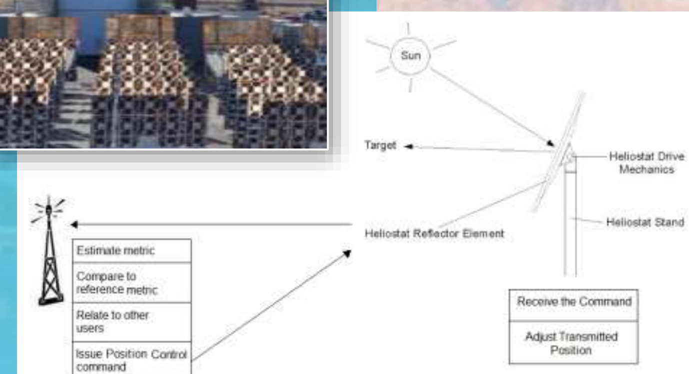
NSTTF HelioCon Wireless Closed-Loop Controls Test Bed Development

SolarPACES2023-14752



Kenneth M. Armijo, Haden Harper, Zachary Bernius, Ansel Blumenthal, Claus Danielson and Luis Garcia-Maldonado

Sandia National Laboratories, Albuquerque, NM

2023 SolarPACES Conference
October 2023, Sydney, Australia

SAND2023-XXXX

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

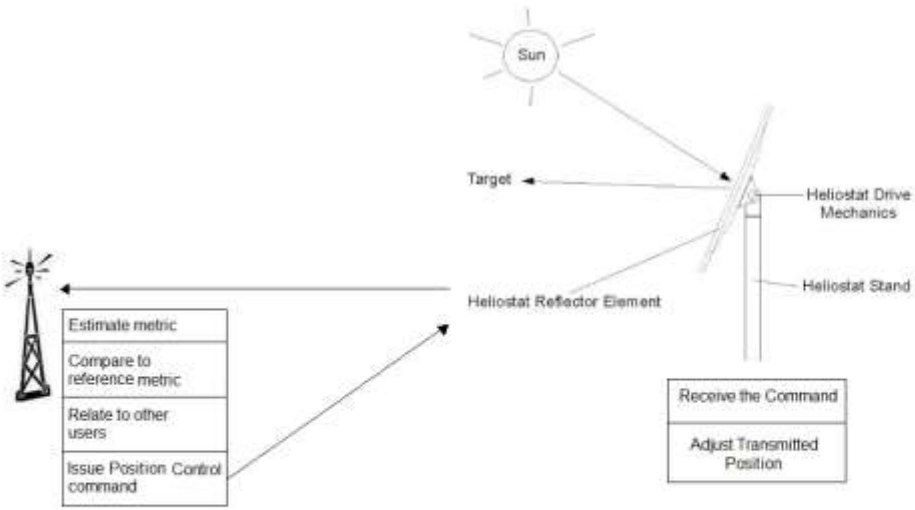
Agenda

Solar Heliostat Controls Challenges

- Closed loop controls test bed is in development at the Sandia National Laboratories solar tower facility as part of the U.S. DOE SETO HelioCon program
- Preliminary development of advanced feedback controls for a CSP Power Tower & field of 218 heliostats
- Progress of the 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

Overview

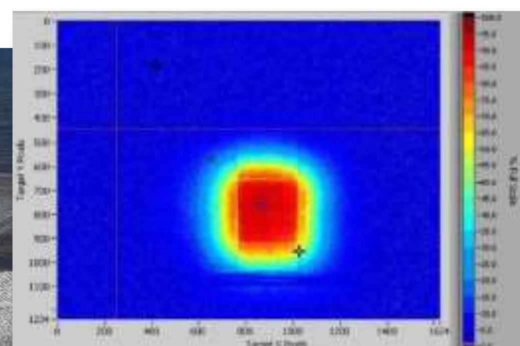
- Closed-Loop Controls
- NSTTF Heliostat Field Refurbishment
- Hardware Development
- Software Development



Conclusions

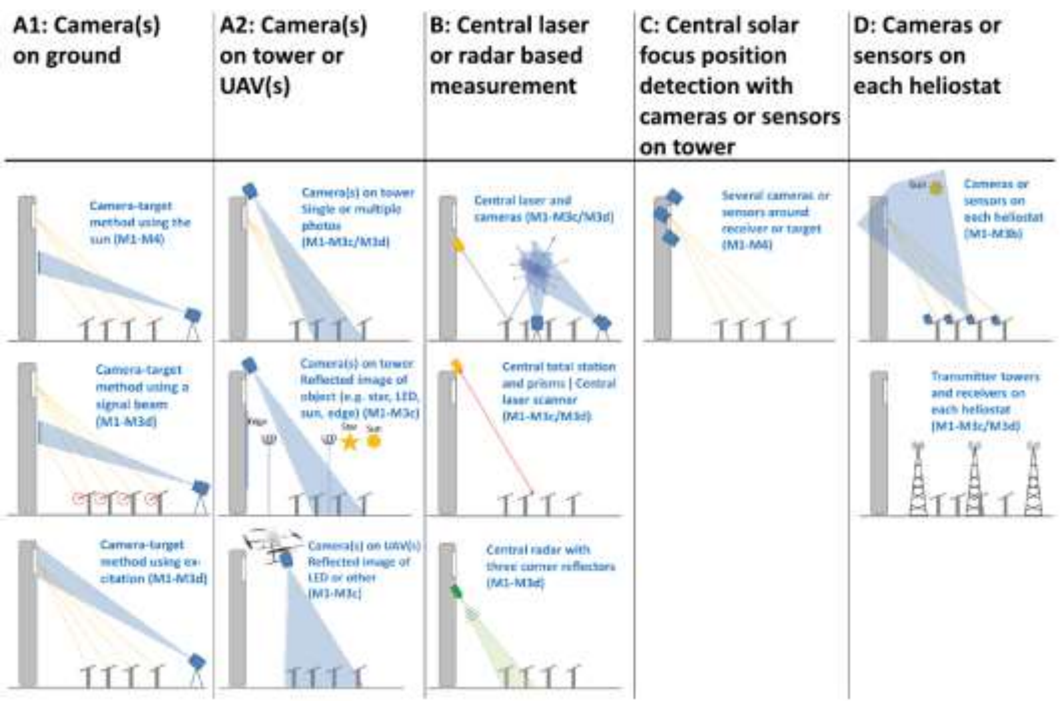
Closed-Loop Controls Overview

- 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.

