U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

An overview of progress on two SIPS projects:

“Development, Validation and Testing of High-Reflectance, Cost-Reducing Composite Heliostat Mirror Facets”

and

“Development of Flexible Wireless Control Architectures for Heliostat Fields”

Matthew Muller

NREL

May 21, 2025

Outline

- Composite facet project goals
- Progress on prototyping and testing of composite facets
- Wireless communication project goals
- Progress on equipment deployment for wireless field testing
- Field data to come
- Questions and discussion

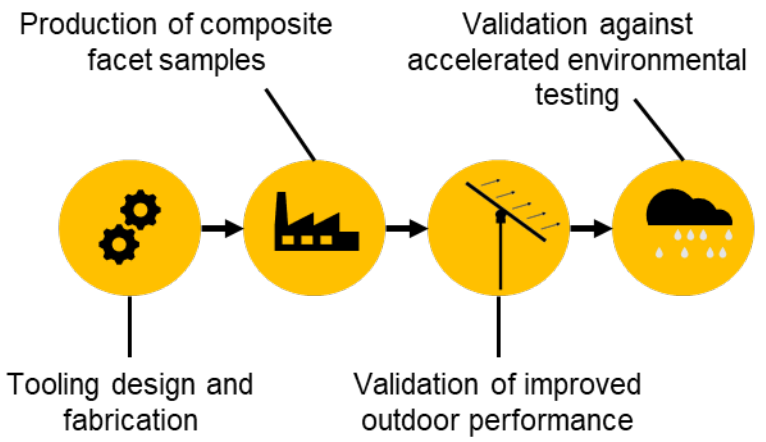
Composite Facet Project

Validation and Testing of High-Reflectance, Cost-Reducing Composite Heliostat Mirror Facets

MATTHEW MULLER / NREL

Project Summary

- Cost reduction to **<50/m²** enabled through validation of composite mirror facets meeting next-generation CSP performance requirements
- **3%** reflectivity increase supports **LCOE<$0.05/kWh**
- 1mm glass with full paraboloid enabling better flux control (beam quality **<1.5mRad**)
- Target **40-year life** through increased protection of silver layer
- Improved thermal and structural stability enables **cost cutting** on heliostat **structural components**
- Enables synergistic work with HelioCon components and controls objectives



Key Personnel/Organizations

NREL: Matthew Muller, Devon Kesseli, Heyaw Getabecha

University of Clemson Composites Center, H.B. Fuller Adhesives

Budget and Timeline

Federal funds: $400k **Cost-share: $100k** **Total: $500k**

Key Milestones & Deliverables

1:	Quantification of optical, mechanical, and environmental properties for a production-ready composite reflector.
2:	SMART milestone: Reflectivity improvement of 3% above state-of-the-art heliostat glass mirrors.
3:	Publication of facet manufacturing methods and full results of optical, mechanical and environmental testing.

Project Impact

- Providing the U.S. CSP industry a path to manufacture 40-year composite facets with a 3% reflectivity increase unlocks multiple pathways for LCOE reduction to $0.05/kWh (increased field performance having most direct impact on LCOE reduction).

Manufacture and validation of high-performing cost-effective composite mirror facets enables hitting DOE CSP targets of $0.05/kWh.

Overall Composite Facet Goals

- Improve reflectivity from 93% to 96%
- Keep cost in line with existing facets plus supporting steel
    - Make composite facet structural to minimize supporting steel
- Demonstrate better performance beyond reflectivity improvement
    - Stiffer mirrors mean less flex in wind and gravity
    - Molded to parabolic shape so less light spillage
- Full durability and performance testing
    - Focal length measured over operational temperature range
    - Hail testing
    - Vibration testing
    - Salt spray
    - Damp heat
    - Temperature cycling with humidity
    - UV plus humidity
    - Reflectivity and slope error measurements

Facet Conceptual Design

1 mm 96% reflectivity glass mirror

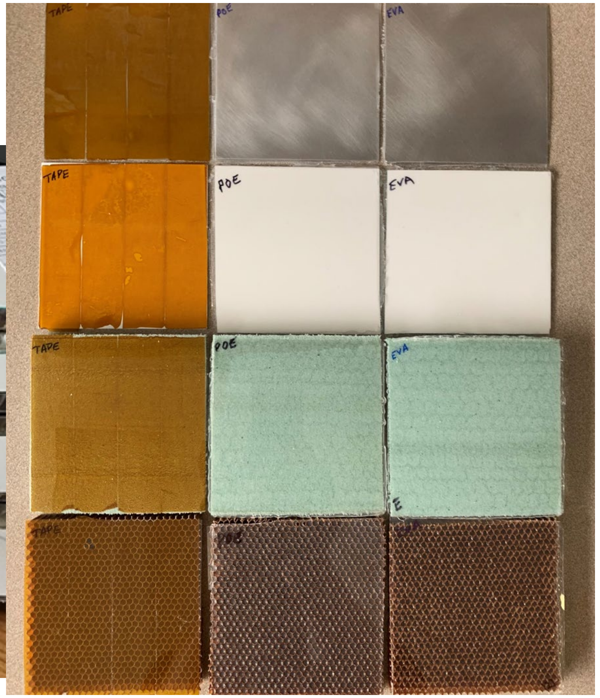
~13 mm core (honeycomb, foam, other)

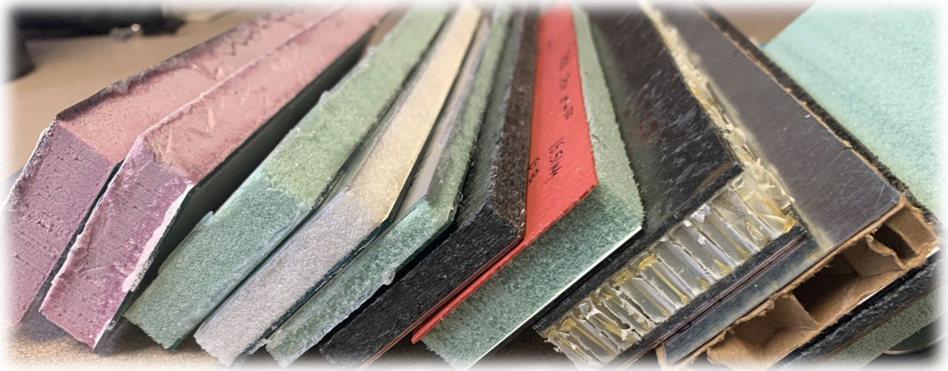
0.6 mm backsheet

Frame providing mounting locations and edge protection

PIB (Polyisobutene) edge seal all sides

Adhesive layer on top and bottom of core material (low cost and minimize manufacturing time)

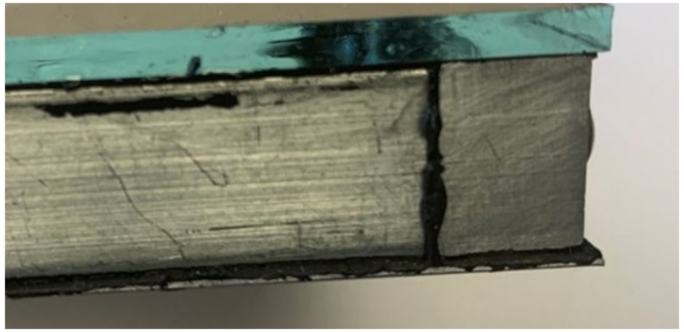


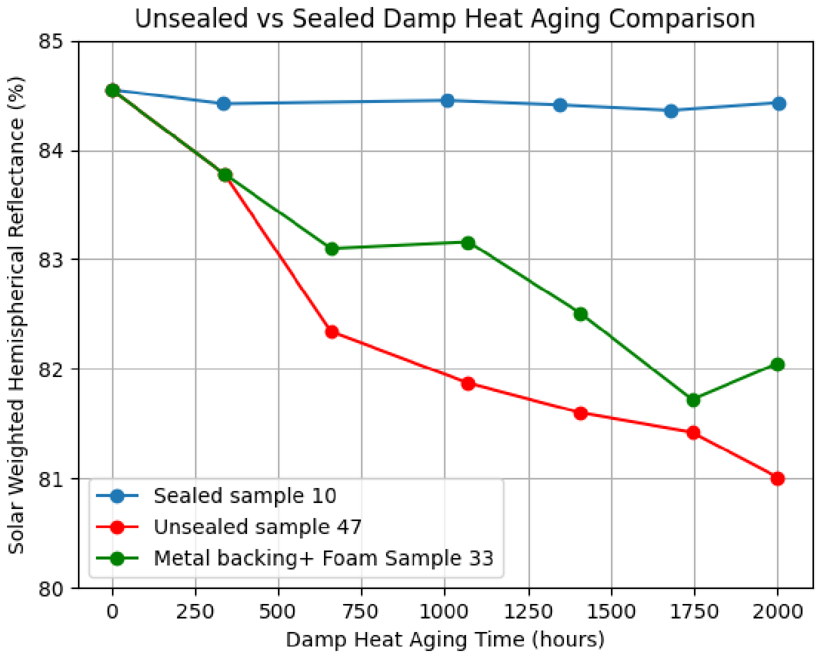


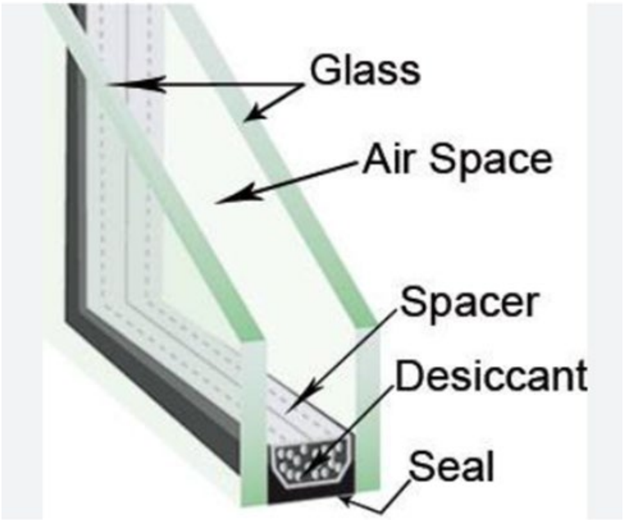
Facet Testing

Environmental degradation testing

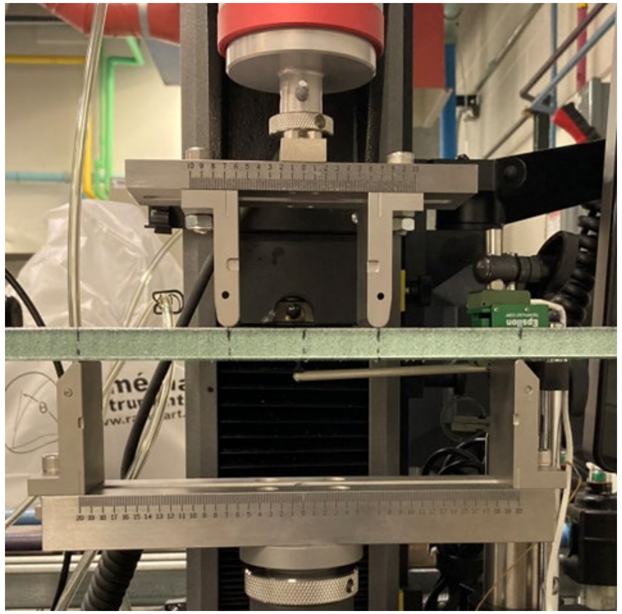
- Leveraging methods from the PV and window industry to seal and protect mirrors from degradation
- Low-cost indoor mirrors used in testing
- No degradation of protected mirror in UV, TCH, and damp heat
- Salt spray to come



