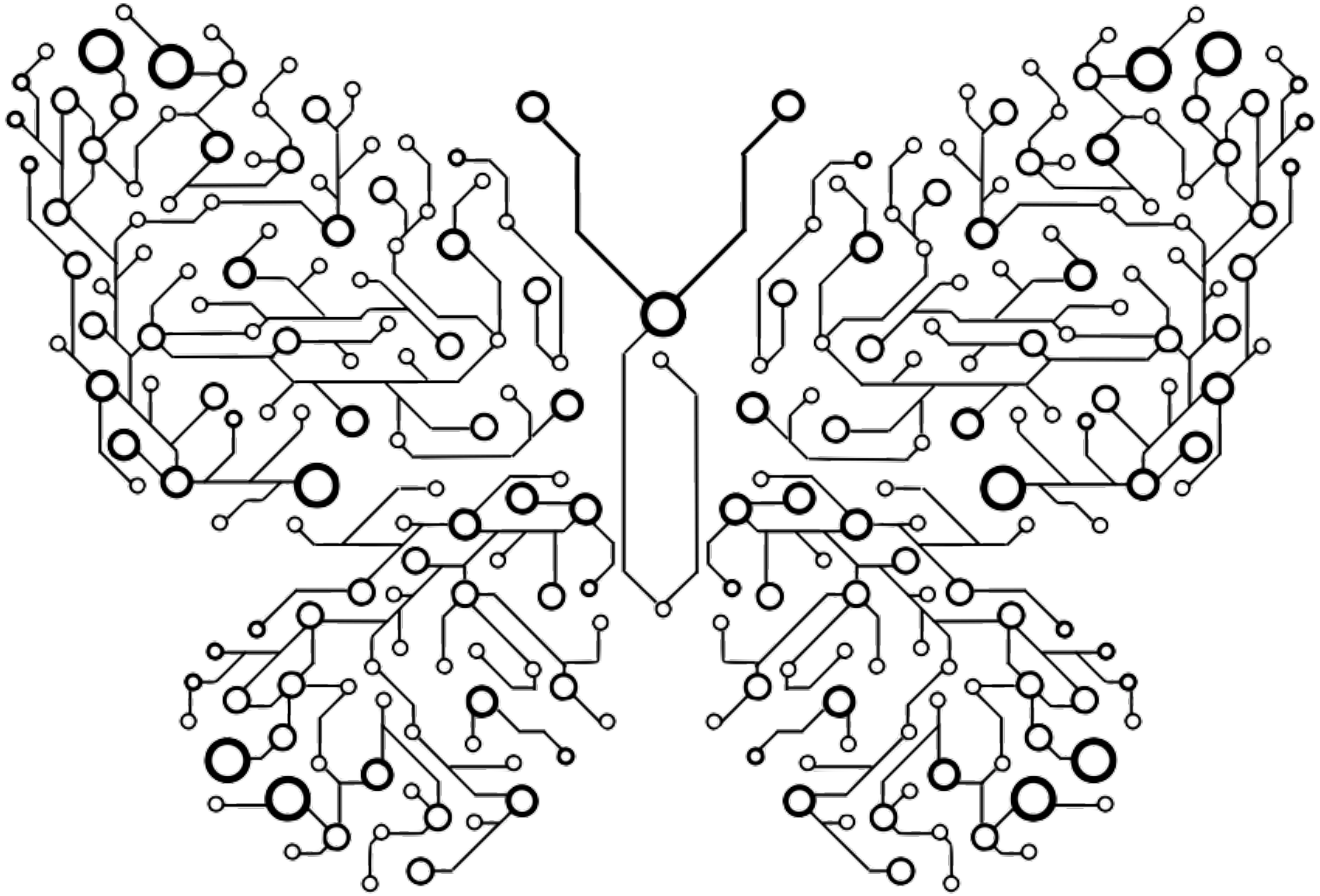
Theory and Applications of Gram-Scale Spacecraft



A dissertation defense

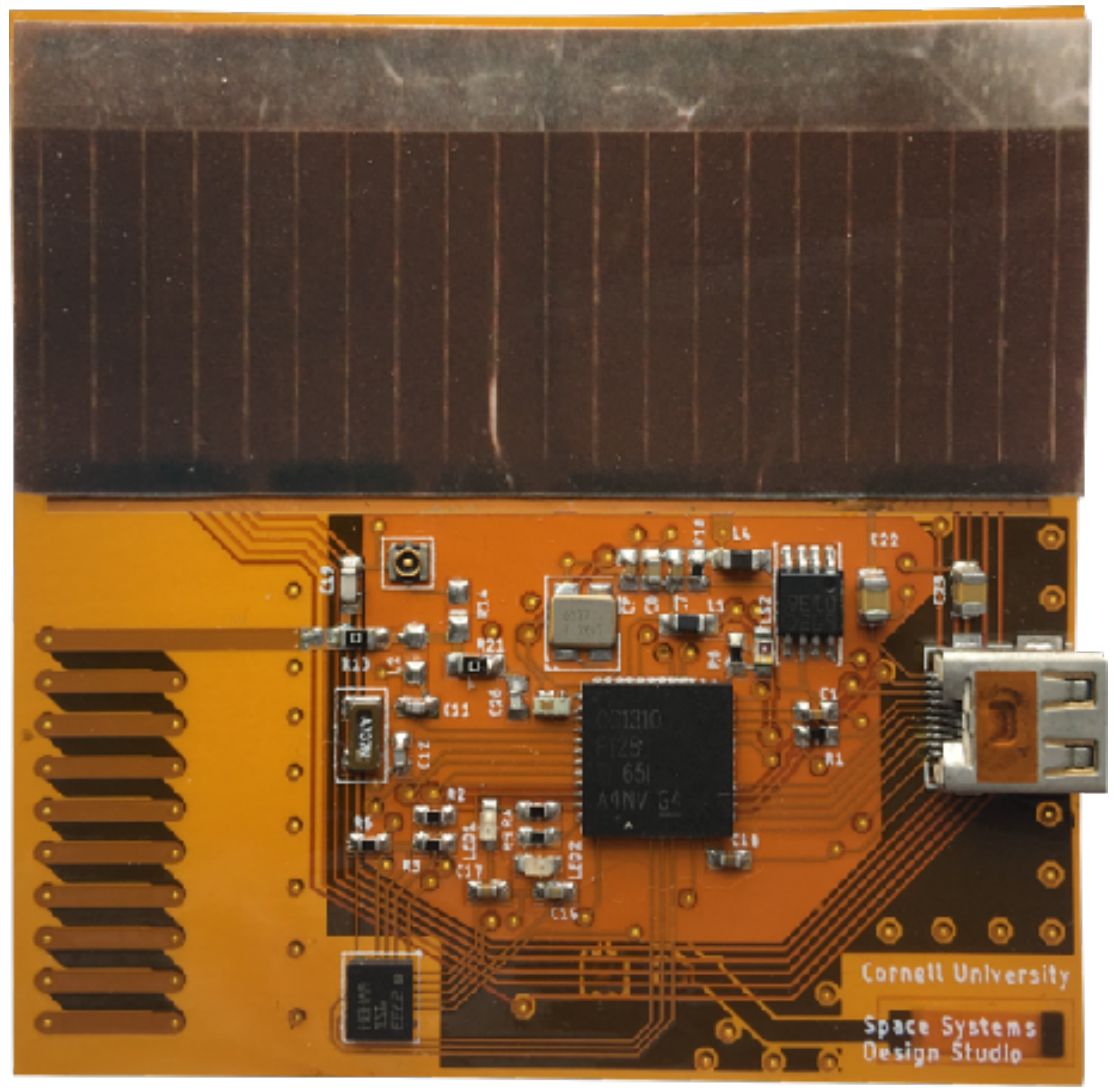
V. Hunter Adams

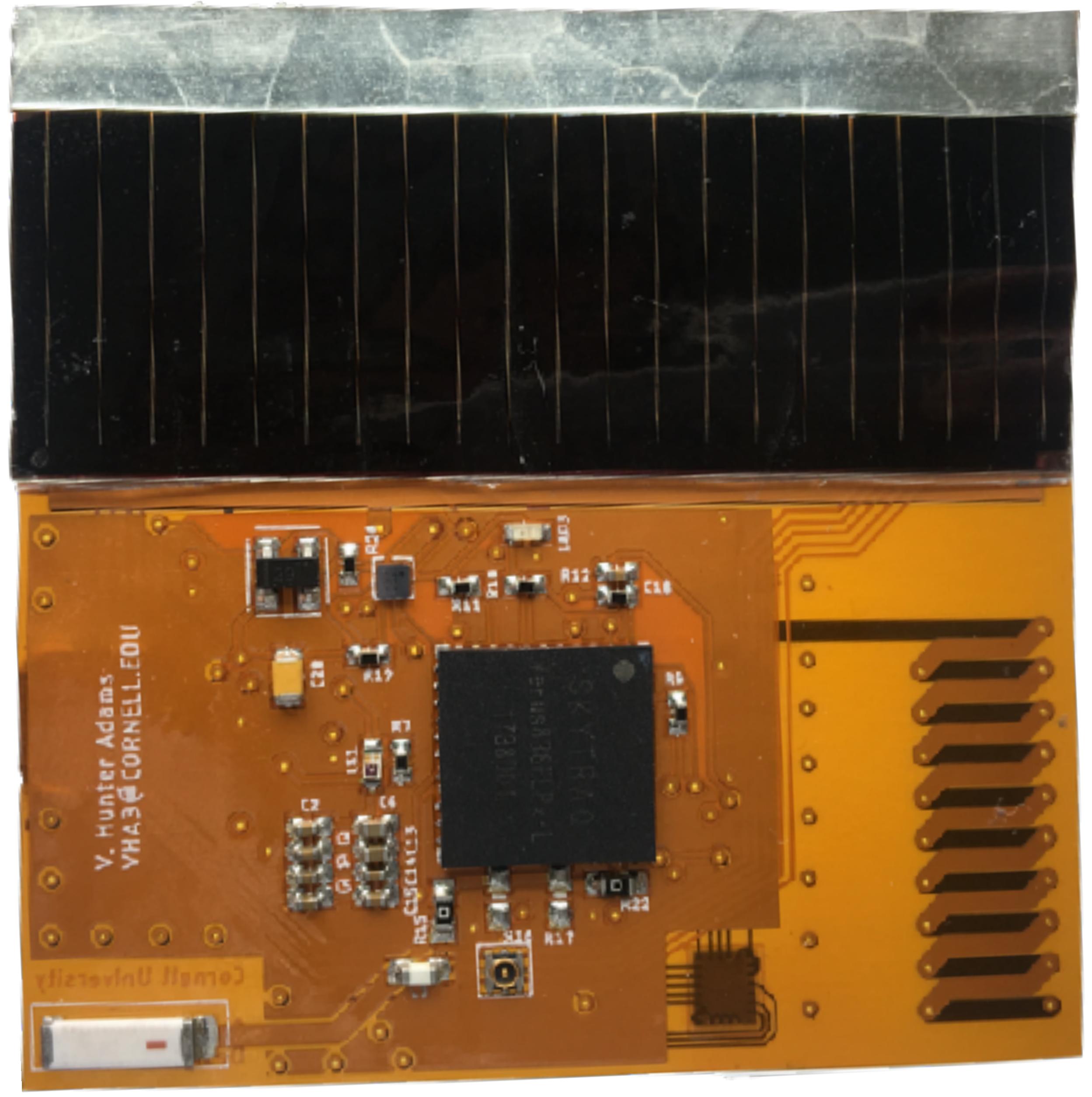
I will defend the following contributions:

1. A new field of study within aerospace engineering: R-selected spacecraft
2. Advancement of the state of the art for chipsats.
3. An algorithm that optimally routes data through a planar swarm of spacecraft.
4. First translational research application for chipsats in digital agriculture.
5. First multi-body optical navigation algorithm that recovers absolute time in addition to trajectory.

1. What are chipsats?
2. Why are they interesting?
3. What are they good for?

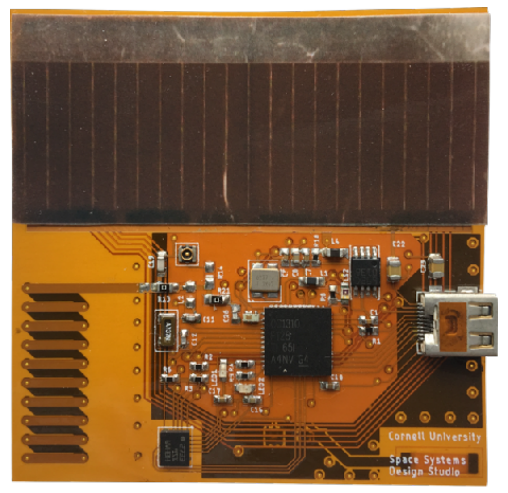
Chipsats use sensors to take measurements, and then radio those measurements to other chipsats and to receiver stations.





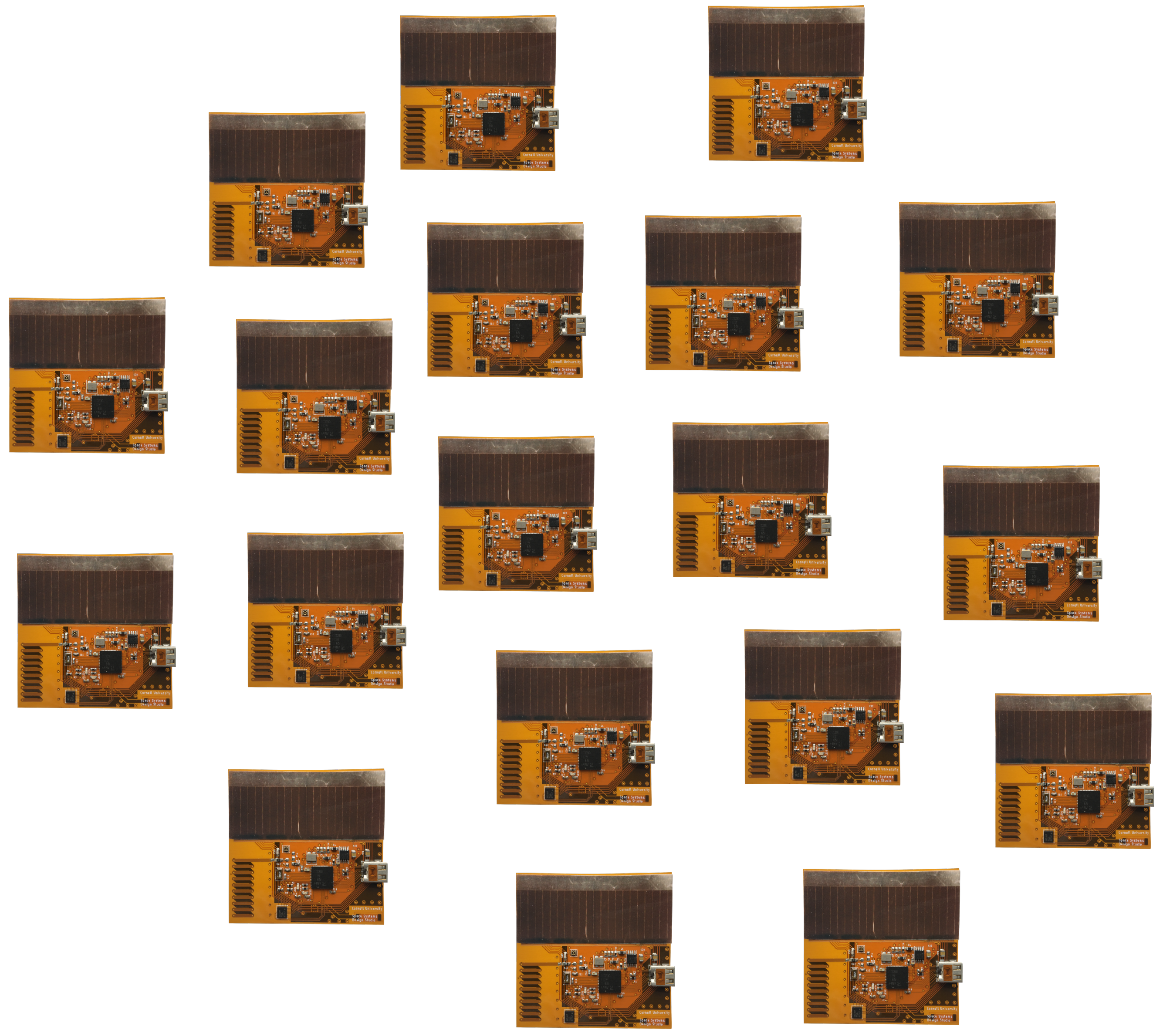
Chipsats are very different from conventional spacecraft.

The fundamental observation



← useless

useful →



The tool is not the chipsat. It is the *collection* of chipsats.

Research questions:

- How do we efficiently route data among a collection of chip-satellites?
- How do we send commands to collections of chip-satellites?
- How do we execute maneuvers with swarms of chip-satellites?
- How do we perform attitude control with chip-satellites?
- How do we plan missions involving arbitrary numbers of spacecraft?
- How do we discuss mission assurance for chip-satellites?
- . . .

Why this research landscape is interesting:

1. There are a lot of open questions.
2. Many of those questions are very fundamental in nature.

My contention:

The nature of the research questions associated with chip-satellites indicates that this technology is fundamentally different from conventional spacecraft technology, as opposed to being an incremental improvement upon conventional spacecraft technology.

Drawing an analogy with R-selection and K-selection

Goal: Make sure enough offspring survive to reproduce in the next generation.

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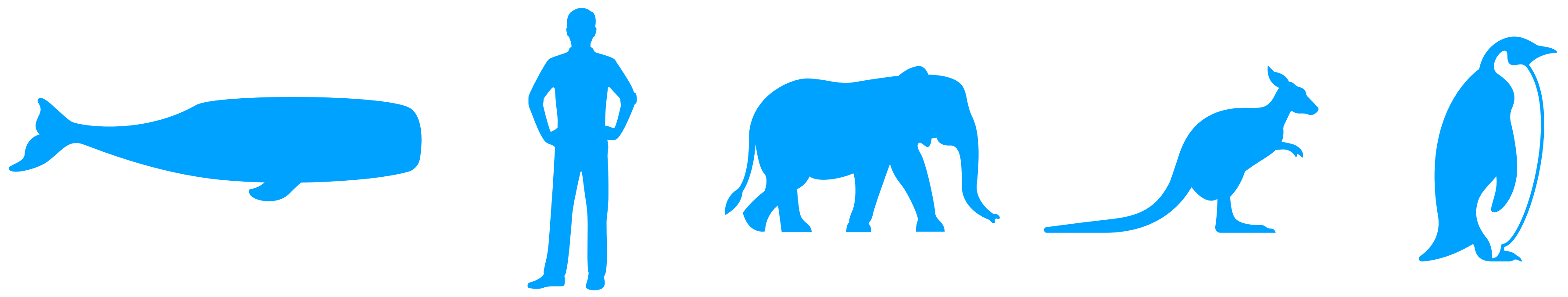
K-Selection

- Produce relatively few offspring, and devote tremendous parental effort to make certain that each is successful.
- Well suited for stable environments where they can rely on long lifespans and low mortality rates
- Spend energy to reduce the probability of offspring failure.



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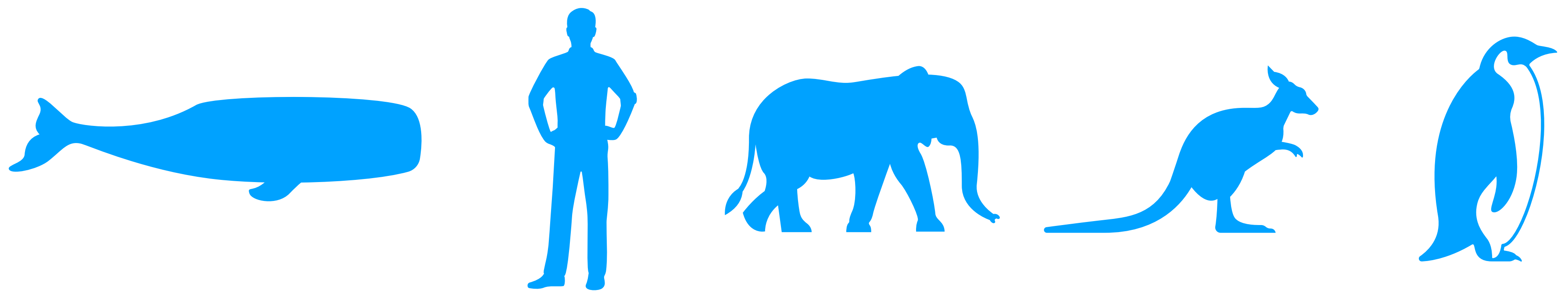
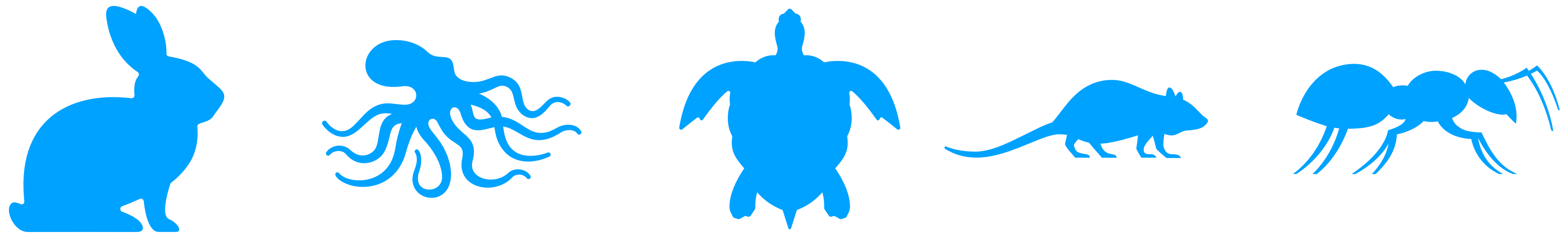


R-Selection

- Produce large quantities offspring, and devote little to no parental effort to make certain that each is successful.
- Well suited for unstable environments where, characterized by short lifespans and high mortality rates.
- Overcome high probability of offspring failure by producing very many offspring



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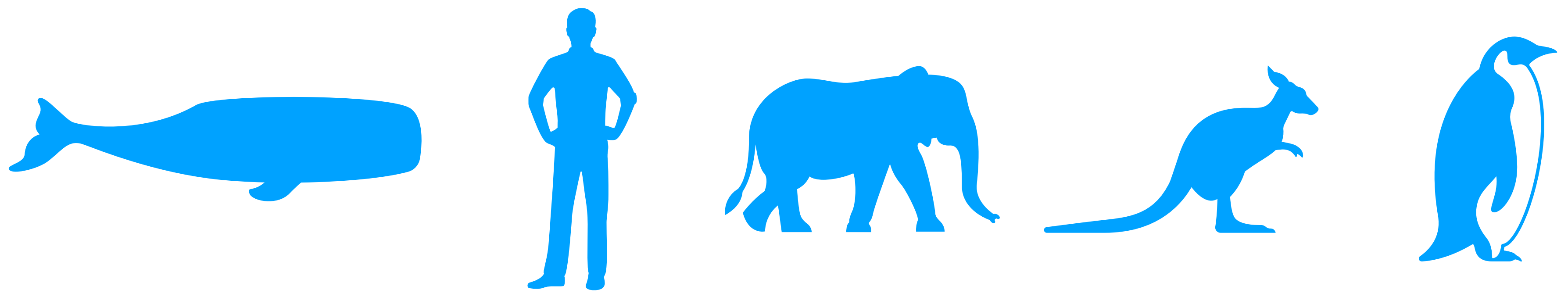