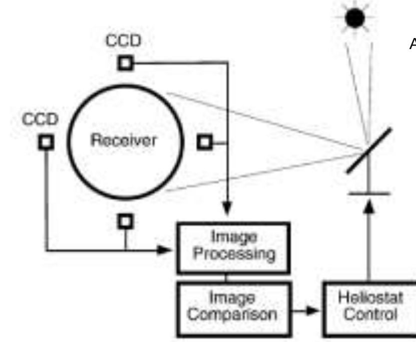


Closed-Loop Controls Design

- Varying control strategies for automation
- For every CSP system, the number of heliostats pointed at the receiver needs to be adjusted depending on the sun's position in the sky
- Closed-loop control allows operator to know exact location & diagnostics for each individual heliostat vs. entire array.

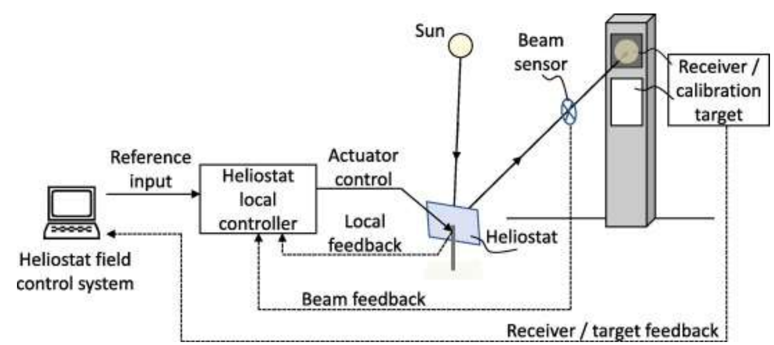


J. C. Sattler *et al.*, "Review of heliostat calibration and tracking control methods," *Sol. Energy*, vol. 207, pp. 110–132, Sep. 2020



A. Kribus et al., Energy 29 (2004) 905-913

The heliostat control loop is closed by acquisition of four images around the receiver aperture, and generating a control signal by image processing.



Pearson, J. and Chen, B., An Assessment of Heliostat Control System Methods, *SERI/SP-253-2390, DE86004416*

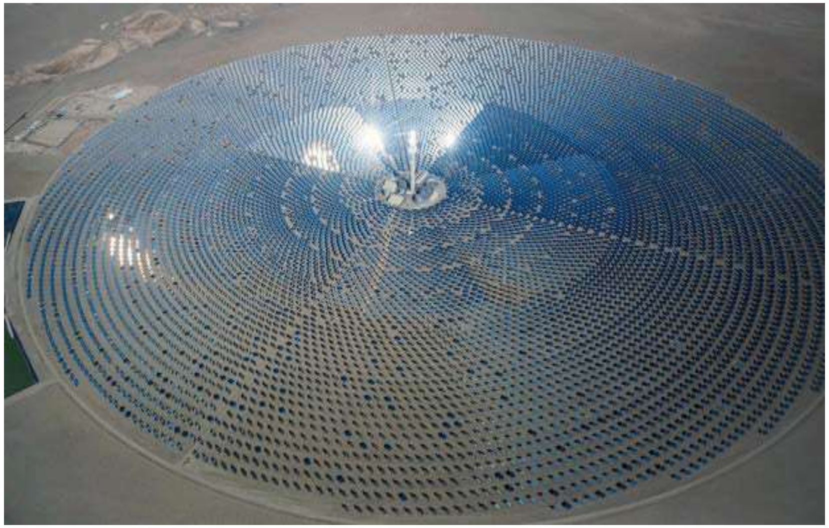
Closed-Loop Controls Design

Park, Y.C., 2009. Heliostat control system. *Journal of the Korean Solar Energy Society*, *29*(1), pp.50-57.

Controls Communication 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.

- **Need for a Closed-Loop Controls Test Bed**



Sandia’s National Solar Thermal Test Facility (active since the 70s)

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

NSTTF Heliostat Field Refurbishment - Hardware

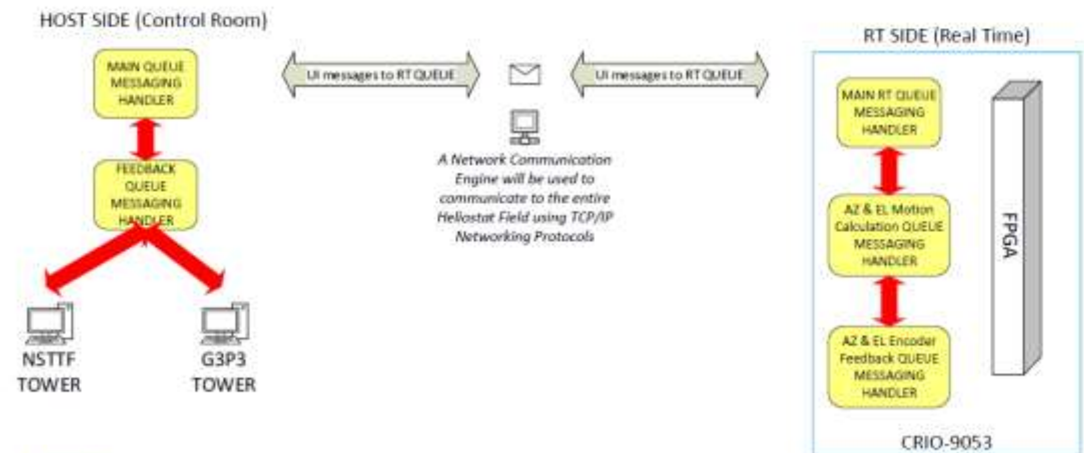
- Current hardware dates to 2003 motion technology
  - The heliostats are driven by 2 axis motors (Azimuth and Elevation)
  - A 16-BIT SSI encoder is used to obtain positioning for each heliostat
  - An open loop GPS timer tracks sun position
  - Each heliostat is controlled by National Instruments (NI) Real Time Controller (CRIO), which is outdated and no longer supported by NI
- New hardware upgrades include a new NI Real Time Controller that is supported by NI for the next 10 years (CRIO 9053)
  - The current Motor Drive Modules (NI 9505) will be used to perform the motion of each axis
- New SCRAM DAQ system for rapid emergency operations
- New GPS time system to track sun position
- New data management system of Heliostat System Status
  - Current system saves local files to a local hard drive
  - New system will be a network attached storage device (NAS) that saves 24/7 Heliostat System Status
- New Communication infrastructure
  - Old communication infrastructure was "Power over Ethernet" limited to 2 Mbps
  - Fiber Optic line will be installed to allow speeds up to 10 Gbps
  - Wireless Communication integration with speeds of 3 Mbps installed alongside hardwire connection