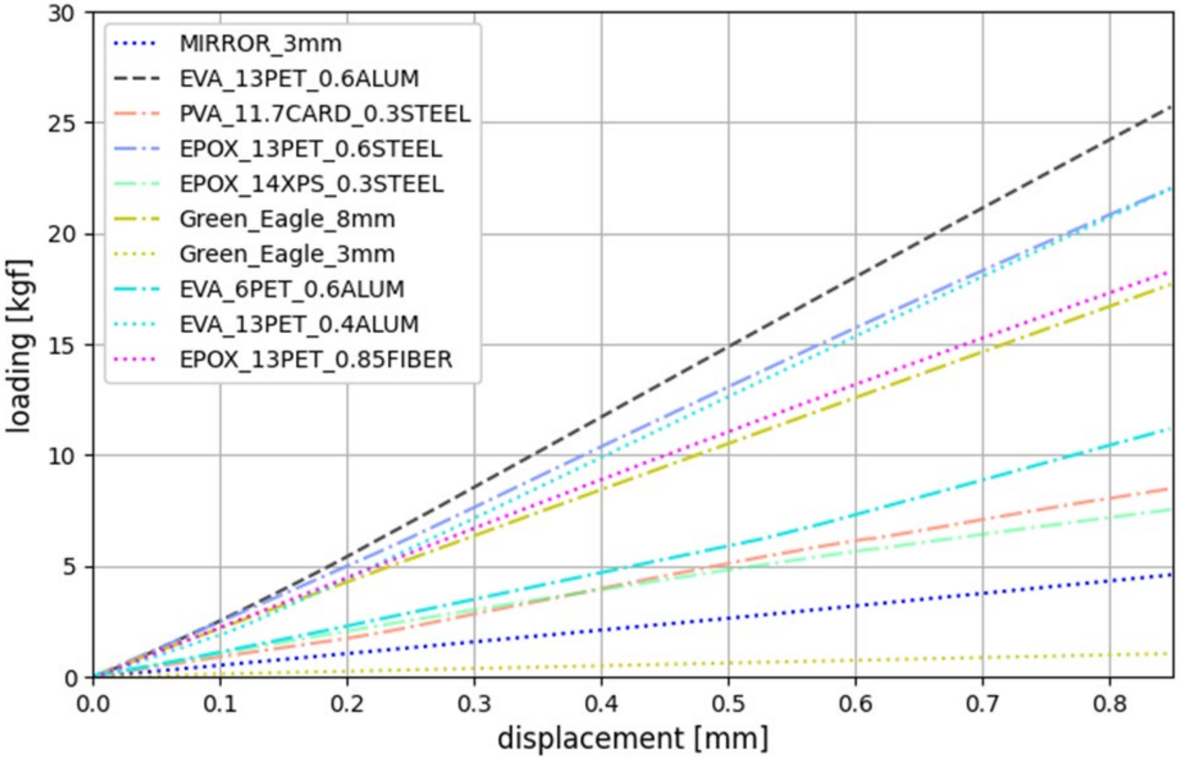




Strength testing per 4-point bend test

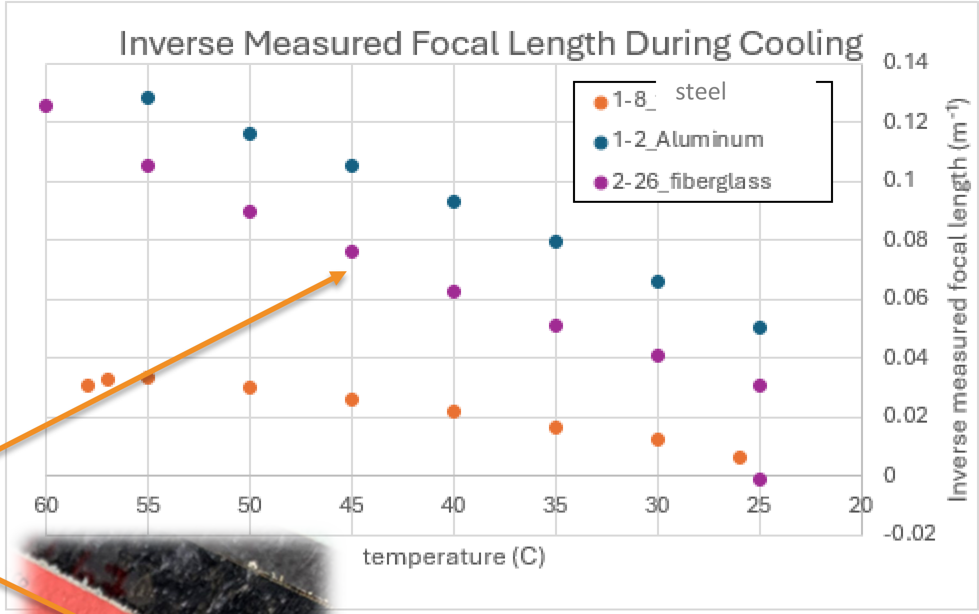


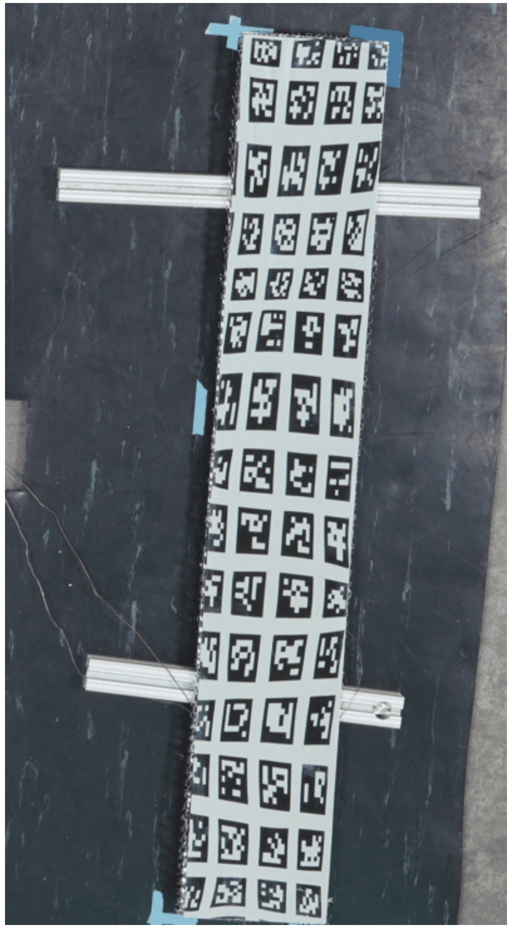
- Consistent with expectations thickness of core and strength of backsheet can be used to increase strength in bending
- More repeat samples will be made of design choices going into final facet designs to understand uncertainty
- It appears that due to EVA thickness being greater than epoxy thickness, this increase in distance between skins has an impact on the overall strength
- There is sufficient flexibility in design to cost-effectively create composites that are significantly stronger than 3mm mirrors



Measuring focal length changes due to CTE mismatch

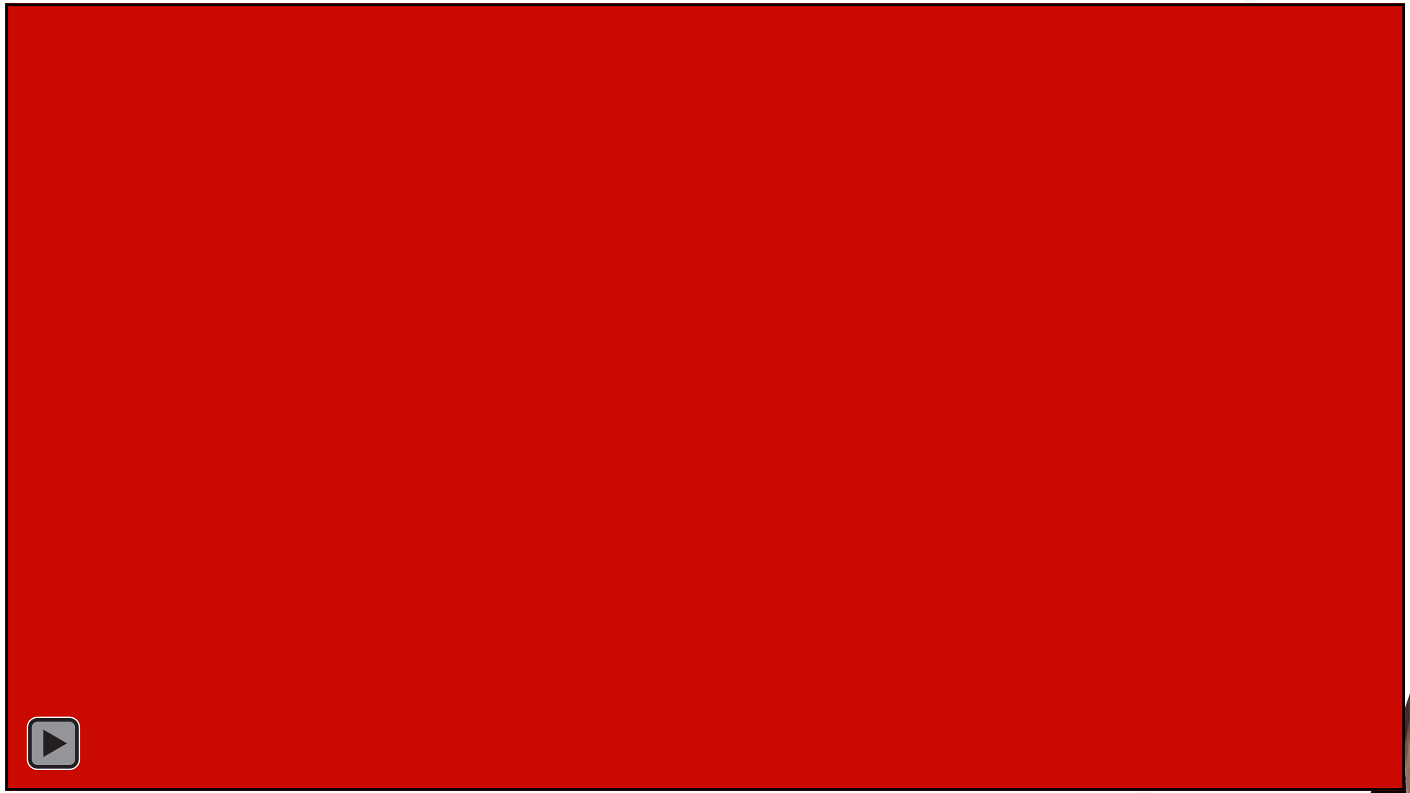
- Here 1/focal length is plotted. This comparison maybe makes more sense, since curvature changes relative to 1/(2f).
- Low iron glass 9.28×10^{-6}m/m°C
- Aluminum $=21\text{-}24\times10^{-6}$m/m°C
- Steel $10.5\text{-}12.5\times10^{-6}$m/m°C
- Random oriented fiberglass CTE depends on resin, fibers, and fiber orientation
- FR4 Woven fiberglass 9×10^{-6}m/m°C

