Lessons Learned Crescent Dunes Heliostat Field Control System

- Design Phase
- Individual Heliostat Testing at Sandia
- Heliostat Field Controller (HFC) Testing at Rocketdyne (120 Heliostat Control Units)
- Field Commissioning of the Heliostat Field 1 HFC at a Time
- Initial Operation Tests
- Damaging the Receiver
- Thawing the Receiver
- Calibrating the Heliostats
- Importance of Simulation Support

Lessons Learned Crescent Dunes Heliostat Field Control System

This seminar will cover lessons learned on this project from the initial design and prototyping phase up through the commissioning and operation of the solar field. The organizational structure of the project with responsibility split between the EPC, Solar Reserve, Rocketdyne and the various subcontracts had a significant impact on technical progress. Some of those impacts will be discussed. Important singular events that will be discussed are the thawing of a frozen receiver and damage to an empty receiver by focusing too many heliostats on it. The calibration of the heliostats with the Beam Characterization System (BCS) will be covered in detail.

The importance of simulation testing and the benefits it provided to the project will be covered. Simulation testing of 3 HCU's helped support the successful installation and testing of 3 Heliostats at Sandia. A full 1000-meter cable setup of several HFCs with 120 heliostat control units were tested at Rocketdyne before the field commissioning helped uncover many issues.

Mark Ayres Short Bio

- Born in Pittsburgh, PA 1953
- Graduated University of Pittsburgh 1977 and started work with Westinghouse Electric Corporation providing Control Center Software for Electric Utilities. In 1989 I joined the Rocketdyne Division of Rockwell International to work on the Electric Power System for International Space Station. At Rocketdyne I worked on several interesting projects, the Advanced Tactical Laser, the Boeing 787 Electric Power System and the Heliostat Field Software for Solar Reserve. I joined Solar Reserve in 2014 and worked on the Crescent Dunes Heliostat Field Control System. I now have my own company and perform as needed consulting work for Crescent Dunes. I am also working with NREL to leverage the Crescent Dunes Software for use in other CSP Plants.

- I enjoy weight-lifting, Korean Language, Dramas (and Food!). My office is in Koreatown, and I enjoy learning the Korean Language and helping some of my Korean friends with the English.

Crescent Dunes Heliostat Field Control System
How I got involved with CSP

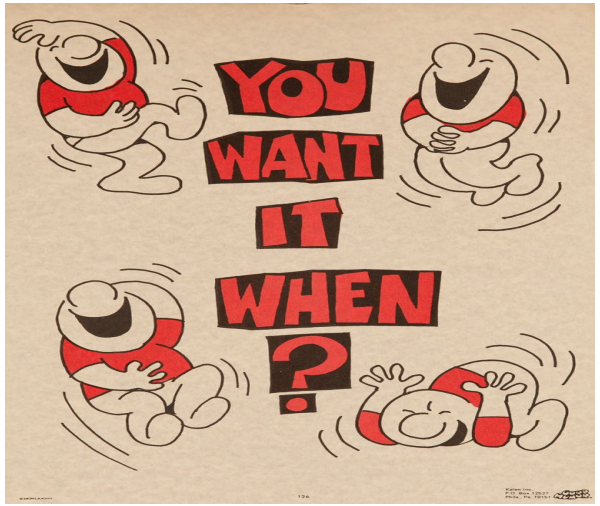
- 2008 I was working on the ORION Project. I was tired of space work and wanted to work to a terrestrial power system project.

- Rocketdyne had a contract with ESCOMM to design a CSP plant. They were also discussing CSP plants in the Mojave with LADWP. This looked attractive to me. I had been using the JPL Ephemeris for Orbital and Solar Simulation of the ORION CEV. I had experience with a framework from Alstom that was a good fit for the control system. So, I put my hat in the ring and joined the project

- Rocketdyne received a contract from Solar Reserve to provide the Receiver and the Heliostats for a project in Cinco-Casas (Andalucia).

They told me that I had 6 months to get the system up and running.

- **Lesson: Beware of an organization that starts a project with an unrealistic goal:**



Crescent Dunes Heliostat Field Control System
Design Phase

- Iterative Approach – Design/Prototype/Simulate/Test . . . Design/Prototype/Simulate/Test

- When I worked at Westinghouse developing control center software we had to develop a Dispatcher Training Simulator. We developed it after designing, testing and deploying the control system.