NSTTF Heliostat Field Refurbishment - Software

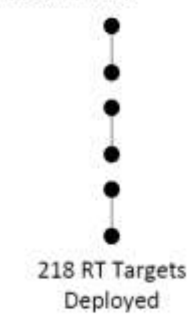
- Flexible solar field distributed control system (DCS) manages the flux distribution of energy across test articles and solar receivers using real-time heliostat-aiming and closed-loop feedback algorithms for solar field.
- Feedback control is facilitated with a variety of sensors, located: 1. On the heliostat, 2. On the tower or 3. At an ancillary field tower station
- System developed to incorporate environmental information to provide real-time feedback into advanced algorithms for solar field management.
- Current Deployed software dates to LabVIEW 8.6 released in 2008
  - Outdated Windows 7 Operating System
  - Open Loop Control procedure
- New Control software will be developed in LabVIEW 2020
  - Each Heliostat Real Time Controller will have the CRIO OS 2020
- The control software will contain a new architecture to allow integration of Closed Loop Control procedures
- New Network communication protocols to allow faster data transfer for high reaction operations

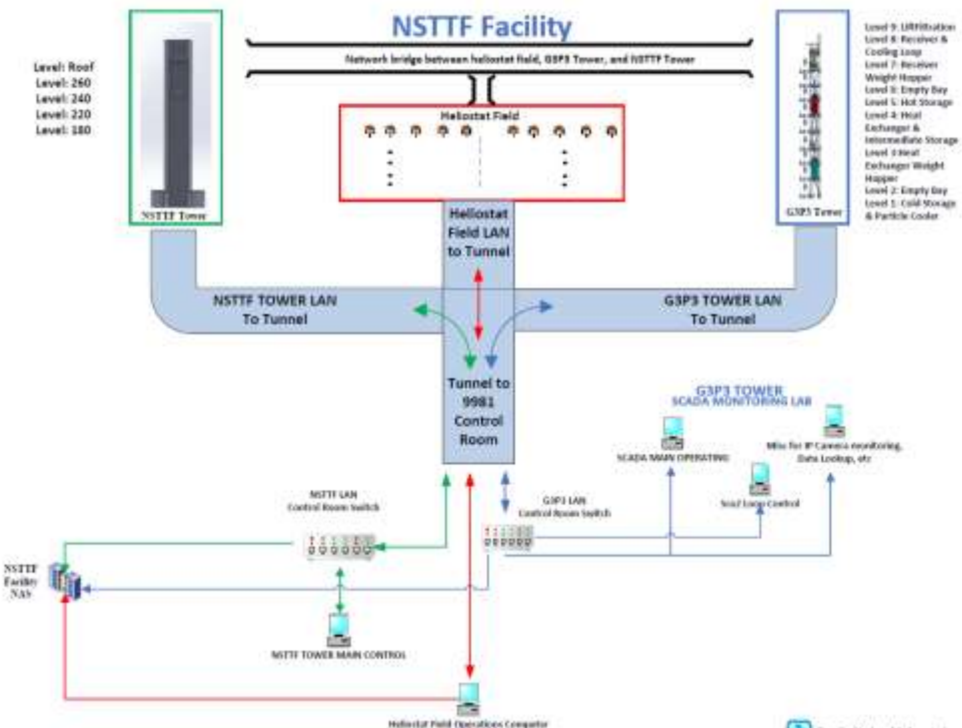
Communications Development

NSTTF NEW HELIOSTAT CONTROL ARCHITECTURE



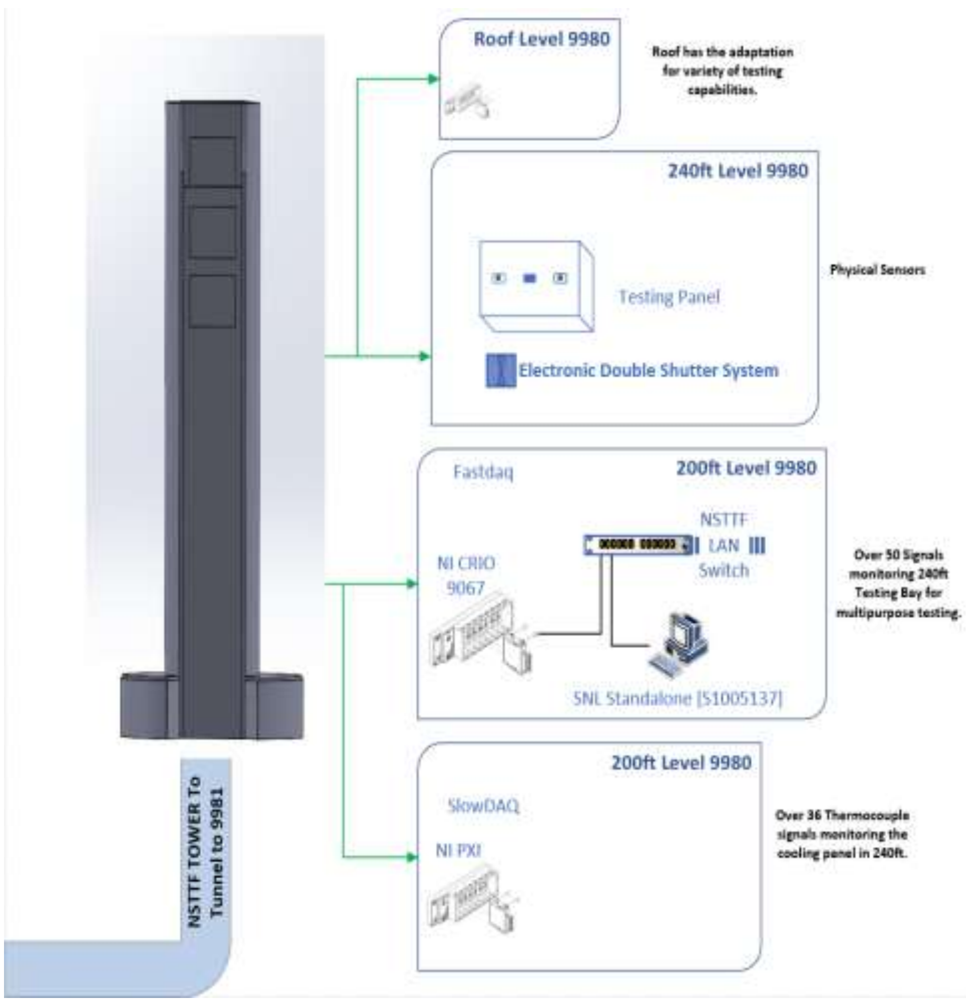
Each CRIO uses FPGA processing for high speed I/O analysis for both Az and El motors and Encoders.