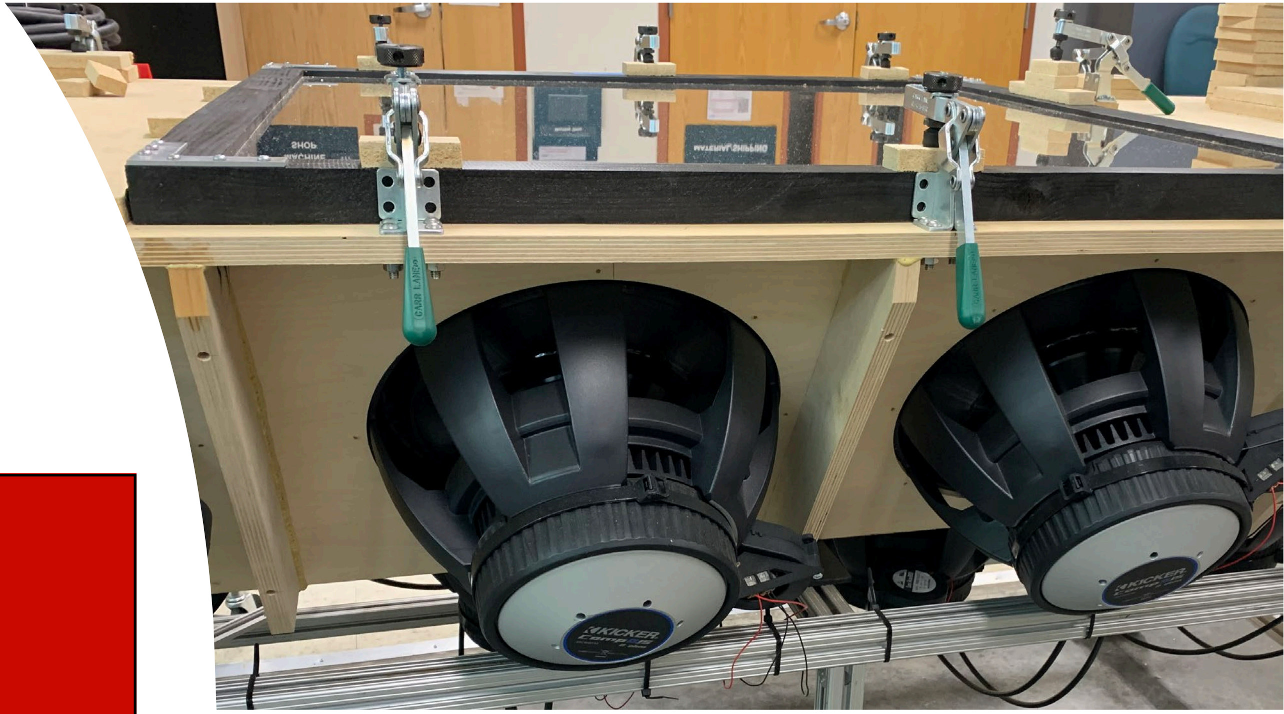




DMX (Vibration testing)

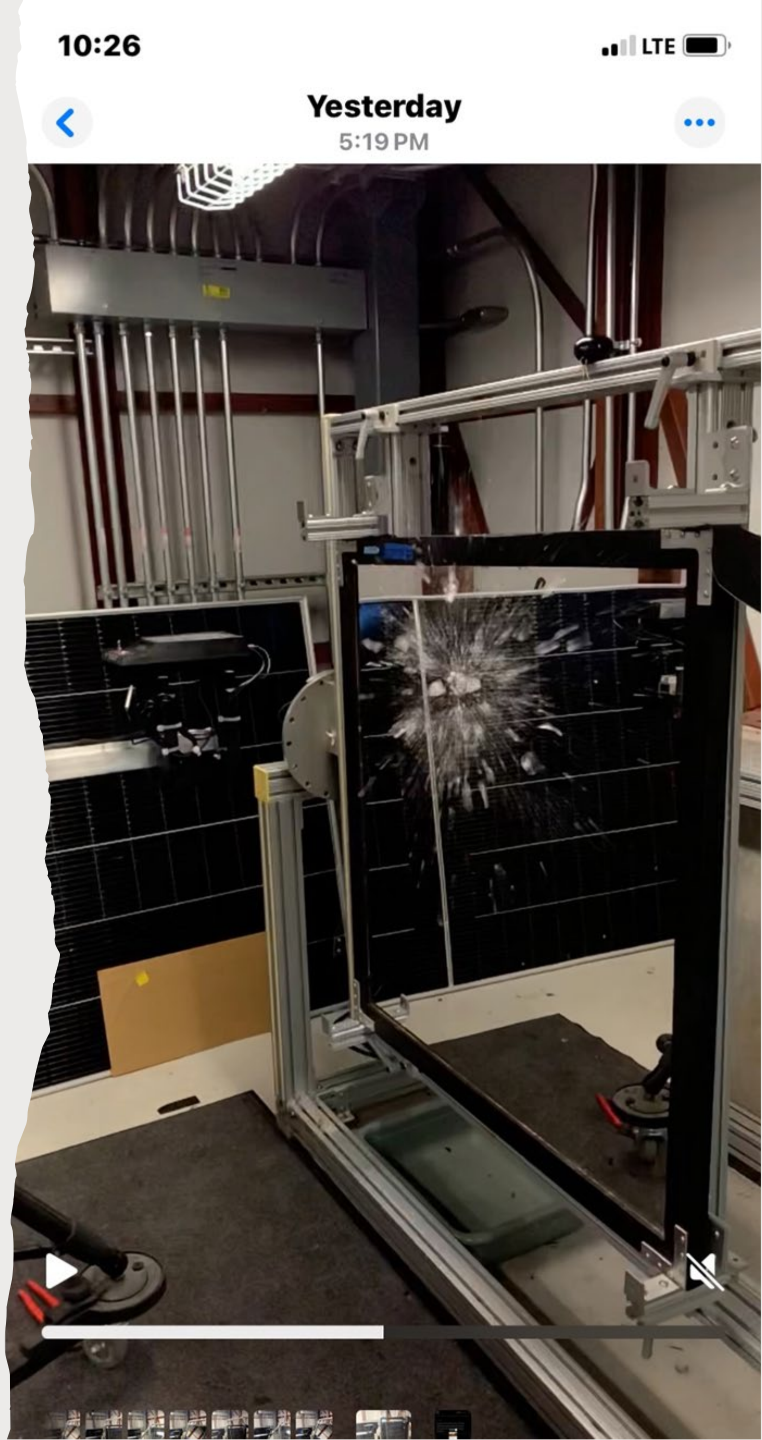
- First 1 m by 1 m mirror under testing
- After testing subject sample to 1000 hours of damp heat then repeat
- +/- 300 Pa, 10 Hz. 1 million cycles





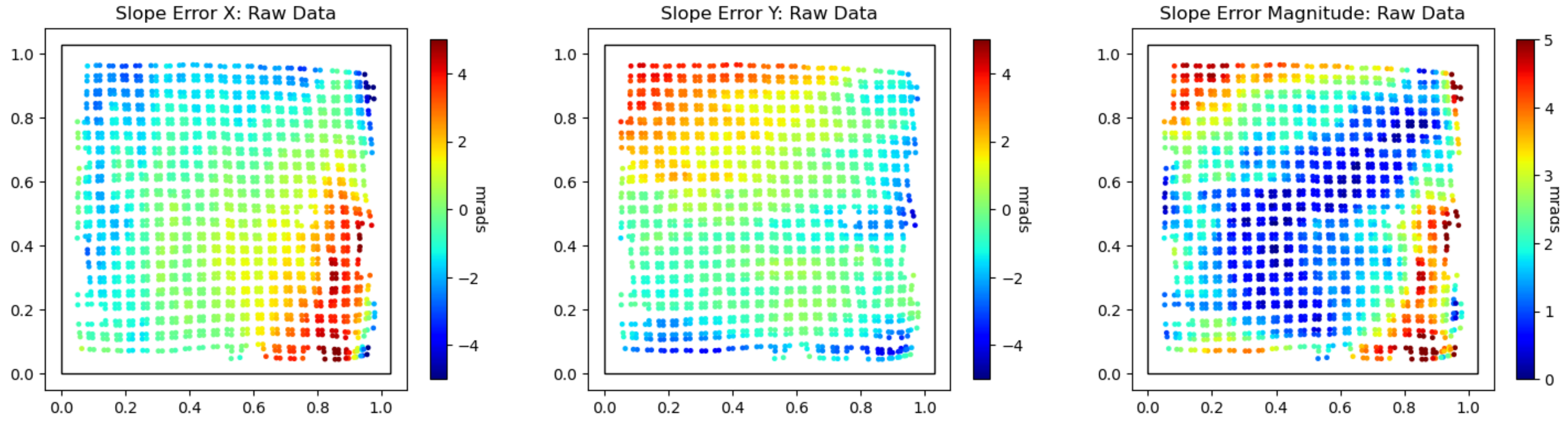
Hail Testing

- 1 m by 1m by 1 mm thick mirror, 11.7mm carboard honeycomb core, 0.6 mm steel backsheet
- Survival of 2" hail ball at 62 degree angle of attack
- Failed 2" hail ball at 45 degree angle of attack

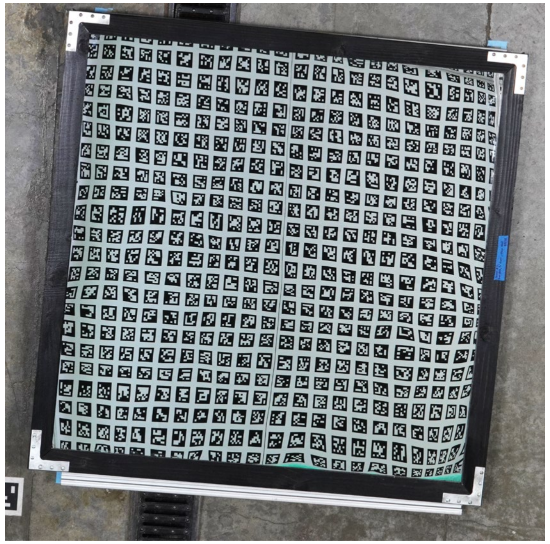


Composite mirror slope error

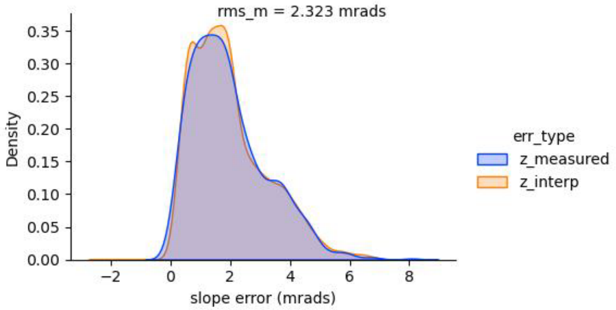
Raw Slope Error

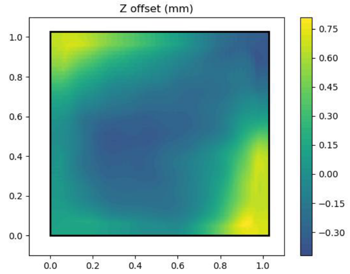


ReTNA visual image of target

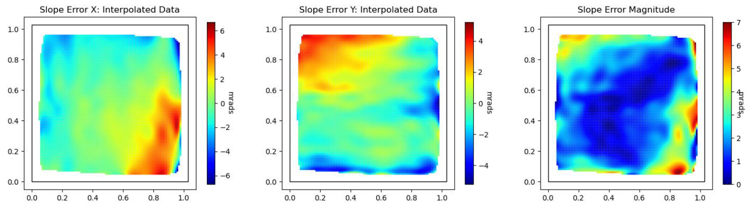


Error distribution





Interpolated Slope Error



	Measured Focal X (m)	Measured Focal Y (m)	RMS Error X Raw (mrads)	RMS Slope Error Y Raw (mrads)	RMS Slope Error Mag Raw (mrads)	RMS Error X Interp (mrads)	RMS Slope Error Y Interp (mrads)	RMS Slope Error Mag Interp (mrads)
Mean measured value	140	128	1.74	1.53	2.32	1.74	1.53	2.34

