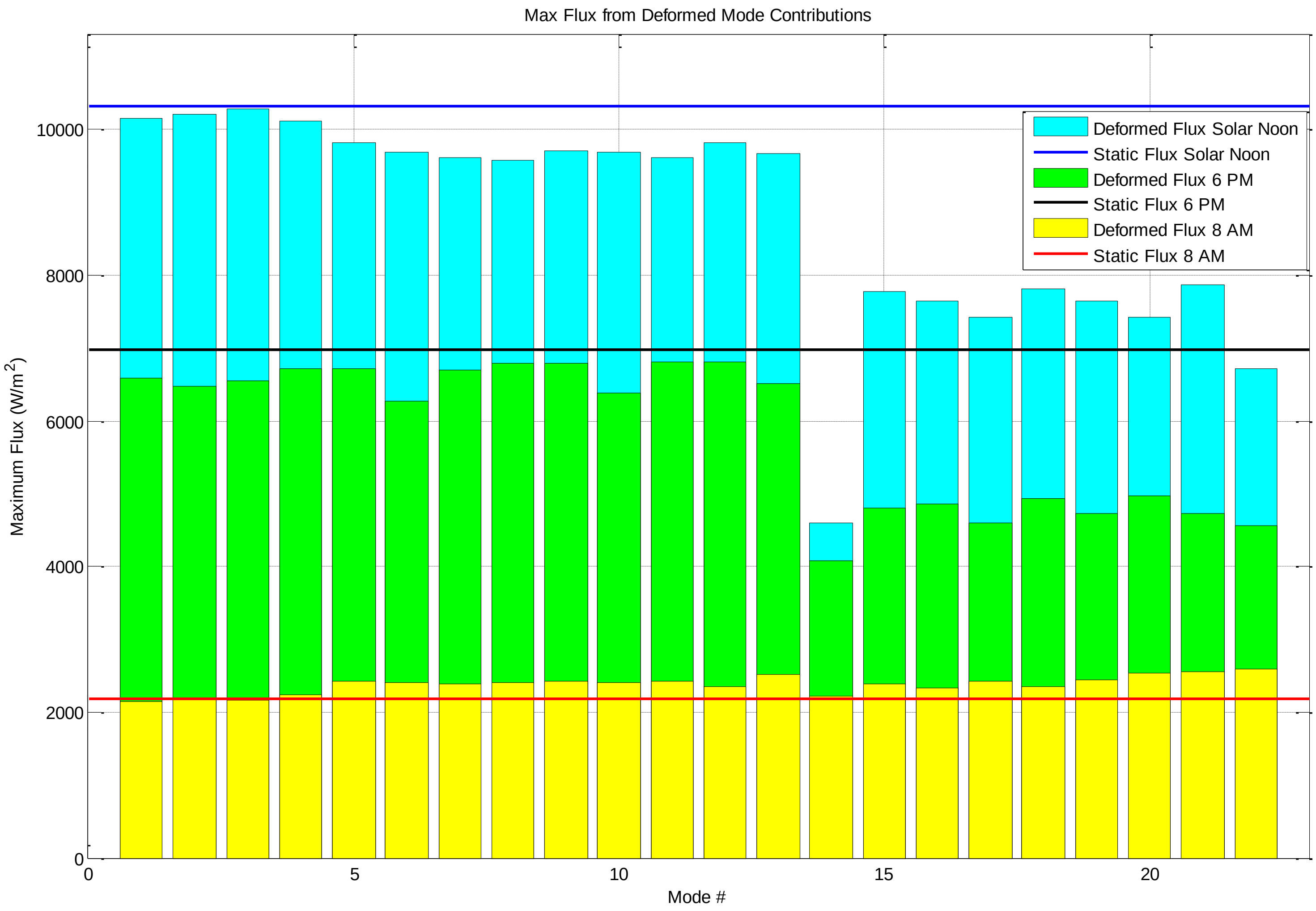
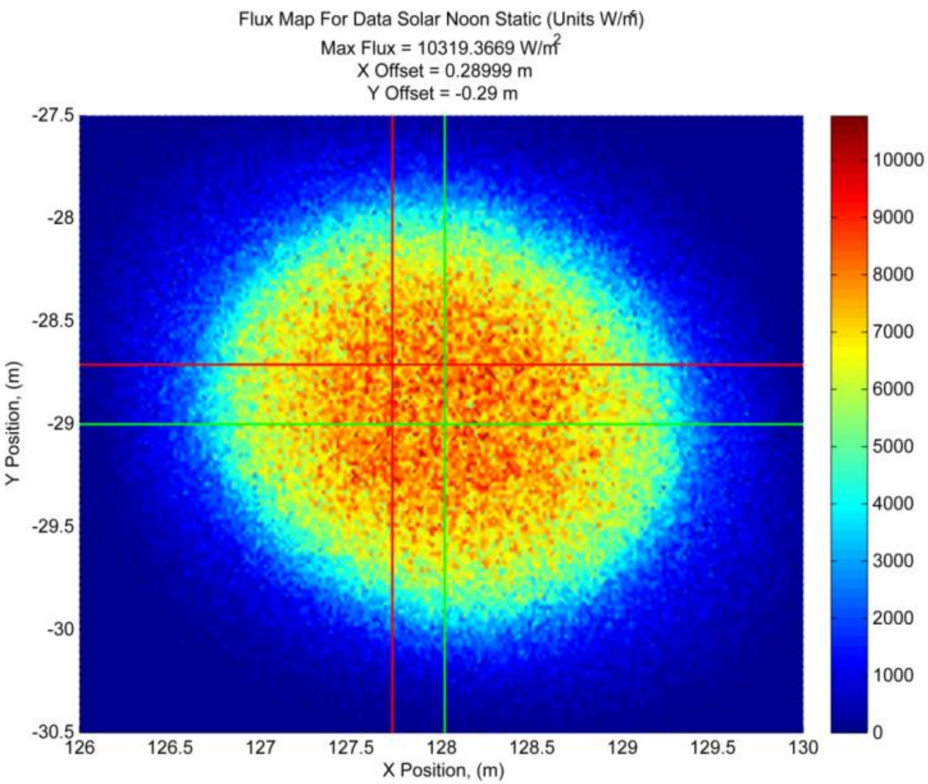
Maximum Flux per Mode Contribution