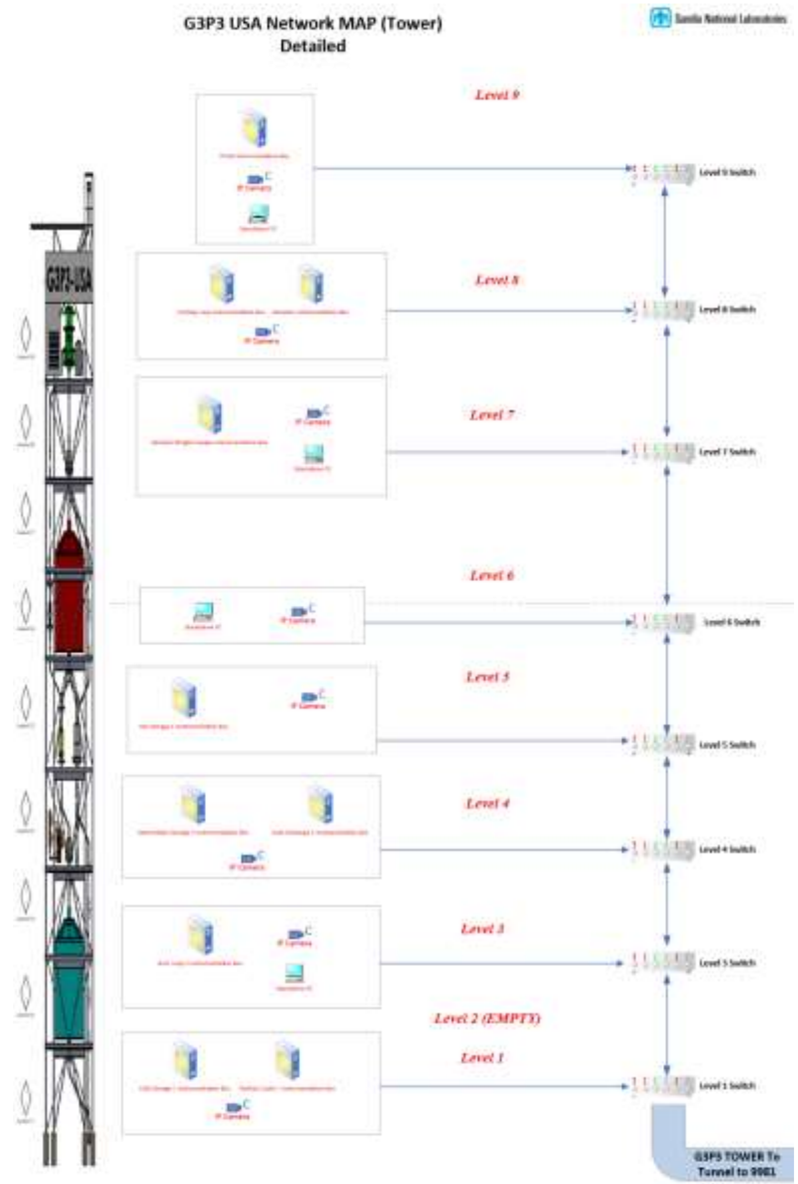




Tower Feedback Controls

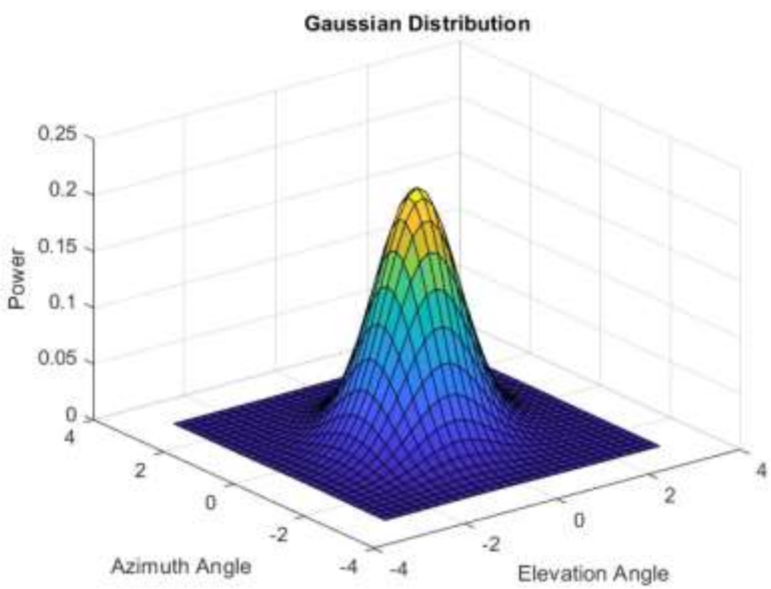
Current NSTTF Tower

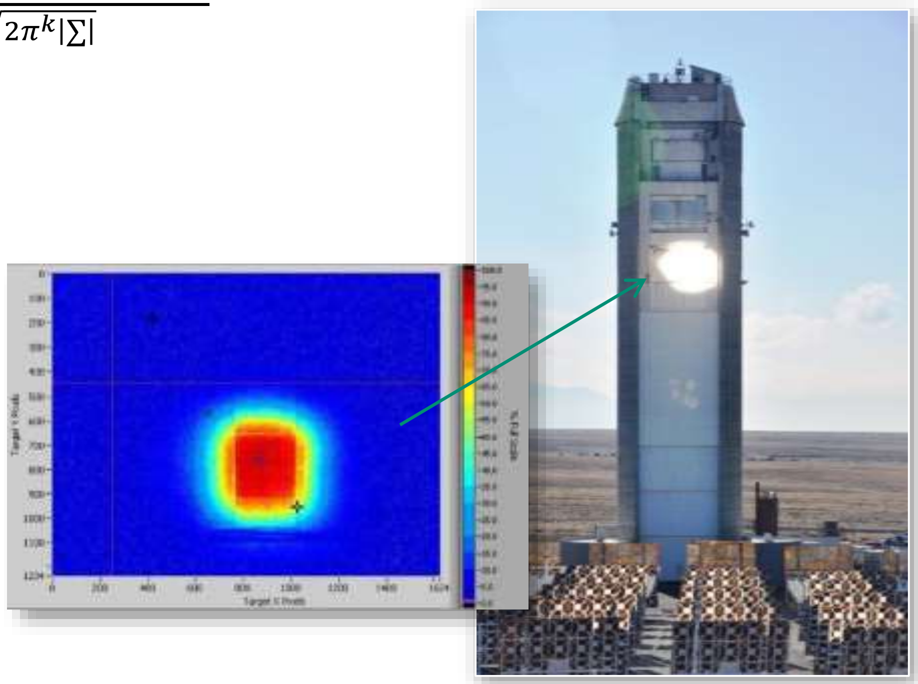




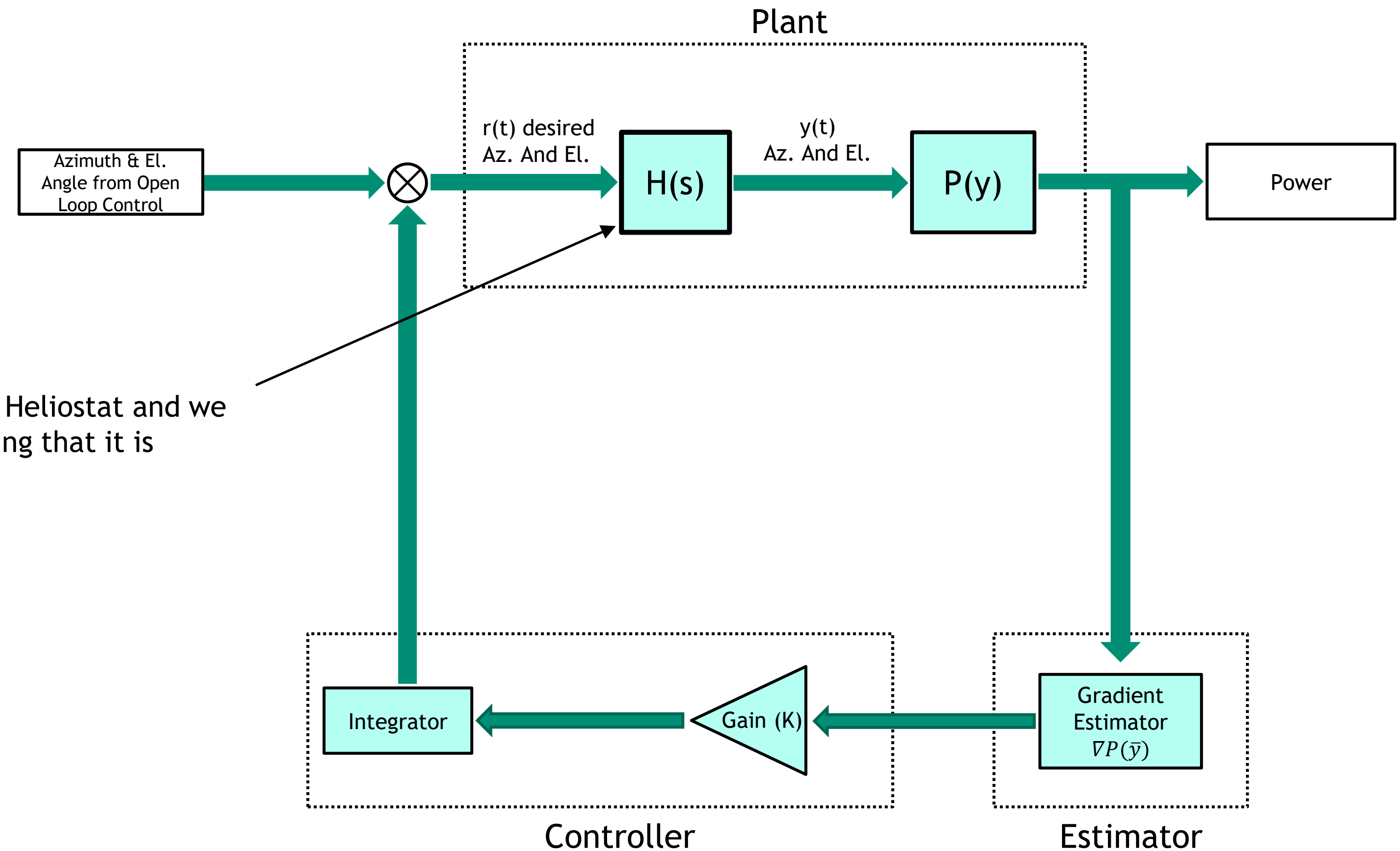
Extremum Seeking Closed-Loop Control

- Extremum Seeking Control algorithm (ESC) was developed with gradient ascent to find the azimuth and elevation angle to adjust individual heliostats to a maximum flux profile
- Feedback loop consists of a batch least squares (BLS) gradient algorithm as well as a controller to send signals to the heliostats to correct their locatiosn.