First attempts at paraboloid composite facet

Materials costs at scale

Comparative sourcing from suppliers on Alibaba

- Continuing investigation of alternative materials to hit performance objectives while targeting low-cost facet
- Per NREL 2022 cost study, ~$7-10 for existing mirror support and adhesives
- Aiming to spend less than $\$4/m^2$ on materials to make this cost effective when including manufacturing

Core	Material Dimensions	Cost per Sq. Meter
PET Foam	0.5in/12.7mm	$2.70
PET Foam	0.375in/9.525mm	$ 2.10
PET Foam	0.25in/6.35mm	$1.60
Polystyrene Foam	0.5in/12.7mm	$0.07
Polystyrene Foam	0.375in/9.525mm	$ 0.05
Polystyrene Foam	0.25in/6.35mm	$0.04
Balsa Wood	0.5in/12.7mm	$21.60
Balsa Wood	0.375in/9.525mm	$15.20
Balsa Wood	0.25in/6.35mm	$13.20
Aramid Honeycomb	0.5in/12.7mm	$?
Aluminum Honeycomb	0.5in/12.7mm	$2.75
Cardboard Honeycomb	15mm	$1.20
Cardboard Honeycomb	10mm	$1.00
Cardboard Honeycomb	6mm	$0.90
XPS Foam	0.5in/12.7mm	$7.03
XPS Foam	0.375in/9.525mm	$5.13
XPS Foam	0.25in/6.35mm	$3.52

Resin	Thickness of Layer	Cost per Sq. Meter
Epoxy	1.5 mm	$3.58
Epoxy	1.5 mm	$10.63
Polyester	1.5 mm	$2.78
Epoxy	0.2mm	$ 0.48

Backplate	Material thickness	Cost per Sq. Meter
Aluminum	0.6mm	$3.33
Aluminum	0.36mm	$3.40
Galvanized Steel	0.6mm	$2.21
Galvanized Steel	0.6mm	$ 2.80
Galvanized Steel	0.3mm	$1.46

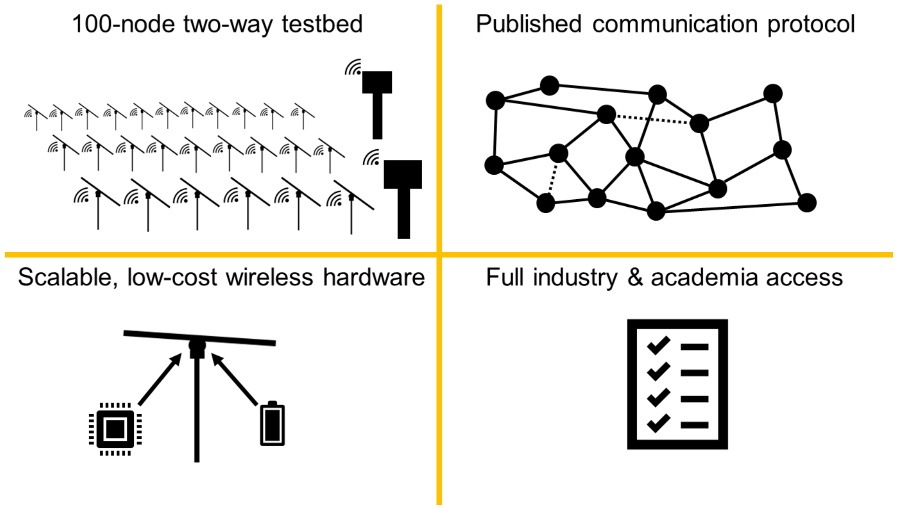
Development of Wireless Control for Heliostat Fields

Development of Flexible Wireless Control Architectures for Heliostat Fields

MATTHEW MULLER / NREL

Project Summary

- Cost reduction to **LCOE<$0.05/kWh** enabled by advanced closed-loop wireless control for improved field performance
- Development of low-cost controllers to support **$50/m^2** heliostat target **(~$10/m^2 controls cost reduction)**
- Open-source hardware and software specifications to support the **United States heliostat industry**
- Flexible wireless controls testbed is synergistic with **HelioCon** components & controls and metrology task and supports Sandia low-cost wireless control efforts
- Leverages **CaribouLabs' wireless heliostat controls experience** to design working software running on field-ready hardware within a one-year performance span.



Key Personnel/Organizations

NREL: Matthew Muller, Heyaw Getabecha

CaribouLabs LTD: David Michaeli

Budget and Timeline

Federal funds: $400k **Cost-share: $200k** **Total: $600k**

Key Milestones & Deliverables

1:	Buildout of flexible NREL wireless control testbed with 100 communication nodes for lab, industry, and academia use
2:	Publication of cost/benefit analysis, design docs, and test results for novel wireless heliostat communications
3:	Broadly communicate results through Heliocon seminars, allowing for synergy with other heliostat wireless projects

Project Impact

- Providing the U.S. CSP industry a communication protocol and **hardware testbed** for the realization of wireless control
- **<250 ms** communication speed enables closed-loop control and autocalibration (lower commissioning cost, higher field efficiency)
- **(~$10/m^2 controls cost reduction)**

Design and hardware-based validation of wireless heliostat communication protocols to underpin fields meeting DOE $0.05/kWh targets

Overall Wireless Project Goals

- Provide access to low-cost wireless hardware that is specialized for heliostat field needs
  - <$30/heliostat (PV, battery, wiring, connectors, printed circuit boards (PCBs) and antenna)
  - 10s of thousands of units communicating with the central tower Point to point communication distance can be greater than a kilometer
- Communication parameters that will work for any heliostat field in open-loop or autocalibration.
  - End-to-end latency <= 250 ms
  - Latency with jamming <= 750 ms
  - Error detection and recovery: Forward-Error-Correction codes (FEC / ECC), and resilience to fading and system-level interferences that is unique to node density in heliostat fields
  - Communication distances between 10 and 1500 m
- Versatile testbed at NREL Flatirons
  - 100 units to be deployed at ~ 1 km distance
  - Hardware will be capable of testing other wireless protocols being developed through Heliocon

Wireless Control to Cut Heliostat Field Cost

- A field of 50,000 heliostats can have a diameter of 2 km (massive amounts of wire)
- Heliostats can be powered by small PV panel so with wireless there is no need for trenching
- Minimal disturbance to field can significantly reduce environmental impacts and costs
- The field in this image has proven wireless can be successful but the solution is proprietary

Why the need for CSP focused wireless hardware

- Zigbee mesh network is cheap and use for PV trackers but it is not applicable to 1000s of heliostats and data transfer rates are too slow

- Analog Devices "Dust" smart mesh network can provide field communication speeds on the order of 5-10 s but this speed is not ideal for autocalibration, faster speeds provide other opportunities for cost reductions. Additional cost is needed for receivers in the field to scale the mesh to 1000s of heliostats

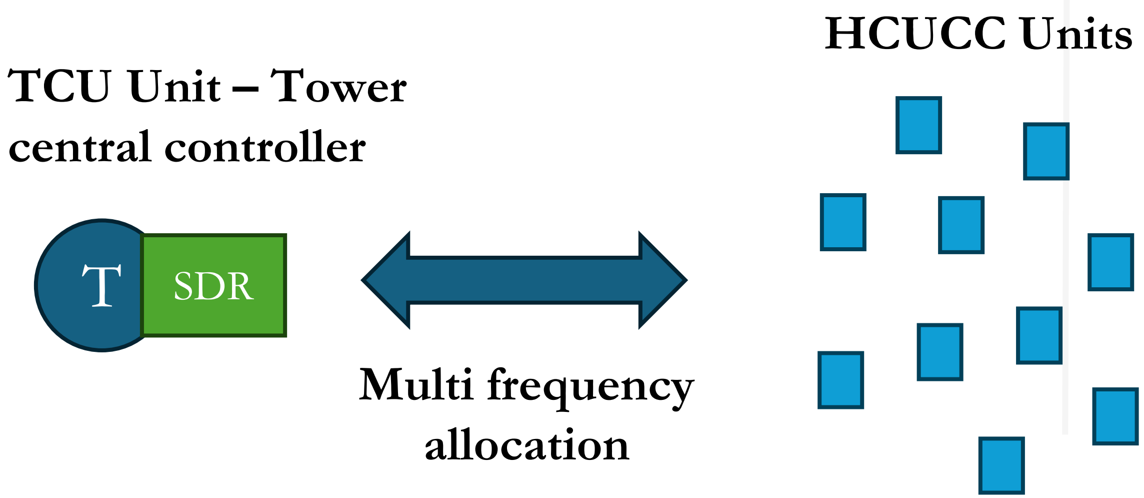
- LoRa, Wi-Fi, Bluetooth, and Sub-1 GHz are not optimized for heliostat fields
    - Depending on the choice: too low data rates, too high of energy use, or too expensive

- Dr Eirini Tsiropoulou (ASU) has a HelioCon RFP project working to use Integrated Access and Backhaul to meet the communication needs of large heliostat fields but the focus is algorithm development
    - There is potential for the low-cost hardware in this SIPS project to provide synergy with ASU work