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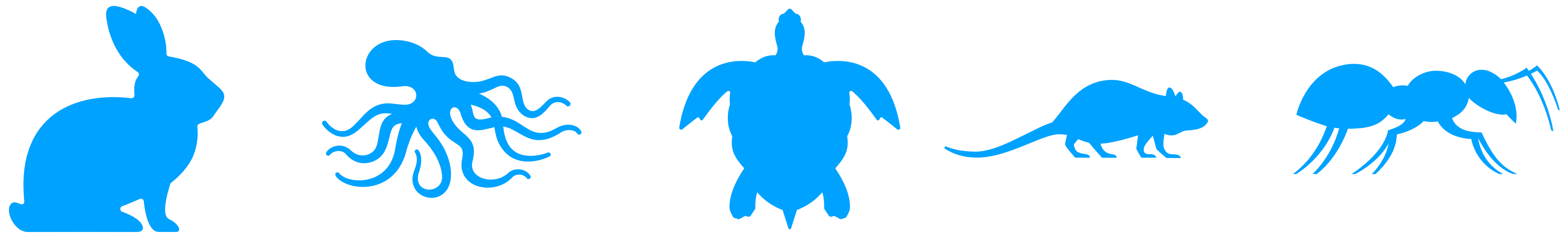

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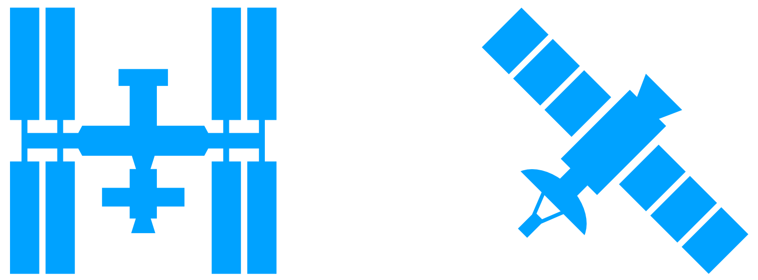

(and every other spacecraft)

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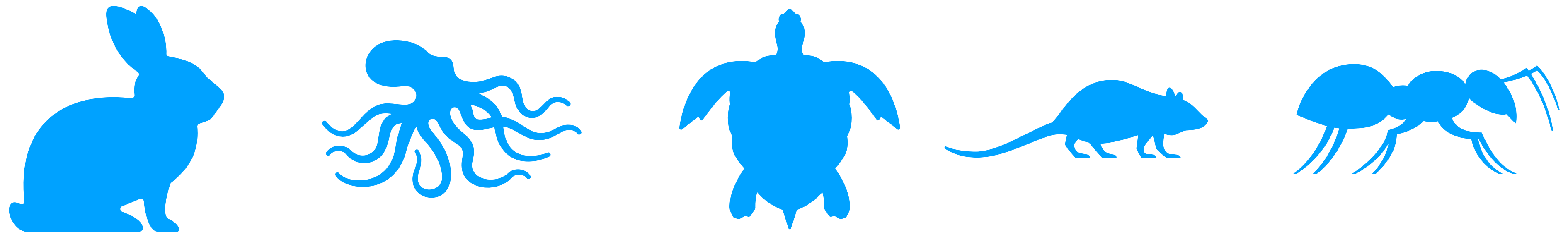

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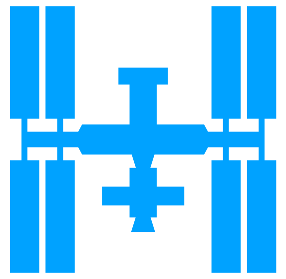

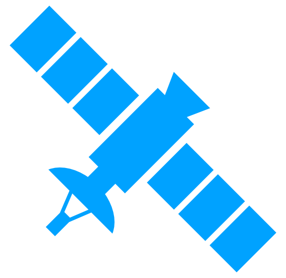

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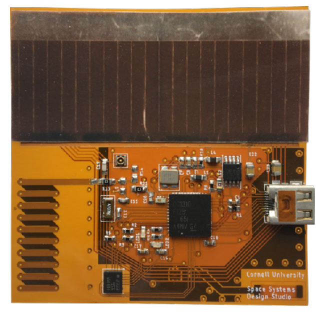

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historically the only feasible method

now a viable alternative, thanks to other industries

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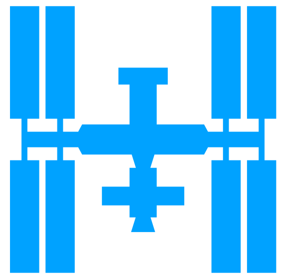
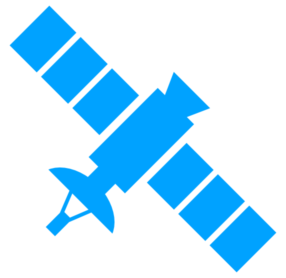
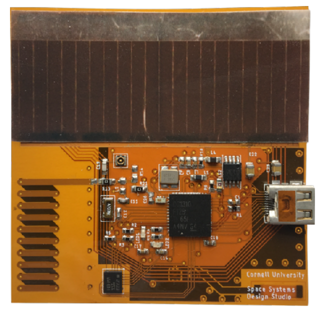




(and every other spacecraft)



Drawing an analogy with R-selection and K-selection

Goal: Make sure enough ~~offspring~~ **spacecraft** survive to ~~reproduce in the next generation~~ **accomplish the mission.**

This is why the research questions associated with chip-satellites are so fundamental. Chipsats do not represent an incremental improvement on existing technology, they represent an entirely new paradigm in spacecraft and spacecraft mission design.

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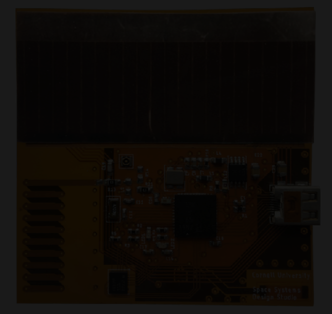
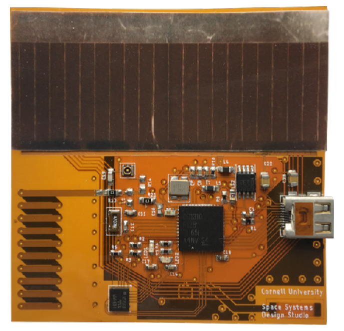
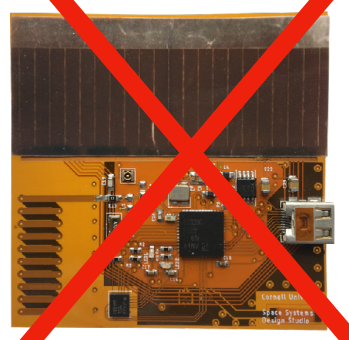


Sputnik → Explorer 1 → . . . → Cubesats →  **?**

(iterative improvement)

Sputnik → Explorer 1 → . . . → Cubesats →  **?**

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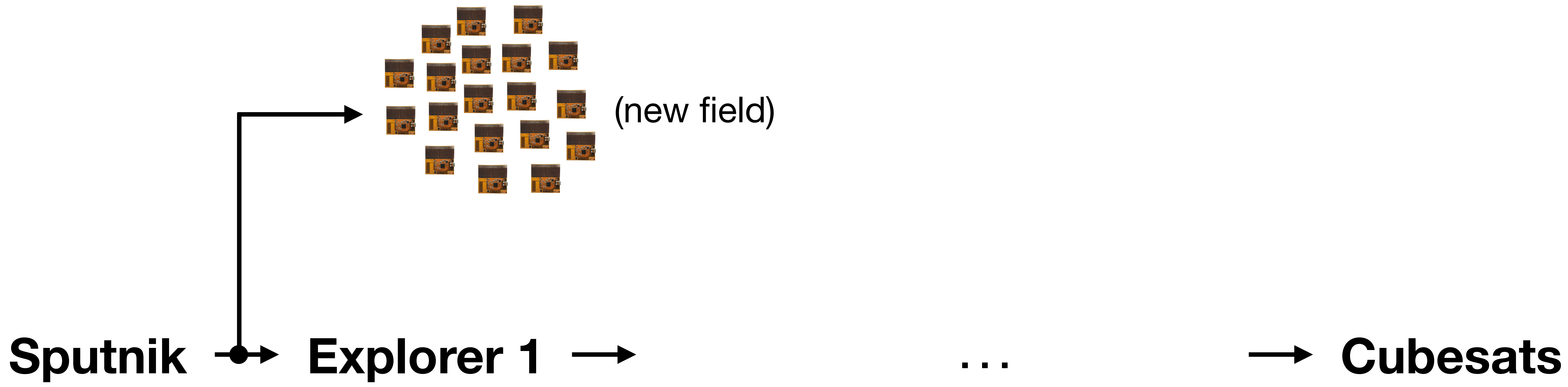

(new field)
Sputnik
Explorer 1
. . .
Cubesats

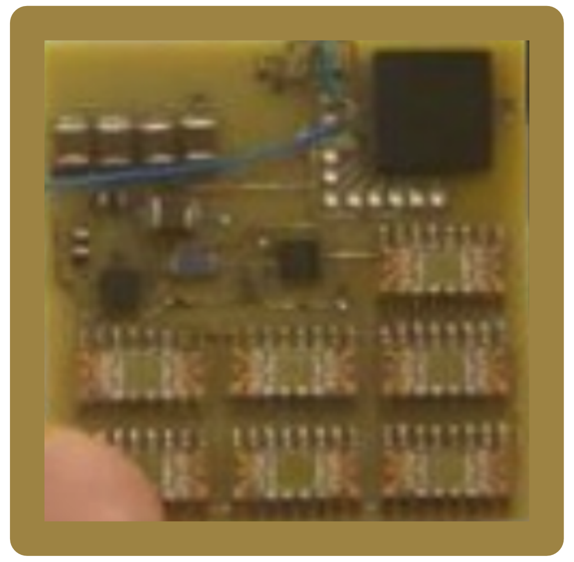
- Helvajian, Henry. Microengineering aerospace systems. AIAA, 1999.
- Cornell: NASA/NIAC Funding 2005-2007 (femtosat concept, technology roadmap, and prototyping)
- Draper/Sandia/Cornell partnerships 2008-2011 (single-chip module design)
- University of Strathclyde: ESA funding for Orbital Dynamics at Extremes of Spacecraft Length-Scale 2009-2014
- Brown University Space Horizons Chipsat Conference 2010
- Atchison, Justin. “Length Scaling in Spacecraft Dynamics.” (2010).
- Cornell ISS/MISSE-8 flight 2011-2014 (validated architecture, survivability of COTS components)
- Cornell Kicksat 1 launch April 2014 (successful integration & test but procedural impediments)
- APL NIAC sponsorship 2014-2016; Draper NIAC sponsorship 2014-2015
- Manchester, Zachary. "Centimeter-Scale Spacecraft: Design, Fabrication, And Deployment." (2015).
- Breakthrough Starshot chipsat element proposed 2016
- **Breakthrough Starshot single-IC mockup July 2016**
- Venta-1 launch June 2017 (successful data from 1500 km distance)
- **Cornell/New Ascent Impact testing in lunar regolith simulant January 2018**
- ISS deployer demonstrated January 2018
- **Cornell: High-power 2 gram GPS prototype complete 2018**
- NASA/Stanford/Cornell: Kicksat-2 Successful deployment and receipt of Sprite transmissions March 29, 2019
- **Hackathon 1: March 15-17, 2019**
- **Adams, Hunter and Mason Peck.. R-Selected Spacecraft. Accepted. AIAA Journal of Spacecraft and Rockets. 2019.**
- **Adams, Hunter and Mason Peck. A Scalable Packet Routing Mechanism for Chip-Satellites in Coplanar Orbits. In Review. IEEE Transactions on Aerospace and Electronic Systems. 2019.**

Contribution 1:

Created a new field of study within aerospace engineering:
R-selected spacecraft

Contribution 2:

Advancement of the state of the art for chipsats.