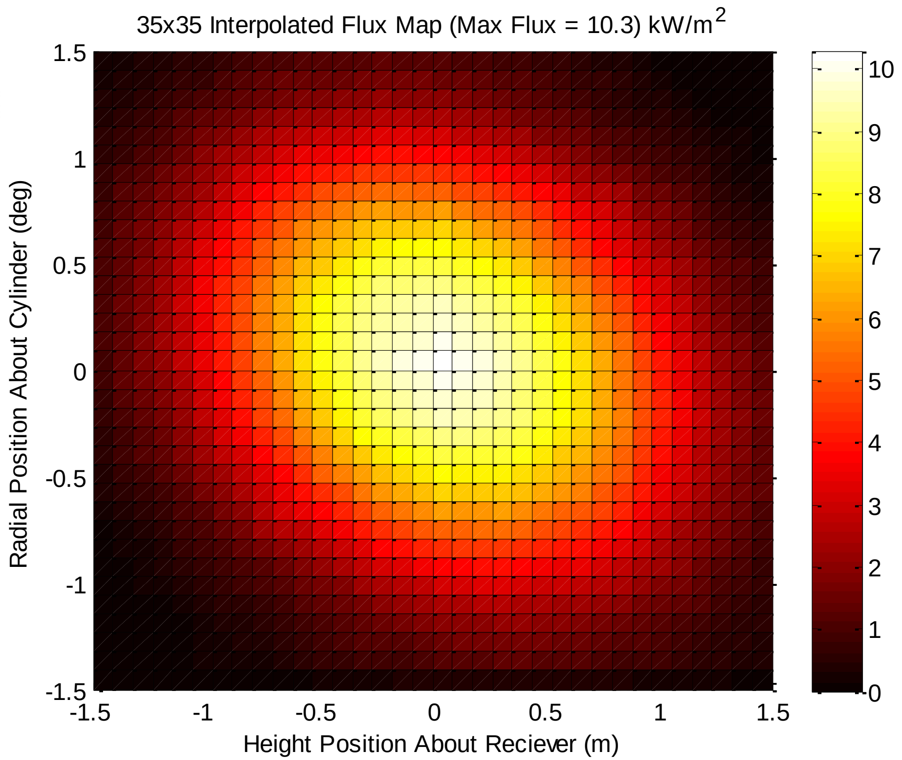


DELSOL Model

APEX Ray Tracing Flux Map



DELSOL Flux Map