Caribou Labs Hardware and Architecture Overview

Wireless hardware: big picture

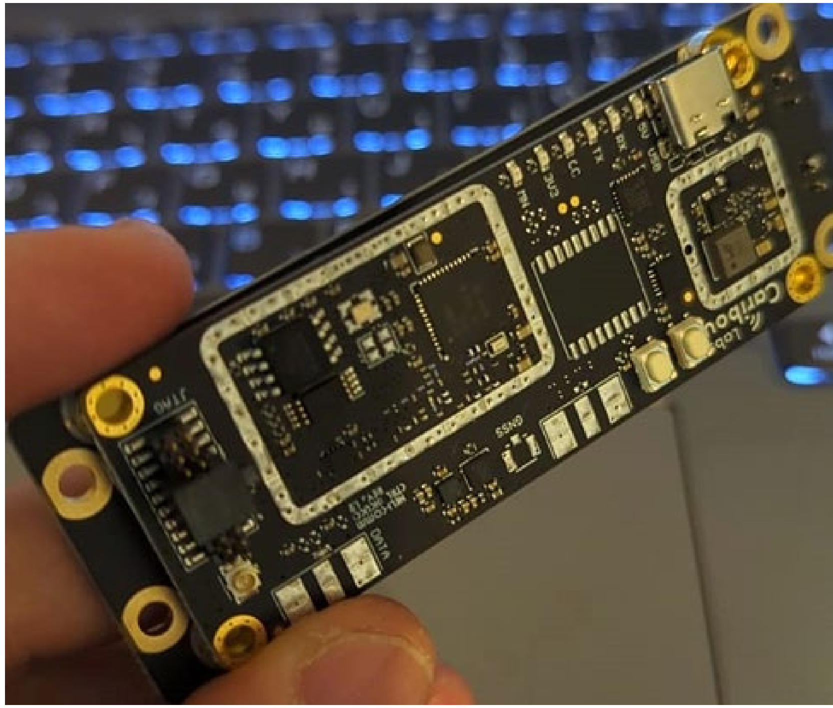
- Asymmetric Communication
  - The HCUCC (Heliostat control unit communication controller) is the end-node on each heliostat
    - low cost, low power, weak RF output (19 dBm or 0.1 watt, 100kbps), battery and small solar panel onboard
    - HCUCC will only be listening for message from SDR in select time periods to conserve energy
  - The central controller (TCU = tower control unit) is more capable, the SDR (software defined radio) communicates with many HCUCC's at once and is at a shifted frequency for outgoing communication compared to incoming from the HCUCCs
    - Transmits at 34 dBm, 1 Mbps
    - Groups of ~ 14 heliostat are targeted in 1 message out but number can vary based on message size
    - 24 bits of message for heliostats address, the field is divided into subnetworks, HCUCC only reads header and ignores if message not for it's address

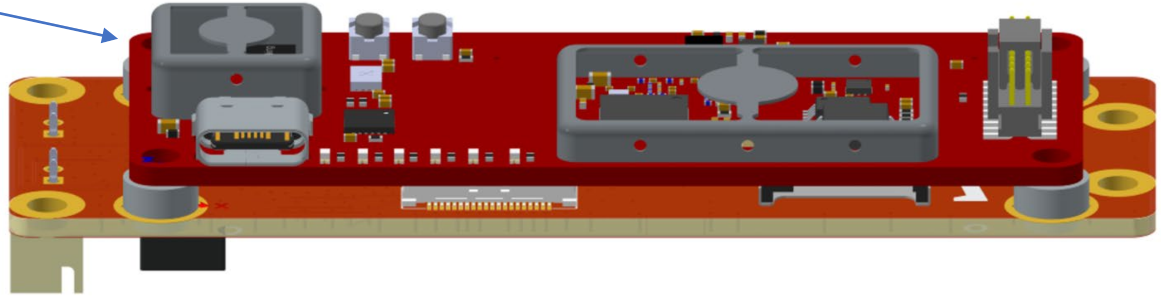


- Each end-node communicates over a random frequency in 902-928 MHz (ISM bands). The SDR consolidates the current multi-system status and controls the field accordingly.

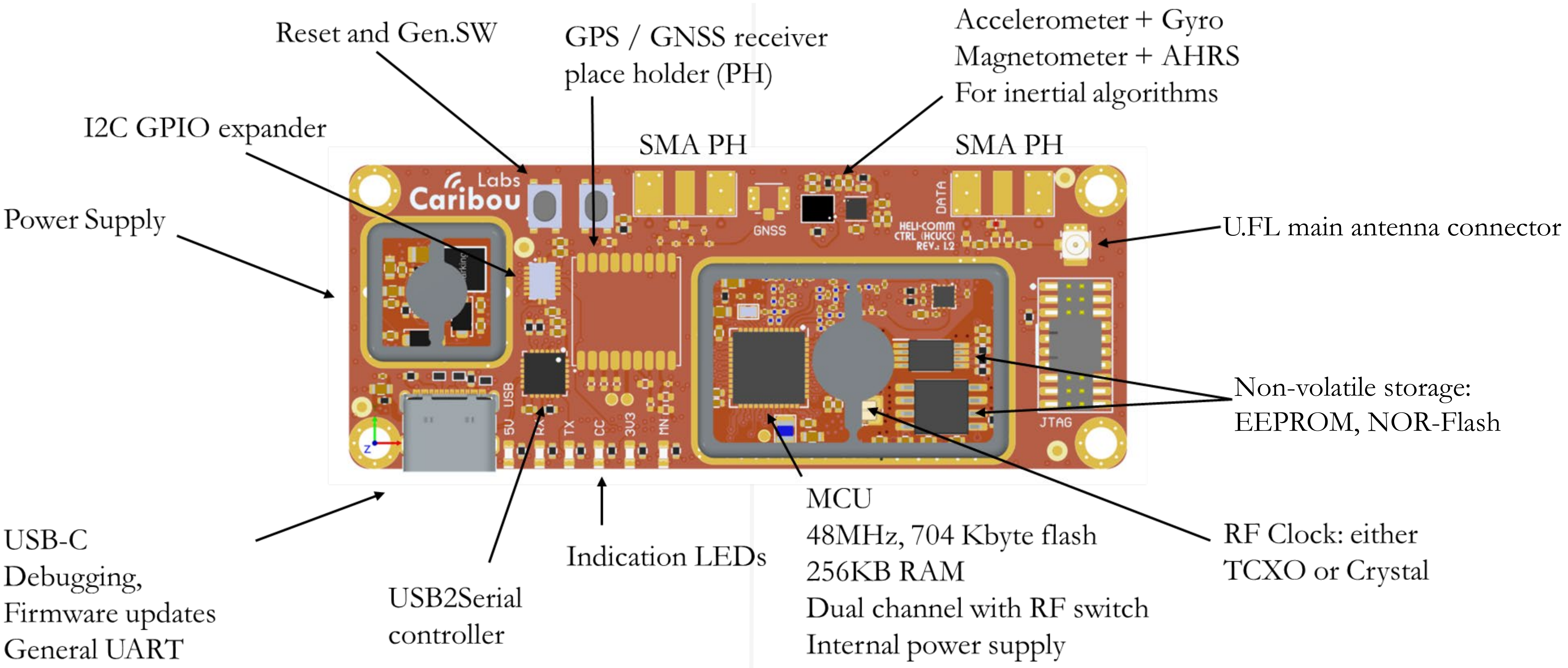
Heliostat Communication Controller Details

- Radio communication capability: 915MHz and 2.4 GHz
- Mass production cost optimized through link asymmetry with an SDR with many parallel channels
- Communication link properties:
  - Telemetry / control refresh rate >5Hz
  - Comm. Range > 1km
  - OTA capabilities (file transfers and FOTA)
  - Cyber security (optional encryption and authentication)
- Opensource hardware @ https://github.com/cariboulabs/heliostat_controller.git





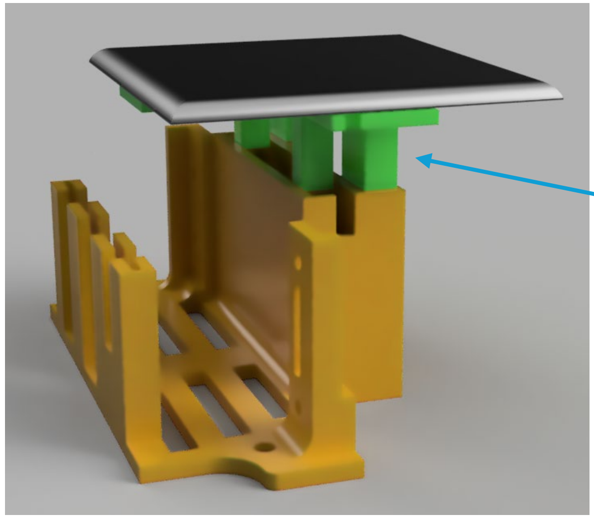
HCUCC Board



NREL Project 51906

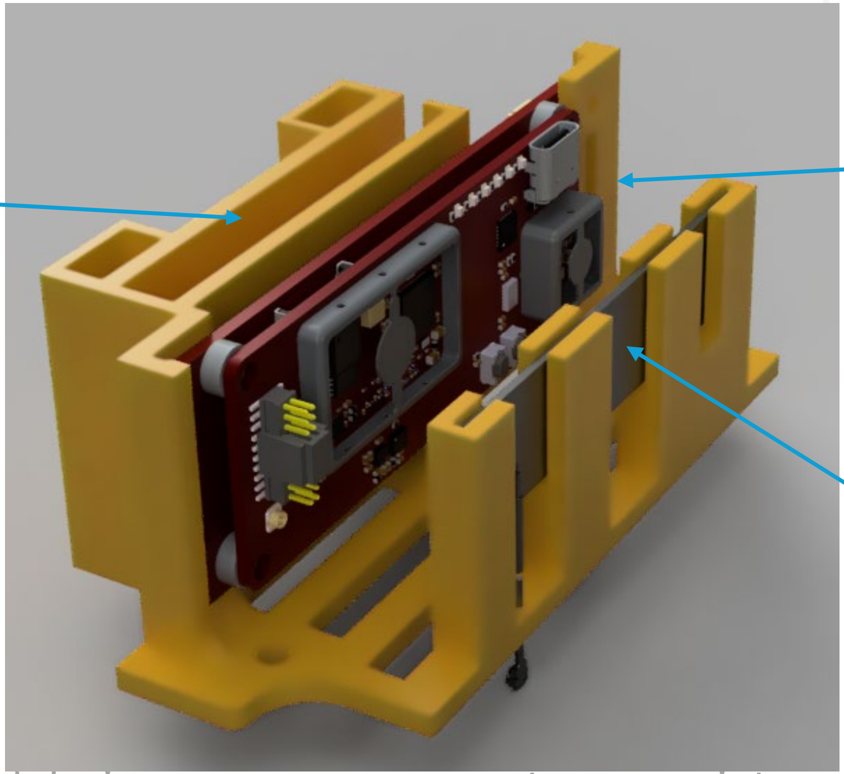
Assembly of mechanical parts

- Internal assembly – two printed parts:
  - PCB + Battery + Antenna Holder
  - PV Holder (glued / stuck) (green)
  - Other parts: 4xM3 screws, LiPo Battery (1.4Ah)
- Yellow assembly holder printed (PETG/ABS)



