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Drop-C: The Drop-In, Ring-of-Power Heliostat

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Kyle Kattke

Kyle.Kattke@SolarDynLLC.com

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Project Structure and Goals

- 3 technologies being developed in parallel
  - Primary: Drop-C Heliostat
  - Supporting technologies: Wireless Mesh Network (WMN) and Rapid Calibration (RC) system

	Drop-C Heliostat	Wireless Mesh Network	Rapid Calibration
Overall Project Goals	1. ≤ $50/m2 installed cost 2. 4mrad calm / 5mrad windy optical error 3. 35mph operational / 94 mph survivable wind speed 4. ≥ 30-year lifetime	1. command response of any controller within ≤30s 2. ability to wirelessly update parameters and firmware 3. wireless controller = $70/unit 4. security fail-safes disallow unintended damage	1. ≤ 0.5mrad error detection sensitivity 2. calibration rate ≥1000 heliostats/day 3. operable within required solar field layouts and heliostat orientations 4. validated to be compatible with surround-type receivers
Period 1: Oct 2017 – Jan 2019	• Wind tunnel scaled testing • Digital prototype • FEA model • Component evaluation testing	• Wireless technology selection • 30-node wireless network test • Conceptual heliostat controller	• Analytical model to test feasibility of RC system • Bench scale rapid calibration test
Period 2: Feb 2019 – Jan 2020	• Component accelerated lifetime testing • Construct 2 x full scale prototypes • Structural and optical testing • Advanced lower-cost design developed	• 250-500 node wireless network test • Prototype heliostat controller	• Design and test camera enclosure • Test RC system at tower facility with multiple full scale heliostats
Period 3: Feb 2020 – Dec 2020	• Drawing package • Construct 3 x full scale prototype • Perform extended qualification testing	• Finalize controller design • Finalize heliostat array controller	• Redesign camera enclosure and retest RC system as needed

Drop-C: Design Motivation

- Commercial utility-scale heliostats
  - Size: range from 20.8m^2 (Brightsource LH2.3) to 178m^2 (Sener)
  - Cost Range: \$120-140/m^2
  - Commonality: pedestal mount design
- Abengoa Solar's Ring-of-Power (ROP) Heliostat
  - Developed in Colorado office under award #EE0003596
  - Novel approach eliminates need for ground anchors
  - Installed Cost: \$114/m^2
  - **Drop-C is an evolution of the ROP**

Novel ballast only carousel design

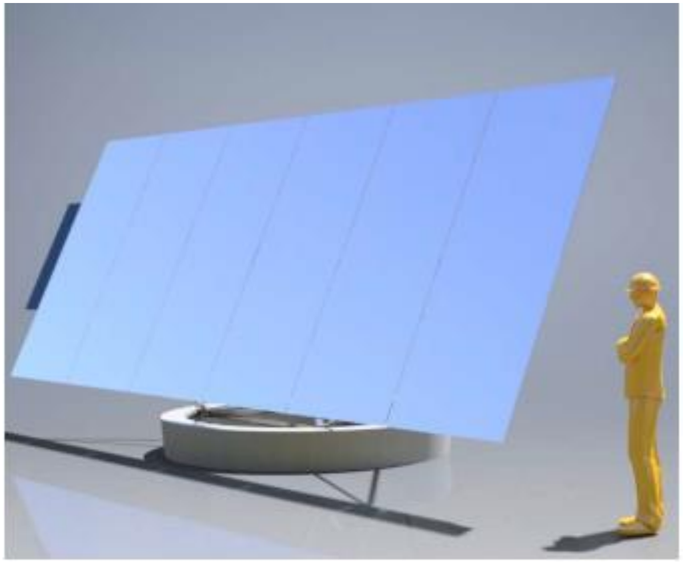
Abengoa Solar's ROP heliostat

Traditional carousel design requiring central ground anchors

Titan Tracker's heliostat

DLR's lay-down heliostat

Drop-C: Overview



Drop-C: Front View

- Attributes
  - Efficient space frame support system
  - Azimuth drive/idler wheels transmit all loads to foundation (no central ground anchor required)
  - Ballast foundation
  - Drop-In place installation
  - Reduced civil work, permitting, and geotechnical risk in the solar field

