Sandia National Laboratories

HelioCon Closed Loop Controls for Heliostat Field Testing

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Agenda

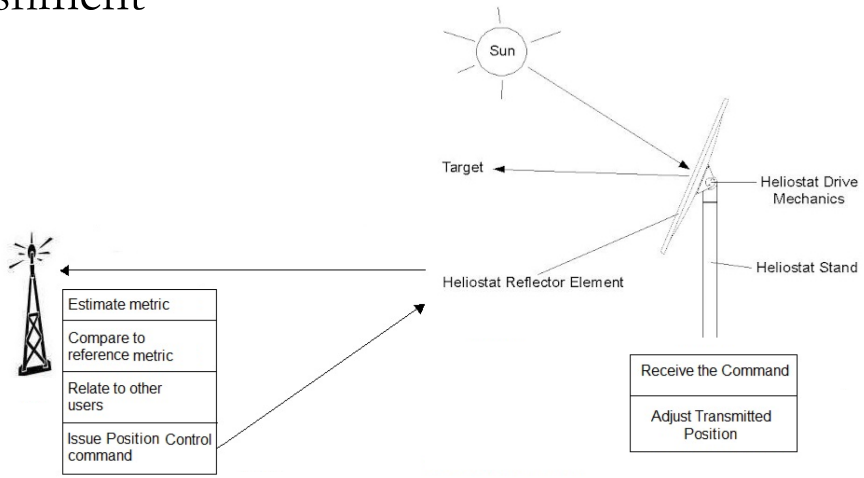
HelioCon Closed-Loop Controls

- Closed loop controls and wireless test bed development at Sandia National Laboratories solar tower facility as part of the U.S. DOE SETO HelioCon program
- Progress of highly-flexible controls and sensors which will be communicating with both wired and wireless protocols.
- Software architectures utilized to determine optimal pointing of each heliostat, accounting for unique metrology considerations
- Wireless comms flexibility between WiFi, Mesh Networks, etc.

Overview

- Closed-Loop Controls & NSTTF Refurbishment
- Wireless Communications
- Extremum Seeking Control Development
- Experimental Validation

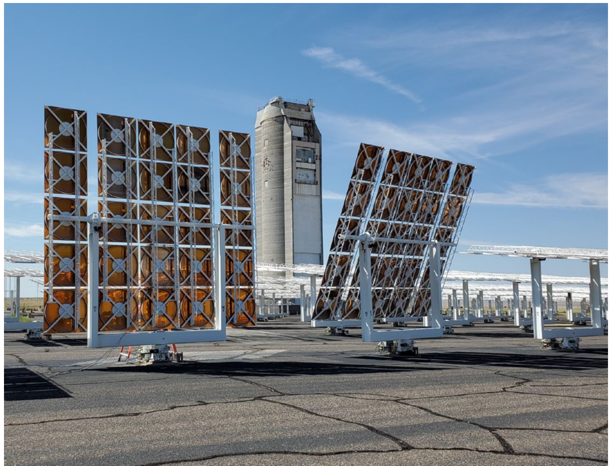
Conclusions



Heliostat Controls

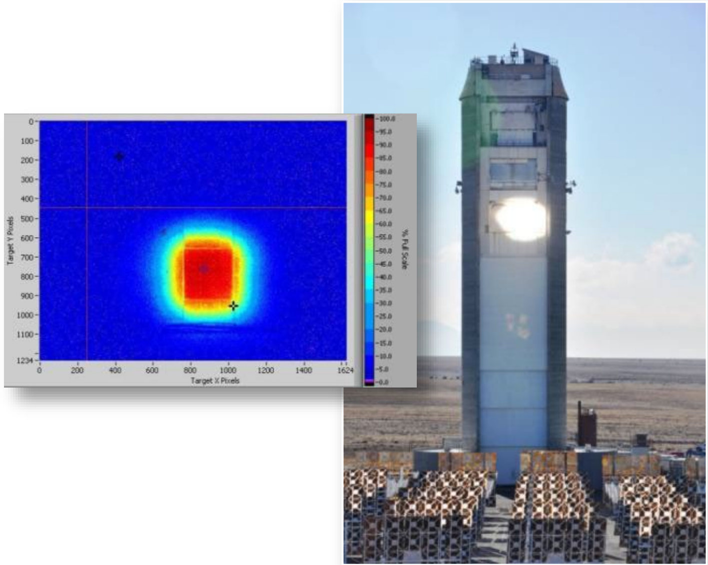
- The operational modes:
  - **Wake-up mode**: Heliostat moves from a stow position to a sun-tracking position
  - **Maintenance mode**: Heliostat is available for manual operation and mechanical and electronic maintenance
  - **Stow mode**: Heliostat is in a storm-protection position
  - **Tracking mode**: Heliostat tracks the sun
  - **Calibration mode**: Heliostat error vector is able to be auto calibrated.

- Movement by two-axis motorized system, controlled by computer.
  - Computer given latitude/longitude of heliostat's position and time/date. Using astronomical theory, controller calculates sun direction (e.g. its compass bearing and angle of elevation).
  - Given direction of receiver, computer calculates required angle-bisector, & sends signals to motors.
  - Sequence of operations repeated frequently with high resolution to keep the mirror properly oriented.
  - Traditionally, primary rotational axis is vertical and secondary is horizontal.



Closed-Loop Controls Overview

- Controls ensure each heliostat tracks angle bisector & controls flux between sun and receiver
- Closed-loop systems possess beam characterization system, provides feedback based on heliostat's receiver aiming.
- Closed-loop control enables automatic calibration as part of commissioning and fine calibration on a daily or even more frequent basis.
- Hardware to enable closed-loop heliostat control capable of feedback for plant-level control
- Software able to decide which heliostats aim at receiver to maximize flux
- Goal to decrease commissioning and O&M cost/increase plant performance.



Controls & Comms Challenges

- Wireless systems approaches must be broadly introduced to capitalize on lower plant cost while wireless risks and technical issues must be avoided. Standardized requirements & testing capabilities are needed.
- Closed loop control must be more broadly applied to achieve higher flux performance and auto alignment/calibration processes.
- Robust signal communication R&D needed for resilient wireless controls. R&D needed for wireless advanced controls architectures and hardware for facilitating single node or mesh networking.
- Reliability research of current interconnection hardware with respect to signal distribution under varying controls scenarios.

- **<u>Need for a Closed-Loop Controls & Wireless Test Bed</u>**

Sandia's National Solar Thermal Test Facility (NSTTF)