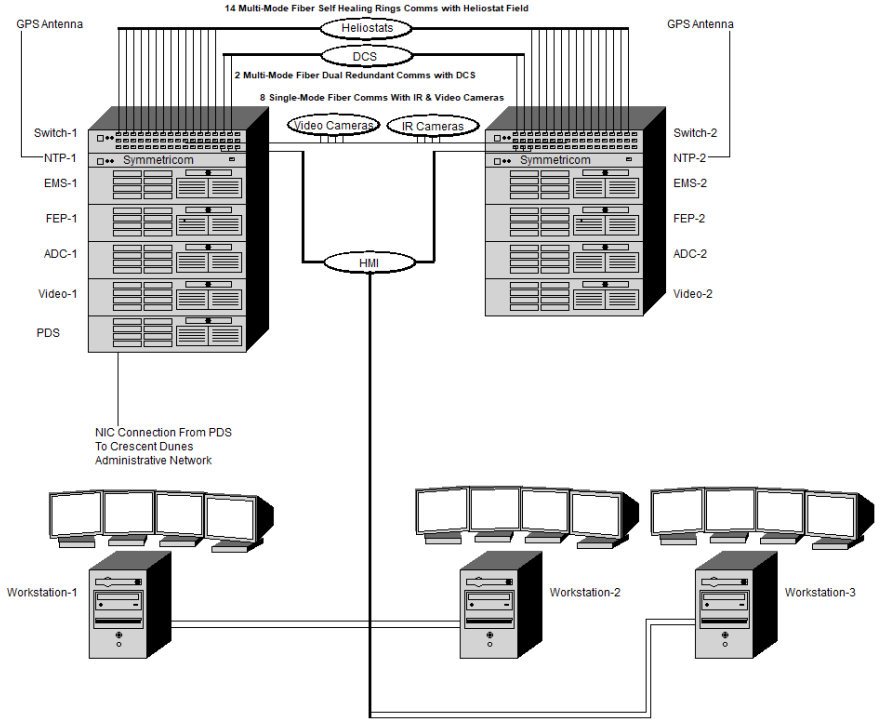
- The Training Simulator Team (5 Engineers) unanimously came to an early realization:

We should have done this 1st , It would have saved us so much time!

- Develop an end-to-end simulation that can accommodate hardware in the loop at the beginning of the Project. **This was a lesson I learned at Westinghouse**, and I've done that on every project that I have worked on since.

Crescent Dunes Heliostat Field Control System
Design Phase / Testing

- The Heliostat Design was moved from Canoga Park, Los Angeles to Huntsville Alabama.
- At Canoga Park we were in the Design/Prototype/Simulate/Test Loop with a full dual redundant system