Drop-C Heliostat Key Metrics	
Reflective area	27 m^2
Overall dimensions	8.46 m wide x 3.21 m tall
Aspect ratio	2.6 (width/height)
Stow height	1.98 m
Mirror shape	Flat, no-canting
Foundation	Ballast
Power	PV plus battery
Control	Wireless

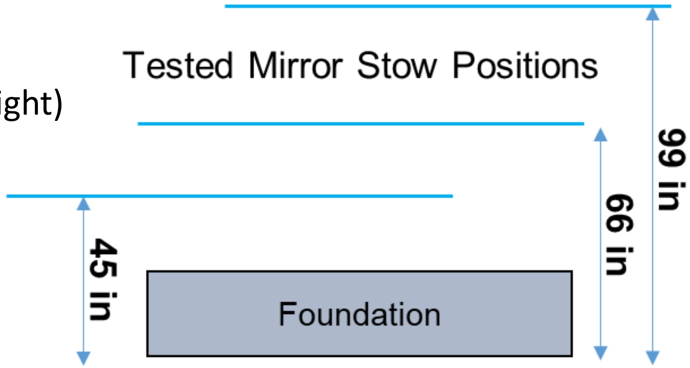
Drop-C: Wind Tunnel Study

Isolated Heliostat Testing

- Parametric tests varying stow height
- Support structure sized by 90°elevation case where loads ≠ f(stow height)
- Foundation mass sized by stow overturning + lift loads

Stow Height vs. Foundation Mass Cost

Stow Height [m]	1.1	1.7	2.5
Foundation Material Cost [\$/m²]	\$5.5	\$5.8	\$9.0



- Savings at lowest stow height not great enough to offset higher structural support and elevation actuator costs
  - 1.98 m stow height selected for Drop-C

Isolated Heliostat Testing

- 59 heliostats in wind tunnel to quantify interior field load reduction due to shielding from upwind heliostats
- Interior heliostat loads achieved at rows ≥ 4 from edge of solar field

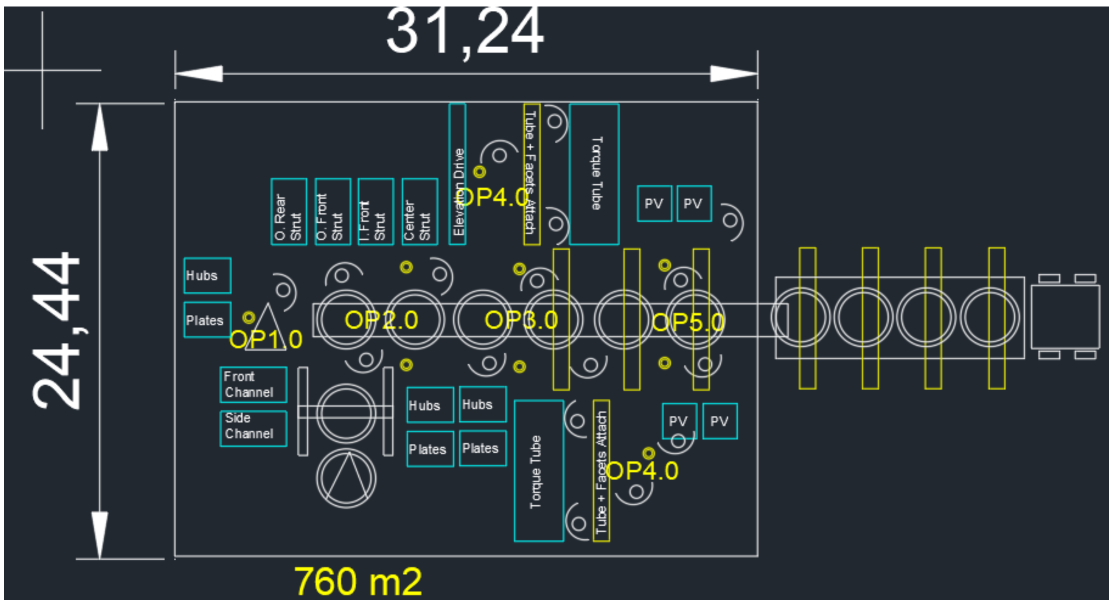
Interior Heliostats Peak Load Reductions for Operational Orientations