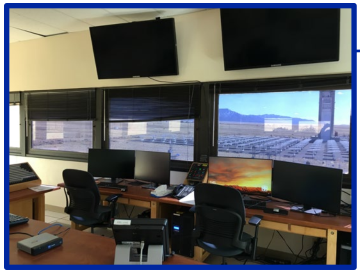
Solar Materials & Selective Absorbers

Power Tower

Molten Salt Test Loop

Apartment Complex

Control Tower



Parabolic Trough R&D

Dish Stirling R&D

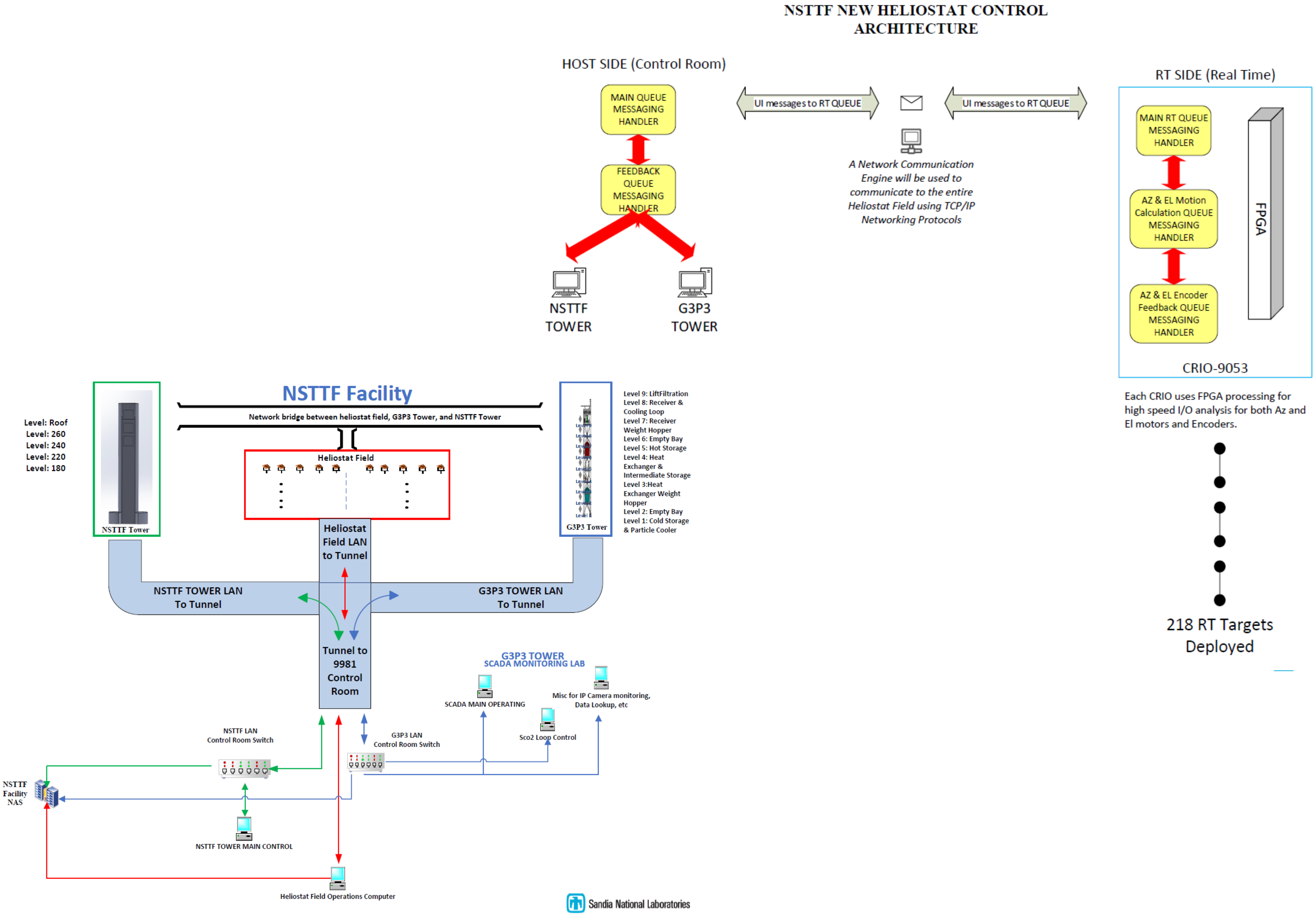
TBC Dishes

Fabrication Facilities
& STCH Solar Fuels Facility

Solar Simulator

Engine Test Facility

Controls Test Bed Development



NSTTF NEW HELIOSTAT CONTROL ARCHITECTURE

A Network Communication Engine will be used to communicate to the entire Heliostat Field using TCP/IP Networking Protocols

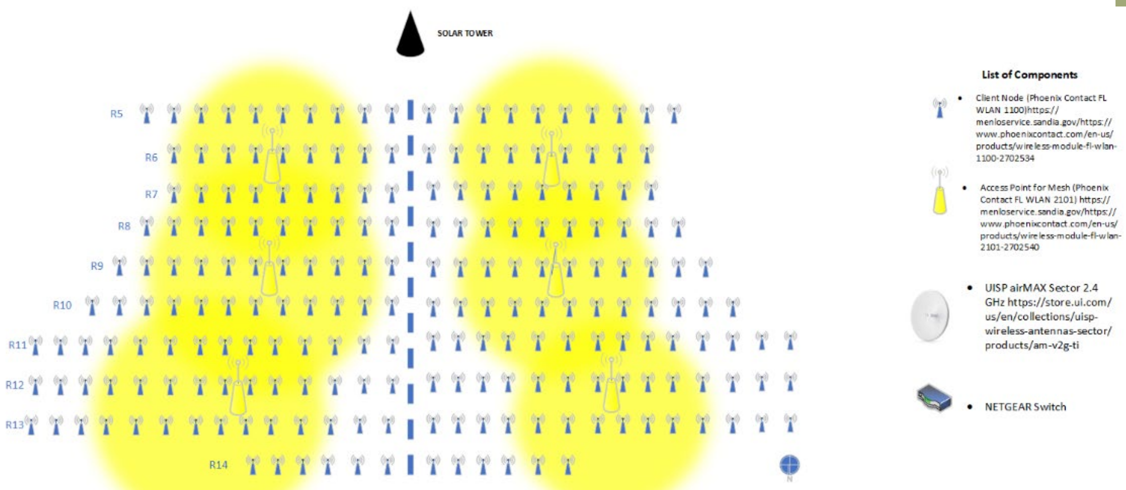
Each CRIO uses FPGA processing for high speed I/O analysis for both Az and El motors and Encoders.

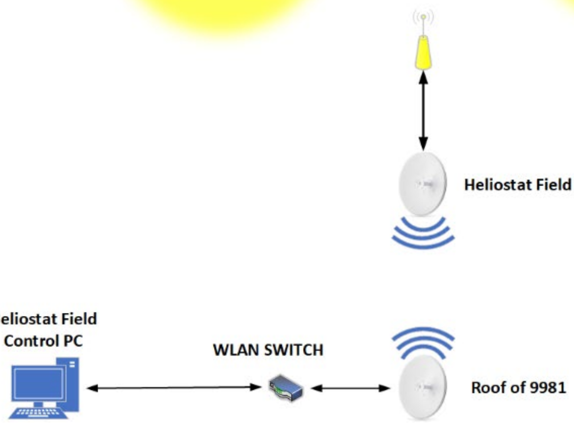
218 RT Targets Deployed

Level 9: LiftFiltration
Level 8: Receiver & Cooling Loop
Level 7: Receiver Weight Hopper
Level 6: Empty Bay
Level 5: Hot Storage
Level 4: Heat Exchanger & Intermediate Storage
Level 3:Heat Exchanger Weight Hopper
Level 2: Empty Bay
Level 1: Cold Storage & Particle Cooler

Communications Test Bed Development

- Facilitated benchtop testing for 2.4 GHz Phoenix Contact wireless modules and continued to verify the functionality of using a pseudo-mesh network.
- Two wireless module types setup: each heliostat uses Phoenix Contact 1100 module to relay signal to Phoenix Contact 2100 which acts as access point.
- Phoenix Contact 2100 allows for communications between 60 unique signals.
- Each Phoenix Contact 2100 relays 36 individual Phoenix Contact 1100 heliostat signals for full heliostat field coverage.
- Pseudo-mesh signals transmitted to in-field UISP airMAX 2.4 GHz antenna.
- Six 1100 modules connecting to one 2100 module were used in the successful benchtop testing.