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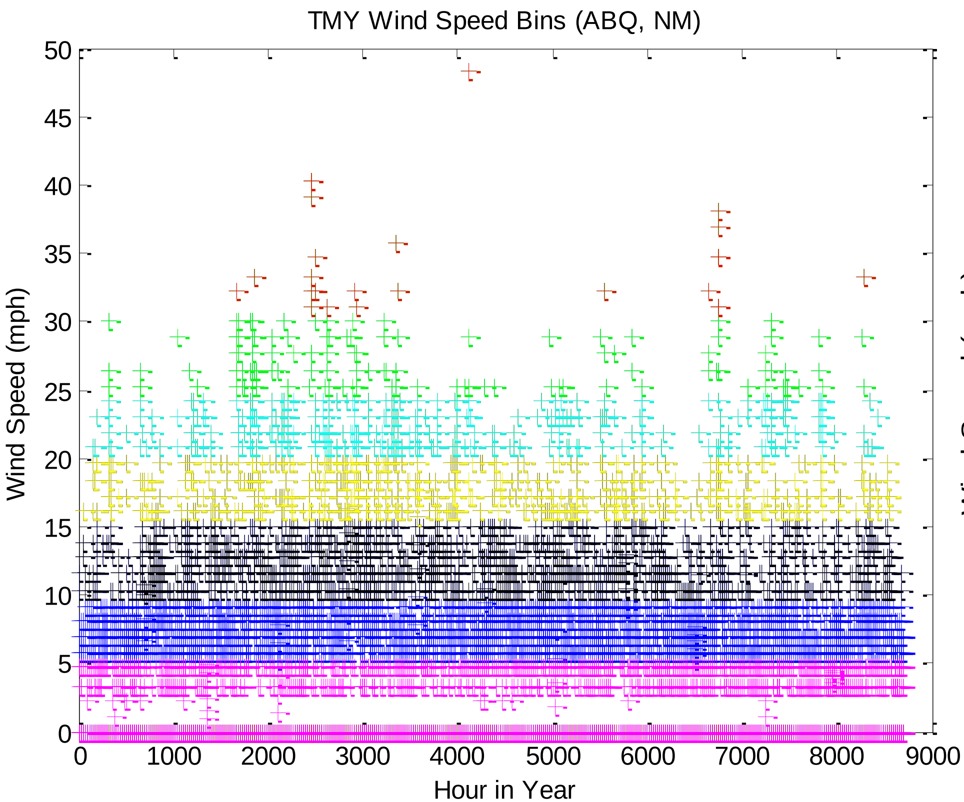
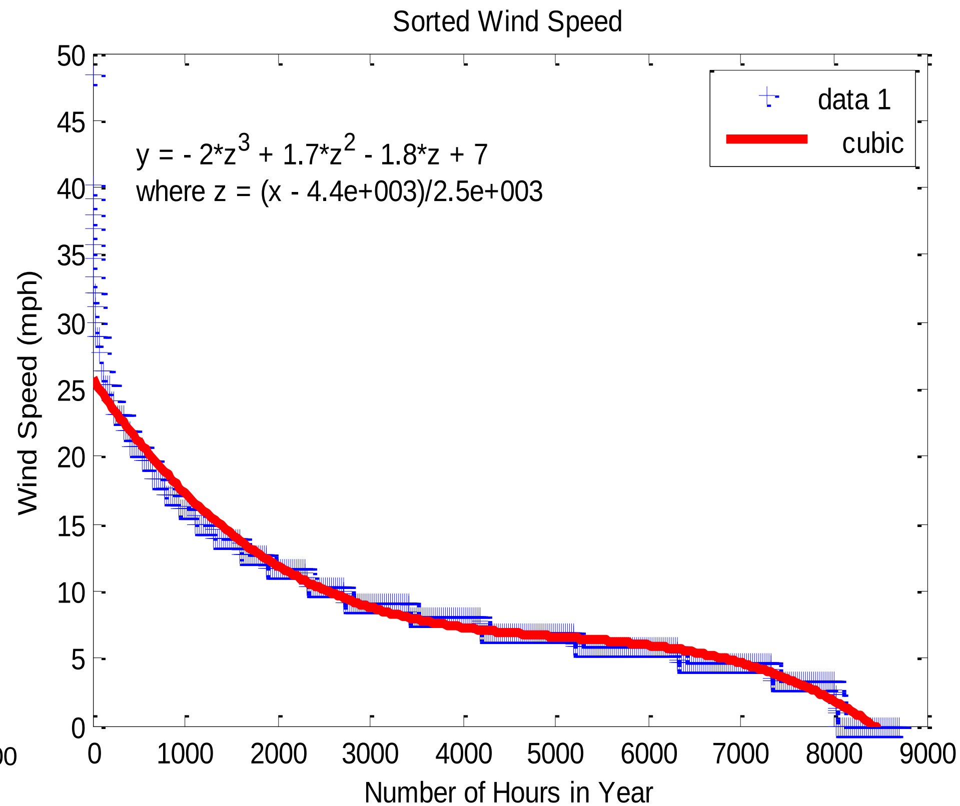
TMY Wind Data