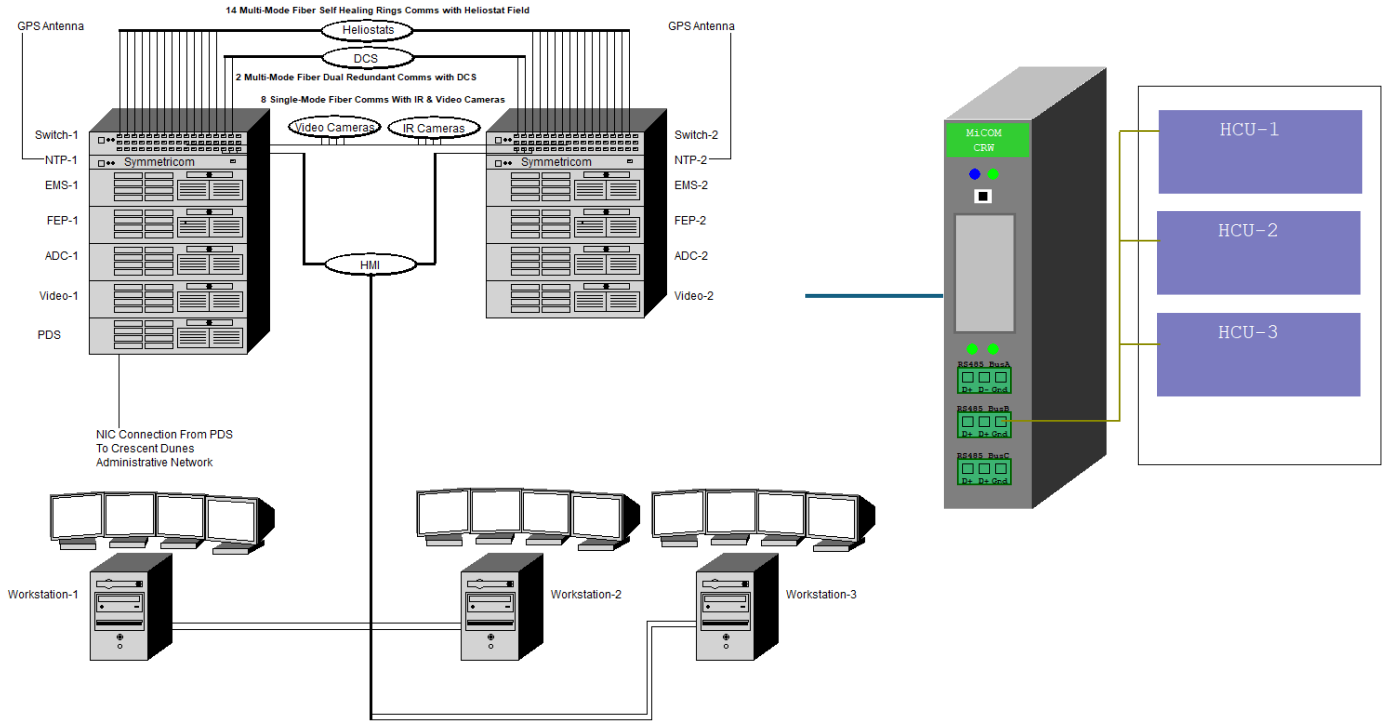


- The control system was far ahead of the Heliostat Design due to the relocation from LA to Huntsville

Crescent Dunes Heliostat Field Control System
Design Phase / Testing

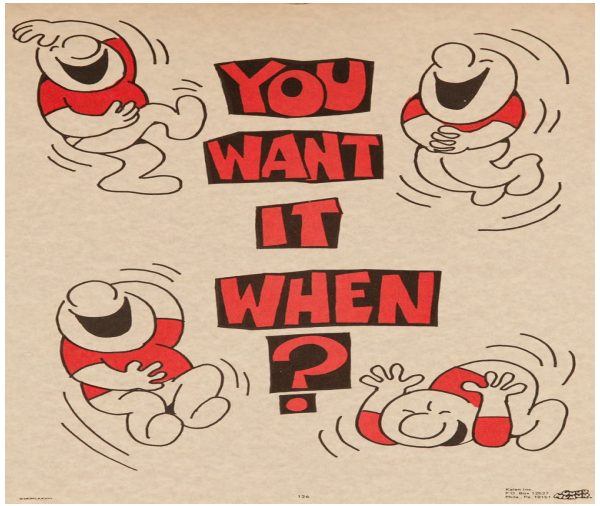
- The Delta Group was selected as the HCU provider. They supplied us with 3 HCU's to integrate into our LA Testbed

- Areva (Having acquired our Control Software Supplier as part of a deal with Alstom) supplied us with an HFC



Crescent Dunes Heliostat Field Control System
Huntsville Shipped A Prototype Heliostat To Sandia

- The Huntsville division had prototyped a Heliostat with Swagelok.
- Against many of the Engineers concerns the decision was made to ship that Prototype to Sandia



- I take it that you are all familiar with that video of the Tacoma Narrows Bridge? Well, Swagelok met a similar fate when confronting 60mph Sandia winds.

Crescent Dunes Heliostat Field Control System Testing At Sandia

- After the Swagelok fiasco, Mark Speir drove his truck into Albuquerque, purchased steel beams and latices and rebuilt the heliostat.

  (One lesson here is: You learn who you can count on when the going gets tough)

- The new heliostat was able to survive the wind loads at Sandia.

- We installed our Control System on a Workstation and shipped that to Sandia.

- I then spent a few years with Delta and the Rocketdyne Sandia team testing 3 heliostats at Sandia.

Crescent Dunes Heliostat Field Control System Testing At Sandia

- For BCS Testing we improvised and used multiple structures as BCS Targets:
  1) The actual target on the tower (water cooled with heat sensing!)
  2) The side of the HARM building (I believe it was ~800m away)
  3) A water tower that was more than 1000m away