- Analysis being performed against BCS and IR Cameras
- Flux and Thermal Gradients to provide fine resolution controls
- Course assessment based on inherent open-loop algorithm controls
- On-Going data collection as training data for improving accuracy
- Heliocon metrology task collaboration for final controls analysis
- 2-variable Gaussian profile: $f(x_1, \ldots, x_k) = \frac{\exp(-\frac{1}{2}(x-\mu)^T \Sigma^{-1}(x-\mu))}{\sqrt{2\pi^k |\Sigma|}}$





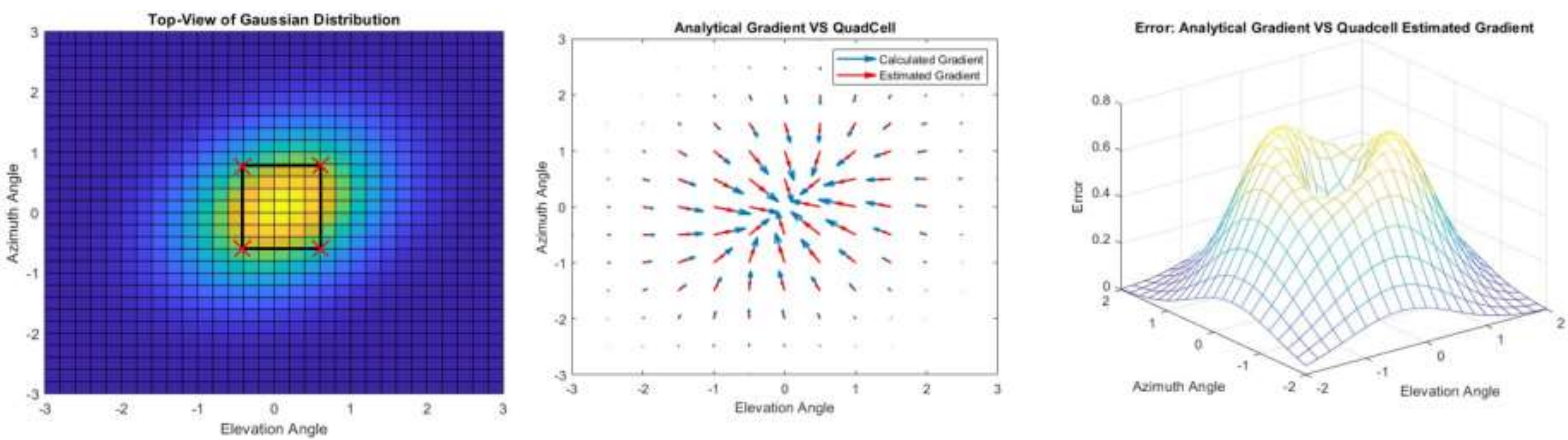
Closed Loop Controls Initial Architecture