International Space Station Demo

2010

Zac

Zac

2013

KickSat 1,2

Venta 1

2016

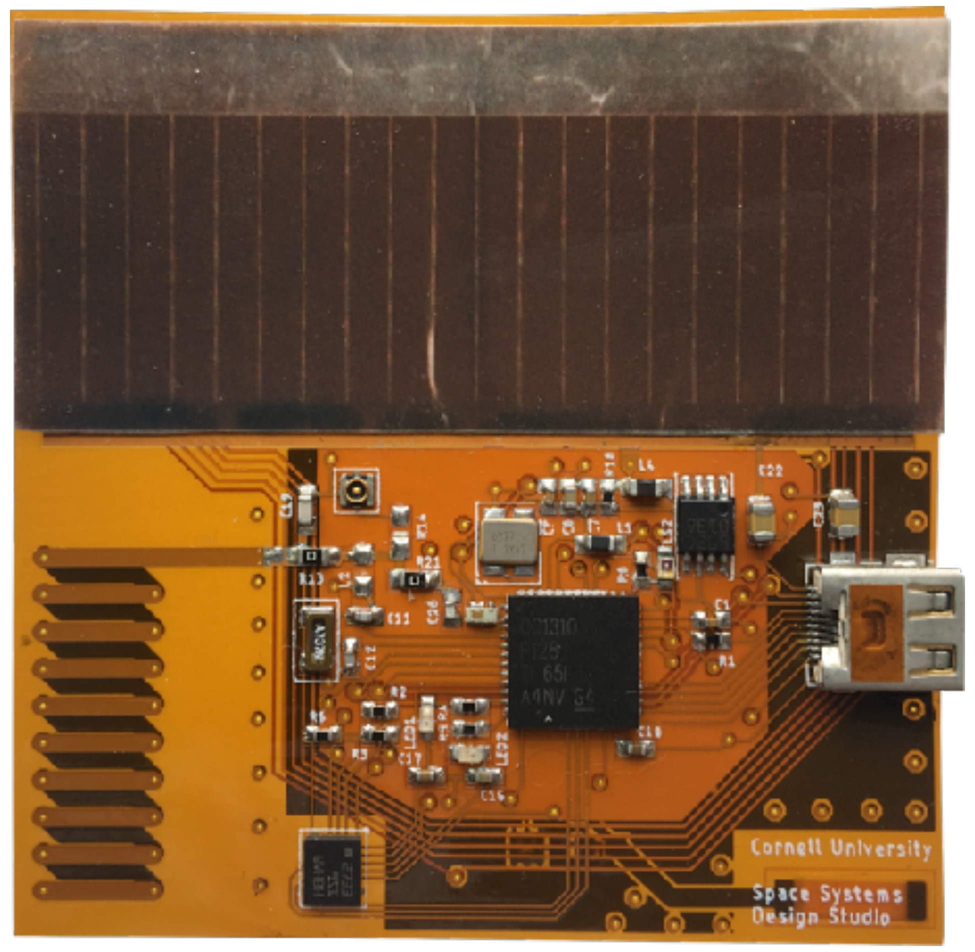
Hunter

Hunter

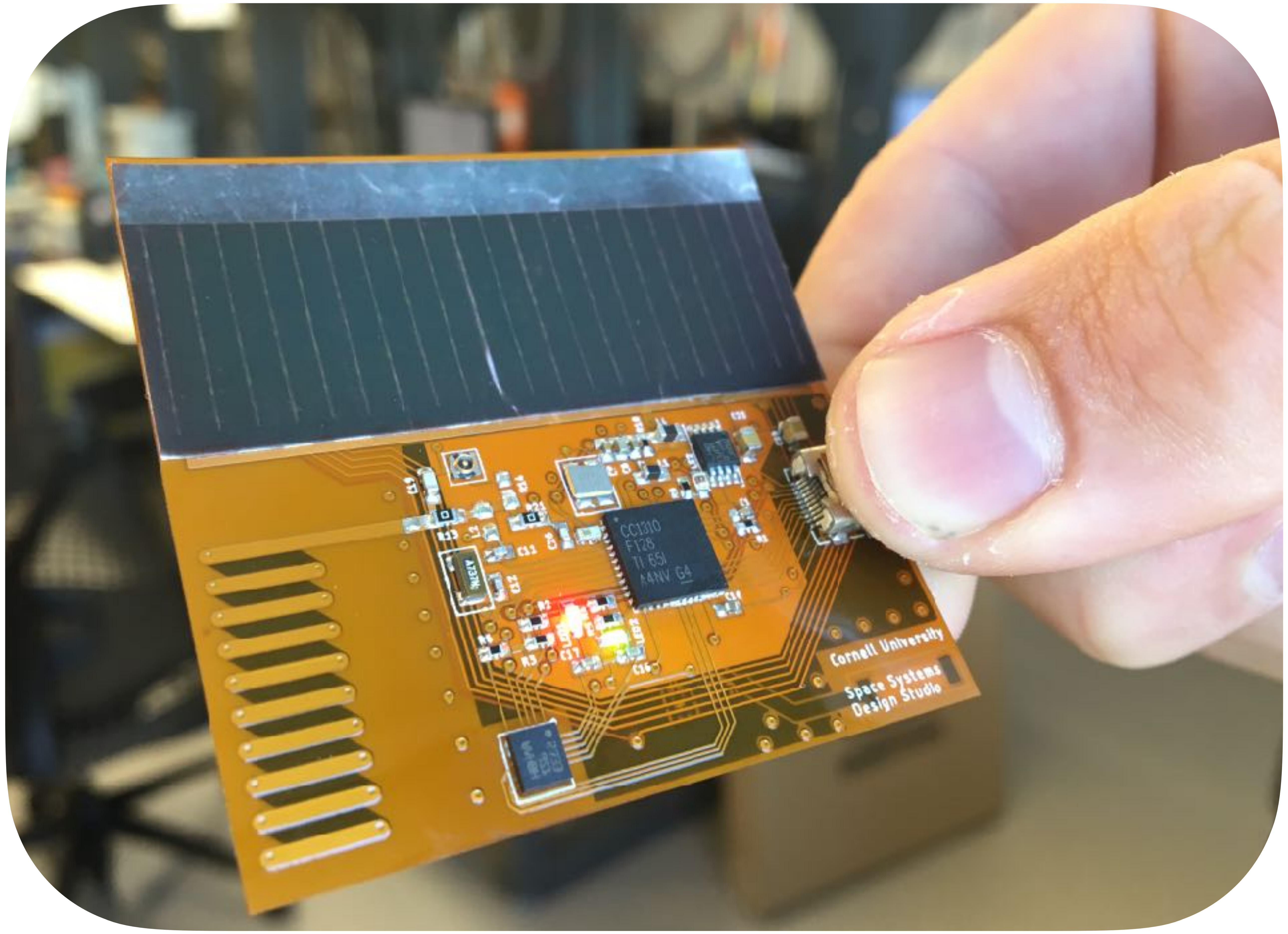
2018-2019

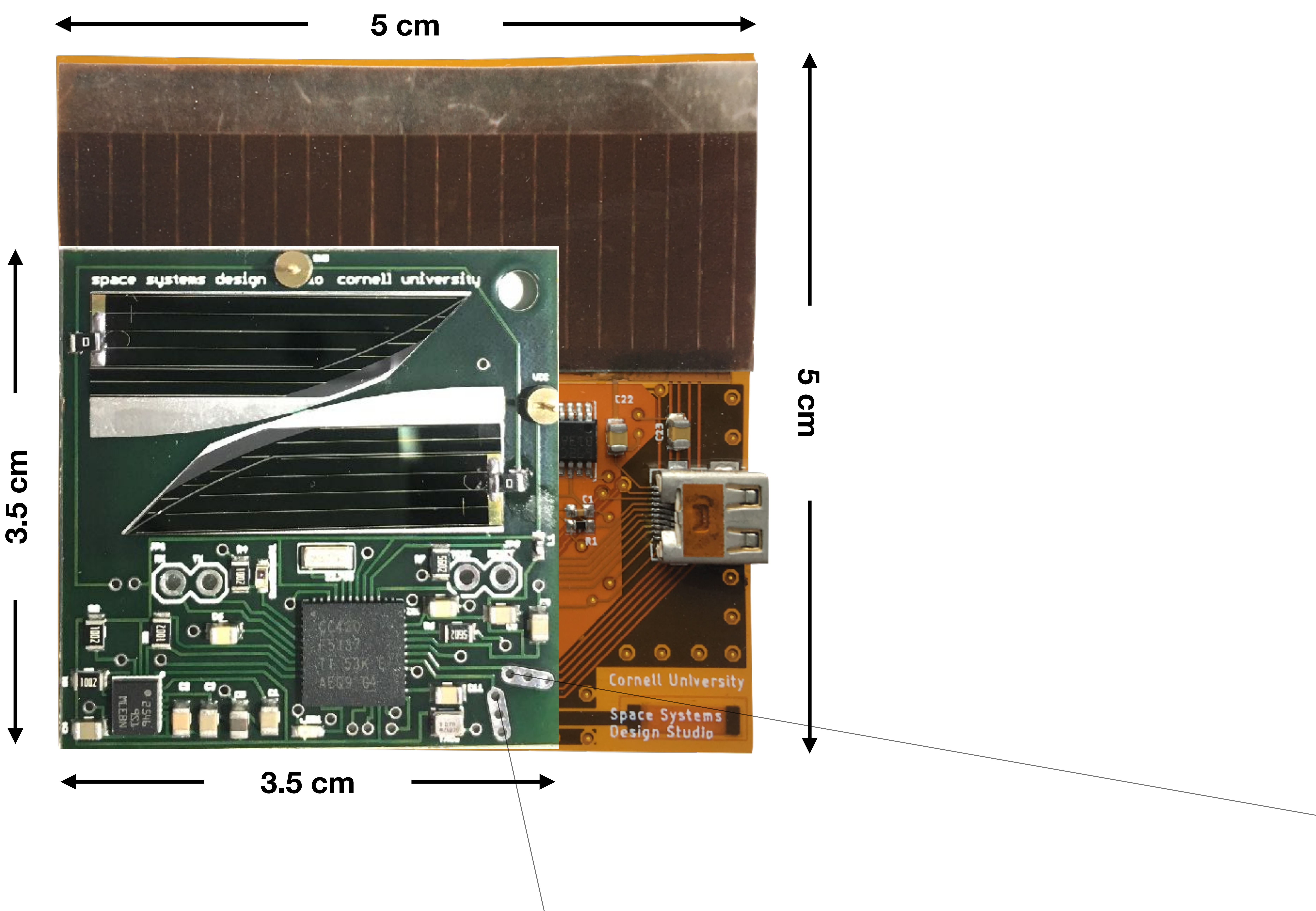
Alpha

JANUS

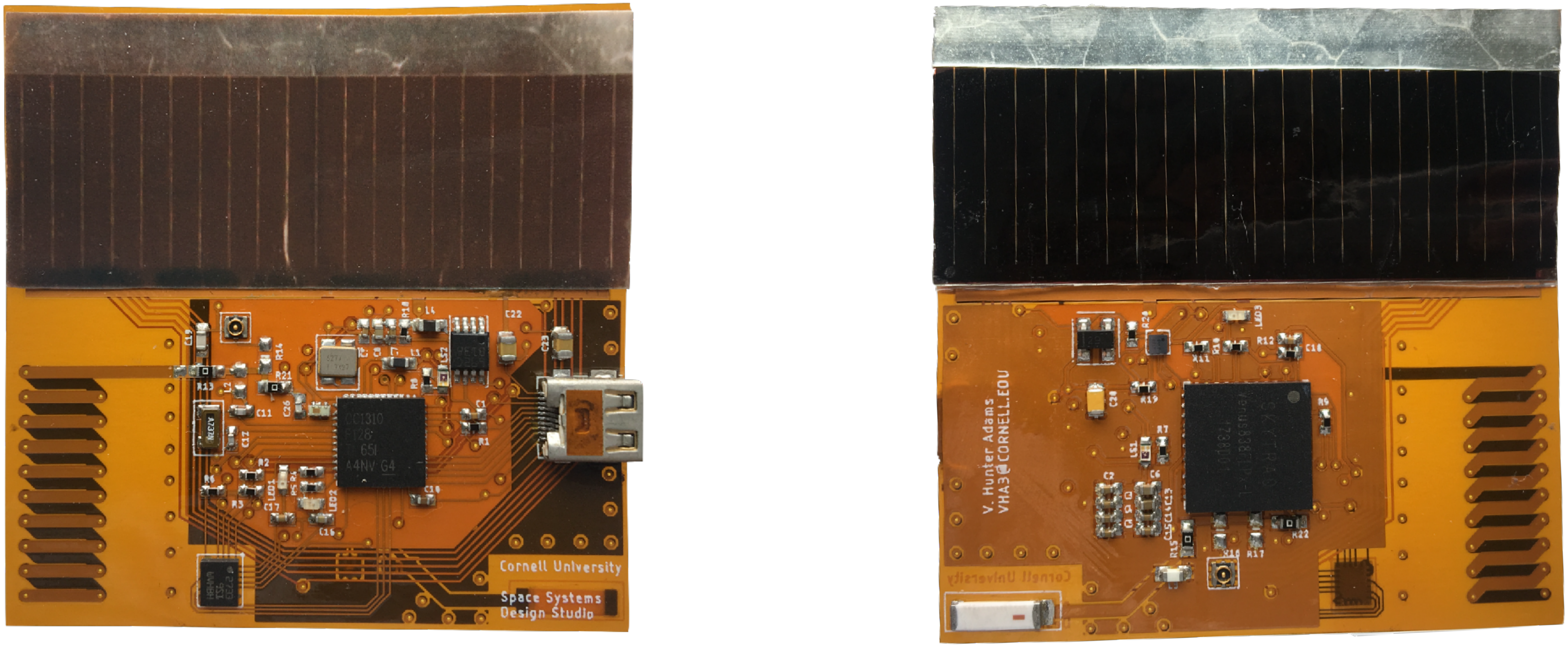


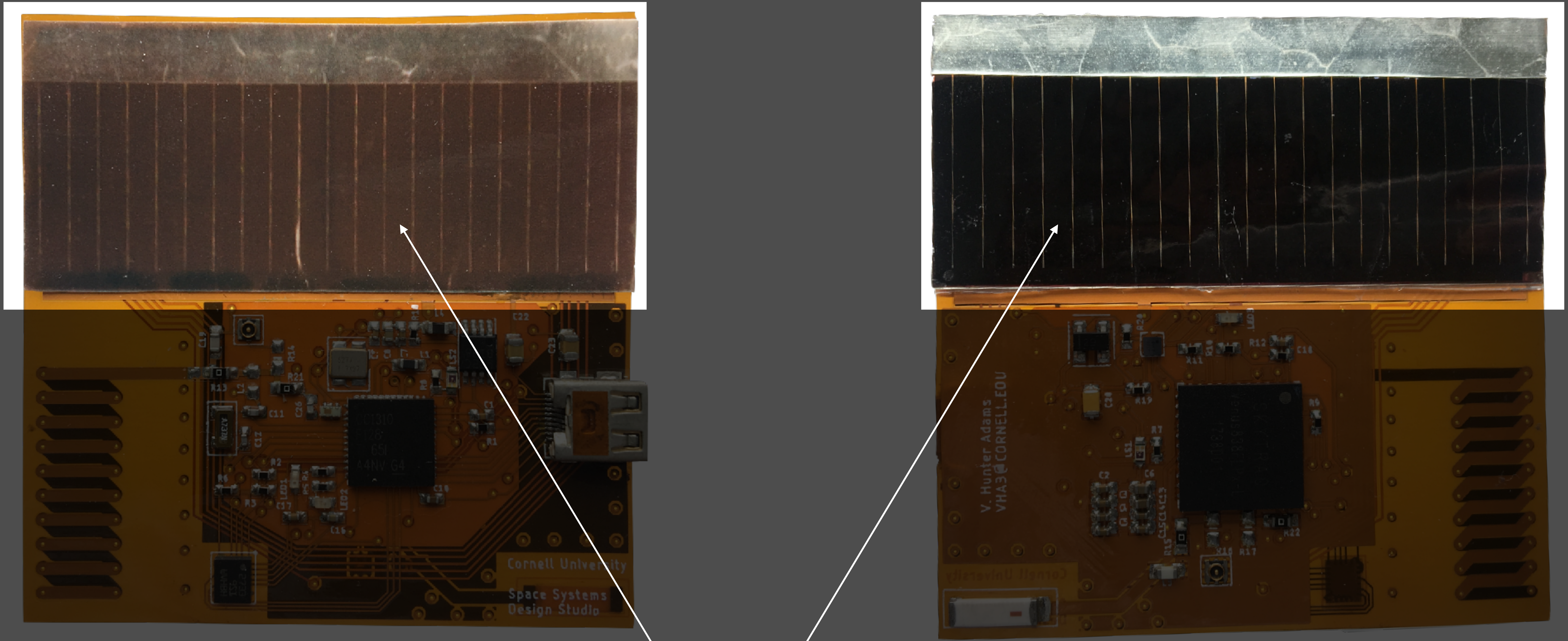
Monarch



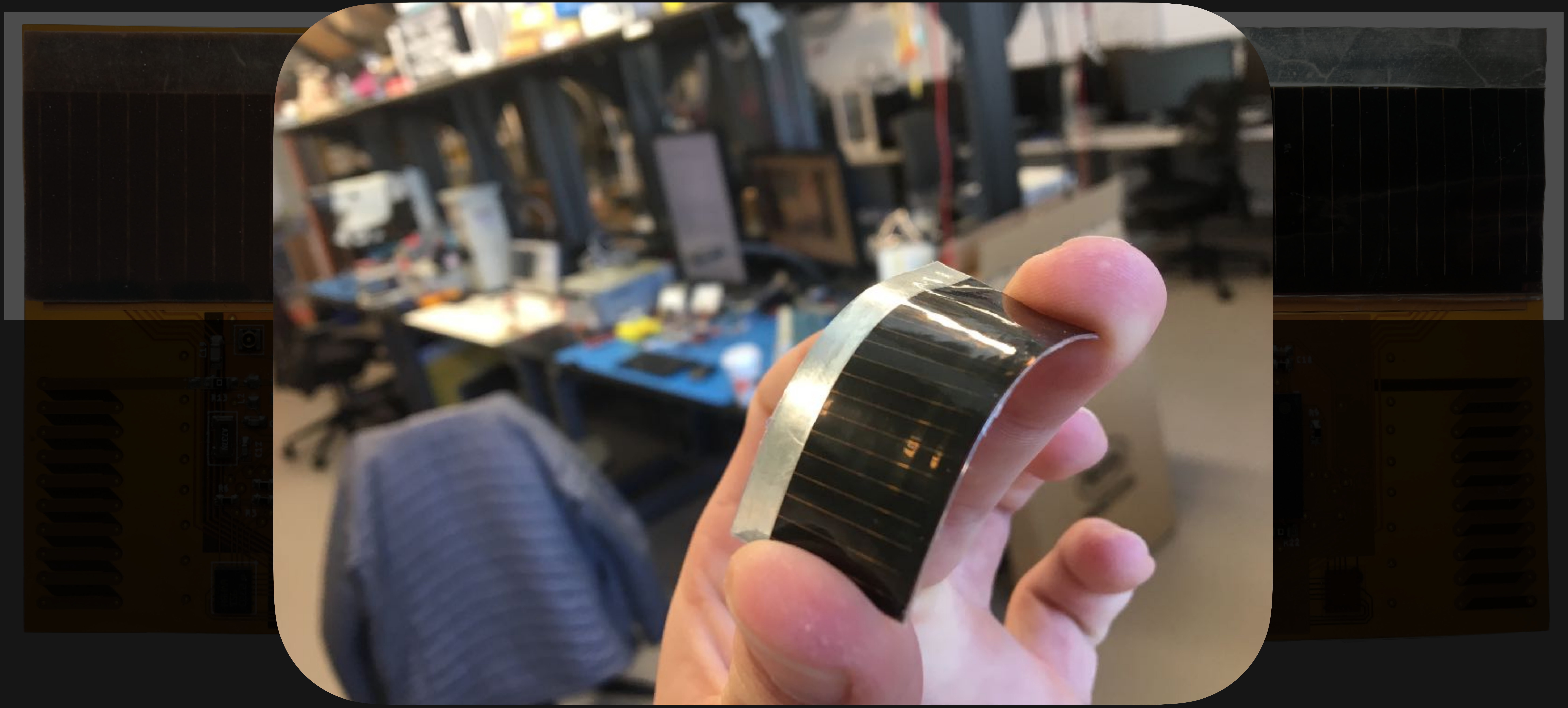


5 cm
5 cm
3.5 cm
3.5 cm
space systems design
cornell university
Cornell University
Space Systems
Design Studio

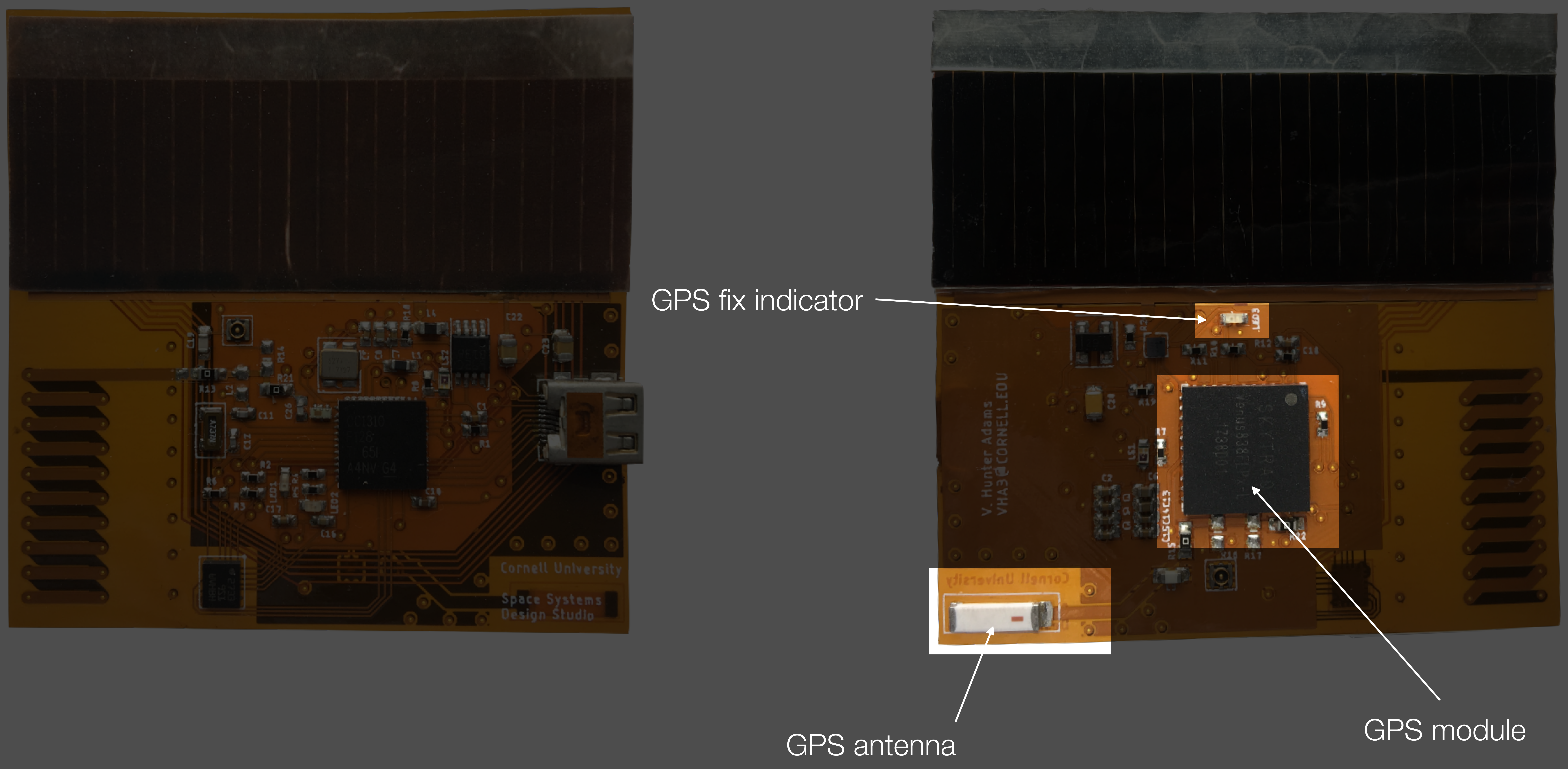

Cornell University
Space Systems
Design Studio
V. Hunter Adams
VHA3@CORNELL.EDU



Alta Devices solar cells - 300 mW each



0.1 grams, and flexible



GPS fix indicator
GPS antenna
GPS module
Cornell University
Space Systems
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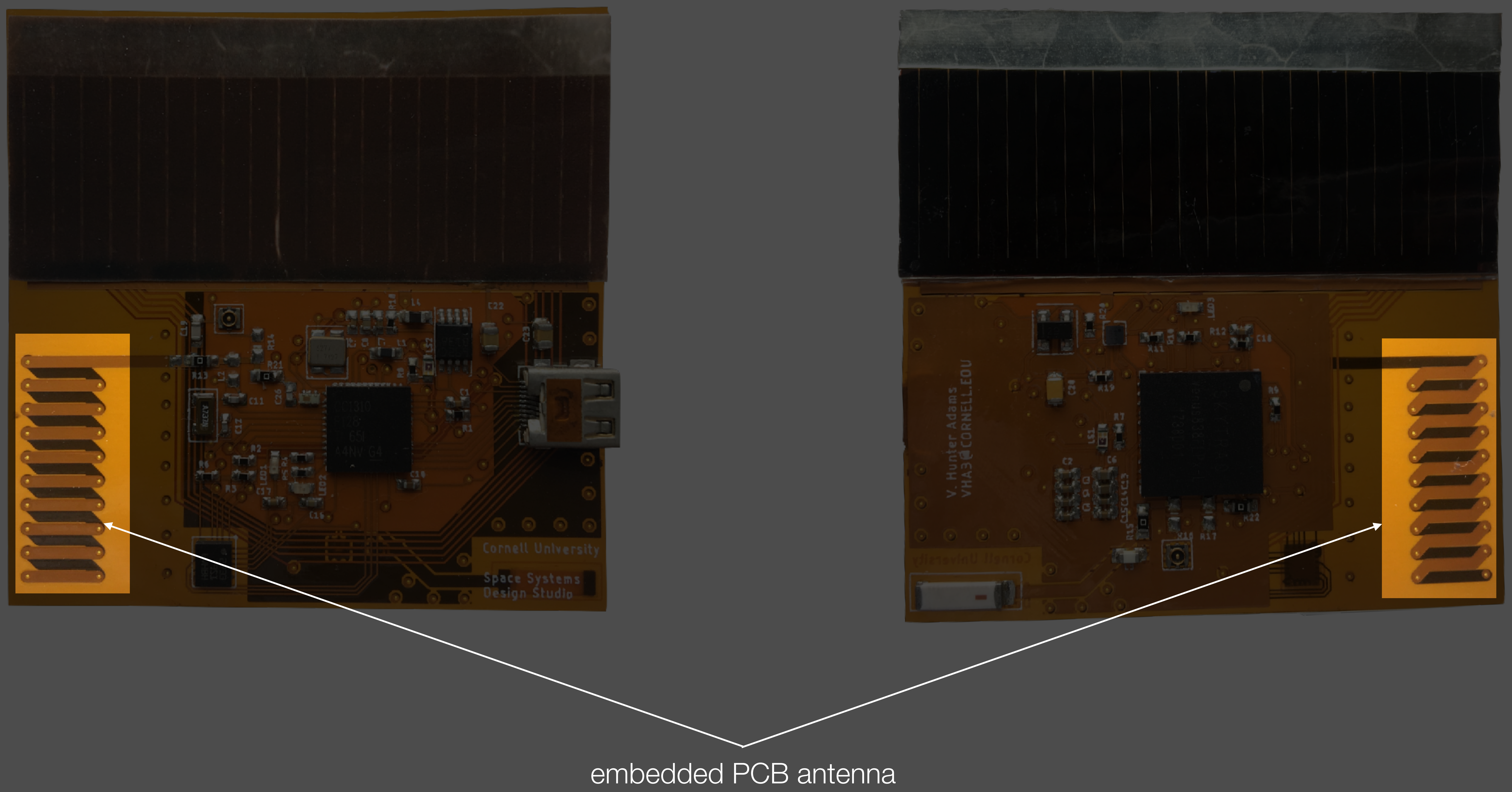
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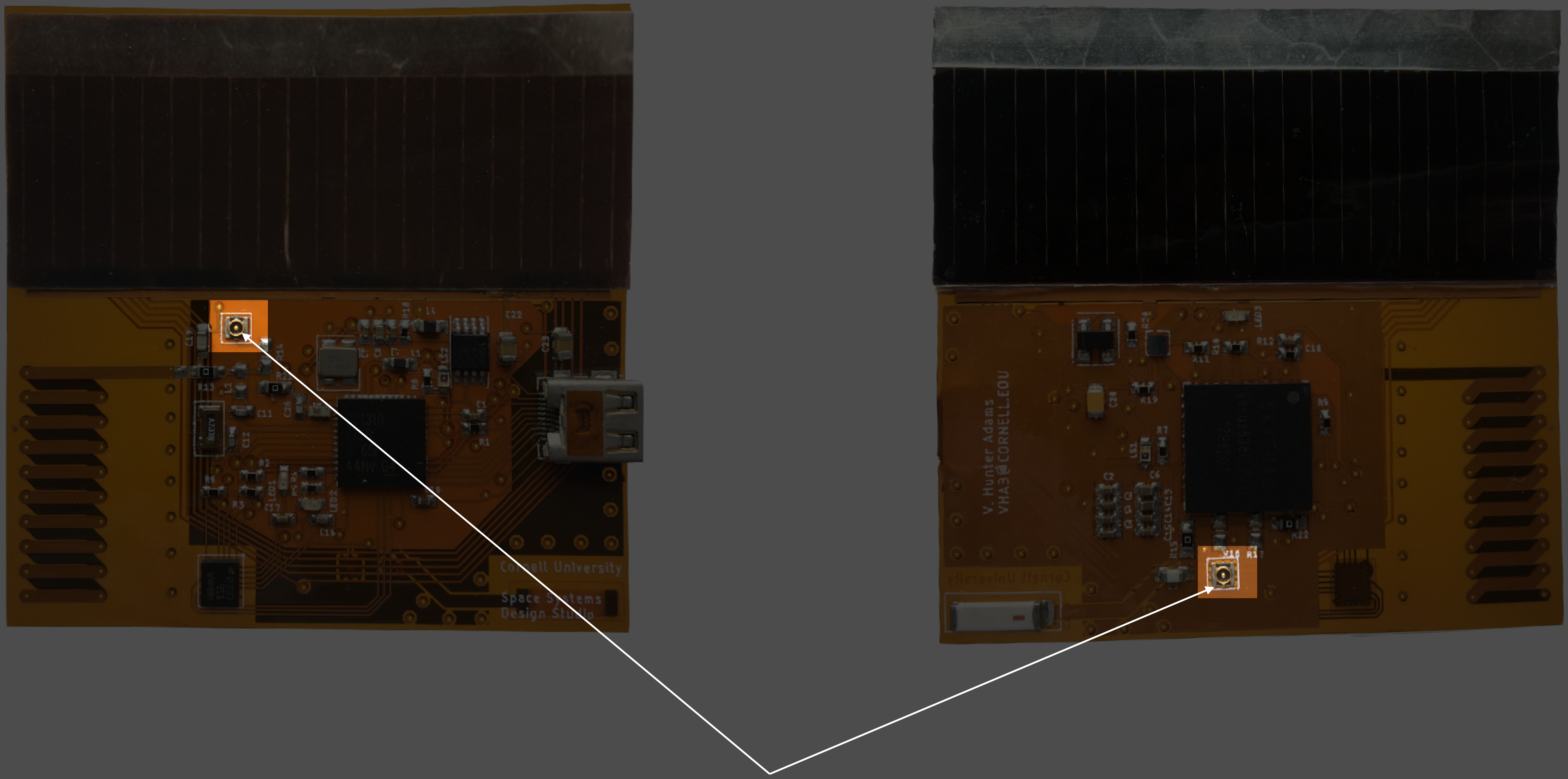
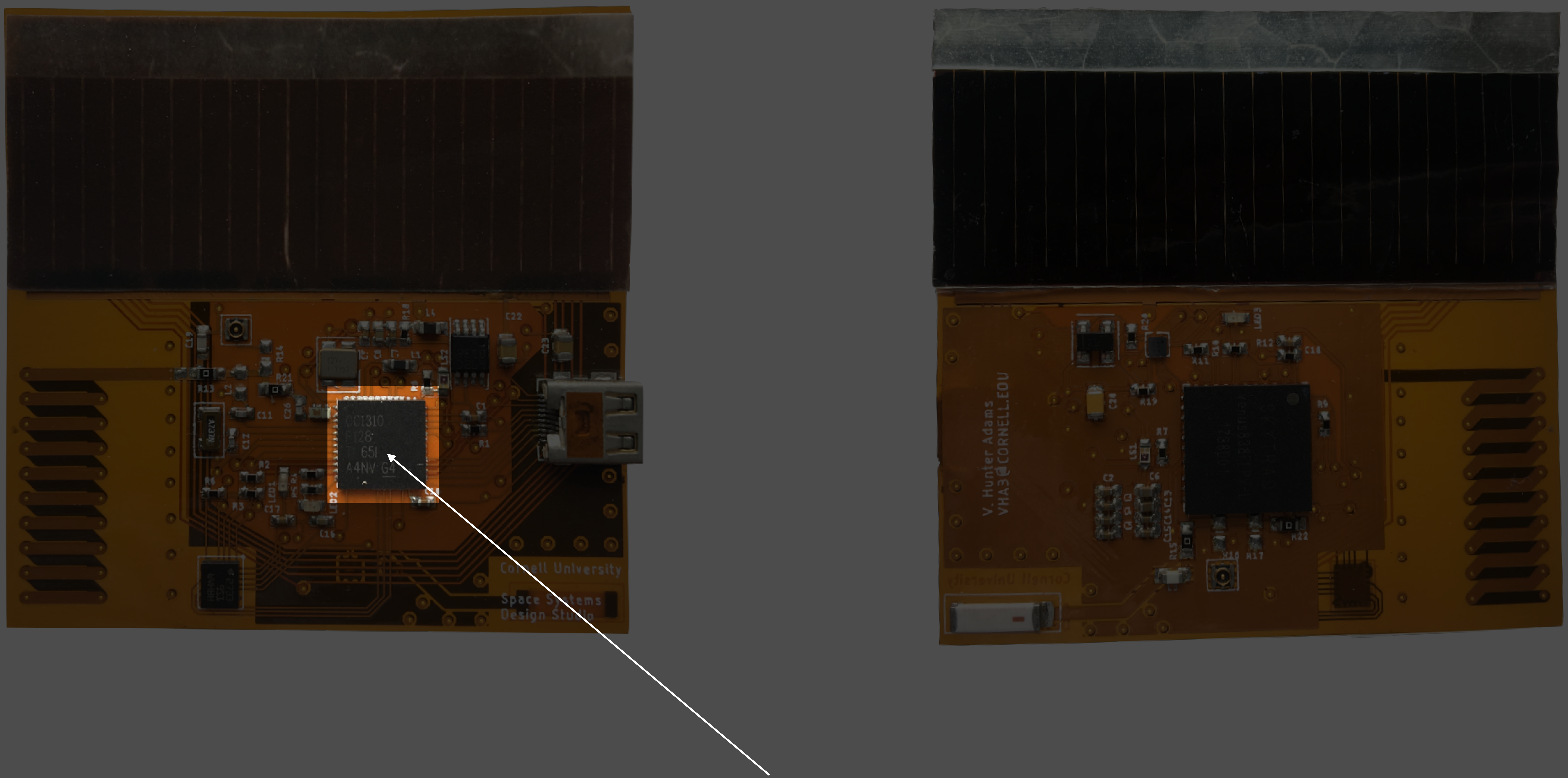
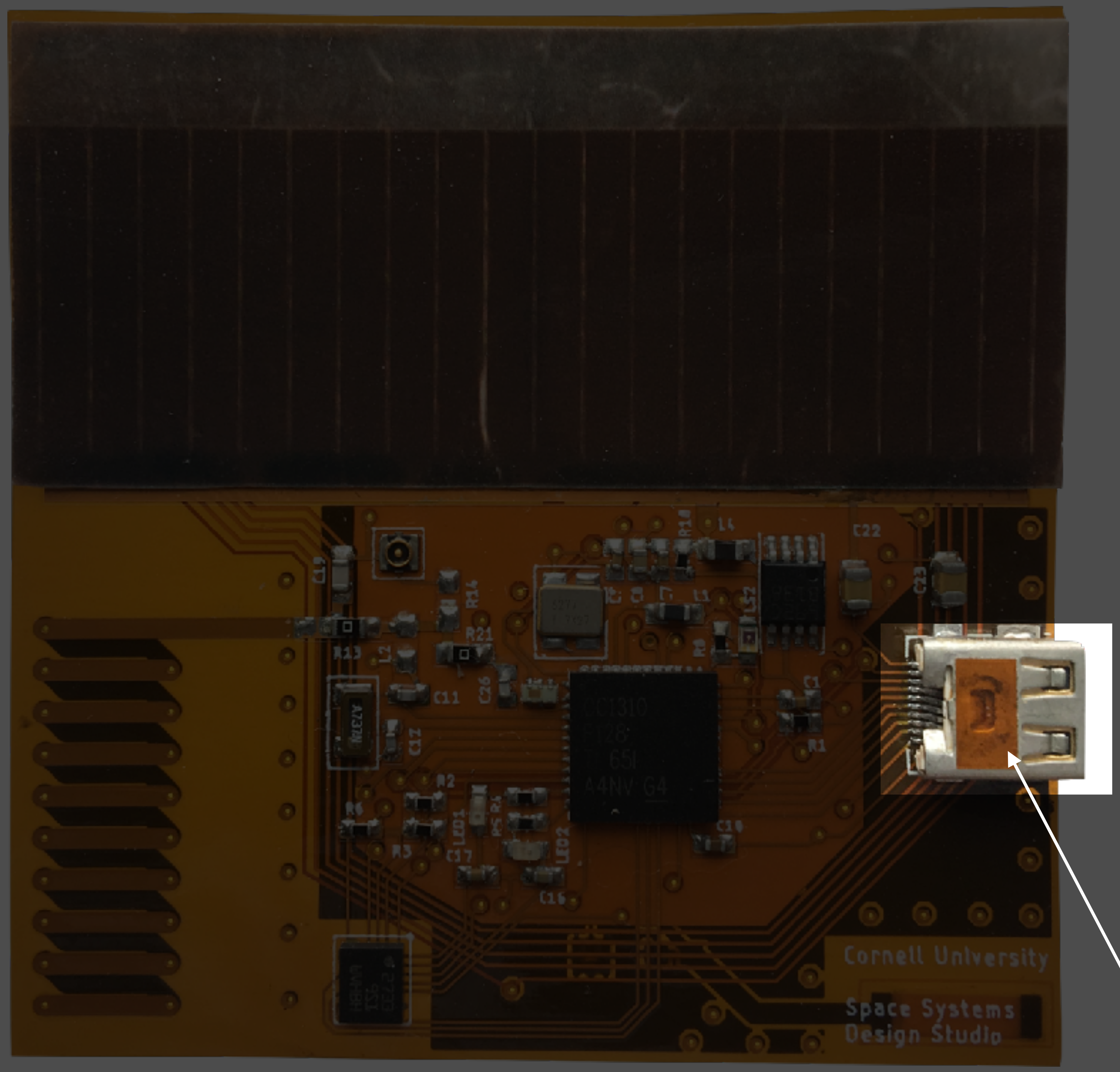
embedded PCB antenna