Load Component	Fx	Fz	Mz	My
Max Interior/Max Exterior Gust Load	52%	72%	60%	73%

Heliostat Field Wind Tunnel Testing

Drop-C: Assembly Plan

- Production rate of 1 heliostat every 7 minutes – solar field constructed in 11 months
- Drop-C assembled in automotive style assembly line with 5 main operations (OP)
  - Infrastructure costs calculated using defined workstations and assembly tent size
  - Number of workers required per workstation calculated to meet production rate



Drop-C Assembly Tent Layout

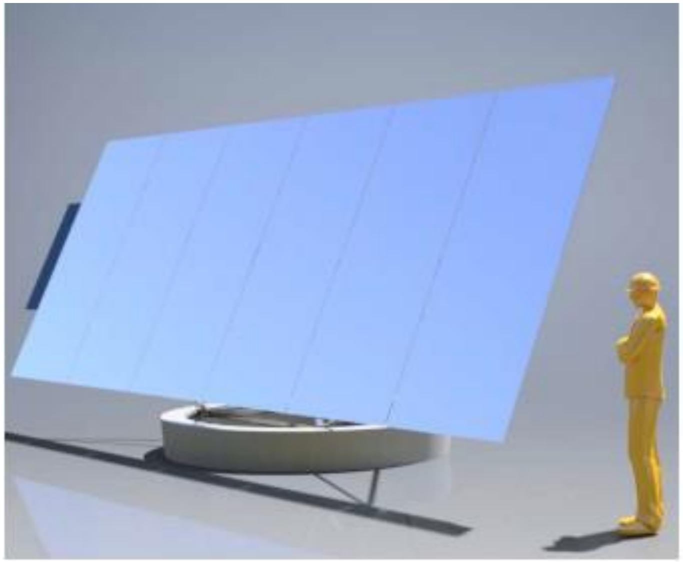
Drop-C Assembly Operations

Operation	Description
OP 1.0	Base triangle sub-assembly
OP 2.0	Base triangle attached to foundation along with partial lower structure and azimuth drive
OP 4.0	Torque tube and facets sub-assembly
OP 3.0	Torque tube/mirror assembly attached along with remaining lower structure and elevation drive
OP 5.0	PV panel installed with all control/power wiring

- Complete Drop-C trucked out to solar field
- Placed in final position with telehandler with gripper attachment

Drop-C: Budget Period 1 Outcomes

- $76/m^2 installed cost estimate
  - Exterior solar field location
  - Arizona project site with 40k heliostat solar field
- Areas for further cost reduction:
  - Create interior solar field specific Drop-C design
  - Fine tune mirror area
  - Add closed loop control through enhanced Rapid Calibration system
  - Replace portion of concrete mass with cheaper ballast (ie. local rock, gravel)