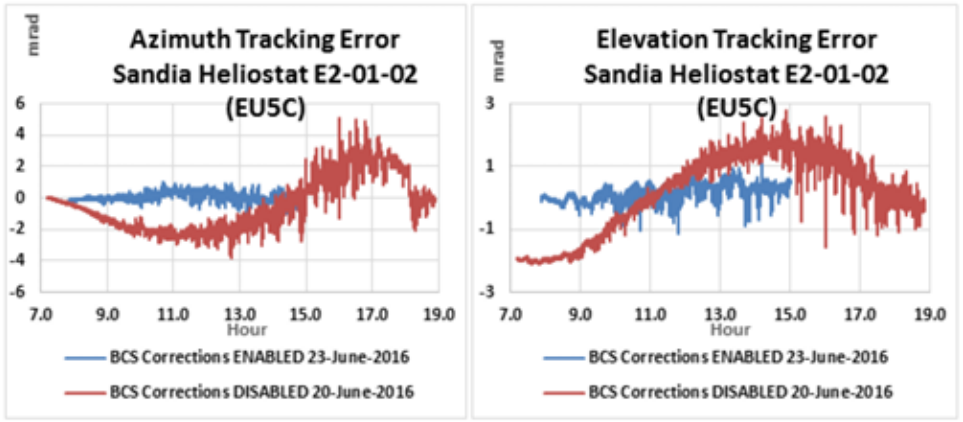
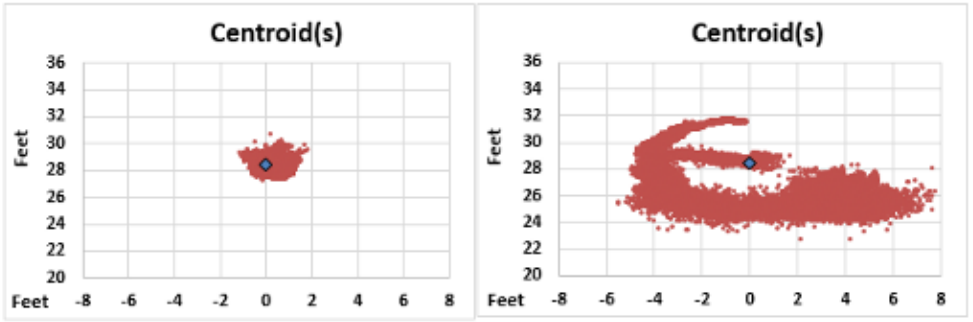


Figure 10. Azimuthal and Elevation Tracking Error Comparison

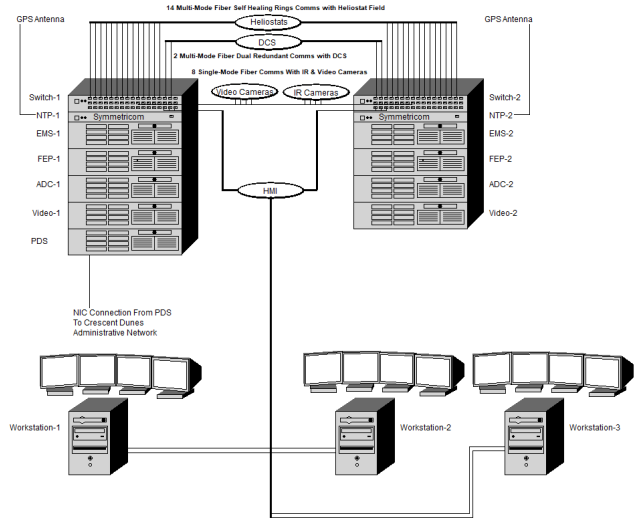


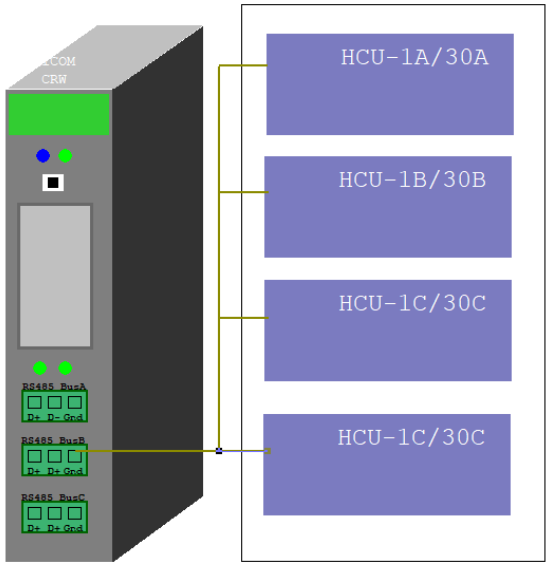
Crescent Dunes Heliostat Field Control System
Testing a full HFC (120 HCU's) At Rocketdyne

- I mentioned to Dave Morse, the Delta VP that I needed HCU's. Delta shipped 120 HCU's to me.
  They arrived at the Space Shuttle Building (There was no paperwork!)
  I drove over there, loaded them onto my Volvo, and drove them 2 miles back to the Space Station Building

  Somehow, I managed to get them through the guards without the paperwork.