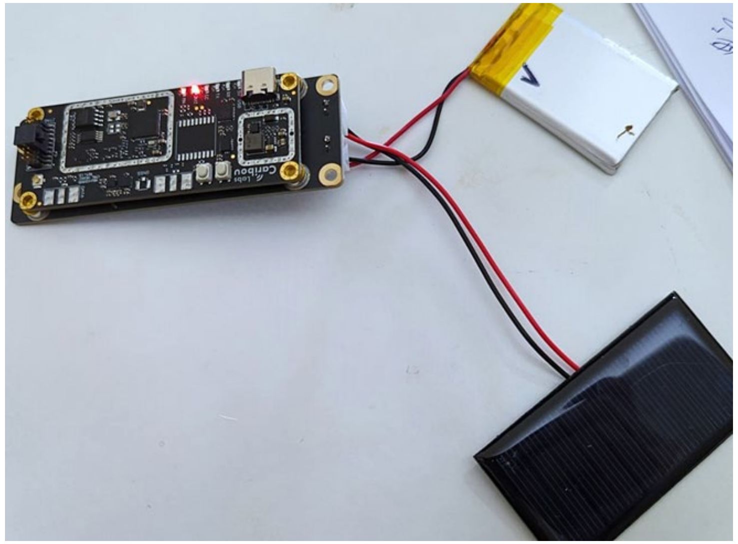
Snap PV Assembly

Battery slides in



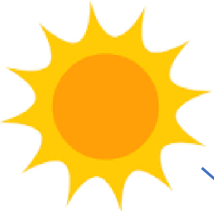
PCB stack

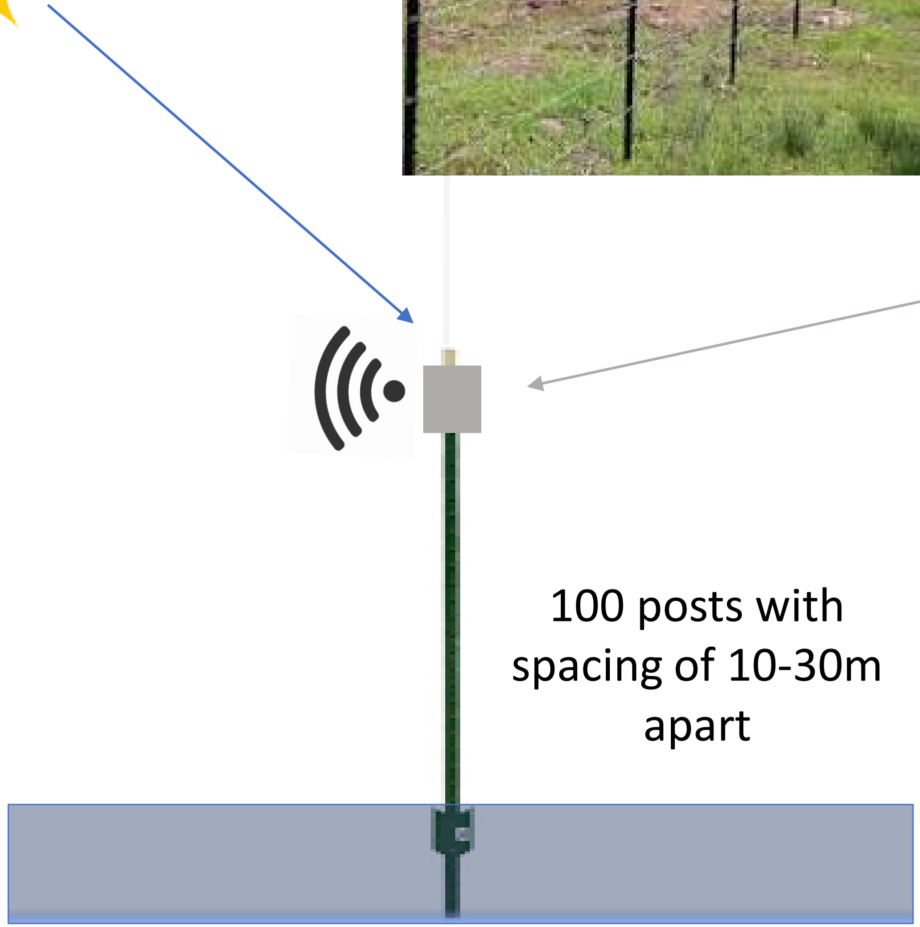
Antenna slides in

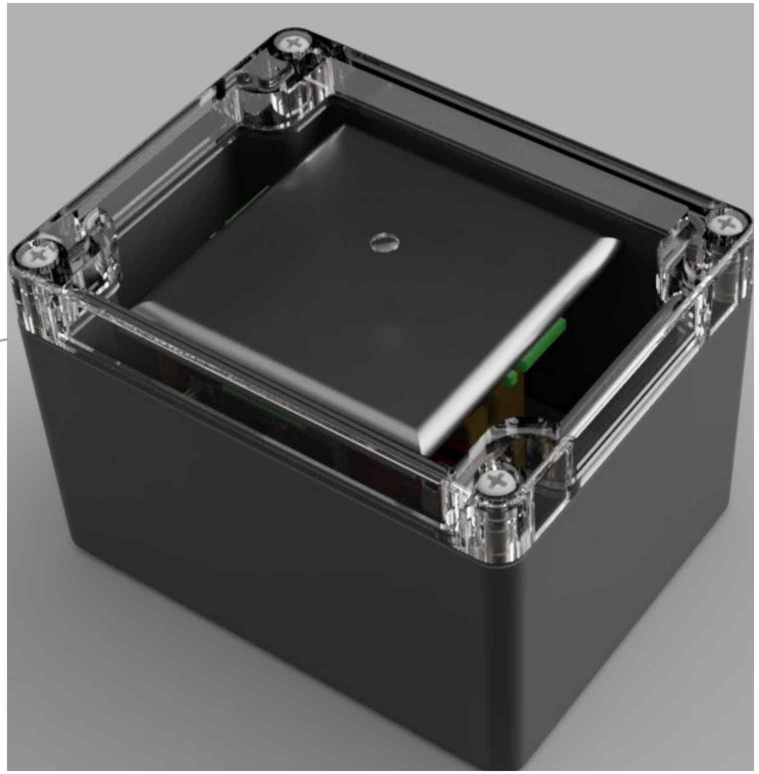


NREL Flatirons 100 Node Testbed for Research

SDR at 25-30m high







100 posts with spacing of 10-30m apart

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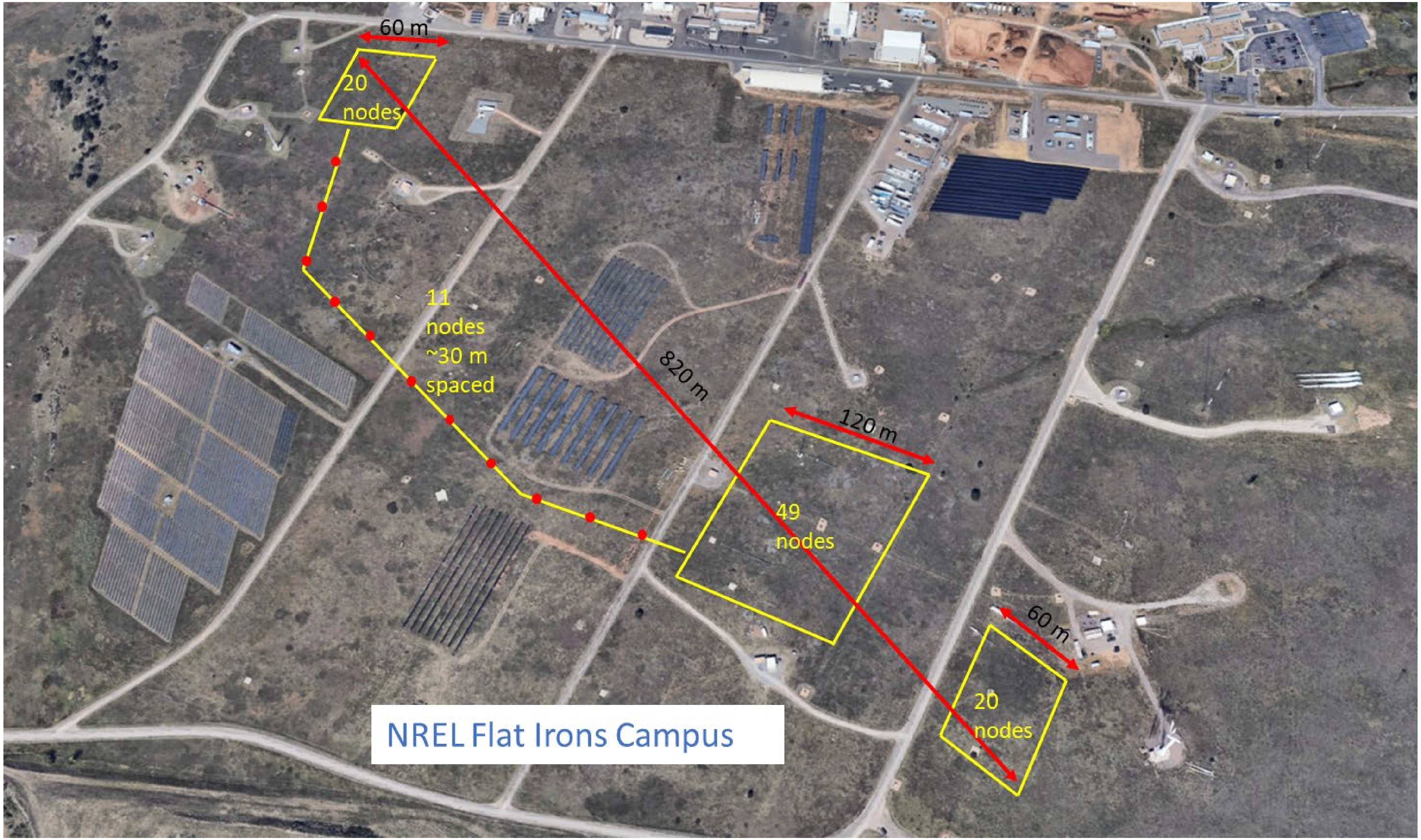
Layout for nodes at Flatirons simulation



Network Stack Simulation

- **MAC – Media Access Layer**
  - Message Structure
  - MAC Listen Before Talk Algorithm
  - Network Channels
- **Network Node Acquisition Algorithm**
- **Operational Messaging**
  - Control
  - Feedback
- **Cipher / Cyber-Security Algorithms**
- **FoTA – Firmware update algorithm**

MAC Layer – Message Structure

- **MAC layer structure**
  - Header including control signals (encryption, TTL and deferred for mesh, and validity check)
  - Payload – encrypted if ENC is 1
  - CRC32 of the payload – on header + payload (L bytes).

- **ECC:**
  - Reed Solomon redundancy check
  - Hamming (7,4) for header and (15,11) for the rest.

- **Encryption layer:**
  - **Currently** AES-256, CTR mode (NIST **SP 800-38A**) – further development needed for higher security level.