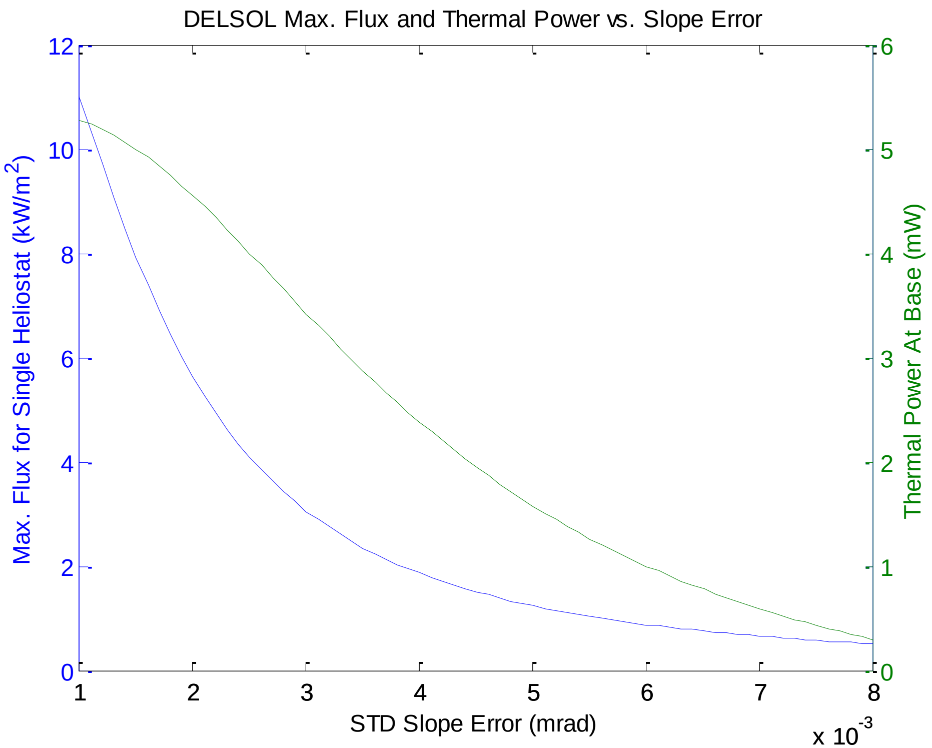


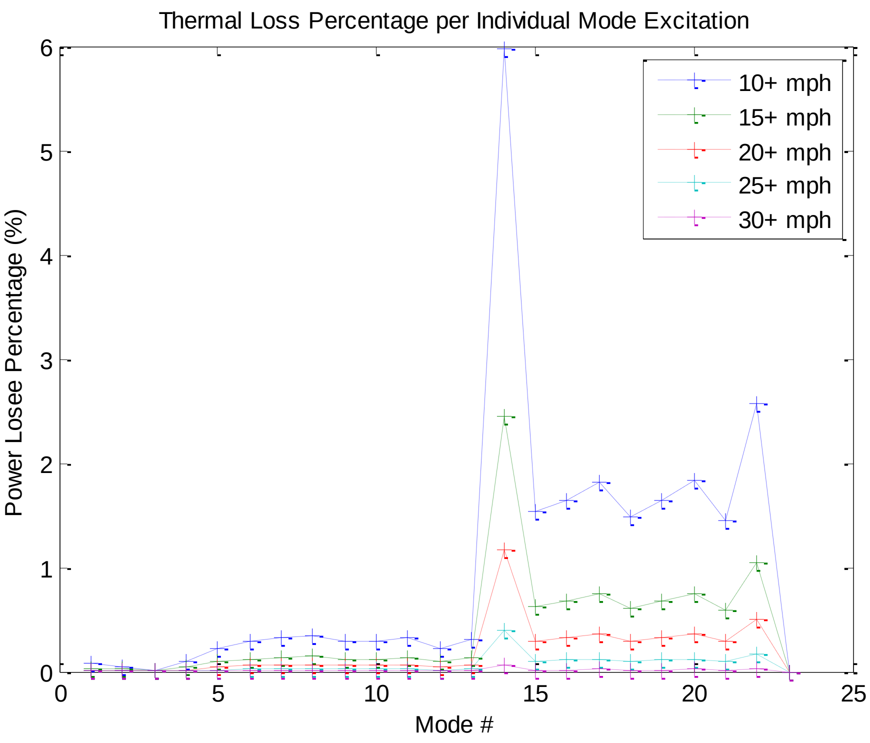
Define Wind Hrs Ratio for Performance Calculations