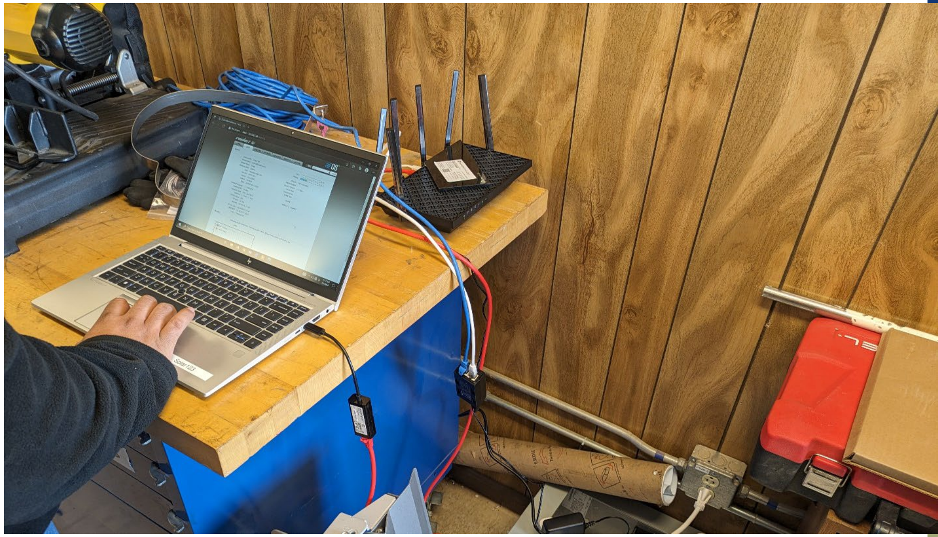


Significance & Impact ("so what")

- New heliostat comms capability for lab
- Potential cost/energy savings for deployments
- Ability to rapidly screen comms technologies

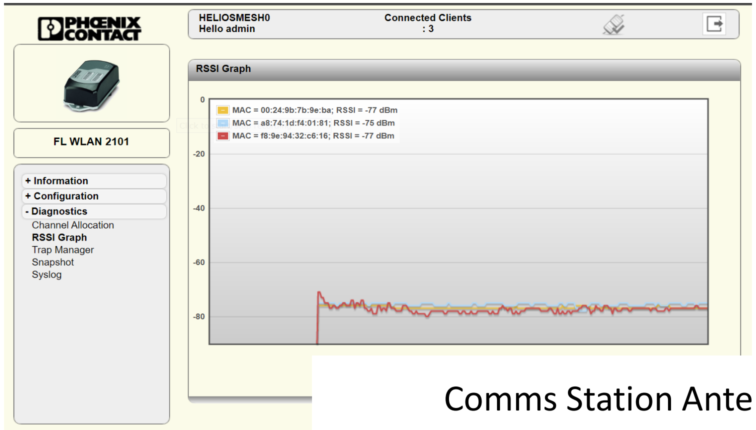
Wireless Communications Development

- Field tests completed to evaluate signal quality of UISP airMAX 2.4 GHz antennas.
- Antennas used as bridge between control tower and Phoenix Contact 2100 modules in heliostat field.
- Initial field tests run from ground level, placing field antenna at transformer station East of heliostat field & installing control room antenna at SWEPT lab.
- SWEPT lab used as comms station, imitating control room, with antenna hooking up to the TP-Link AXE5400 Wifi router purchased for the updated control room.
- Locations for antenna chosen to maximize distance between them to show effects on signal quality.
- Both kept at ground level to see how foliage, structures, and barriers effect signal strength.



WiFi Communications Development

- Phoenix Contact wireless modules & antennas with proved functionality of entire Wi-Fi system.
- Phoenix Contact 1100 modules paired to one Phoenix Contact 2100 module, relayed signal to field antenna.
- Phoenix Contact 1100's placed at heliostats 12E3 and 12W3, with Phoenix Contact 2100 at center of row 12.
- Signal quality between antennas tested with rows 13 and 14 in "face south" position for increased potential signal disruption.
- Test was successful, with data transmission from Phoenix Contact 1100 modules being received at control room antenna.

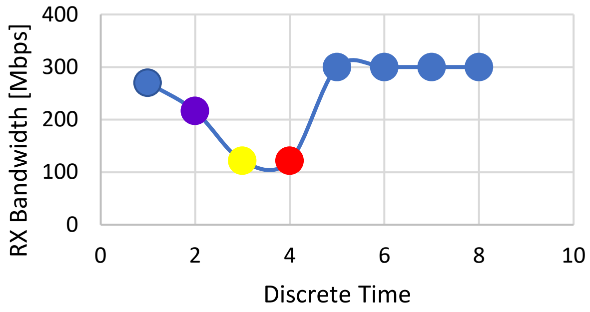


HELIOSMESH0
Hello admin

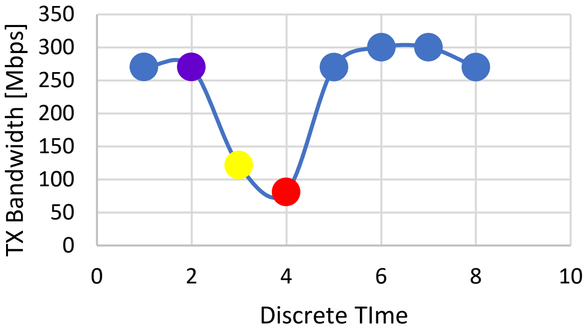
Connected Clients
: 3

MAC = 00:24:9b:7b:9e:ba; RSSI = -77 dBm
MAC = a8:74:1d:f4:01:81; RSSI = -75 dBm
MAC = f8:9e:94:32:c6:16; RSSI = -77 dBm

Comms Station Antenna
Received Signal (RX)

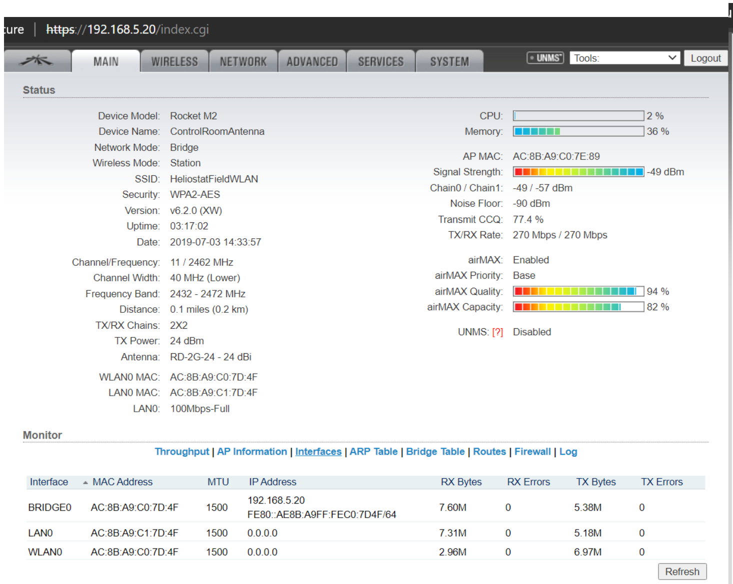


Comms Station Antenna
Transmitted Signal (TX)



Communications Test Bed Development

- With successful Wi-Fi combined system field tests, control room antenna moved to its permanent location, atop the control room
    - This will allow for continual Wi-Fi tests to be performed inside the control room tower, allowing for the most accurate representation of how the system will be run during regular heliostat operations.