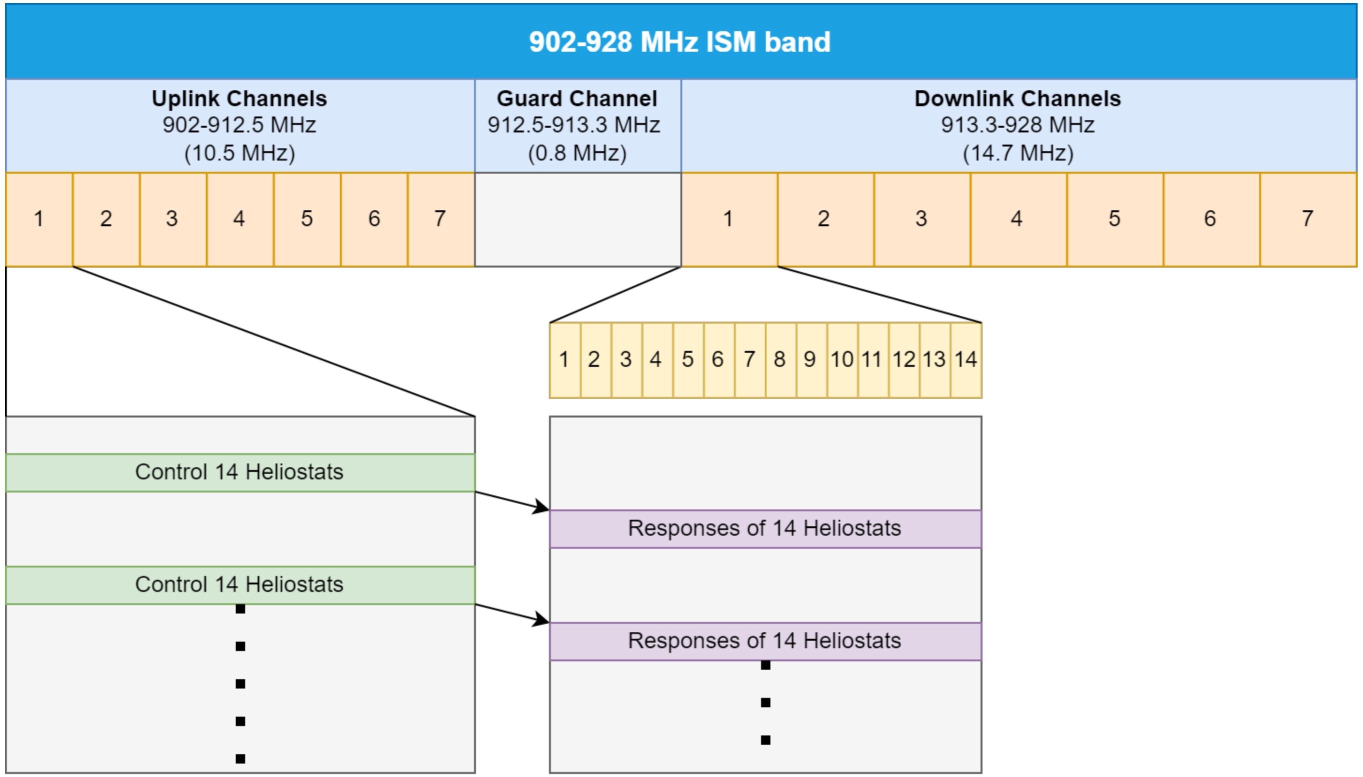
PREAMBLE	HEADER	PAYLOAD	ECC
6 bytes	8 bytes (16 bytes ECC)	L + 4 - variable	6 bytes

Type	Enc.	Deff.	Mcst	Res.	Len	Src.	Dest.	Seq#	TTL	CRC8
2 bit	1 bit	1 bit	2 bit	2 bit	8 bits	16 bits	16 bits	6 bits	2 bits	8 bits

Data	CRC32
L - variable	4 bytes

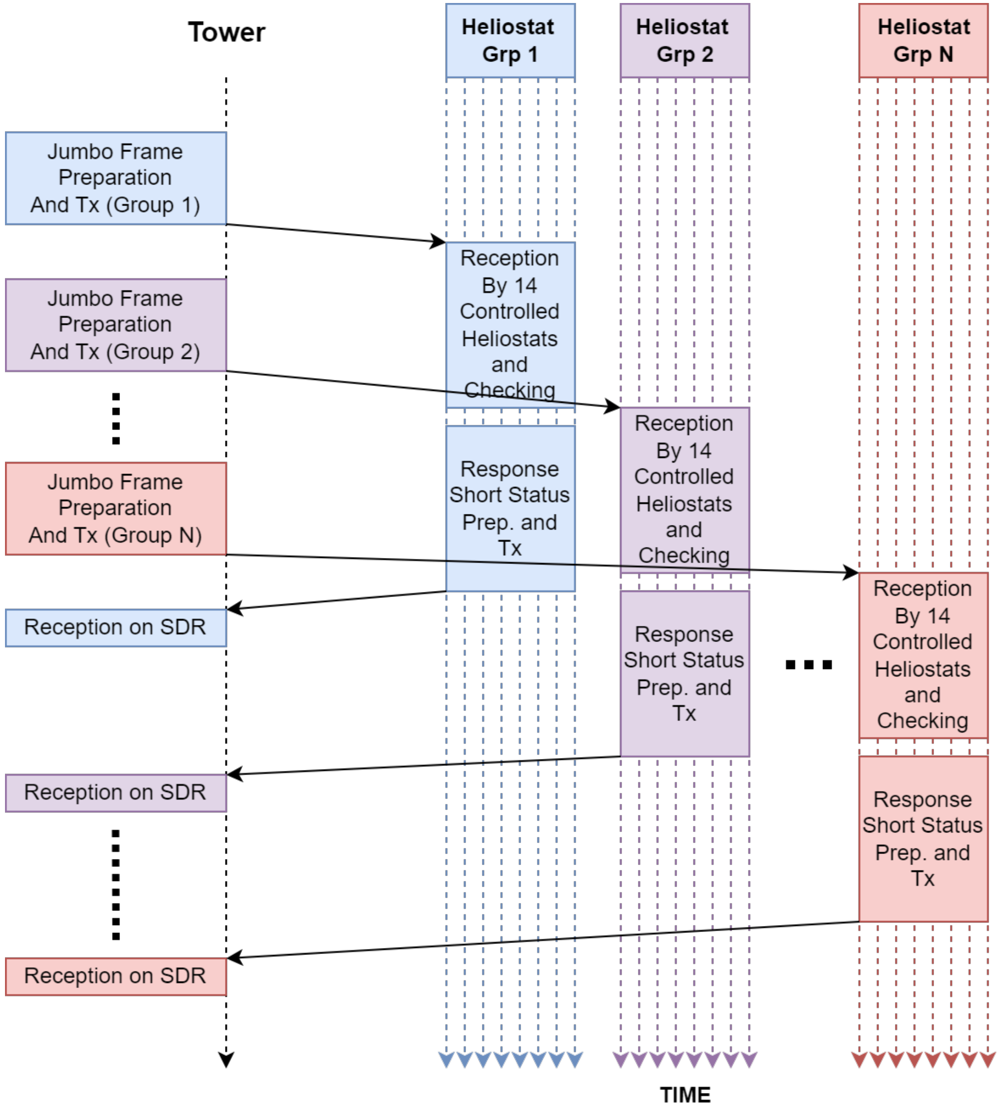
MAC Layer – Network Channels

- **ISM Band (915MHZ):**
  - Subdivided between **Uplink** and **Downlink** regions.
  - Each region contains 7 networks with maximal separation within the band.
  - **Uplink channel** ~1.5MHz
  - **Downlink channel** ~150 kHz.
  - **Command => Response** sequences
  - The Tower works in "**full duplex**" (transmitting while receiving).



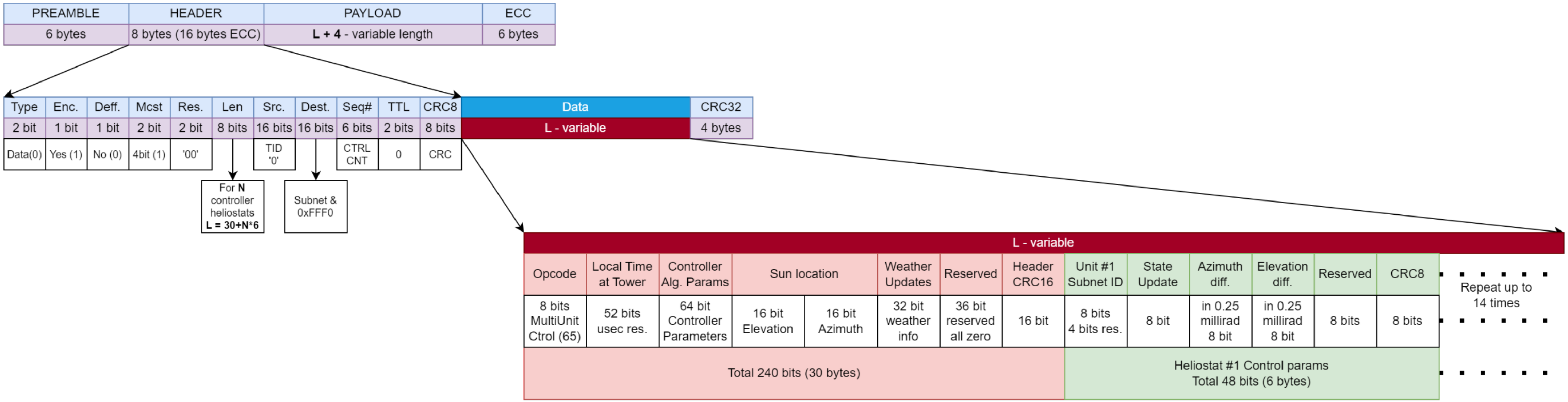
Operational Messaging

- Tower transmitter:
  - Prepares and transmits a jumbo frame for controlling up to 14 different heliostats at once. The message structure is described further after.
  - The SDR is always receiving signals at the correct band
- Upon reception each heliostat returns a short response with status on its sequential order within the jumbo frame.
- In the meantime, the Tower continues the Tx messages and receives the responses at once.
- This sequence repeats periodically.