$$W_{bin} = \frac{hr_{bin}}{8766}$$

Plant Performance

$$G_{thermal} = G_{vib} * W_{bin} + G_{Static} * (1 - W_{bin})$$





Conclusion

- Full scale modal analysis and tests have been conducted on NSTTF heliostat
    - FEA and test mode shapes and frequencies match well for most modes
    - Rigid body modes due to motion in drives are characterized

- Wind excited modes range from ~0.8 – 20 Hz
    - Higher Frequency modes dominate response leading to largest displacement
    - Modes dampen out after ten Hz

- Out of plane modes lead to greater optical and thermal losses annually
    - NSTTF power plant simulations result in ~1-6 % power loss
    - Future wind excited data will verify this loss

- Turbulent wind and vortex shedding is attributed to majority of excitation

Future Work

- **Continue to monitor and capture wind events**
  - Create field position profile for wind excited displacements
  - Analyze field performance with interior wind speed profile
  - Automate monitoring program to trigger wind recording

- **Profile wind loads and characterize fatigue in heliostat structure**
  - Compare to Paterka model
  - Develop novel design approaches to mitigate wind induced vibrations and improve optical performance

- **Lower LCOE on future heliostat designs using dynamic design approach to mitigate fatigue and optical effects**

Questions?

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Apendix

Wind Excitation

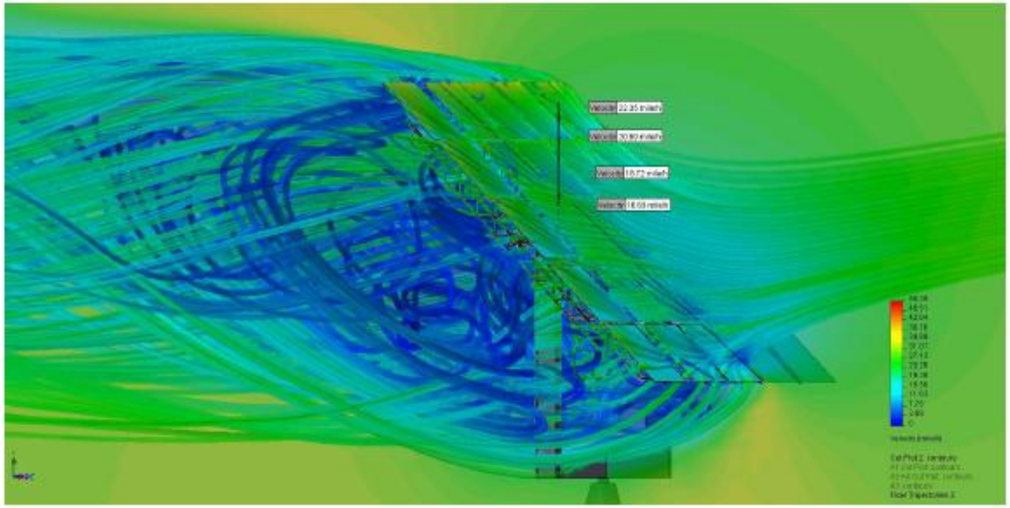
- Mean wind spectrum contributes to low freq response (<~ 1Hz)

- Wind gust spectrum excites mid range frequencies

- Vortex Shedding causes oscillating flow on interior heliostats
    - Strouhal number defines vortex shedding frequency

$$S_t = \frac{fD}{v}$$

Chen et al., 1996



*Courtesy J. Sment

Plant Performance

$$G_{thermal} = G_{vib} * W_{bin} + G_{Static} * (1 - W_{bin})$$

Scaled based on Output performance not on max flux