Status

Device Model: Rocket M2
Device Name: ControlRoomAntenna
Network Mode: Bridge
Wireless Mode: Station
SSID: HeliostatFieldWLAN
Security: WPA2-AES
Version: v6.2.0 (XW)
Uptime: 03:17:02
Date: 2019-07-03 14:33:57

Channel/Frequency: 11 / 2462 MHz
Channel Width: 40 MHz (Lower)
Frequency Band: 2432 - 2472 MHz
Distance: 0.1 miles (0.2 km)
TX/RX Chains: 2X2
TX Power: 24 dBm
Antenna: RD-2G-24 - 24 dBi

WLAN0 MAC: AC:8B:A9:C0:7D:4F
LAN0 MAC: AC:8B:A9:C1:7D:4F
LAN0: 100Mbps-Full

CPU: 2 %
Memory: 36 %

AP MAC: AC:8B:A9:C0:7E:89
Signal Strength: -49 dBm
Chain0 / Chain1: -49 / -57 dBm
Noise Floor: -90 dBm
Transmit CCQ: 77.4 %
TX/RX Rate: 270 Mbps / 270 Mbps

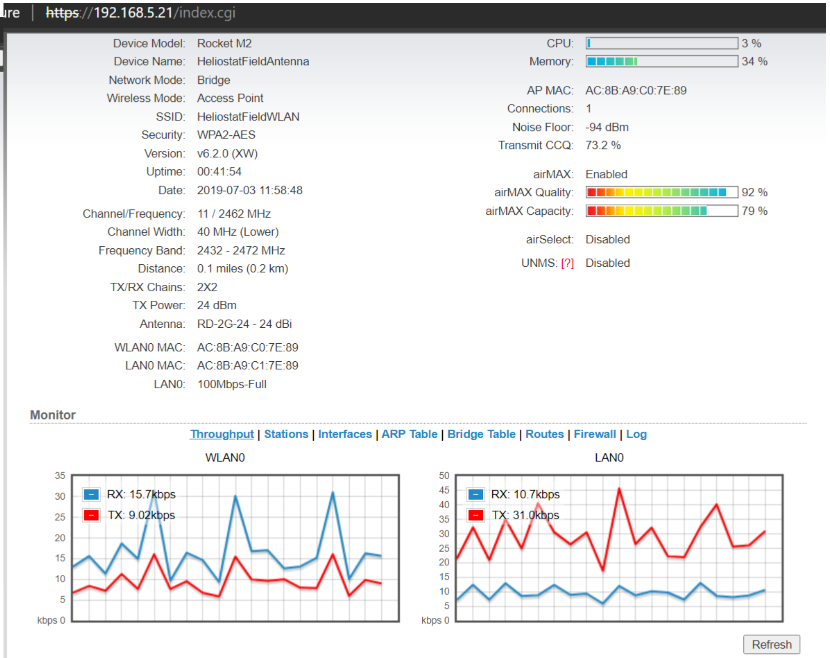
airMAX: Enabled
airMAX Priority: Base
airMAX Quality: 94 %
airMAX Capacity: 82 %

UNMS: [?] Disabled

Monitor

Throughput | AP Information | Interfaces | ARP Table | Bridge Table | Routes | Firewall | Log

Interface	MAC Address	MTU	IP Address	RX Bytes	RX Errors	TX Bytes	TX Errors
BRIDGE0	AC:8B:A9:C0:7D:4F	1500	192.168.5.20 FE80::AE8B:A9FF:FEC0:7D4F/64	7.60M	0	5.38M	0
LAN0	AC:8B:A9:C1:7D:4F	1500	0.0.0.0	7.31M	0	5.18M	0
WLAN0	AC:8B:A9:C0:7D:4F	1500	0.0.0.0	2.96M	0	6.97M	0



Device Model: Rocket M2
Device Name: HeliostatFieldAntenna
Network Mode: Bridge
Wireless Mode: Access Point
SSID: HeliostatFieldWLAN
Security: WPA2-AES
Version: v6.2.0 (XW)
Uptime: 00:41:54
Date: 2019-07-03 11:58:48

Channel/Frequency: 11 / 2462 MHz
Channel Width: 40 MHz (Lower)
Frequency Band: 2432 - 2472 MHz
Distance: 0.1 miles (0.2 km)
TX/RX Chains: 2X2
TX Power: 24 dBm
Antenna: RD-2G-24 - 24 dBi

WLAN0 MAC: AC:8B:A9:C0:7E:89
LAN0 MAC: AC:8B:A9:C1:7E:89
LAN0: 100Mbps-Full

CPU: 3 %
Memory: 34 %

AP MAC: AC:8B:A9:C0:7E:89
Connections: 1
Noise Floor: -94 dBm
Transmit CCQ: 73.2 %

airMAX: Enabled
airMAX Quality: 92 %
airMAX Capacity: 79 %

airSelect: Disabled

UNMS: [?] Disabled

Monitor

Throughput | Stations | Interfaces | ARP Table | Bridge Table | Routes | Firewall | Log

Baseline Closed-Loop Controls

- Developed control room architecture to be flexible with different closed loop controls algorithms.
- Developed a base line extremum seeking closed loop controls algorithm to test overall software architecture and to be a nominal approach to serve as a baseline to compare to other commercial or R&D approaches.
- Baseline closed-loop control algorithm uses batch least squares to calculate the gradient and calculate a new reference position for the system using power data from a BCS camera.
- When system moves to new reference position, process starts again.
- Algorithm continues until it finds a position where gradient is zero, which is peak of a unimodal distribution.
- To test any algorithm, small-scale test bed constructed using three motors to move a BCS camera on two axes, a flashlight, and a Laplacian target that hangs above the camera.
- Flashlight points at Laplacian target and creates a distribution of intensity values that can be measured by the BCS camera.

Error Count: 0

Step 1: Select the Heliostats to use **All On**
Step 2: Pick **Named Targets**
Step 3: Enter XYZ target location
Step 4: Press **Set Target(s)**
Step 5: Press **Execute Move**