- Rocketdyne set up a full HFC Testbed with 1200 meters of shielded RS485 cable.

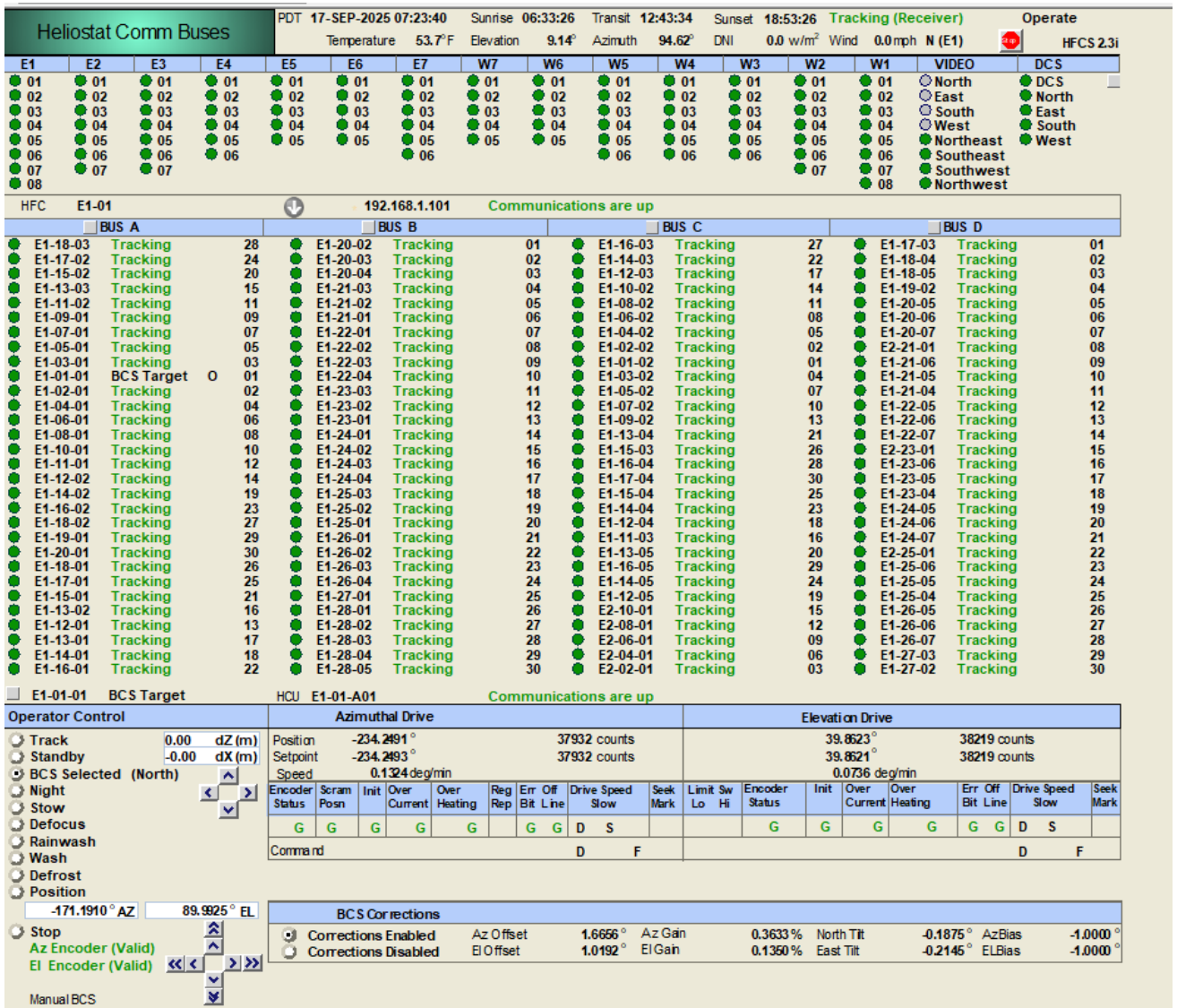




1200 meters of actual RS485 Cabl

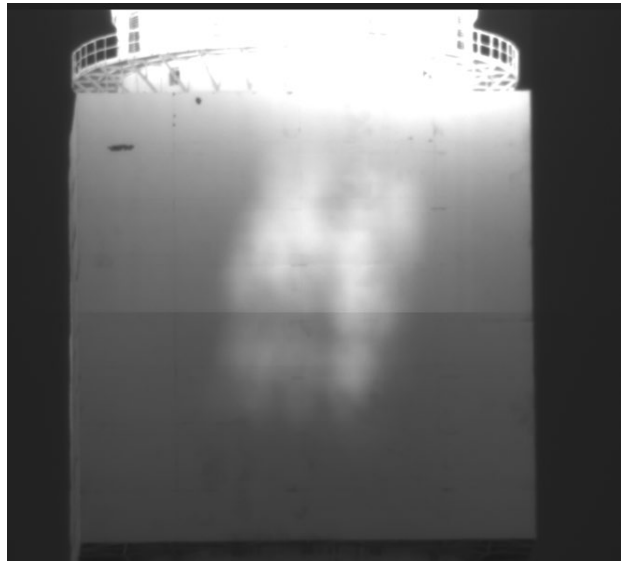
Crescent Dunes Heliostat Field Control System
Testing a full HFC (120 HCU's) At Rocketdyne

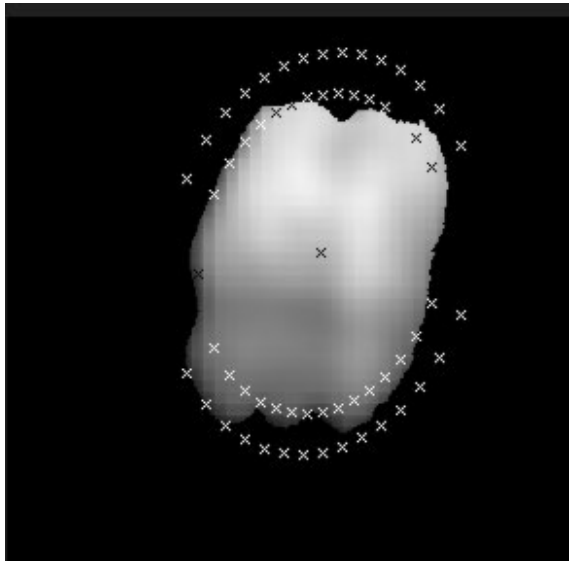
This display was developed from the 120 HCU Testbed. It was very important for the initial field calibration of the Heliostats at Tonopah.



Crescent Dunes Heliostat Field Control System
Calibrating the Heliostats

- We purchased 4 powerful DELL Servers and installed the HFCS Control System on each one.
- 4 Teams in the Field at Tonopah would perform a Manual BCS Capture on each Heliostat. The BCS cameras had not yet arrived, or we would have done this from the comfort of the control room.
- We merged the 4 databases into the initial database for the Control System at Tonopah





The field techs calibrating the heliostats became the operators of the system when we went on-line

- **Lesson: Use the same software throughout the Design, Test, Installation and Operation of the System**

Crescent Dunes Heliostat Field Control System
Frost on the Heliostats –> Burning a Hole in the Receiver

- I drove into the plant one morning and noticed ~ 6 inches of Frost on the Heliostats. I immediately knew that this was not a good thing!

- As good as Rocketdyne was in planning and preemptive action, no one had any plans in place for this. It had not even been considered.

- I initiated, on my own, a plan to update the HFCS to have a Defrost State and point all the Heliostats at the sun to melt the ice as quickly as possible.

- I developed most of this in the simulation, but I had to do a lot of on-line testing. I would install a test version, get feedback and then remove the test version.

- I was not working with Santa Monica or Madrid. I was off on my own. They were getting concerned that I was in Cowboy mode and they started to put brakes on me. This was unfortunate because it led to a serious incident where the HFCS burned a hole in the receiver.

- **Lesson Learned: It is good to show initiative and solve problems on your own – but you should keep the other stakeholders in the loop.**

Crescent Dunes Heliostat Field Control System
Frost on the Heliostats –> Burning a Hole in the Receiver

- I was keeping Sandia and Tonopah synchronized. I put identical software on both systems. Mark Speir was very good at testing and giving me feedback for new features.

- I was installing test versions on the on-line system to get vital feedback for the Defrost State.

- Santa Monica management got fed up with me constantly installing new software and they froze the software on the HFCS.

- Mark Speir was testing, and he reported to me that the Defrost State was sometimes pointing the heliostats at his tower and not at the sun!

- I was so involved in trying to convince Santa Monica to allow me to continue on-line testing and I was not acting on Mark's findings.

- Eventually the Tonopah Engineers were testing Defrost Mode. And the problem Mark found + other issues conspired in a perfect storm to result in damage to the Receiver.