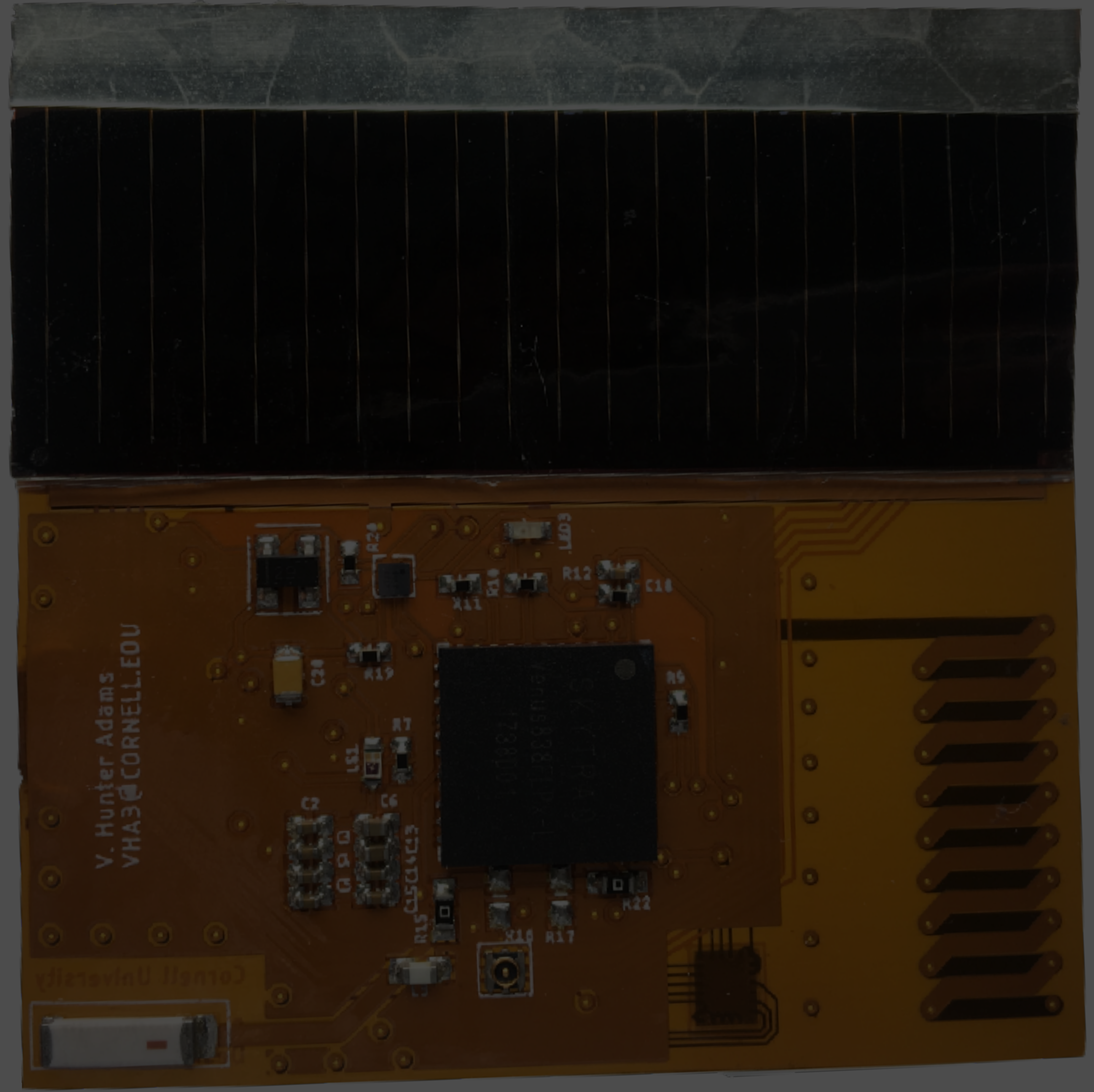


coaxial interfaces to antennas

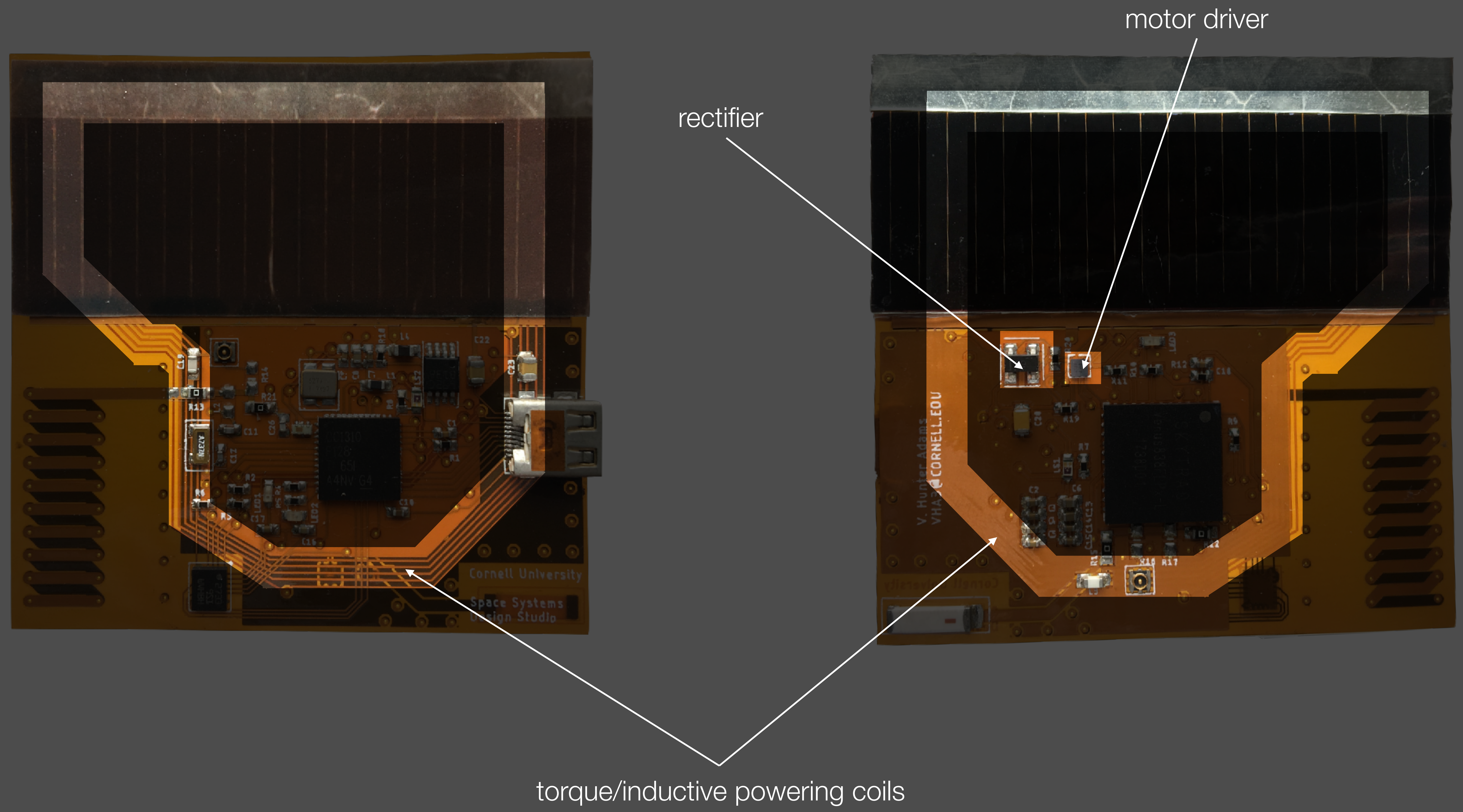


ARM processor and radio, running real-time operating system





JTAG interface through HDMI port



motor driver
rectifier
torque/inductive powering coils
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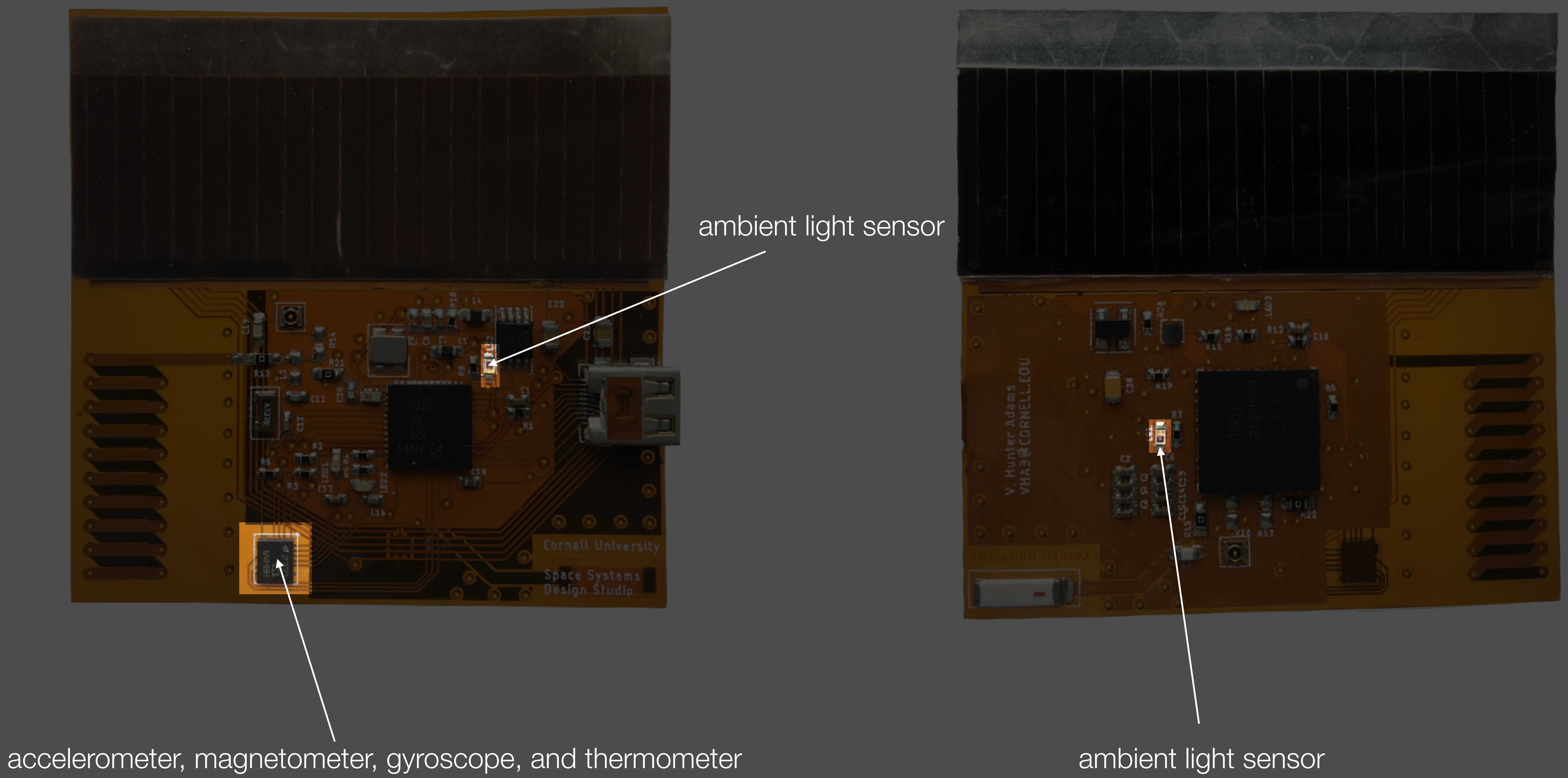
ambient light sensor
accelerometer, magnetometer, gyroscope, and thermometer
ambient light sensor
Cornell University
Space Systems
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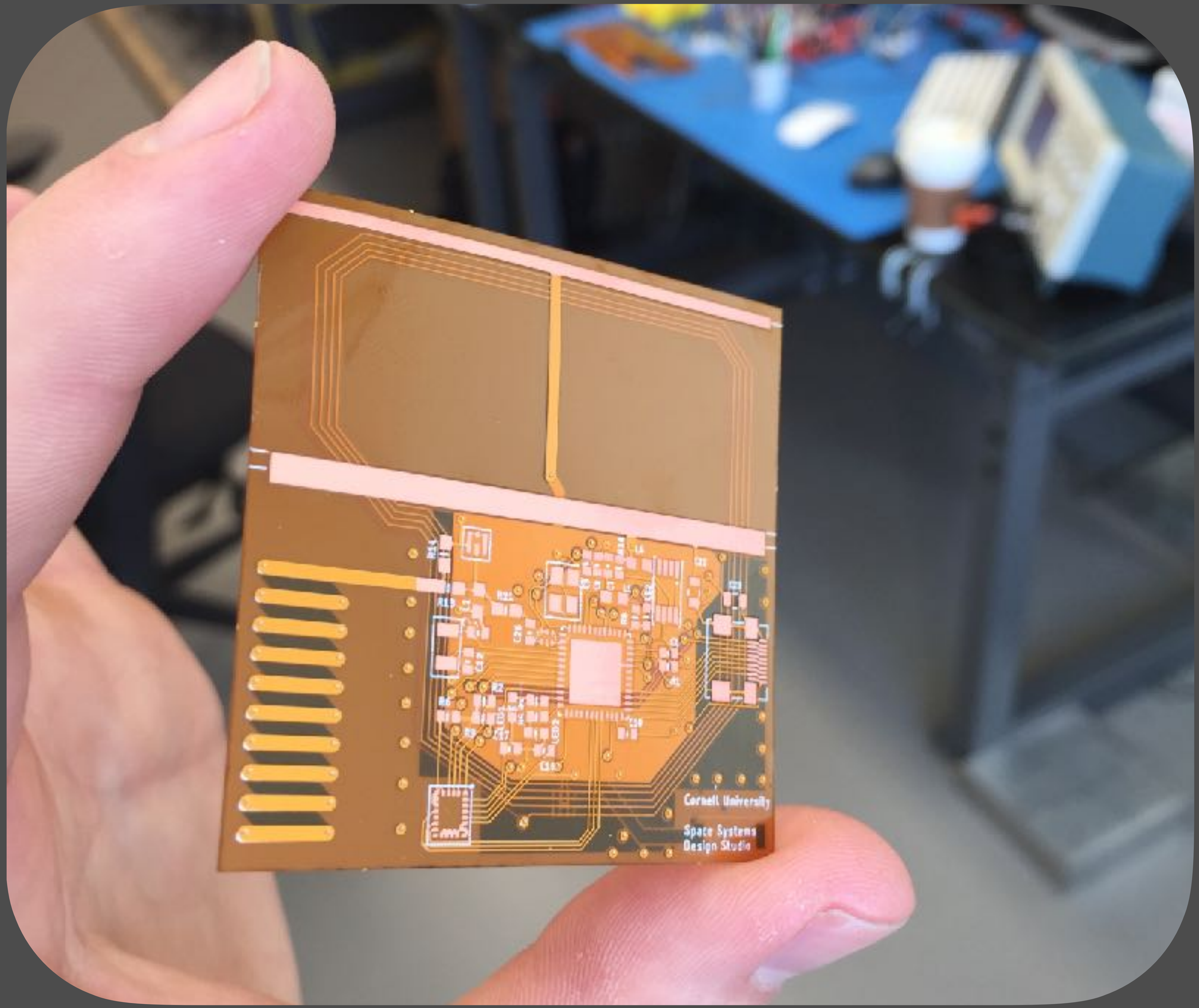
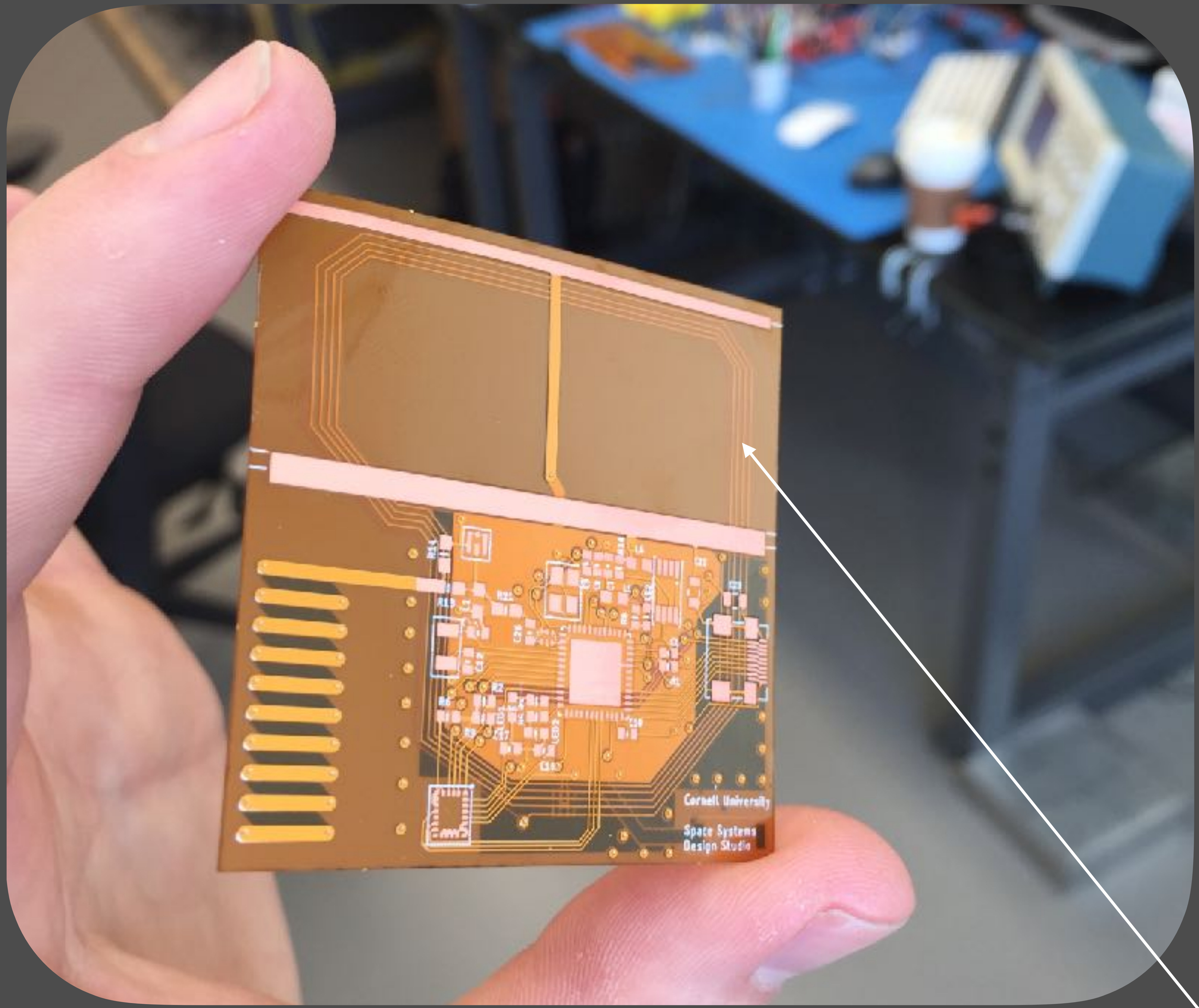