H(s) is our Heliostat and we are assuming that it is servoed

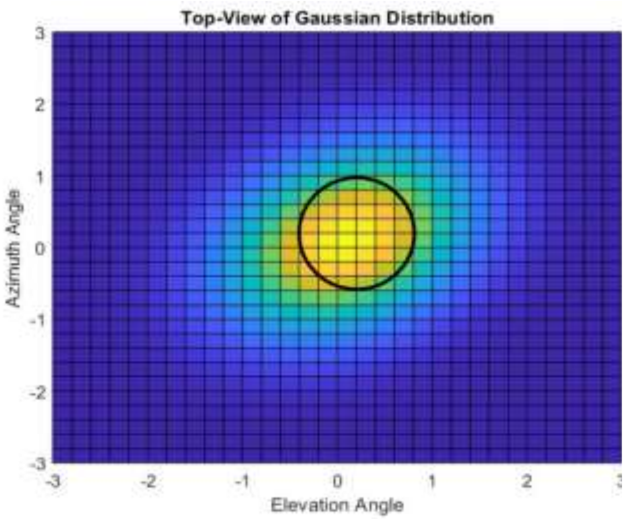
QuadCell Approach Simulation

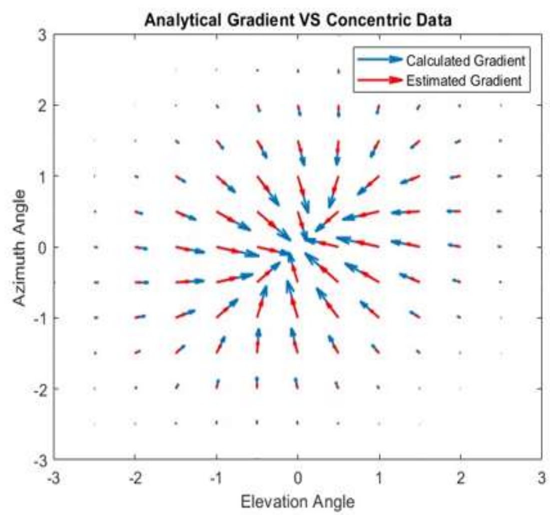
- 4 four heat flux sensors used in a configuration to determine the peak power.
- Simulation goal to compare data collection method and estimation with true gradient at each point.
- When box is centered power at each point will be distributed with zero gradient across four sensors.
- Validation that BLS estimator will give an accurate location for optimal azimuth and elevation.