Failsafe: No-op

Named Targets: LINE BOTTOM

X (m): 60
Y (m): 0
Z (m): -20
AZ: 0
EL: 0

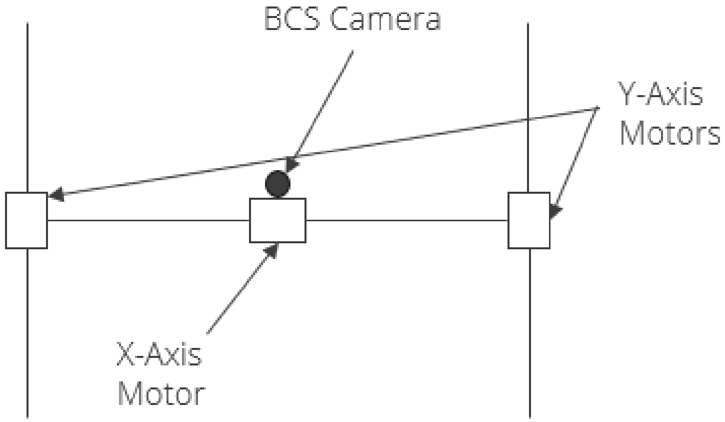
Current time: 11:50:43 AM 5/8/2024

Standby Size: 81

# of exits: 0

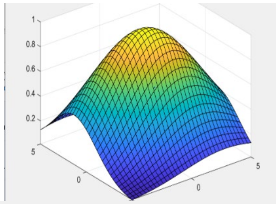
Small Scale Experimental Setup

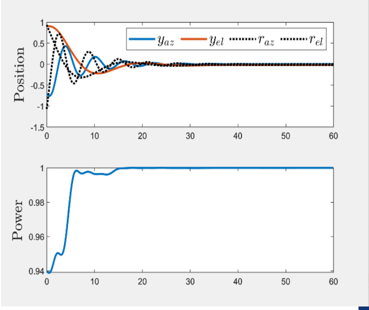
- To validate the real time optimization algorithm, the NSTTF has built a small scale experimental setup to test closed-loop control algorithms before putting them on a heliostat
    - This allows the NSTTF to validate any algorithm that researchers would like to test on the heliostat field
    - This ensures that the algorithms will not damage heliostats at the NSTTF
    - The NSTTF has used the small scale experimental setup to validate the RTO algorithm before heliostat testing
- The small scale setup uses three motors to move a BCS camera along two axes, with the BCS camera being mounted on the X-axis motor
- A Laplacian target is held above the BCS camera and motor setup
    - This allows us to simulate a sunspot using a flashlight
- The distances and velocities are measured in number of pixels and pixels/second, respectively
    - Using System ID, the velocity of the motors was found to be 15.5 pixels/second
- The system has a proportional controller that uses pixel distance and the velocity of the motors to calculate the amount of time to run the motors in each direction



Closed-Loop Controls Screening Test Bed

- LABVIEW code takes an image, runs algorithm, and moves motors.
- Algorithm outputs new pixel location used to tell motors what direction to move and for how long.
- Using this and new pixel location, it can be calculated how long the motors need to move.
- Small-scale test bed constructed using three motors to move a BCS camera on two axes, a flashlight, and a Laplacian target that hangs above the camera.
- Working with linear matrix inequality (LMI) and software-defined parameters (SDP) methods to find a gain that optimizes performance.
- Developed a base line extremum seeking closed loop controls algorithm to test overall software architecture and to be a nominal approach to serve as a baseline to compare to other commercial or R&D approaches.



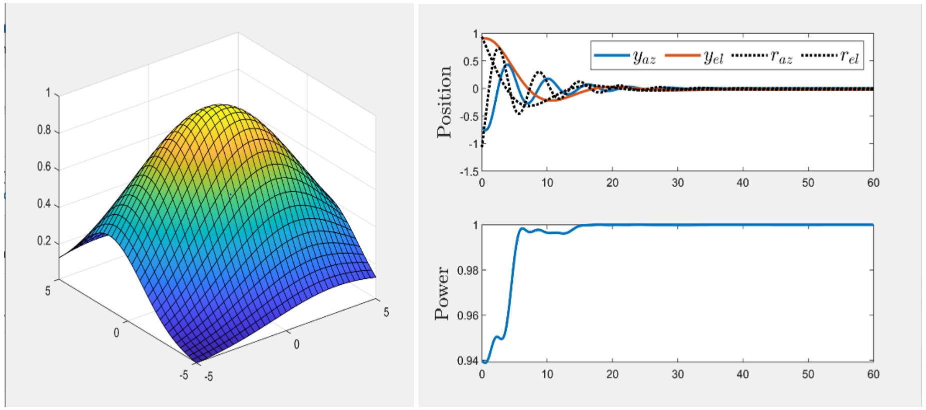


Significance & Impact

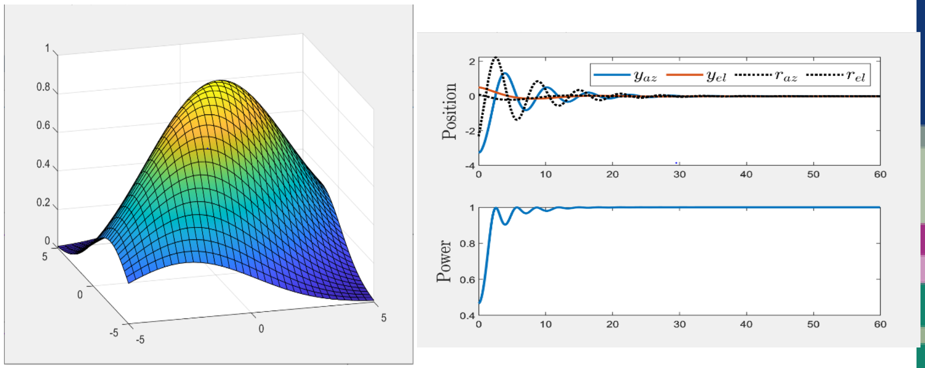
- Novel way to screen controls architectures prior to heliostat evaluation.
- Ability to de-risk controls that could damage heliostats

Baseline Closed-Loop Controls

- To optimize performance of code, gain can be altered.
- Working with linear matrix inequality (LMI) and software-defined parameters (SDP) methods to find a gain that optimizes performance.
- Many gains that stabilize system, meaning peak value of distribution is reached.
- Developing method to find a gain that stabilizes the system, is robust to varying distributions, and optimizes performance.
- Three simulations; the first two having oblong distributions and last one having a more uniform distribution. For each simulation, the distribution and start position are randomized.
- In all simulations, system lags behind reference positions because system takes time to reach each reference.
- Each simulation shows the system being stabilized and the peak power being reached.



First BLS Output Finding Optimal Location.



Second BLS Output Finding Optimal Location.

Architecture Block Diagram

- H(s) is the MIMO transfer function of the heliostat
  - Input: Desired Azimuth and Elevation angle
  - Output: Actual Azimuth and Elevation angle

$$x_{k+1} = Ax_k + Br$$
$$y_k = Cx_k$$

- The power function P(y) is a nonlinear, non-dynamic reward function
  - Input: Actual Azimuth and Elevation angle
  - Output: Power

$$\mathrm{P(y)} = \exp\left(-\frac{1}{2}(y - r^*)^T \Sigma^{-1} (y - r^*)\right)$$

- Gradient Estimator
  - We use the real-time dataset below to provide feedback

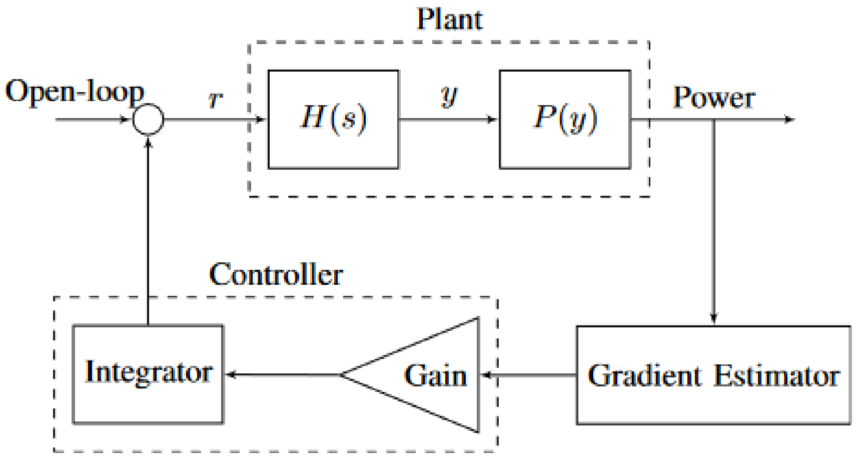
$\{P_i, y_i\}_{i=1}^N$ where $P_i = P(y_i)$