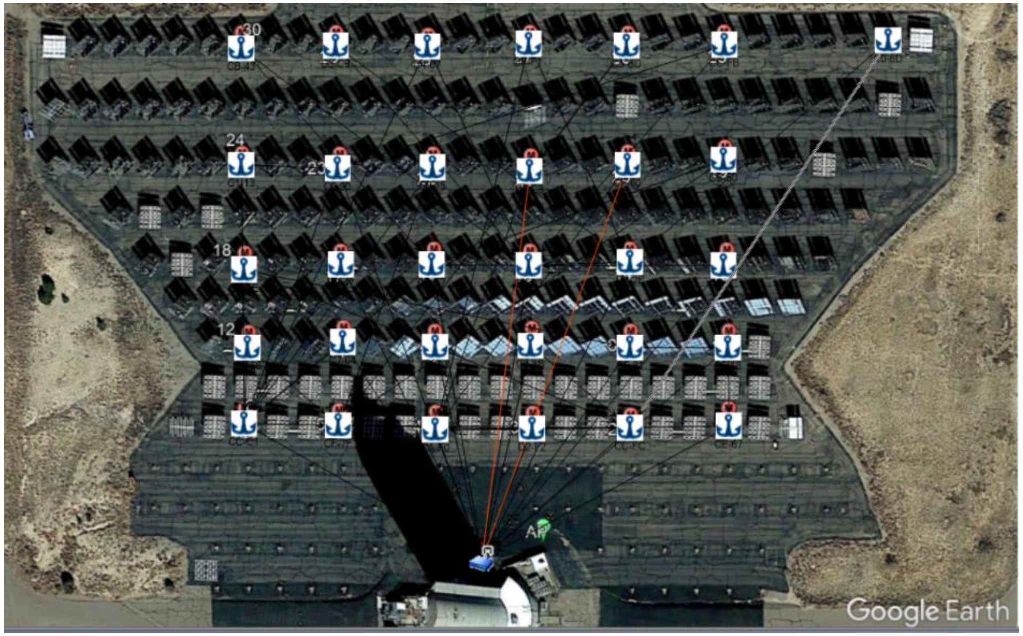


Drop-C: Front View

Wireless Network: Design and Testing

- SmartMesh IP wireless mesh network within solar field
  - Benefits: scalable 50k nodes, suitable for dense networks, commercial product with developer resources
  - Risk: only analytically proven at 50k scale (same risk applies to all wireless technologies)

- Budget Period 1 Testing
  - 30 node network test
  - Good network performance measured with heliostats tracking throughout the day
  - < 13 sec command/response speed
- Budget Period 2 Testing
  - 250-500 node network test



30-node WMN test layout at Sandia's NSTTF

Rapid Calibration System (RCS): Overview

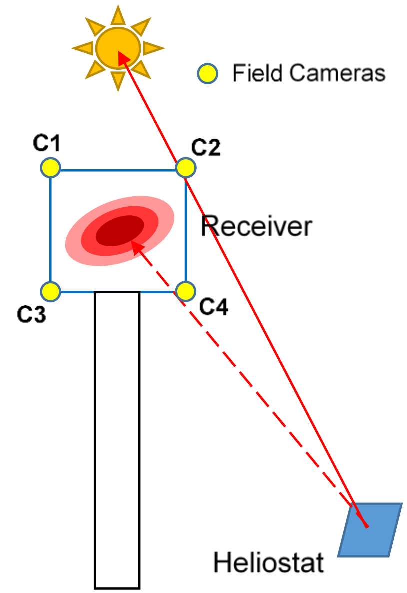
- RCS measures tracking error of 100's-1000's of heliostats simultaneously
  - Heliostat's images remain on receiver during measurement
  - Five measurements are taken each day to recalibrate a heliostat

RCS system description

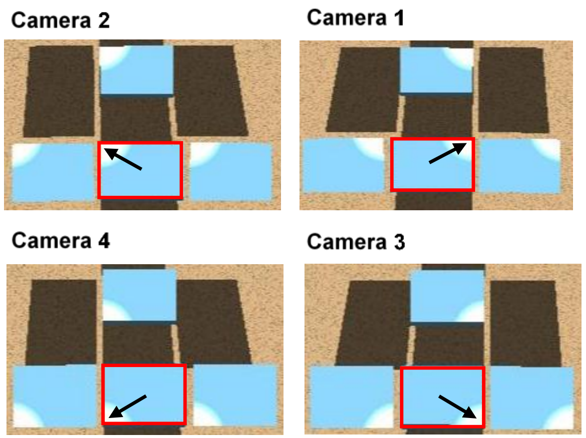
- Set of 4 cameras installed around/embedded within receiver
  - Each 4 camera set has narrow field of view (FOV) of the solar field
  - Multiple 4 camera groups installed to image entire solar field
- Each camera in 4 camera set simultaneously takes an image, then for each heliostat in FOV:
  - Image processing identifies each heliostat and its associated pixels
  - Using pixel intensities, define a vector from the heliostat center to center of sun image
  - Intersection of vectors from each camera predicts the heliostat's reflected image centroid

Testing

- RCS shown to work analytical with ray casting tool
- Bench-scale experimental, outdoor testing is on-going



RCS Schematic



RCS Simulated Field Cameras

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Drop-C Project: Value Proposition

- **Cost Competitive CSP**
  - State-of-the-art heliostat costs reduced by up to 60% enabling cost competitive CSP against fossil fuel generation. Fixed costs per heliostat lowered with Wireless Mesh Network.

- **Drop-In Place Heliostat Enables Multiple Use Cases**
  - Drop-In place minimizes the fixed permitting and installation cost per solar field along with smaller size makes the Drop-C appropriate for multiple receiver sizes enabling small demonstration projects as well as utility scale plants.

- **Increased Production**
  - The rapid calibration system can reduce tracking errors in existing and planned projects. Results in increased production or relaxed heliostat design criteria.

- **Field Diagnostics with Quick WMN Deployment**
  - The Wireless Mesh Network enables sensors to be distributed in existing solar fields with real time data collection.

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