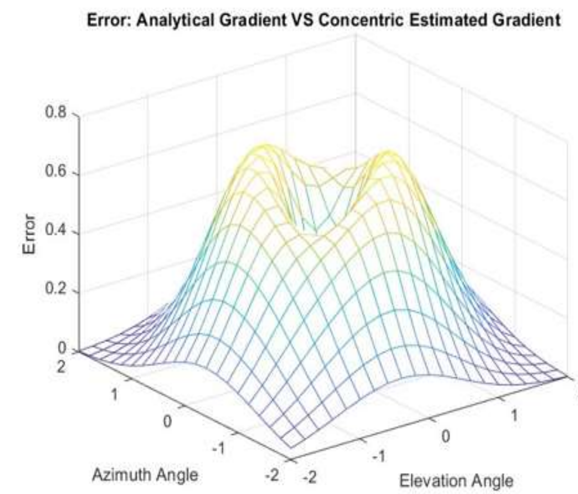


Concentric Approach Simulation

- Concentric heat flux approach used to measure circumference of a circle.
- Concentric heat flux gauge results show error between the calculated and estimated gradient approach zero as algorithm approaches optimal azimuth and elevation.
- Results parallel Quadcell simulation and further validates the estimator because the estimated gradient is consistently accurate through different data collection methods.
- This validates BLS estimator to give an accurate location for optimal azimuth and elevation.

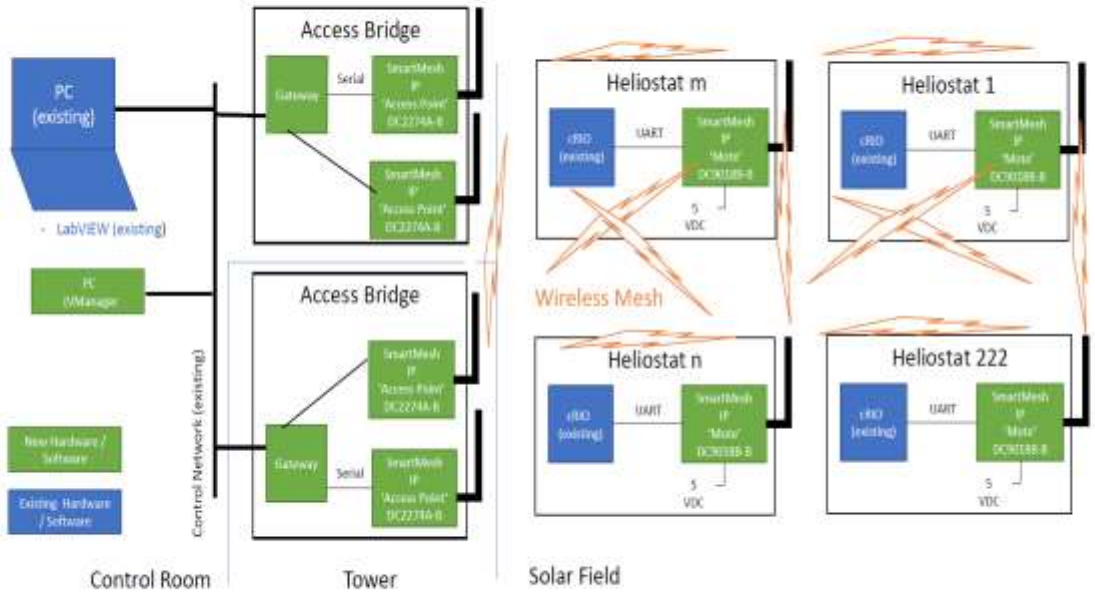




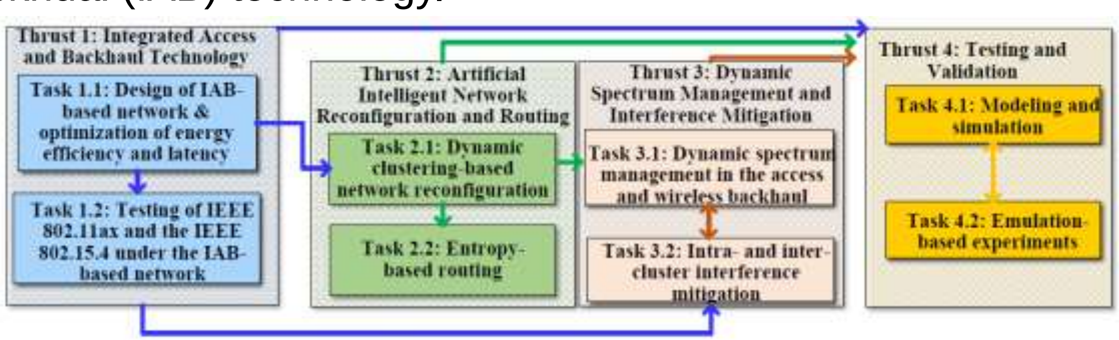


Heliocon RFP Controls Projects

- Solar Dynamics Mesh Network
  - Demonstrate reliable solar field wireless control system to replace wired networks.
  - Wireless Radio Frequency (RF) demonstration system.



- UNM Mesh Network Protocol
  - HELIOCOMM resilient wireless communication protocol system based on Integrated Access & Backhual (IAB) technology.