- **Repeat Lesson Learned: It is good to show initiative and solve problems on your own – but you should keep the other stakeholders in the loop.**

Crescent Dunes Heliostat Field Control System
BCS Corrections For the Heliostat

- The BCS Corrections are parameters derived from processing Heliostat Centroids from multiple images
  The differences between the actual centroid and the calculated centroid location are used in a Weighted Least Squares (WLS) algorithm with Bad Data Detection/Rejection to calculate the correction parameters

- To calculate tracking error, we leave the last centroid measurement out of the WLS algorithm. We calculate the Az and El angles for focusing the Heliostat on that last centroid. This is compared to the actual Az and El angles that focused the last measurement.

- The next slide show the improvement that we obtained over the course of the project

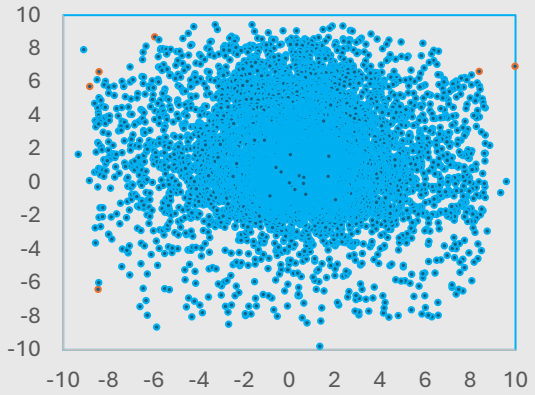
- **Lesson Learned: Once you have sufficient centroid measurement, Keep the last measurement out of the WLS calculations and use it to assess your tracking error.**

TonopahSolar Field Deployment

- Assessment after Construction and Initial Installation.

Heliostat Pointing Assessment 30-DEC-2016 14:35:48 PST		
Azimuthal Error Mean	-0.4293	(mrad)
Azimuthal Error Stdv	2.5862	(mrad)
Elevation Error Mean	-1.0089	(mrad)
Elevation Error Stdv	2.3630	(mrad)
Tracking Error Mean	-1.3188	(mrad)
Tracking Error Stdv	3.4256	(mrad)
Heliostats Evaluated	6730	(number)

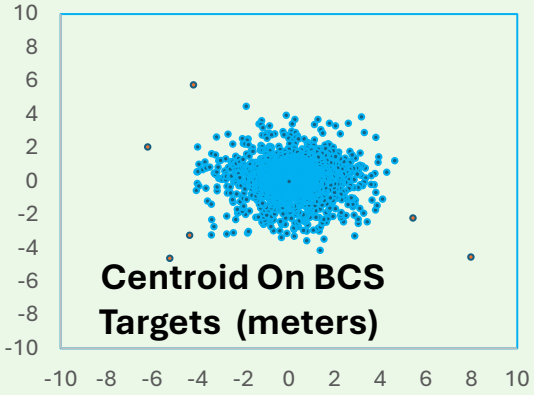
Heliostat Slope Error Assessment 31-OCT-2015		
Surface X-axis Slope Error	1.5000	(mrad)
Surface Y-axis Slope Error	2.2000	(mrad)

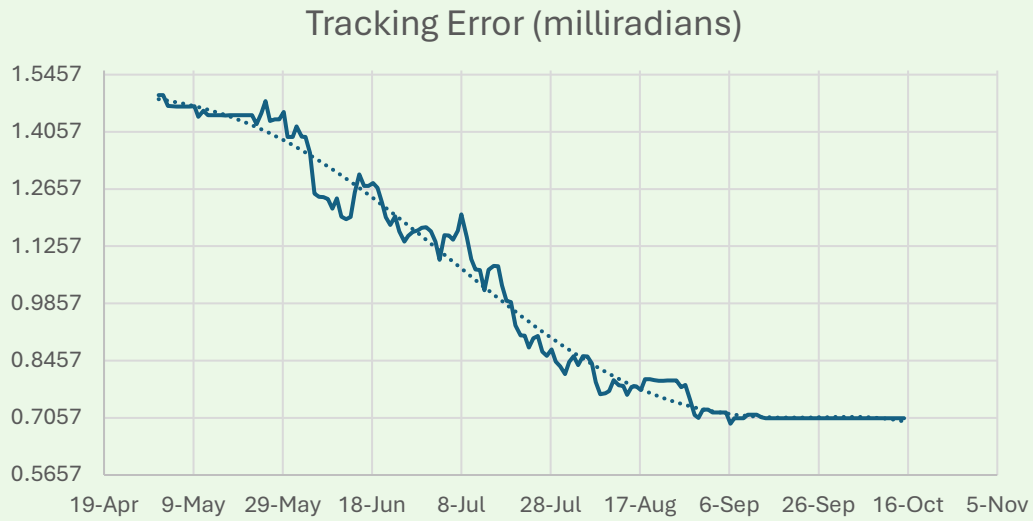


- We decided to concentrate on improving tracking and made many improvements to our Automated Beam Characterization System