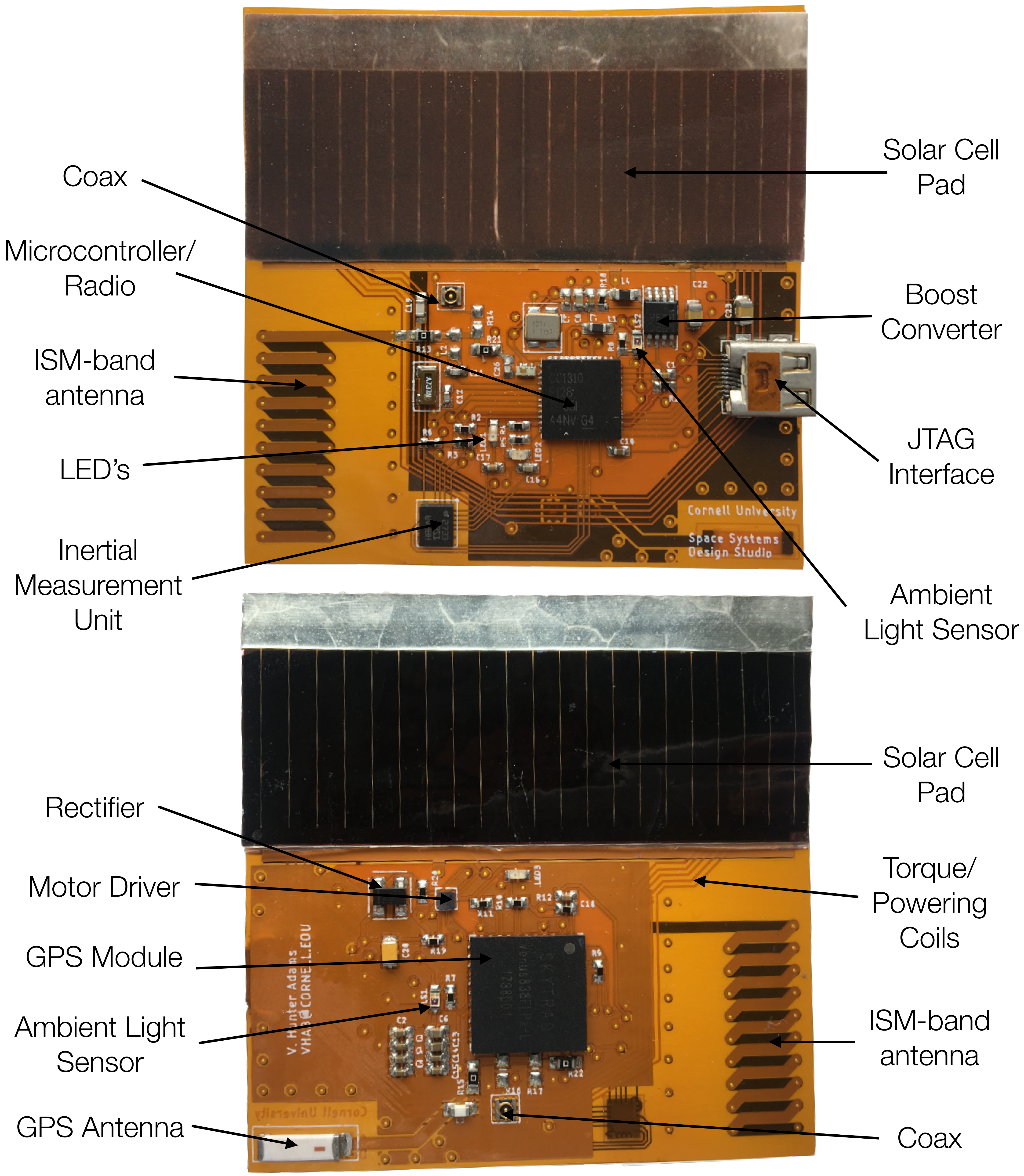
lightweight, flexible Kapton substrate

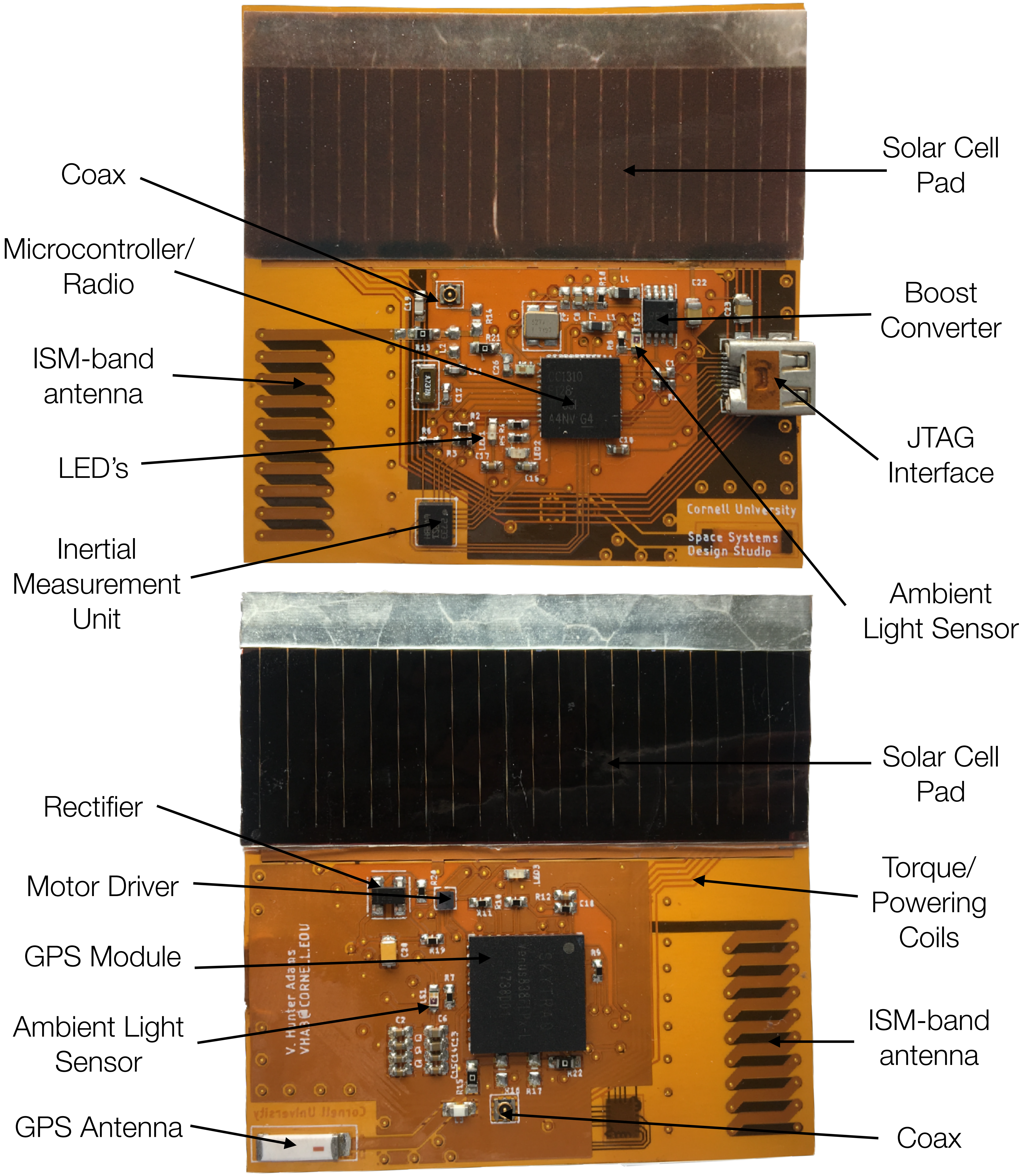


better view of torque/inductive powering coils

Hardware:

- two Alta-devices solar cells (300 mW each)
- CC1310 ARM processor running RTOS
- 25 mW radio chip
- accelerometer, magnetometer, and gyroscope
- embedded ISM-band antenna (915 MHz)
- GPS
- onboard GPS chip antenna
- JTAG interface
- two ambient light sensors
- embedded torque coils for attitude manipulation
- motor driver for torque coil control
- embedded inductive powering coils
- LED's for user feedback

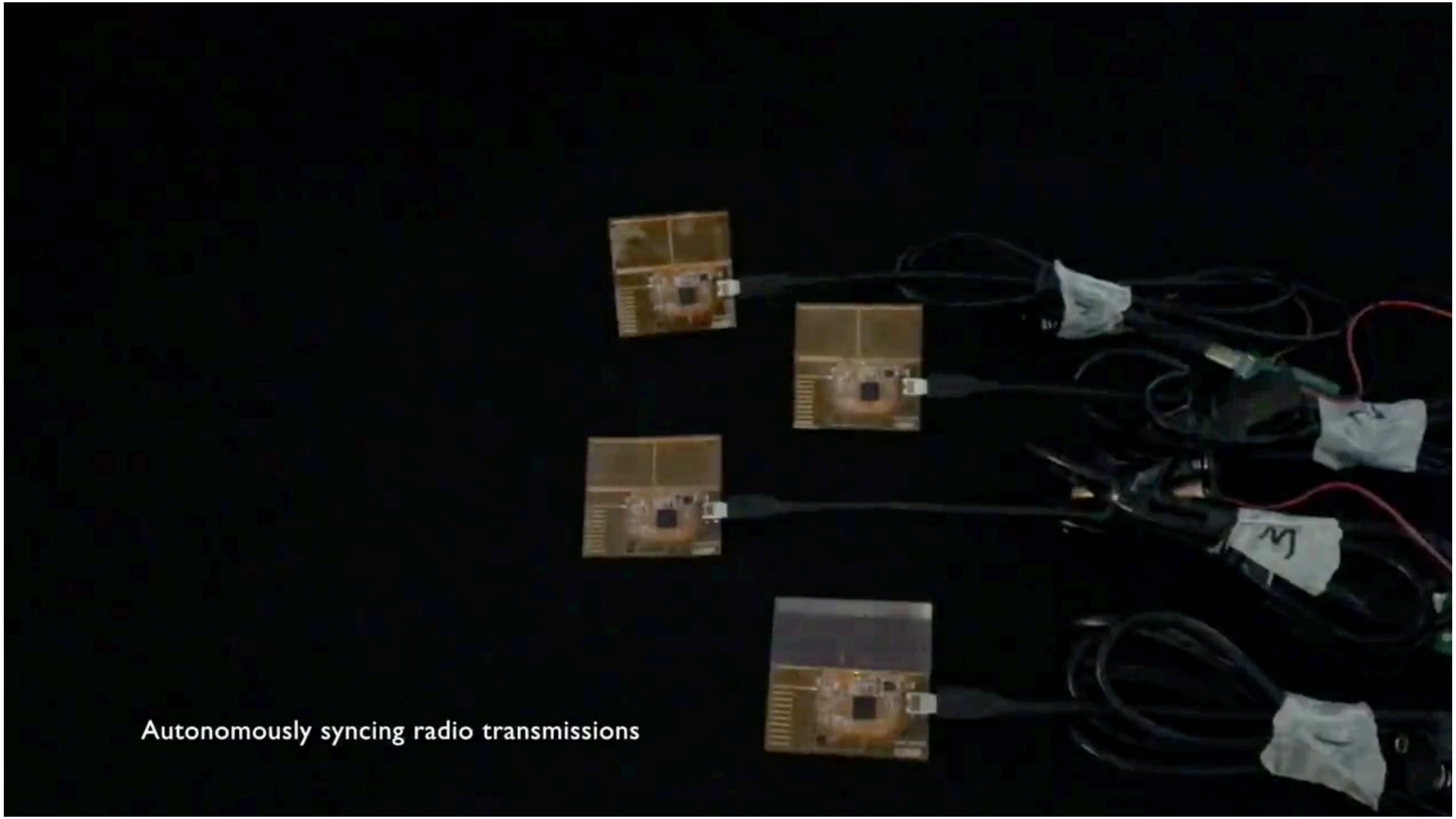




Capabilities:

- chip-to-chip communication capability
- chip-to-receiver communication capability
- GPS acquisition in 30 seconds
- powering by sun and/or inductive coils
- communication among many of chips on a single ISM-band frequency
- extremely shock-proof (27,000 g's)
- can generate their own magnetic field
- stable flight in 0 g's
- flexible (to an extent)
- capable of accommodating any sensor that meets size and power requirements
- operating temperatures from -40 to +85 C

Link to demonstration video



Classes of missions for which chipsats are well suited:

1. Distributed sensing/monitoring missions.
2. Missions that pose high risk to individual chipsats (e.g. planetary impact)

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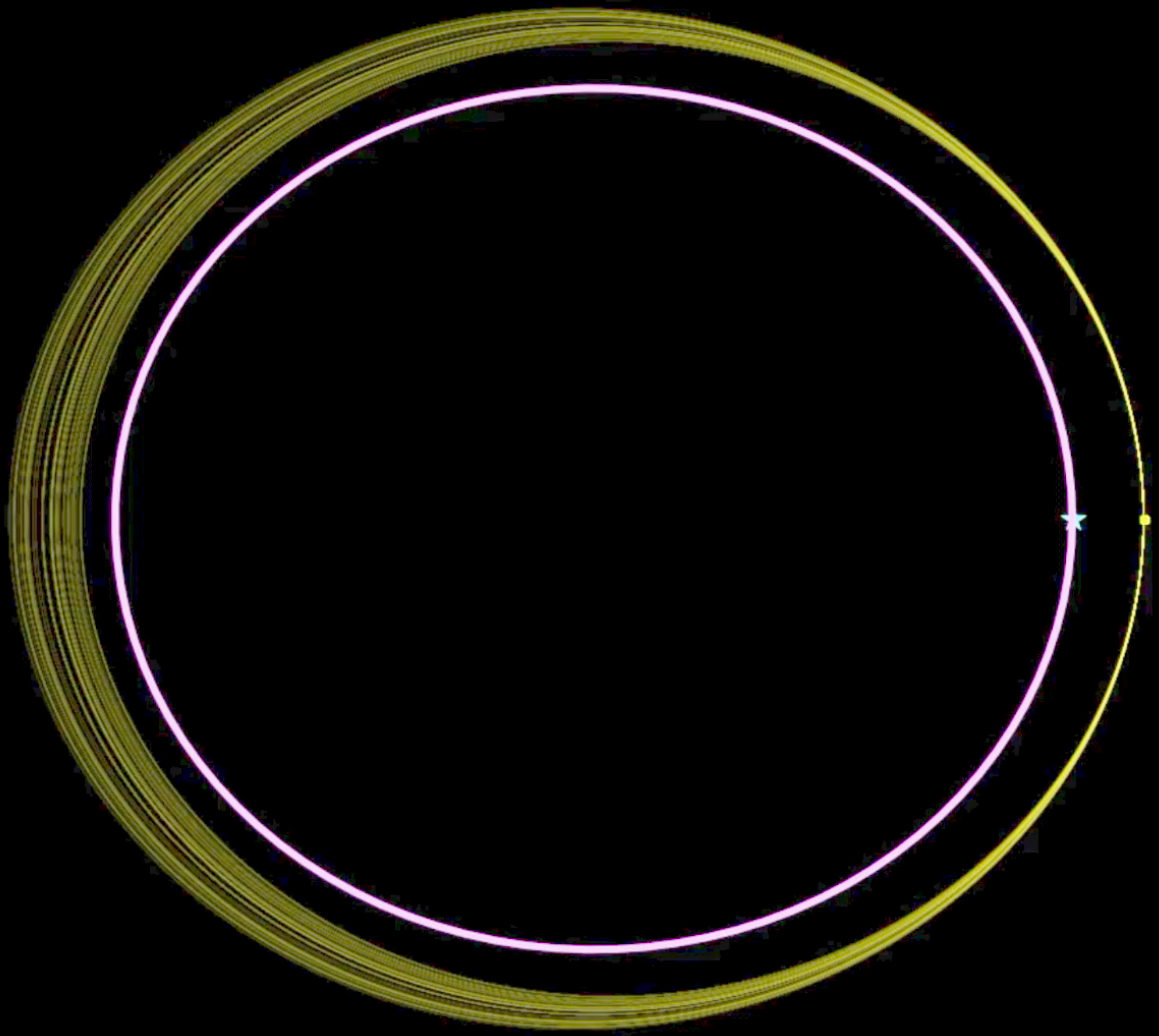
1. **Distributed sensing/monitoring missions.**
2. Missions that pose high risk to individual chipsats (e.g. planetary impact)

Contribution 3:

An algorithm that optimally routes information through a planar swarm of spacecraft.

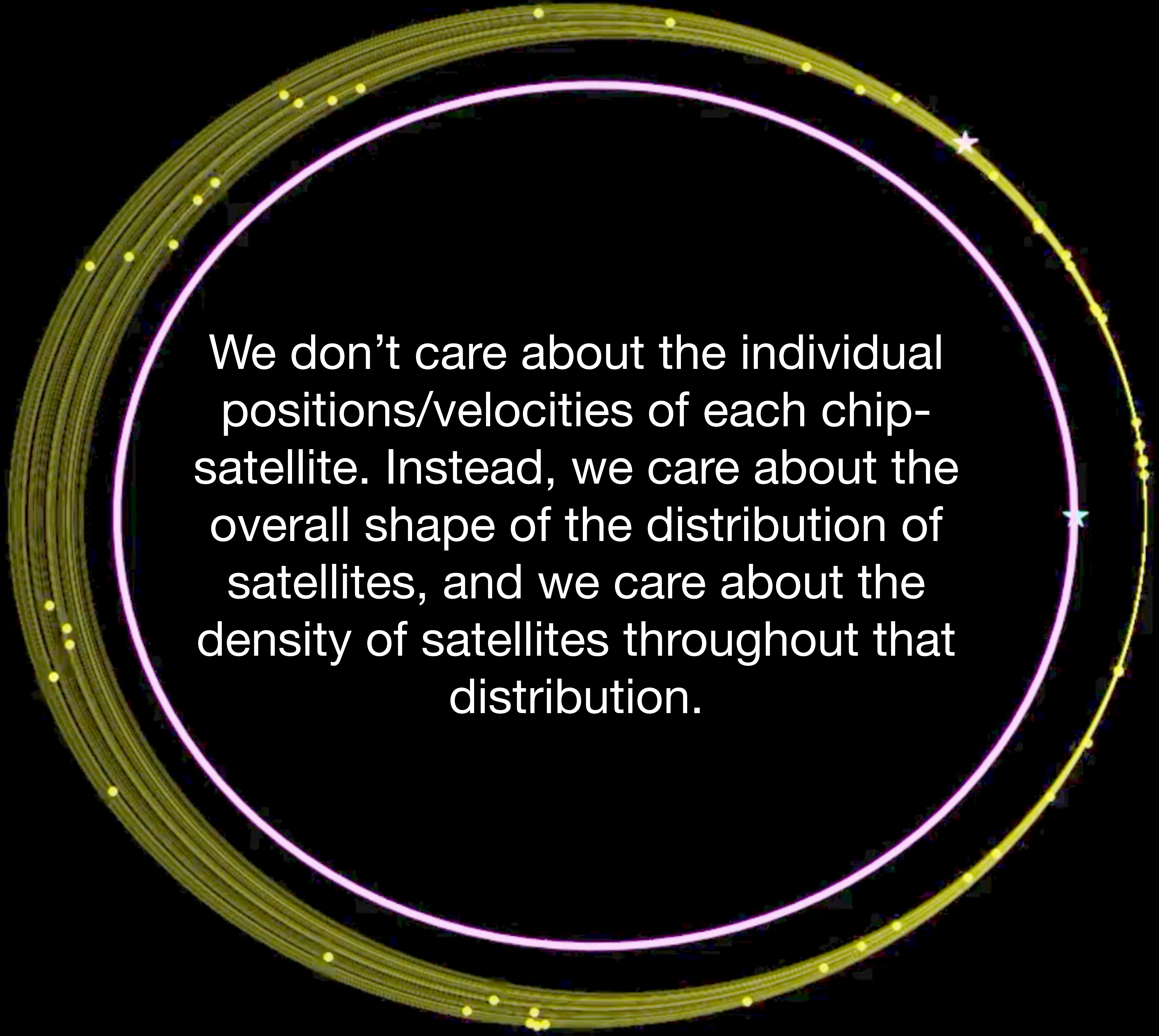

Ground Stations, Aggregating Data and Distributing Swarm Commands
Mothership deploying chip-satellites in low-Earth orbit
Sensor/Radio-Equipped Monarch Node



How do we represent these systems mathematically?

Conventional spacecraft: differential equations

$$\ddot{r}_{ec} = -\frac{\mu_e}{\left(\mathbf{r}_{ec}^T \mathbf{r}_{ec}\right)^{\frac{3}{2}}} \mathbf{r}_{ec} + \mu_m \left(\frac{\mathbf{r}_{em} - \mathbf{r}_{ec}}{\left(\mathbf{r}_{cm}^T \mathbf{r}_{cm}\right)^{\frac{3}{2}}} - \frac{\mathbf{r}_{em}}{\rho_{em}^3} \right) + \mu_s \left(\frac{\mathbf{r}_{es} - \mathbf{r}_{ec}}{\left(\mathbf{r}_{cs}^T \mathbf{r}_{cs}\right)^{\frac{3}{2}}} - \frac{\mathbf{r}_{es}}{\rho_{es}^3} \right)$$



We don’t care about the individual positions/velocities of each chip-satellite. Instead, we care about the overall shape of the distribution of satellites, and we care about the density of satellites throughout that distribution.

Chipsats: probability density functions

$$p(\theta) \approx \frac{(1-e)^{\frac{3}{2}}}{2\pi \left(\frac{1}{e+1}\right)^{\frac{3}{2}} (e\cos\theta + 1)^2}$$

To derive a routing policy, we need to decide on the rules.

Which information is it reasonable to assume that a chip-satellite can access?