  - We can estimate $\nabla P(\bar{y})$ using a Taylor series expansion

$$P_i \approx P(\bar{y}) + \nabla P(\bar{y})^T (y_i - \bar{y}) = \theta^T \Phi_i$$
$$\Phi_i = \begin{bmatrix} 1 \\ y_i - \bar{y} \end{bmatrix}, \theta = \begin{bmatrix} P(\bar{y}) \\ \nabla P(\bar{y}) \end{bmatrix}$$

- The controller uses the gradient to generate a new reference using the steepest ascent optimization algorithm

$$r_{k+1} = r_k + F\nabla P$$
$$r_{k+1} = r^* \ when\ \nabla P = 0$$



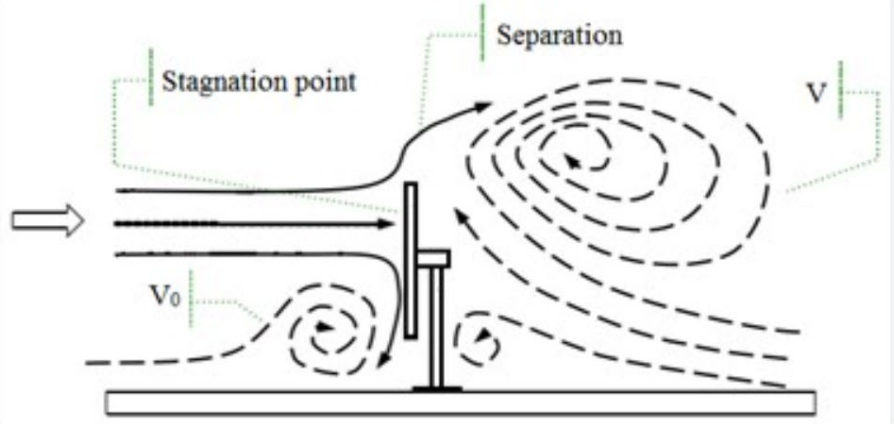
Challenges

- The power distribution is not known beforehand; therefore, the true gradient cannot be calculated and must be estimated. Since this is a data-driven method, measurement noise impacts the gradient estimation.

- Disturbances, such as wind, impact the heliostat alignment.

- The feedback-loop can go unstable with improper choice of the gain F.

- The feedback-loop can go unstable if our initial setpoint is too far from the optimal.



Heliostat Simulation Model

- H(s) state-space

$$A = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\zeta\omega_n \end{bmatrix}, B = \begin{bmatrix} 0 \\ \omega_n^2 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$\omega_{n,az} = 0.1$, $\zeta_{az} = 1.1$, $\omega_{n,el} = 0.05$, and $\zeta_{el} = 0.9$

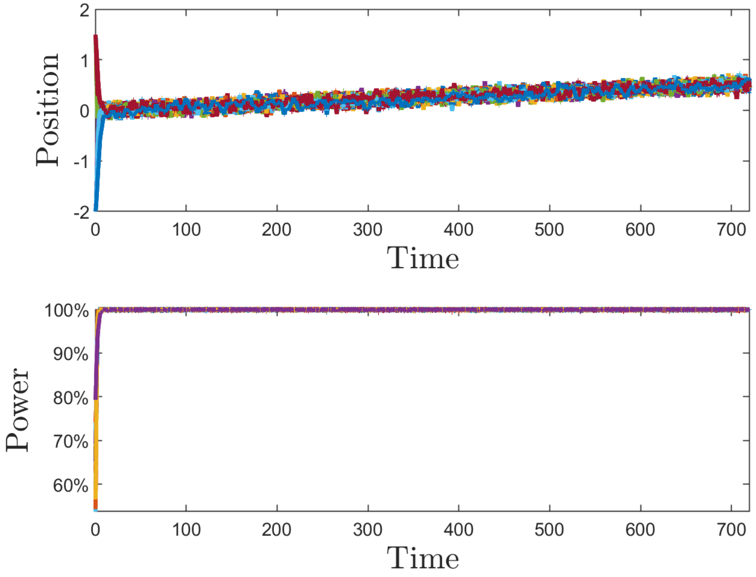
- The overall transfer function becomes

$$H = \begin{bmatrix} A_{az} & 0 \\ 0 & A_{el} \end{bmatrix}, \begin{bmatrix} B_{az} & 0 \\ 0 & B_{el} \end{bmatrix}, \begin{bmatrix} C_{az} & 0 \\ 0 & C_{el} \end{bmatrix}$$

then convert to discrete time

- For our gradient estimator we use least-squares

$$\theta = (\Phi\Phi^T)^{-1}\Phi P_i$$



Simulation with 25 Distributions with 1% Noise. This simulation shows the actual position (y_{az}, y_{el}) vs time (top) and power $P(y)$ vs time (bottom) for each power distribution.

Single Heliostat Closed-Loop Controls Test Plan

- Test Plan (8 tests total)
  - 4 Tests of one directional moves
  - 4 Tests of two directional moves
  - All Tests will start using the open loop to get a single heliostat on target and then moving it manually off of the center to the desired location for each test.
  - Once moved off center the Closed Loop system will be used to move the spot to the optimal reference
- Goals of Testing
  - Ensure that RTO algorithm tracks in all directions
  - Ensure that RTO algorithm is stable when tracking in all directions.
  - Ensure optimality of the RTO algorithm when tracking in all directions.

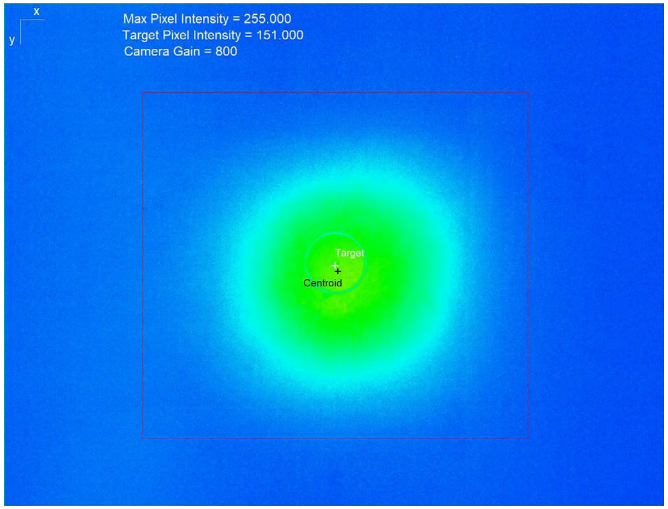
Test Number	Task
1	Move spot in the negative x direction 0.25 meters
2	Move spot in the positive x direction 0.25 meters
3	Move spot in the negative z direction 0.25 meters
4	Move spot in the positive z direction 0.25 meters
5	Move spot in the negative x direction 0.25 meters and negative z direction 0.25 meters
6	Move spot in the negative x direction 0.25 meters and positive z direction 0.25 meters
7	Move spot in the positive x direction 0.25 meters and positive z direction 0.25 meters
8	Move spot in the positive x direction 0.25 meters and negative z direction 0.25 meters

Controls Test Bed Evaluation – Single Heliostat

- With the updated tracking algorithm, the heliostat does not shift back and forth on the azimuth and elevation angle gears solving three previous problems:
    - Unnecessary movement of spot on tower
    - Unnecessary wear on heliostat gearing
    - Ability to stay within 0.02 degrees of desired location
- Smooth transition from high speed on approach to BCS into tracking
    - No overcorrection issues
    - Current draw well within acceptable range for highest speeds produced

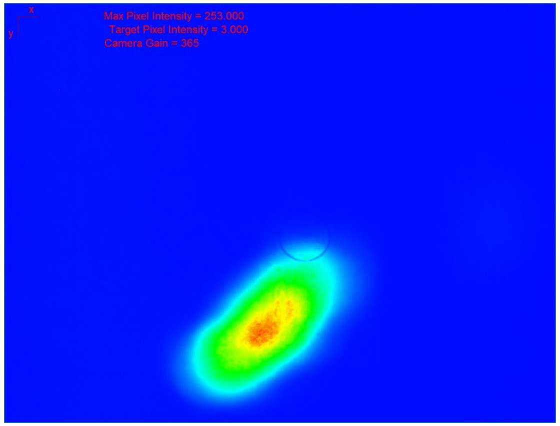
Field Test

- First beam on tower with new software
- Excellent resolution
- 5 minute, 10 minute, and 20 minute tests recorded in control room with beam tracking.
- High precision and accuracy
  - ○ Throughout recording period the beam never lagged more than 0.02 degrees from the desired location.