- Last assessment

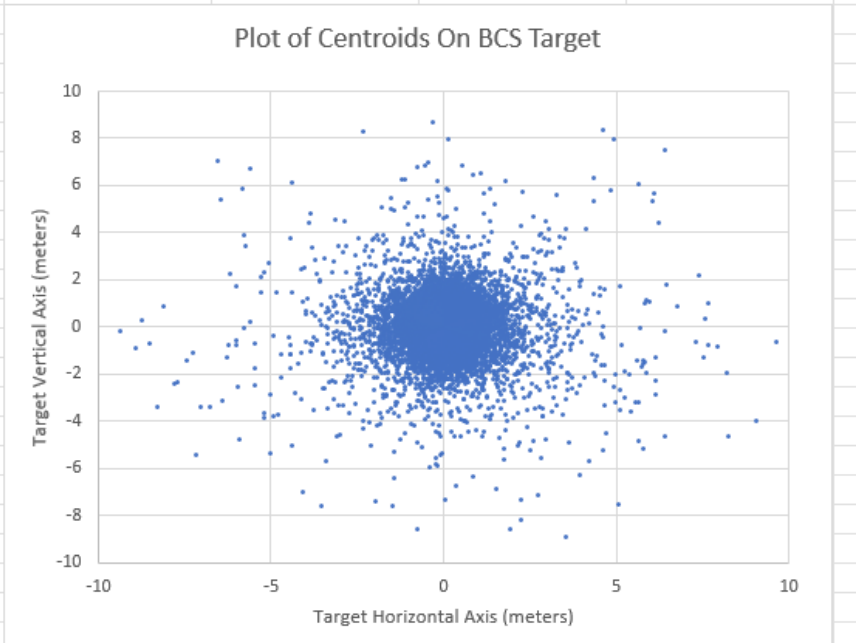
Heliostat Pointing Assessment 13-SEP-2020 15:29:20 PDT		
Azimuthal Error Mean	-0.0136	(mrad)
Azimuthal Error Stdv	0.4901	(mrad)
Elevation Error Mean	-0.0570	(mrad)
Elevation Error Stdv	0.5092	(mrad)
Tracking Error Mean	-0.0812	(mrad)
Tracking Error Stdv	0.7045	(mrad)
Heliostats Evaluated	10214	(number)





Crescent Dunes Heliostat Field Control System
BCS Corrections For the Heliostat

Crescent Dunes BCS Analysis			
Number of BCS Images Analyzed: 116886			
Pointing Error Mean Value (mrad)		Pointing Error Standard Deviation (mrad)	
μ (Az)	μ (El)	α (Az)	α (EL)
-0.0725	-0.0217	0.6784	0.6672
Date of Evaluation		Population Size (>4 BCS)	
03-August-2023 03:00:05 PDT		10175	Heliostats



Crescent Dunes Heliostat Field Control System
Thawing a Frozen Receiver

- We had a failure in the Heat-Trace for the Receiver Drain System and the entire receiver salt inventory froze in place

- Meeting were held in Santa-Monica to determine how to thaw the receiver. Solar 2 recommendations were to thaw each panel separately.

- We ran simulations and found that, with our large heliostats, we could inadvertently melt a section of an adjacent panel midstream. This would cause a tube rupture

- We recommended full circumferential thawing from the bottom up. This worked in our simulation without causing tube rupture. The engineering staff at Santa Monica were not convinced that our simulation results were correct.

- We had a meeting with the CEO, and he heard both sides and elected to go with our recommended circumferential thawing approach.

- We were able to thaw the receiver without damaging it.

- **Use a previous Lesson Learned: Keep the stakeholders In the Loop.**
- **Lesson Learned: High fidelity simulations are indispensable in complex systems like CSP plants**

Crescent Dunes Heliostat Field Control System
Thawing a Frozen Receiver

- We chose our most accurate heliostats as “Melters”
- Less accurate, but still good tracking, heliostats were chosen as “Warmers”
- The “Melters” were used to slow ascent the Receiver the salt. The “Warmers” were used to keep the already melted sections war, so the salt wouldn’t refreeze.
- The IR Cameras proved their worth here, helping the operators manage the process.

  This is the way I would thaw a receiver in the future.

  Not exactly a lesson – But a proven way to move forward.