Reasonable	Unreasonable

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Reasonable	Unreasonable
• Current position and velocity (GPS) • Angular rate of Earth • Elapsed time	

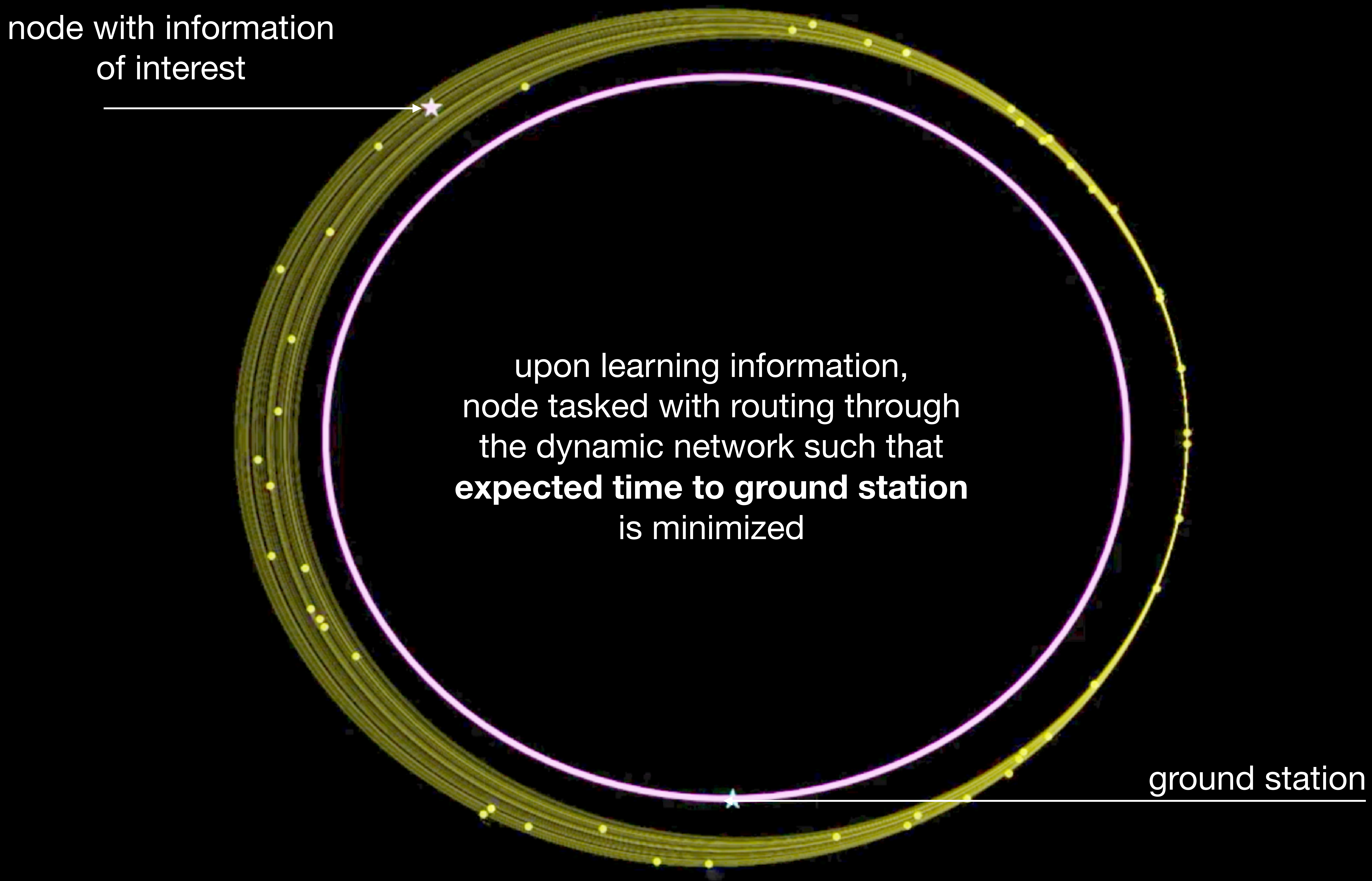
Which information is it reasonable to assume that a chip-satellite can access?

Reasonable	Unreasonable
• Current position and velocity (GPS) • Angular rate of Earth • Elapsed time	• Number of nodes in the network • Topology of the network • Locations of ground stations • Position/velocity of any other nodes in the network

Which information is it reasonable to assume that a chip-satellite can access?

Reasonable	Unreasonable
• Current position and velocity (GPS)	• Number of nodes in the network
• Angular rate of Earth	• Topology of the network
• Elapsed time	• Locations of ground stations
	• Position/velocity of any other nodes in the network

The more information available to each node, the better the routing efficiency. I think any more information than this is purely academic.


node with information
of interest
upon learning information,
node tasked with routing through
the dynamic network such that
expected time to ground station
is minimized
ground station


should I relinquish my data to this spacecraft or not?
routing is a series of optimal stopping problems
ground station

state representation:

$$x_\phi \in \begin{cases} p & \text{perigee of spacecraft orbit} \\ a & \text{apogee of spacecraft orbit} \\ \theta & \text{angle from perigee of current spacecraft position} \end{cases}$$

indexed by swept Earth angle,
not by time

state update:

$$x_{\phi_+} \in \begin{cases} p_+ & \text{calculated directly from GPS} \\ a_+ & \text{calculated directly from GPS} \\ \theta_+ & \text{calculated directly from GPS} \end{cases}$$

$$\phi_+ = (\theta_+ - \theta_0)\frac{T_{Earth}}{T_{Earth} - T_{Node}}$$

control input:

$$u_\phi \in \begin{cases} 1 & \text{relinquish data to encountered spacecraft} \\ 0 & \text{retain data} \end{cases}$$

terminal cost:

$$c_{\phi=2\pi} = 0$$

stopping cost:

$$\begin{aligned} c_s &= \text{optimal expected time to ground station} \\ &= \text{expected time to ground station for nested orbits (myopic is optimal)} \\ &\approx \text{expected time to ground station for stochastic orbits (myopic is suboptimal)} \end{aligned}$$

expected time to ground station:

$$= \frac{1}{2\pi - \phi_0}\int_{\phi_0}^{2\pi}\left[\frac{T_{node}T_{Earth}}{2\pi(T_{Earth} - T_{node})}\int_{\phi_0}^{x}\frac{(1-e)^{\frac{3}{2}}}{\left(\frac{1}{1+e}\right)^{\frac{3}{2}}\left(e\cos\left((\theta_0+\phi)\frac{T_{Earth}}{T_{Earth}-T_{node}}\right)+1\right)^2}d\phi\right]dx$$

stage cost:

$$c_\phi(x_\phi, u_\phi) = \begin{cases} 0 & u_\phi = 0 \\ c_s & u_\phi = 1 \end{cases}$$

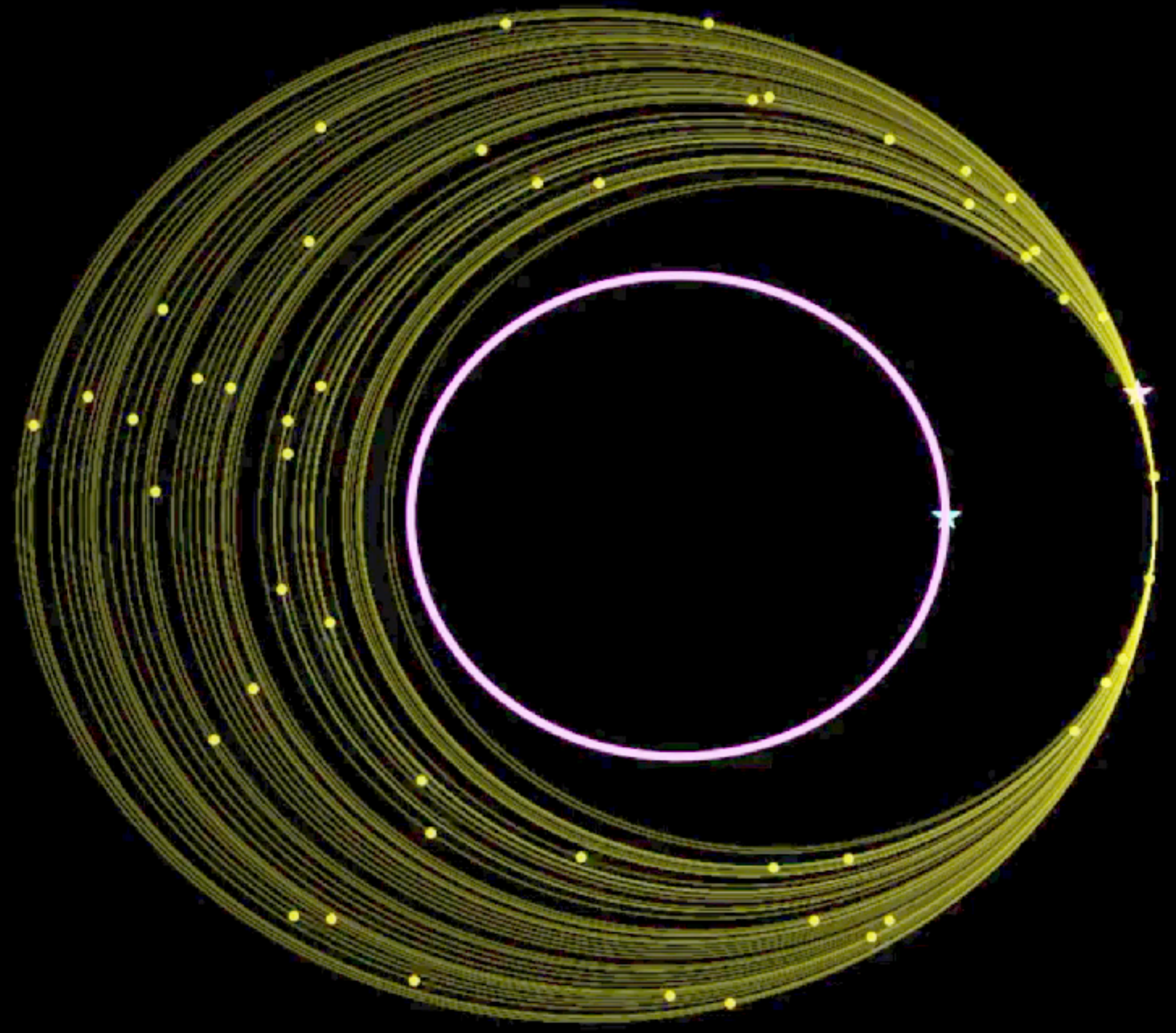
optimal value function:

$$\begin{aligned} V_\phi^* &= \min_{u\in\{0,1\}} E\left[c_\phi(x_\phi, u_\phi \in \{0,1\}) + V_{\phi_+}^*(x_{\phi_+})\right] \\ &= \min\left[c_s, V_{\phi_+}^*(x_{\phi_+})\right] \end{aligned}$$

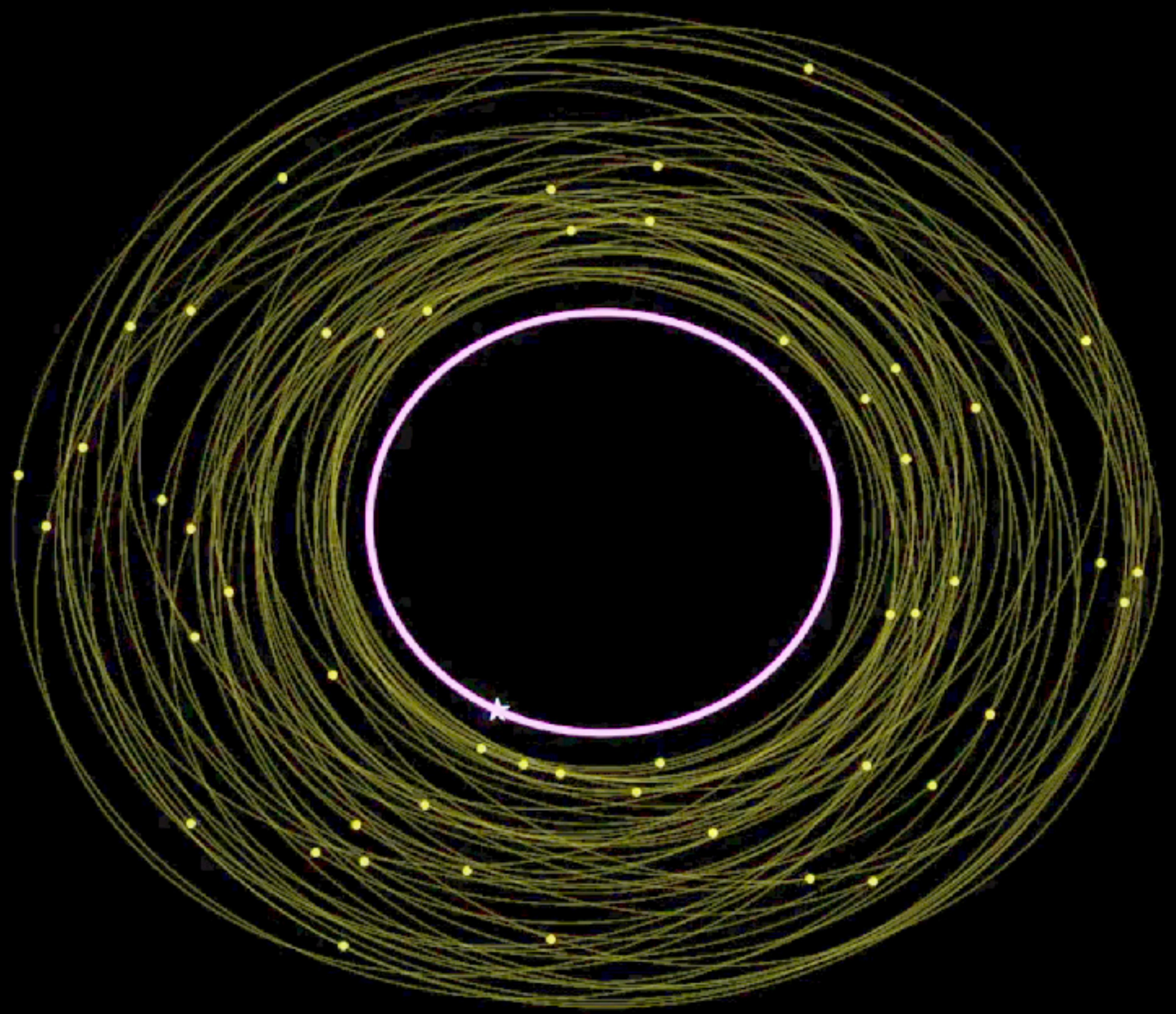
nested orbits: myopic policy is optimal
stochastic orbits: myopic policy suboptimal,
but the best that one can
do under given assumptions

optimal policy:

$$g_\phi^* = \begin{cases} 1 & c_s < V_{\phi_+}^*(x_{\phi_+}) \\ 0 & c_c \geq V_{\phi_+}^*(x_{\phi_-}) \end{cases}$$



routing over nested swarm



routing over stochastic swarm

Classes of missions for which chipsats are well suited:

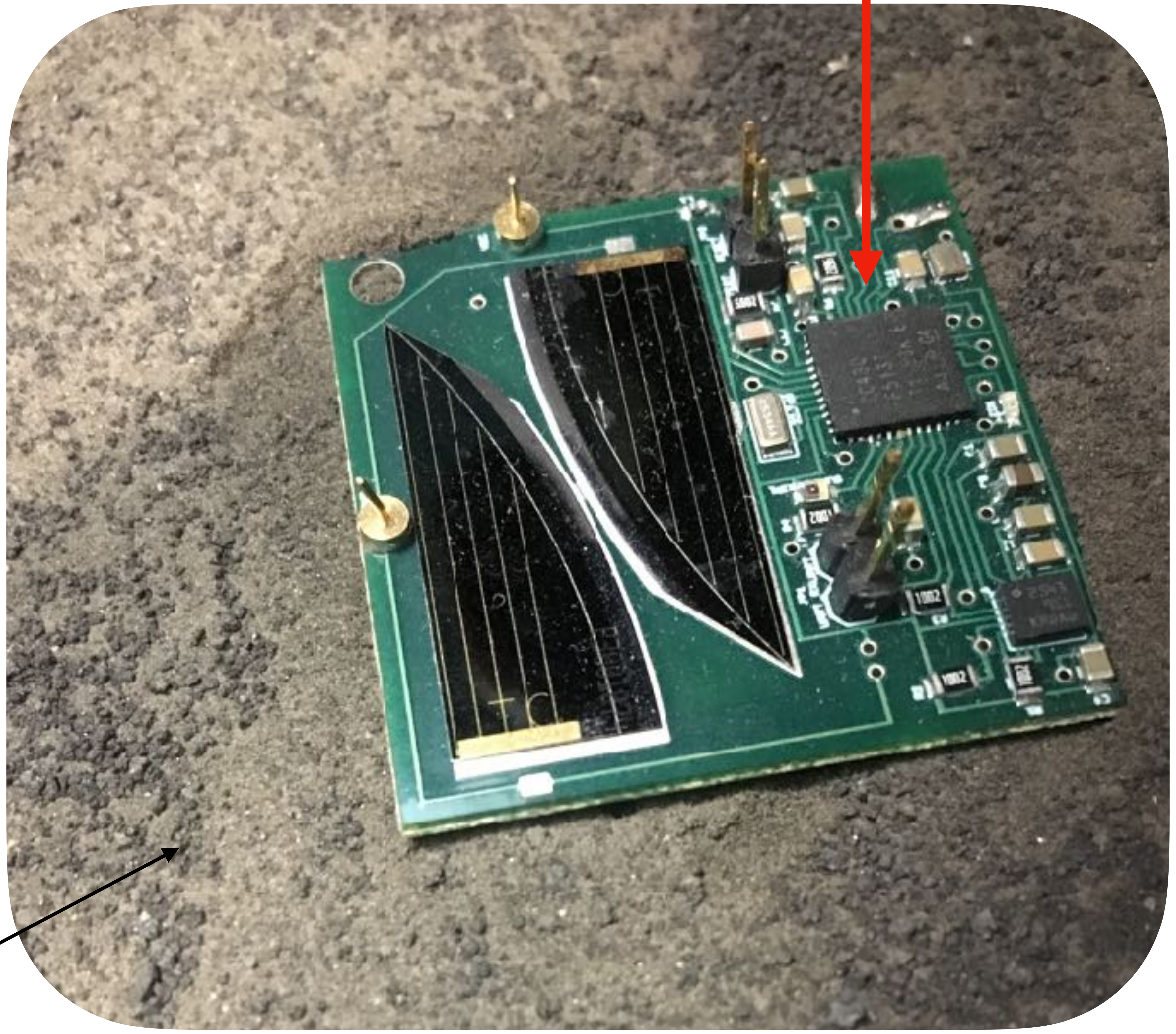
1. Distributed sensing/monitoring missions.
2. **Missions that pose high risk to individual chipsats (e.g. planetary impact)**

Mothership Communicating to Earth
Mothership Aggregating Data and Distributing Swarm Commands
Sensor/Radio-Equipped Monarch Node

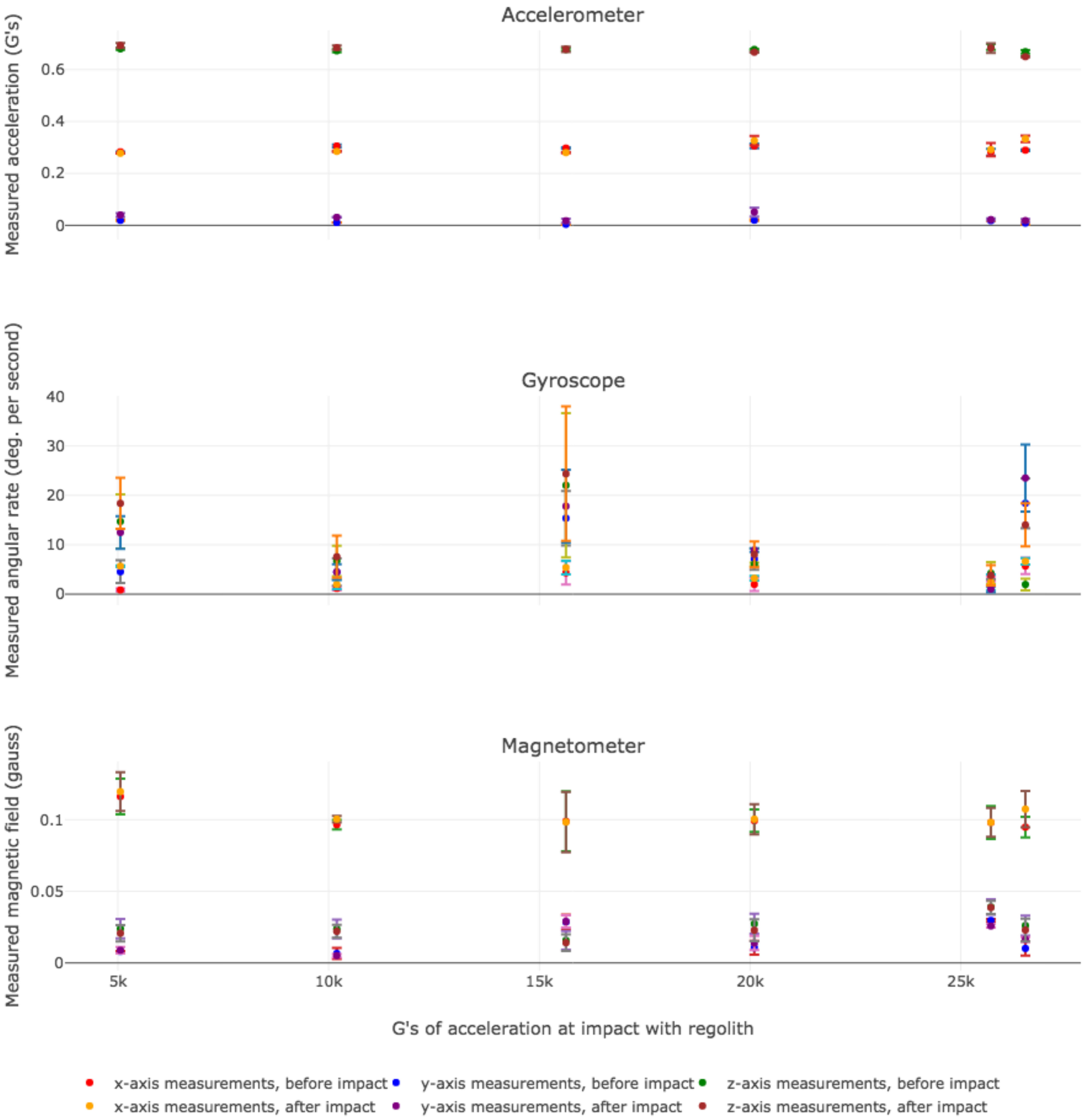
Would the spacecraft survive impact?