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.
- Proved through two methods (QuadCell and Concentric approaches) to achieve zero pointing error through ESC BLS methodology.
- 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.

Acknowledgements

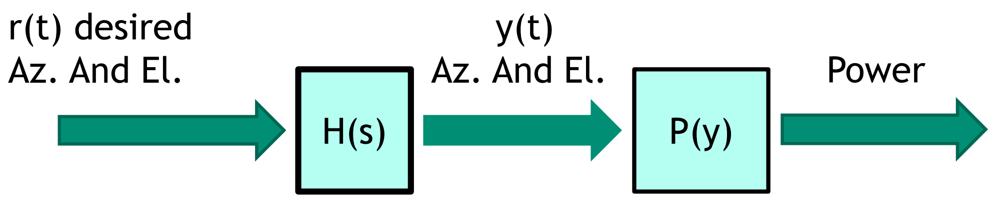
This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under DOE-SBV-86243.
Disclaimer: report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

kmarmij@sandia.gov

Thank you.

Plant



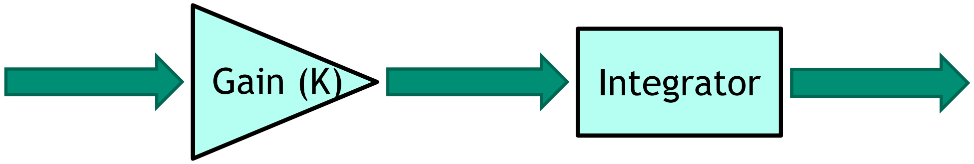
- H(s) is the transfer function of our Heliostat
  - Dynamic System
  - Input: Desired Azimuth and Elevation angle
  - Output: Actual Azimuth and Elevation angle
- P(y) is our reward function which is our power and is nonlinear
  - Algebraic function which is non-dynamic
  - Input: Actual Azimuth and Elevation angle
  - Output: Pointing & Power
- Integrate open loop algorithm to get desired azimuth and elevation which acts as a feedforward coarse controller
- Goal: Maximize our power on the tower

$$P(t) \rightarrow P^* = \max P(y^*)$$

- An associated optimal Azimuth and Elevation that give P^*

$$y(t) \rightarrow y^* = (az^*, el^*)$$

Controller



- Extremum Seeking Control is an optimization algorithm
  - Finds direction needed to improve the reward function ($\nabla P(y)$)
  - Moves the heliostat in the necessary direction

$$Goal: r^+ = r^*$$

  - Using the steepest ascent optimization algorithm below

$$r^+ = r + K\nabla P$$
$$r^+ = r^* \ when \ \nabla P = 0$$

- Goal of the controller is to track the ever improving reference

$$y(t) \rightarrow r(t) \rightarrow r^* and \ P(t) \rightarrow P^*$$

Estimator

- Trying to Maximize P(y) {Reward Fxn}
- Measure: Power versus Position

$$P_i = P(y_i)$$

  - Using the real-time dataset below to provide feedback:

$$\{P_i, y_i\}_{i=1}^{N}$$

- Goal: $Estimate\ \nabla P(\bar{y})$

$$P_i = P(\bar{y}) + \nabla P(\bar{y})^T (y_i - \bar{y}) = \theta^T \Phi_i$$

$$\Phi_i = \begin{bmatrix} 1 \\ y_i - \bar{y} \end{bmatrix}$$

$$\theta = \begin{bmatrix} P(\bar{y}) \\ \nabla P(\bar{y}) \end{bmatrix}$$

Estimator

- Approach: Least-Squares Estimator

$$E = \frac{1}{2}\left(P_i - \begin{bmatrix} P(\bar{y}) \\ \nabla P(\bar{y}) \end{bmatrix}^T \begin{bmatrix} 1 \\ y_i - \bar{y} \end{bmatrix}\right)^2$$

$$E = \frac{1}{2}(P_i - \theta^T \Phi)^2$$

- To minimize estimator cost we take derivative with goal to find when derivative equals 0:

$$\frac{dE}{d\theta} = \Phi P_i - \Phi \Phi^T \theta$$

- Challenge with this is that we must have data such that:

$$\Phi \Phi^T = \begin{bmatrix} a & b \\ b & c \end{bmatrix}^{-1}$$

- Take condition number where higher the condition number the better the data is.
  - Quality of data vs. Quantity of data.

Field Hardware Timeline

- cRIO 9053 Hardware Update: June 2022 – Aug 2022
  - 218 cRIO 9053 delivered to NSTTF and passed quality check: June 2022 – July 2022
  - Operating System Update: June 2022 – July 2022
- Field-programmable gate array (FPGA) Interface for cRIO 9053: July 2022 – Oct 2022
  - Synchronous Serial Interface (SSI) Encoder: July 2022 – Aug 2022
  - Test Interface: Aug 2022 – Sept 2022
  - Simulation & Validation (Installation onto 9053 Test module): Sept 2022 – Oct 2022
- Heliostat Field cRIO Deployment: Jan 2024 – Mar 2024
- SCRAM, GPS, & NAS Deployment: April 2024
- Wireless Communication Installation: Jun 2024 – Aug 2024

Control Software Timeline

- RT Interface: Sept 2023 – Jan 2024
  - Communication with FPGA: Sept 2023 – Oct 2023
  - Develop calculations and Connections: Sept 2023- Dec 2023
  - Simulation Testing: Oct 2023 – Jan 2024
  - Validation: Dec 2023 – Jan 2024

- Closed Loop Controls: June 2023 – July 2024
  - Single Heliostat Algorithm: June 2023 – Nov 2024
  - Small Cluster Heliostat Algorithm: Sept 2023 – Mar 2024
  - Large Cluster Heliostat Algorithm: Feb 2024 – July 2024

- Closed Loop Interface: Jan 2024 – Mar 2024
  - Sensors for DNI, wind, weather, camera: Jan 2024 – Feb 2024