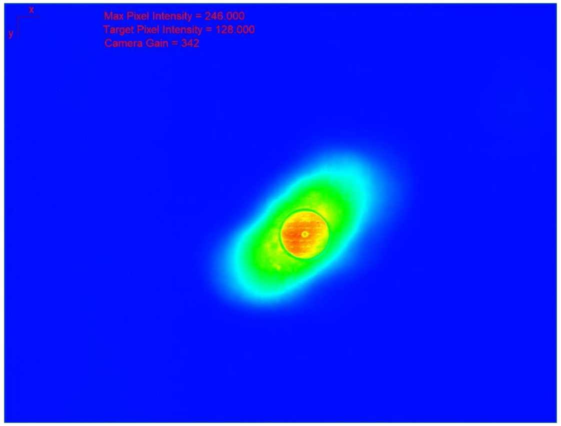


Max Pixel Intensity = 255.000
Target Pixel Intensity = 151.000
Camera Gain = 800

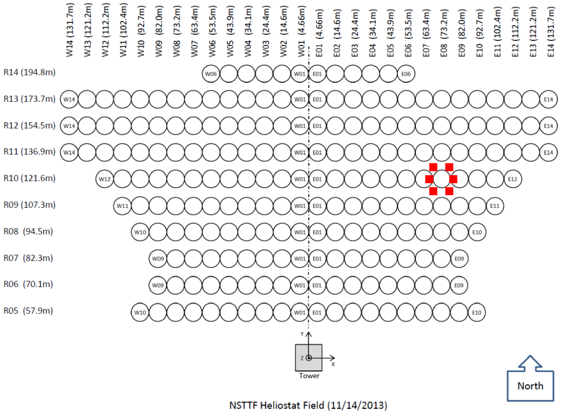
Actual Heliostat Closed Loop Controls Test Offset



Actual Heliostat Image. This figure shows the heliostat alignment before using the RTO algorithm



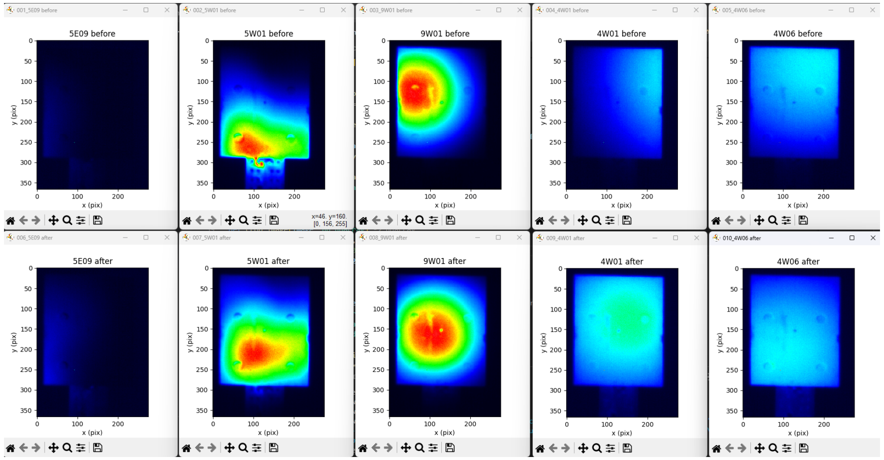
Actual Heliostat Image. This figure shows the heliostat alignment after using the RTO algorithm.



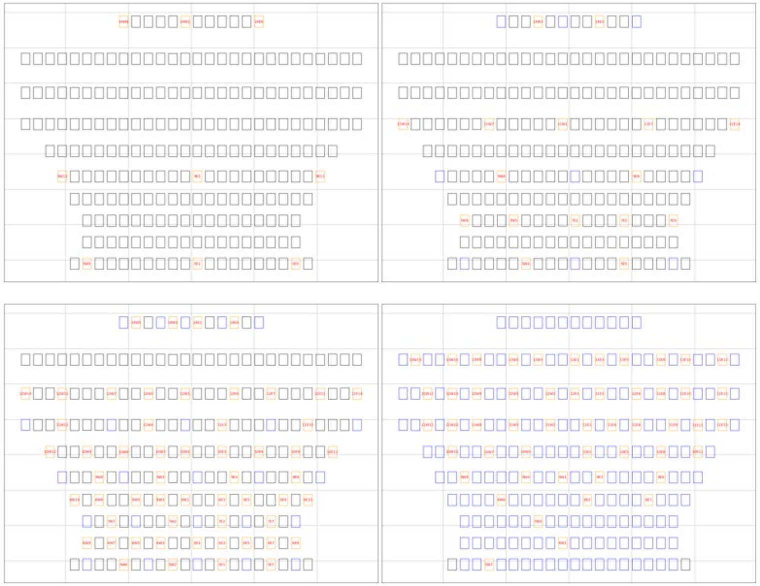
NSTTF Heliostat Field (11/14/2013)

NSTTF Initial Pointing Corrections Utilizing HelioCon Controls Tools

- Extremely accurate pointing required for NASA testing, where Heliocon Controls and Metrology tools are utilized for NSTTF tower top flux evaluations.
- Initial work facilitated in batch process, though automation is also being developed for improving the pointing.
- Improvements made that contributed to min. 30% improved flux values already. Further testing is required to complete the flux corrections to achieve a min. 220 W/cm^2 goal.


Before:

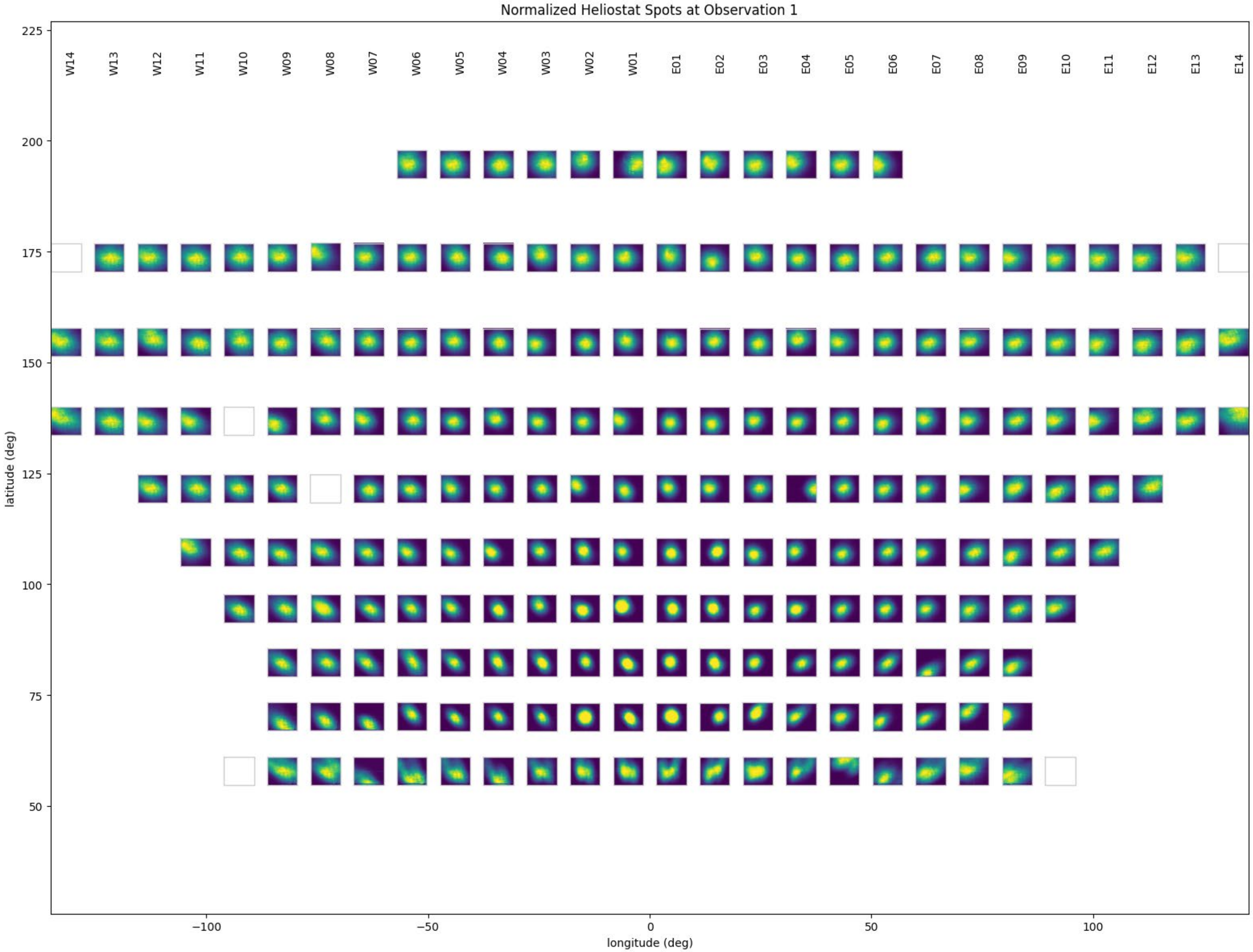
After:



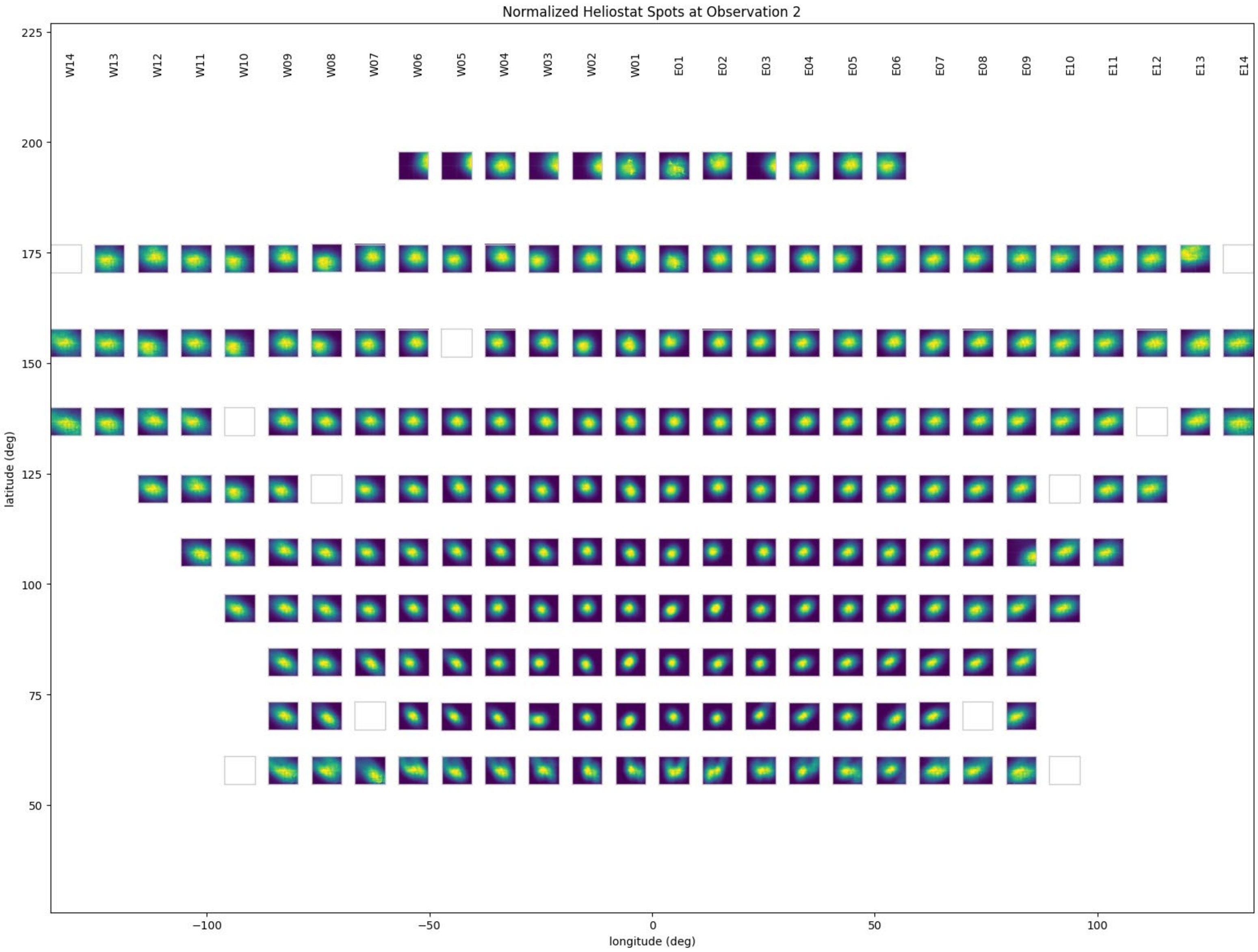
Significance & Impact

- Ability to rapidly improve flux pointing with closed loop controls and optical metrology.
- Ability to achieve high flux levels needed for industrial process heat applications.

Positions


Normalized Heliostat Spots at Observation 1
W14
W13
W12
W11
W10
W09
W08
W07
W06
W05
W04
W03
W02
W01
E01
E02
E03
E04
E05
E06
E07
E08
E09
E10
E11
E12
E13
E14
latitude (deg)
225
200
175
150
125
100
75
50
longitude (deg)
−100
−50
0
50
100

Corrected Spots after Controls Algorithm Implementation



Conclusions & Future Work

- NSTTF Heliostat Field Controls/Comms Refurbishment to support G3P3.
- DOE Heliocon Closed-Loop Controls Test Bed Architecture Development.
- Closed-Loop Controls algorithm development based on initial hybrid Least Squares Law & Open Loop initialization.
- Heliocon RFP projects to support Wireless Mesh Network Communication hardware and software protocol development
- Future work required to obtain training controls data for improving pointing and controls.
- Looking for users of the Closed-Loop Controls and Wireless Heliostat Field test bed.

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Thank you.