Lunar Impact Survivability Testing

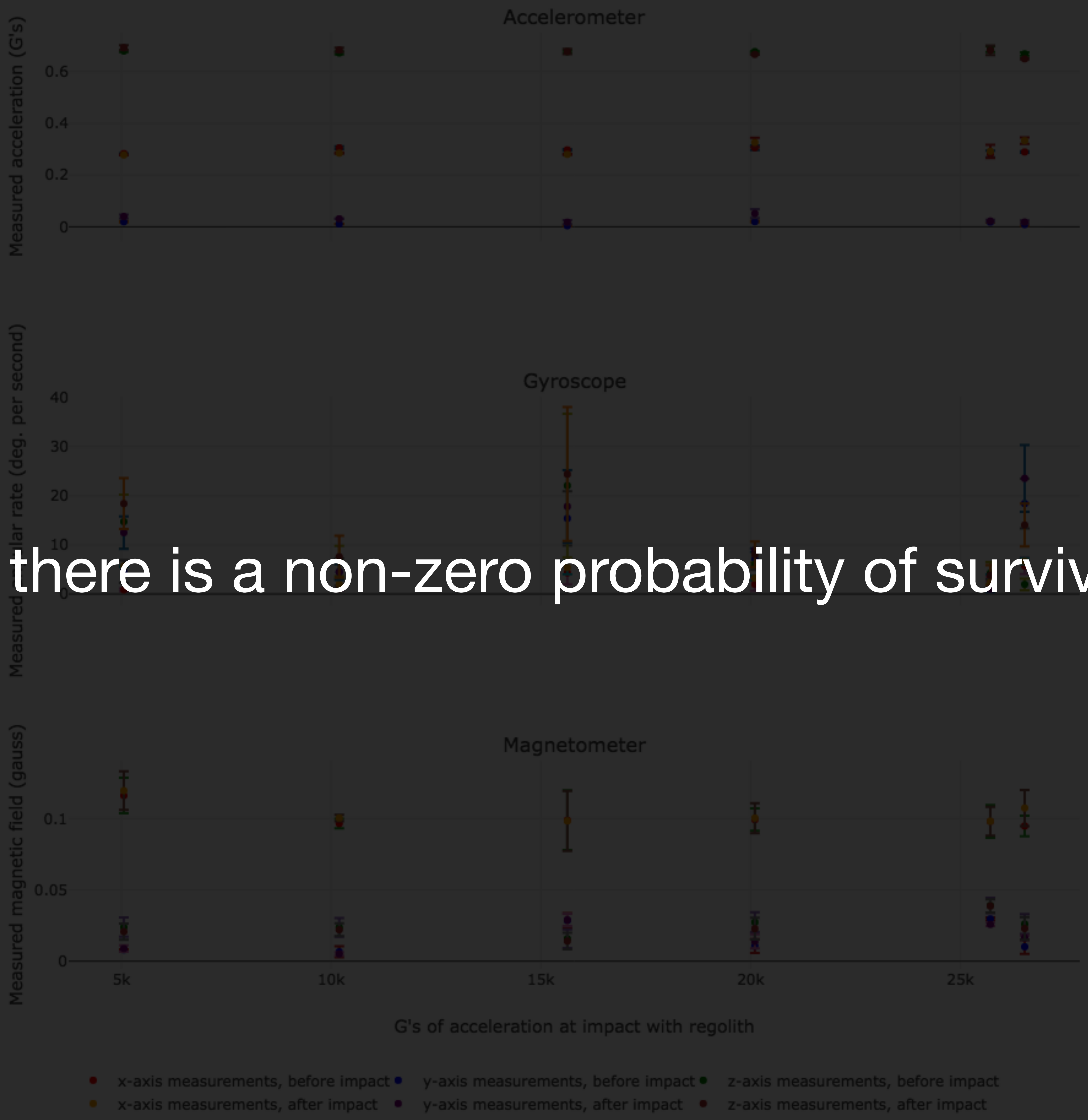
5000 - 27,000 g's normal
to the board surface



lunar regolith simulant



Accelerometer
Measured acceleration (G's)
0.6
0.4
0.2
0
Gyroscope
Measured angular rate (deg. per second)
40
30
20
10
0
Magnetometer
Measured magnetic field (gauss)
0.1
0.05
0
5k
10k
15k
20k
25k
G's of acceleration at impact with regolith
x-axis measurements, before impact
y-axis measurements, before impact
z-axis measurements, before impact
x-axis measurements, after impact
y-axis measurements, after impact
z-axis measurements, after impact



Perhaps there is a non-zero probability of surviving impact.

Suppose that's true. What is the likelihood of mission success?

Mission Success:
At least j chipsats alive on the surface of the body for M days.

Assumptions:

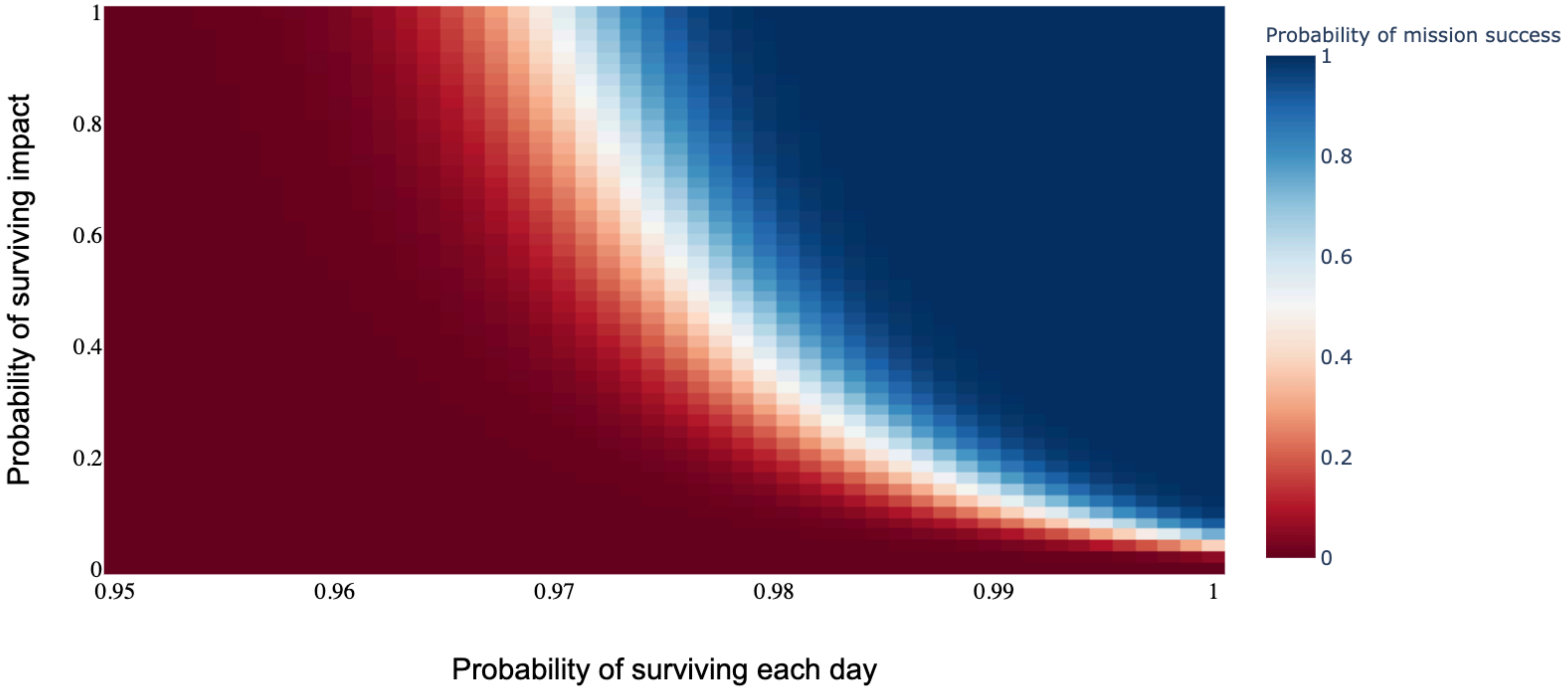
- N > j chipsats deployed to the surface
- Probability p1 of surviving impact
- Probability p2 of surviving each day
- Probabilities do not change with time
- Chipsat failures are uncorrelated

Mission Assurance:
Given j, M, N, p1, and p2, what is the probability of mission success?

$$p = \sum_{k=j}^{N} \left[\frac{N!}{k!\,(N-k)!} p_1^k \left(1 - p_1\right)^{N-k} \cdot \sum_{i=j}^{k} \frac{k!}{i!\,(k-i)!} \left(p_2^M\right)^i \left(1 - p_2^M\right)^{k-i} \right]$$

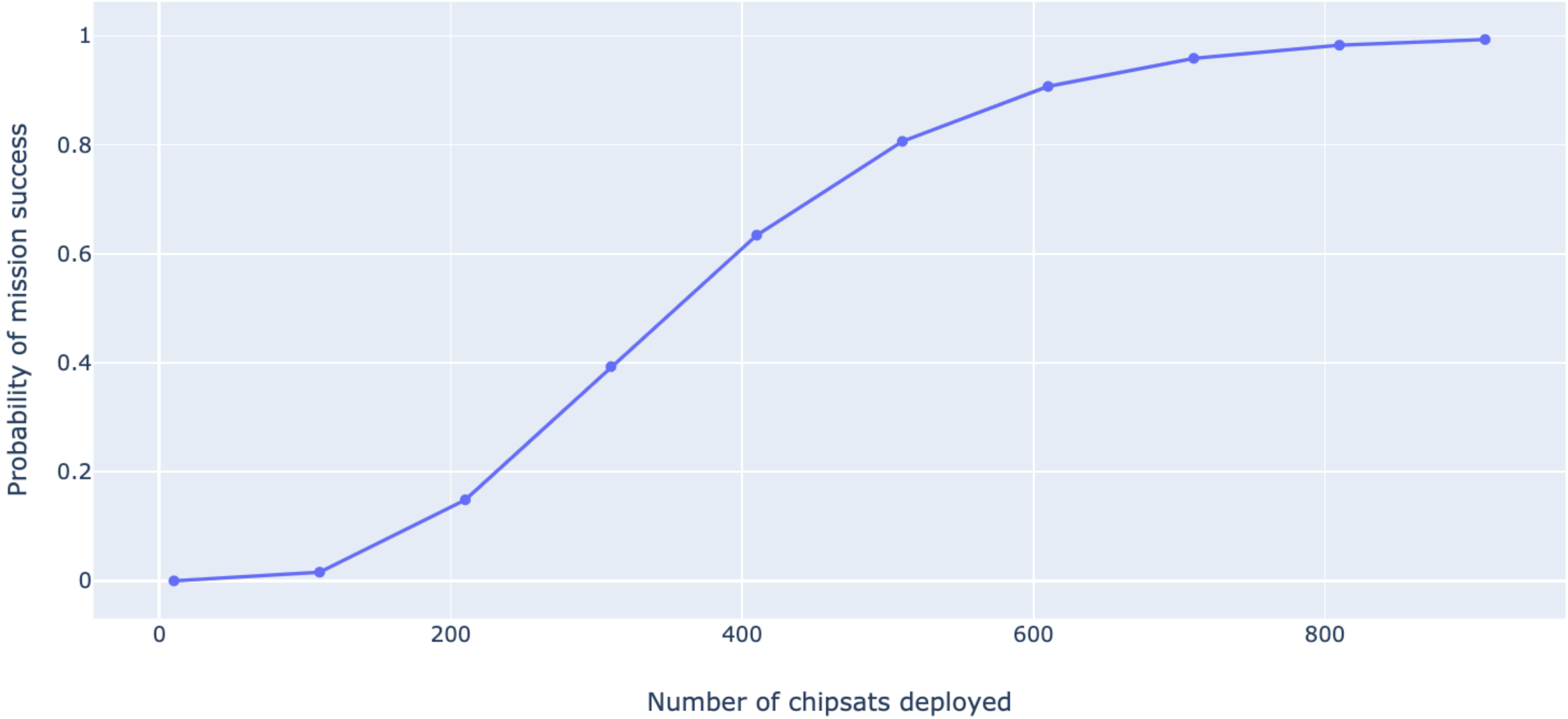
$$p = \sum_{k=j}^{N} \left[\frac{N!}{k!\,(N-k)!} p_1^k \left(1 - p_1\right)^{N-k} \cdot \sum_{i=j}^{k} \frac{k!}{i!\,(k-i)!} \left(p_2^M\right)^i \left(1 - p_2^M\right)^{k-i} \right],$$

$$N = 100, \quad M = 100, \quad j = 5, \quad p_1 = \text{free}, \quad p_2 = \text{free}$$



$$p = \sum_{k=j}^{N} \left[\frac{N!}{k!\,(N-k)!} p_1^k \left(1-p_1\right)^{N-k} \cdot \sum_{i=j}^{k} \frac{k!}{i!\,(k-i)!} \left(p_2^M\right)^i \left(1-p_2^M\right)^{k-i} \right],$$

$$N = \text{free}, \quad M = 100, \quad j = 5, \quad p_1 = 0.1, \quad p_2 = 0.98$$



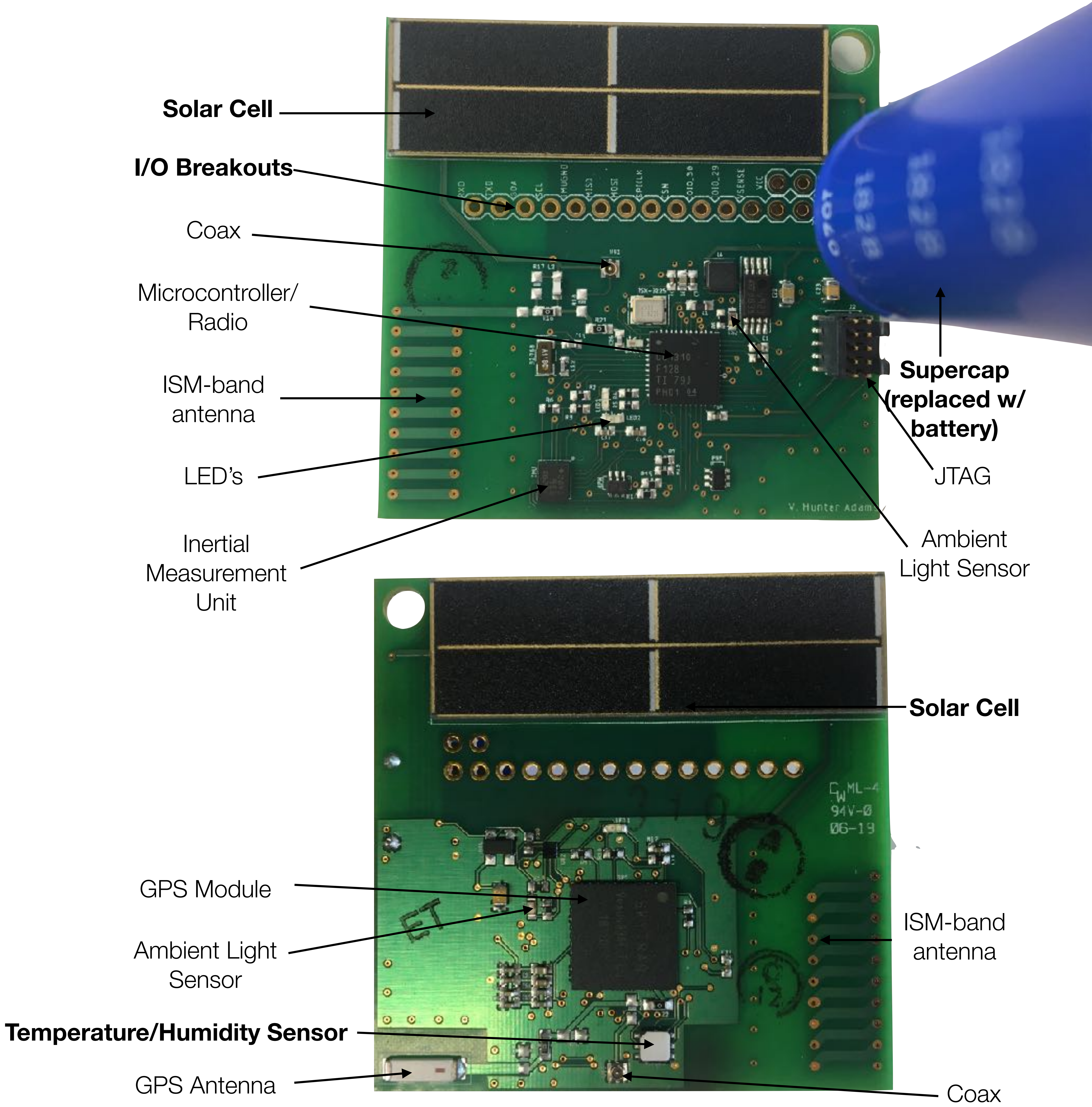
If only I had access to a planet to conduct some case studies . . .

Contribution 4:

The first translational research application for chipsats in digital agriculture.

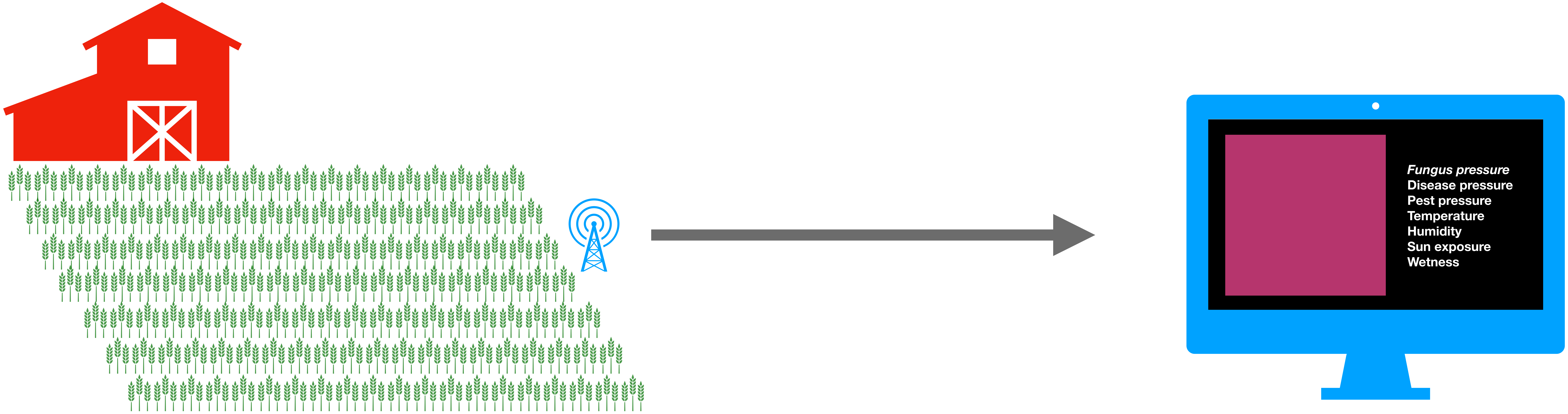
Hardware:

- two solar cells
- CC1310 ARM processor running RTOS
- 25 mW radio chip
- accelerometer, magnetometer, and gyroscope
- temperature sensor
- humidity sensor
- embedded ISM-band antenna (915 MHz)
- GPS
- onboard GPS chip antenna
- JTAG interface
- two ambient light sensors
- embedded torque coils for attitude manipulation
- motor driver for torque coil control
- embedded inductive powering coils
- LED's for user feedback
- battery



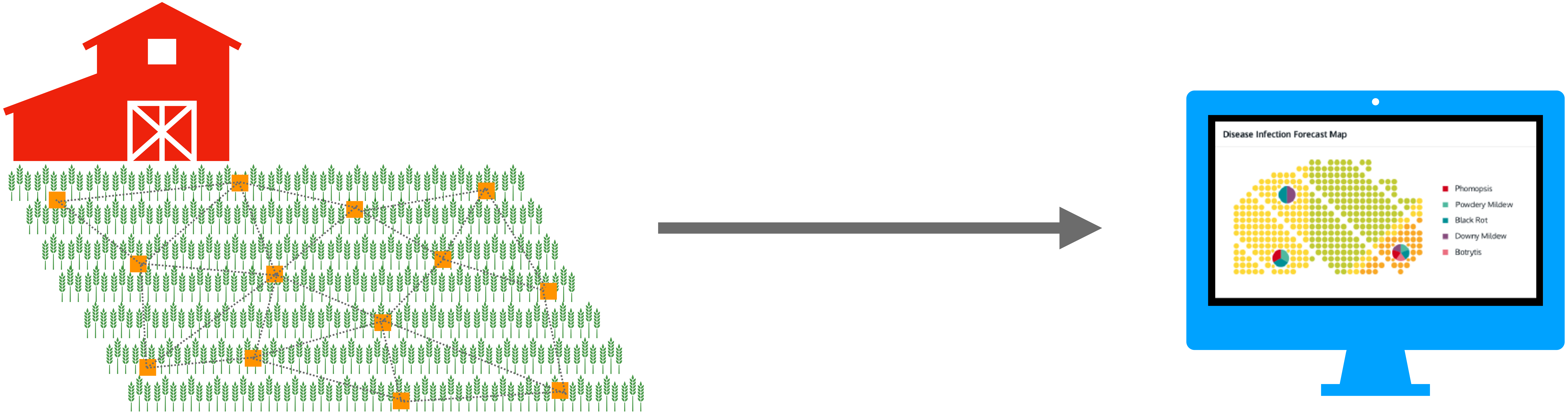

Monarchs gather data that enable cool-climate vineyard managers to take preventative action against wine grape loss to frost and fungus by providing realtime, in-canopy temperature, humidity, and wetness data.

Conventional Vineyard Monitoring



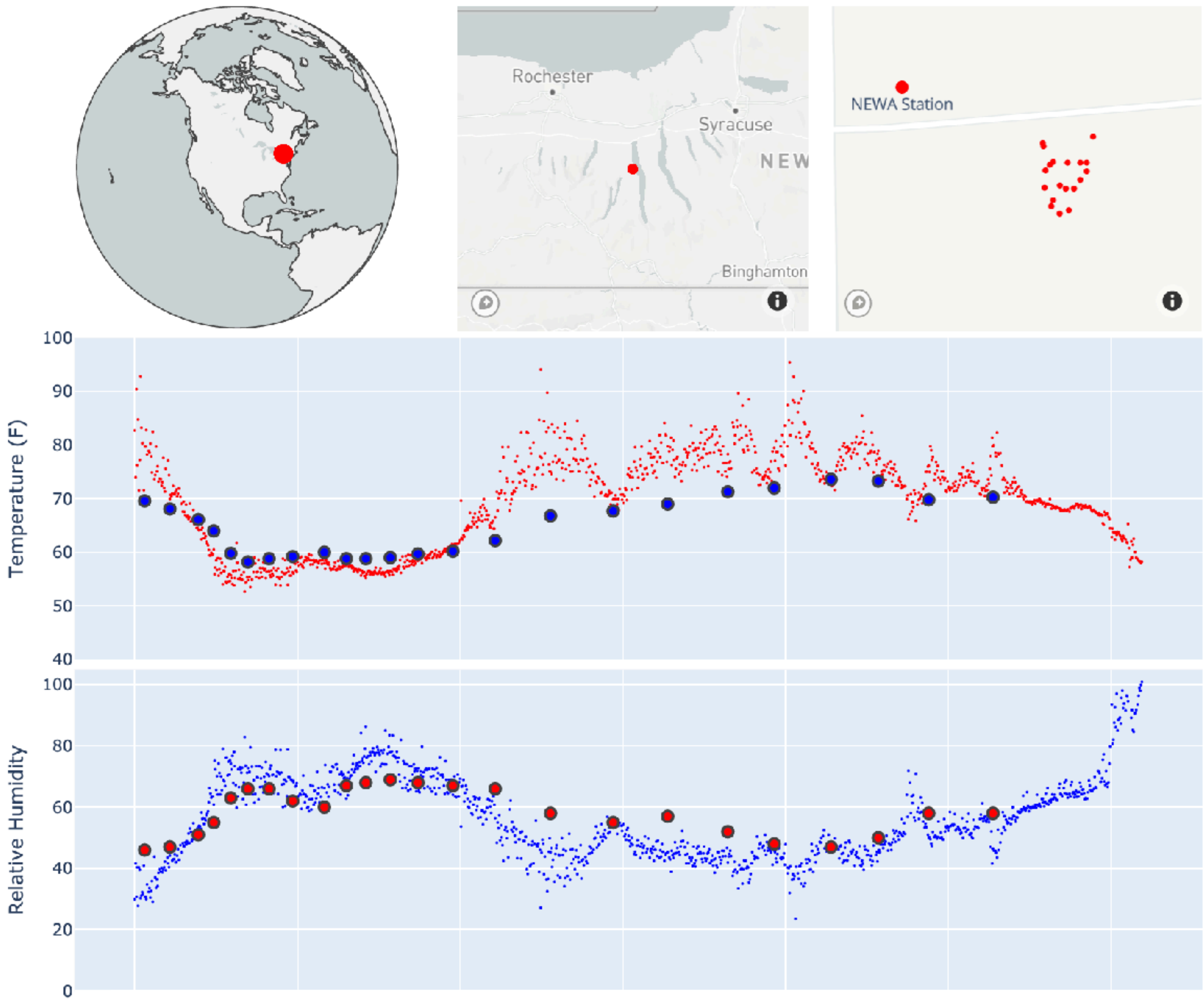
Because vineyard managers to not know how conditions vary across their land, they must apply chemical sprays as often as is legal, rather than as often as is necessary. This is expensive, both in labor and materials.