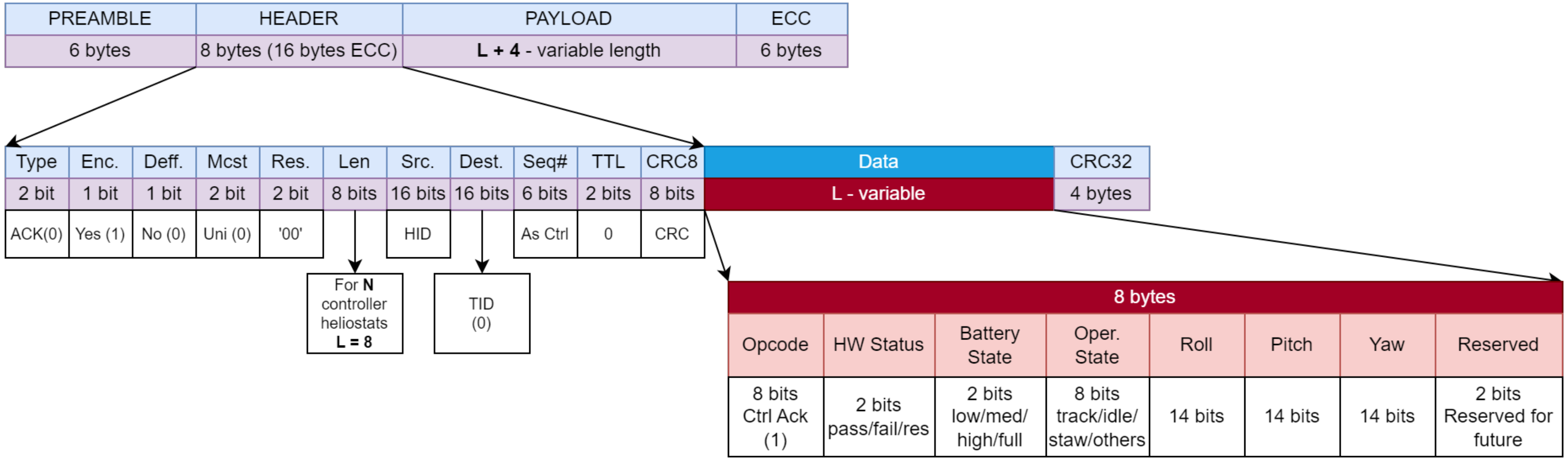
Operational Messaging - Control

- The Jumbo frame structure is described below.
- The payload data contains
    - **Communal data**: applicable for all units
    - **Unit specific control data** – applicable to each heliostat separately
    - **The message opcode is 65**. Additional opcodes can be introduced to vary for different algorithms



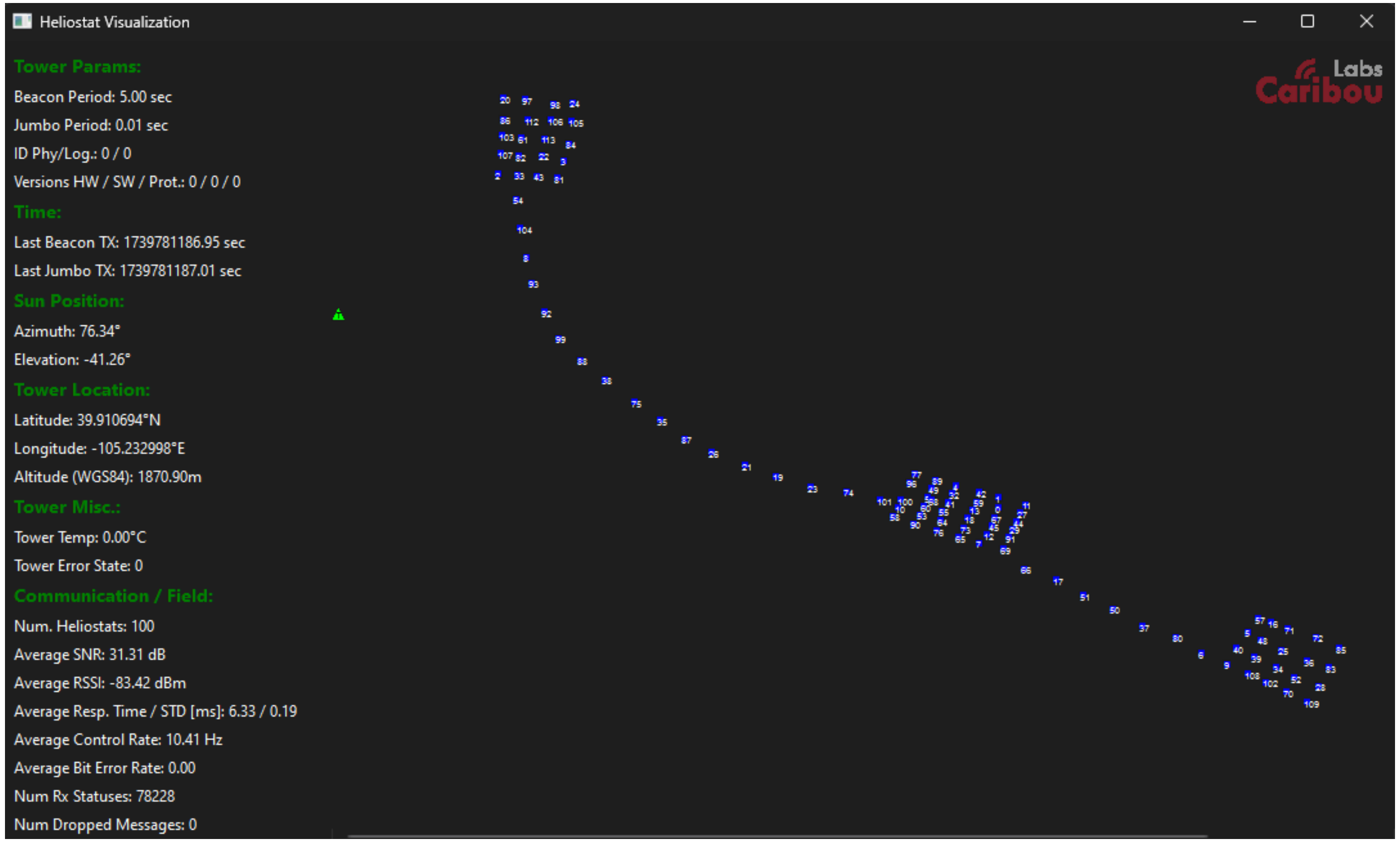
Operational Messaging - Feedback

- The feedback (ack) message contains a header and status information
- The basic message structure contains the current heliostat HW and operational states, including various capabilities for future expansion.
- Message multiplexing possible to vary the information types (through the opcode field).



Network Acquisition Algorithm

- **Performance:**
  - **Time to full Acq.:** <15 sec.
  - **# dropped nodes:** 0
  - **Avg. rate:** ~6 nodes/sec
  - **Extrapolation for 1000 nodes:** ~170 sec = **3min.**
- During this process, the network is re-adapted and re-built and all logical addresses are assigned.



Operational Messaging

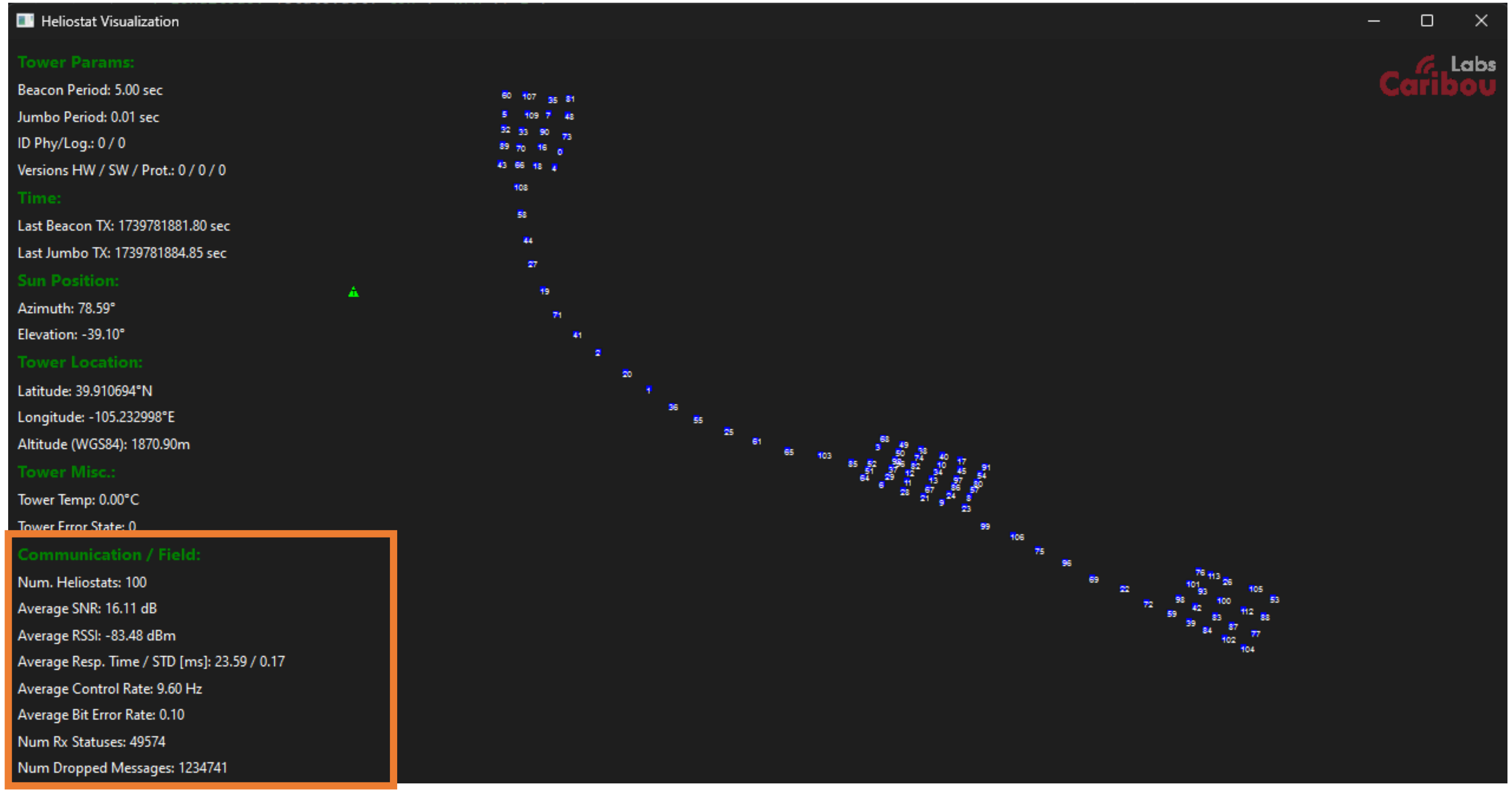
- Once the system is operational, data transactions are performed in a closed loop process.

- **Performance:**
  - **Average SNR**: ~31dB
  - **Average RSSI**: -83dBm
  - **Average response time**: ~6.33ms
  - **Response time STD**: 0.18 ms
  - **Average control loop rate**: 10.41 Hz
  - **Average BER**: 0
  - **Num Dropped messages** (from 350000 messages): 0

Operational Messaging – Jammed Tower

- Tower jamming emulated through the raised noise floor significantly.

- **Performance:**
  - **Average SNR**: ~16dB
  - **Average RSSI**: -83dBm
  - **Average response time**: ~23.6ms
  - **Response time STD**: 0.18 ms
  - **Average control loop rate**: 9.6 Hz
  - **Average BER**: 0.1
  - **Num Dropped messages**: **Growing**



Wireless Project Timeline

- Simulation of the exact layout at Flatirons in complete
- Radios have been benchtop tested and are being installed at the 100 node locations
- SDR is to be installed in the next 2 weeks
- Field turn-on and trouble shooting is expected in June
- Communications data collection ongoing in the summer
  - Analysis of data in comparison to the simulation
  - Modification of the simulation as needed
- First publication of results expected in the fall

Summary and Conclusions

- Composite facet mirror project on track with protypes
  - 96% reflectivity
  - ~1.5 mrad RMS slope error but continuing to improve
  - Stronger then standard 3-4 mm glass mirrors
  - 2” hail survival
  - No degradation to UV, damp heat, temperature cycling
  - Still evaluating impacts of focal length changes due to CTE
- Wireless project on-track to demonstrate hardware <$30/heliostat
  - Subsecond latencies per simulation
  - ~km transmission distance in our field test
  - Wireless testbed near complete
  - Published field results in the fall

Thank You!

Please ask questions and you are welcome to email for further discussion

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