Monarch Vineyard Monitoring

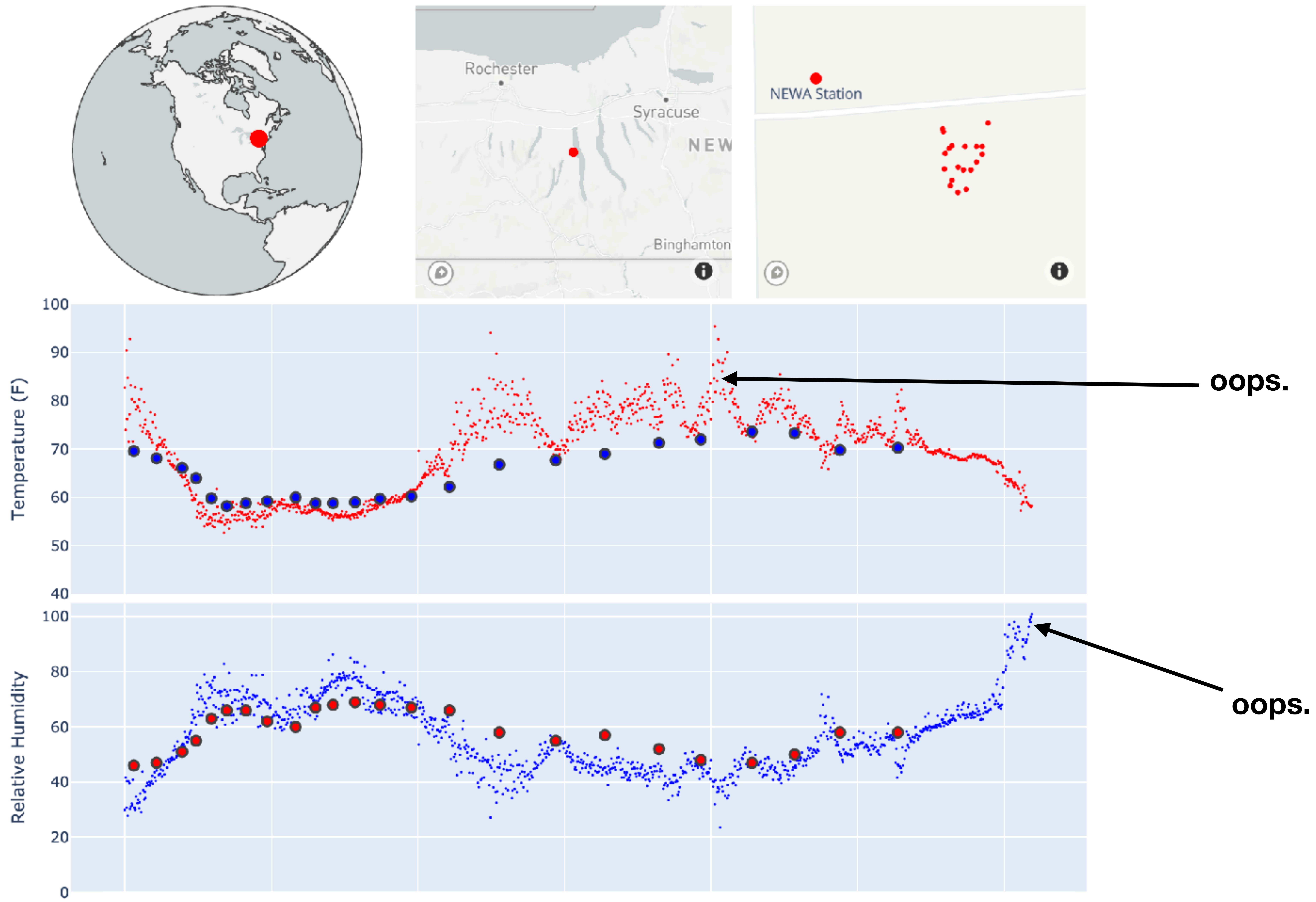


Distributed environmental measurements from within leaf canopies across the vineyard measure microclimates, enabling managers to only perform chemical sprays when and where they are necessary.

Anthony Road Winery, Penn Yann, NY



June 18-19, 2019

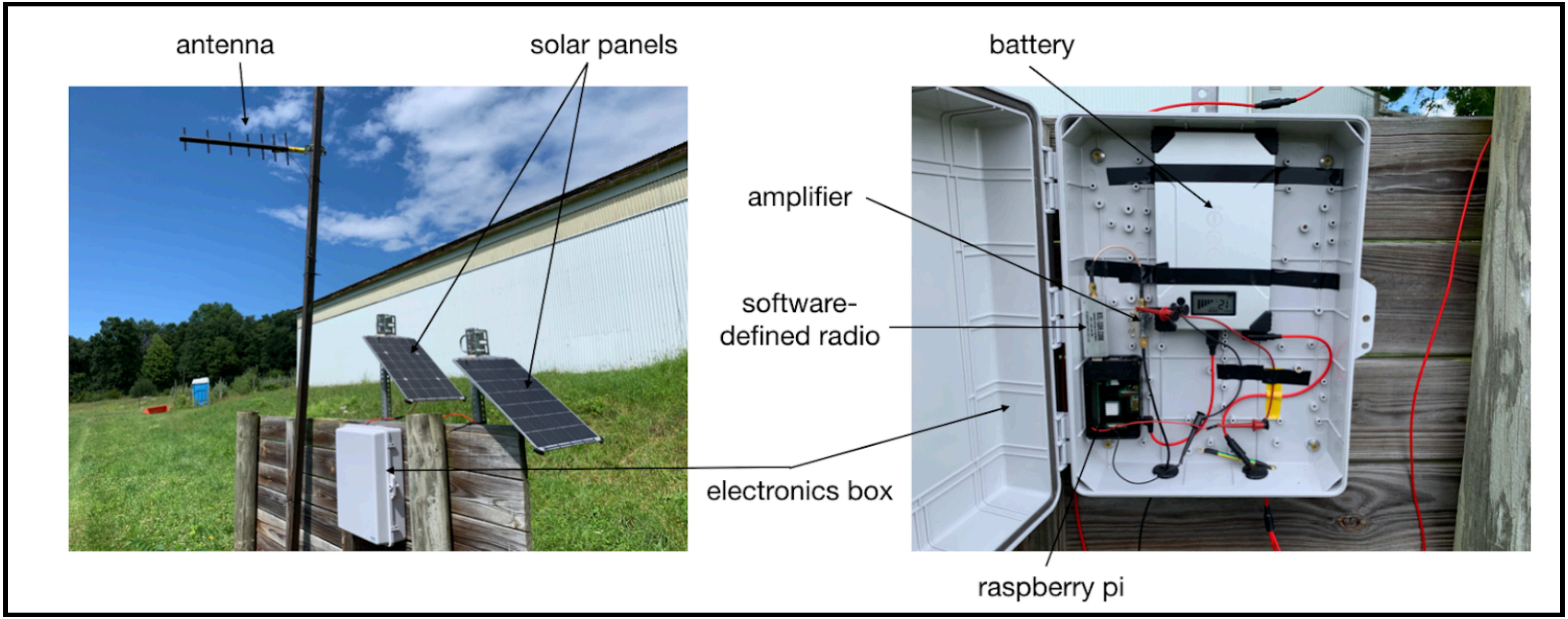


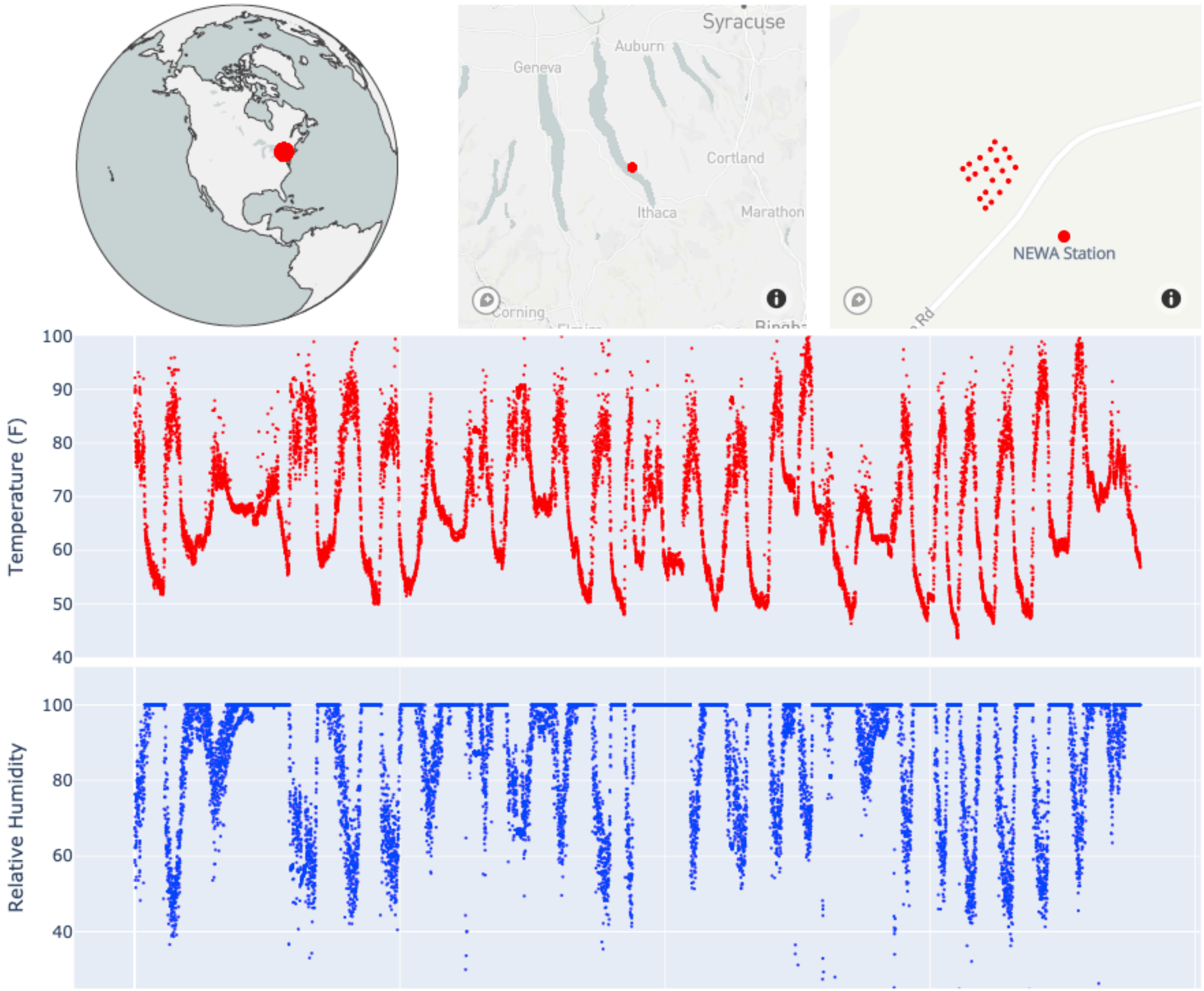
June 18-19, 2019

Cornell research vineyard, Lansing, NY

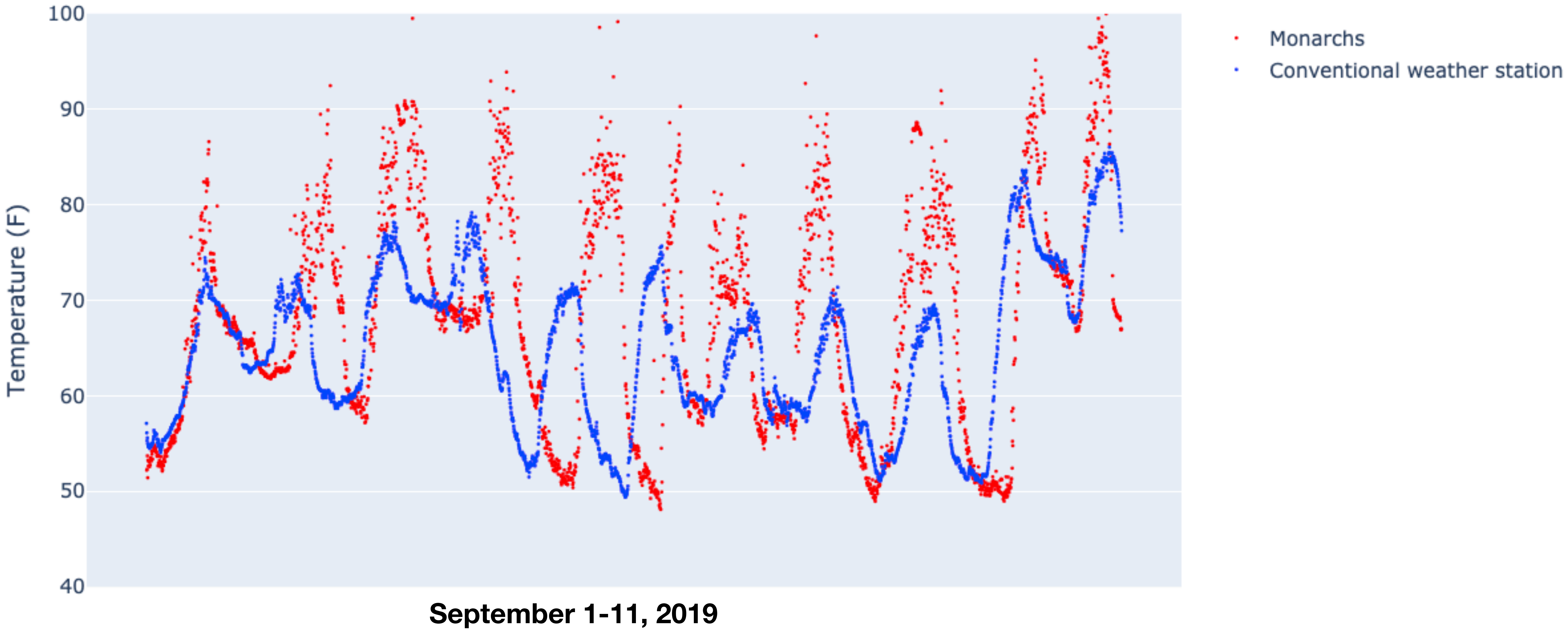
receiver in Lansing

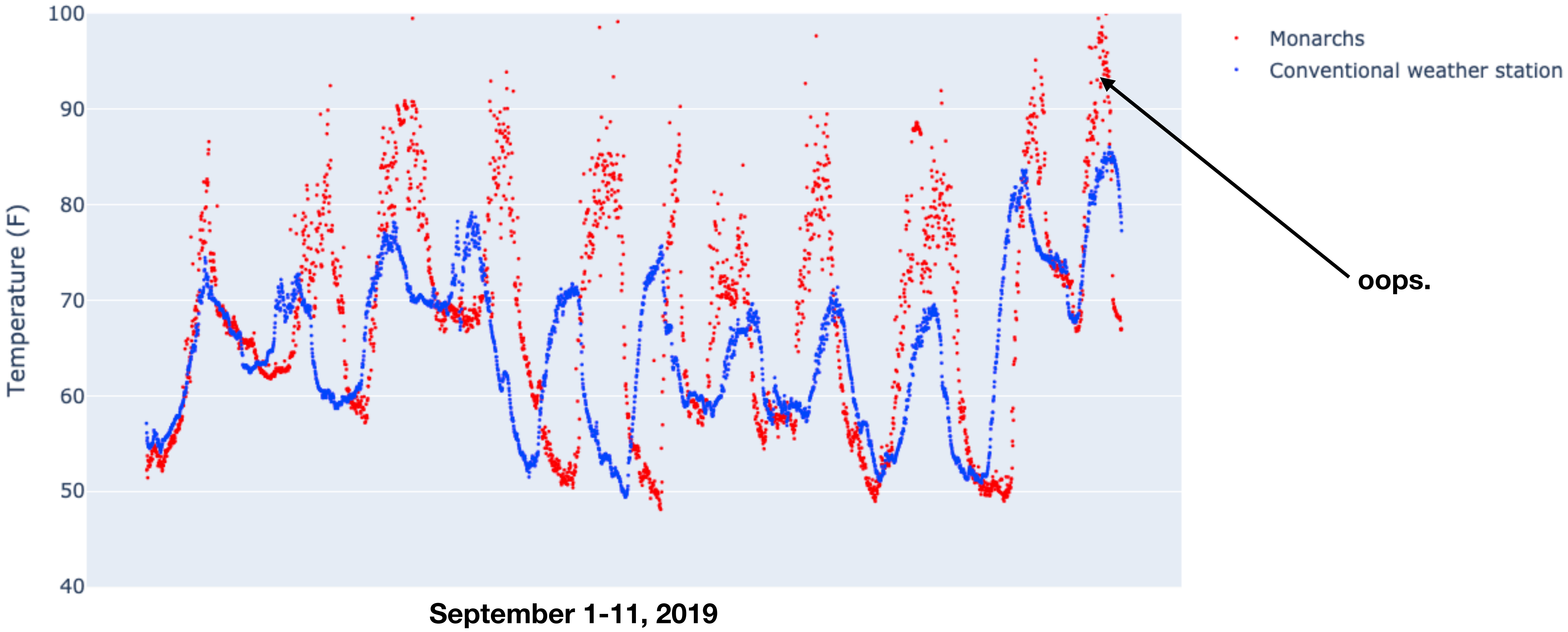
web application


antenna
solar panels
battery
amplifier
software-
defined radio
electronics box
raspberry pi

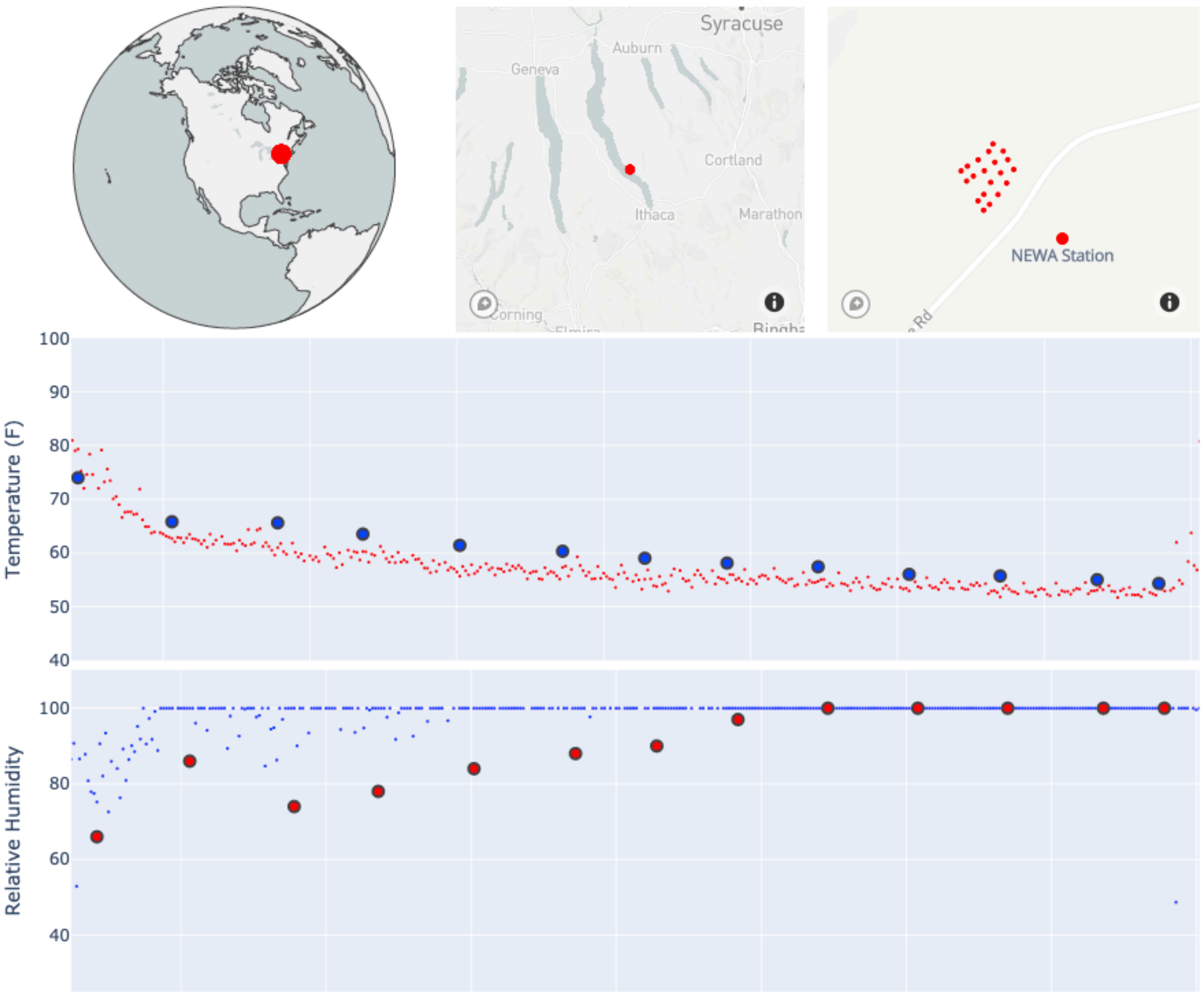


Syracuse
Auburn
Geneva
Cortland
Ithaca
Marathon
Corning
NEWA Station
Temperature (F)
100
90
80
70
60
50
40
Relative Humidity
100
80
60
40


100
90
80
70
60
50
40
Temperature (F)
Monarchs
Conventional weather station
September 1-11, 2019



100
90
80
70
60
50
40
Temperature (F)
Monarchs
Conventional weather station
oops.
September 1-11, 2019



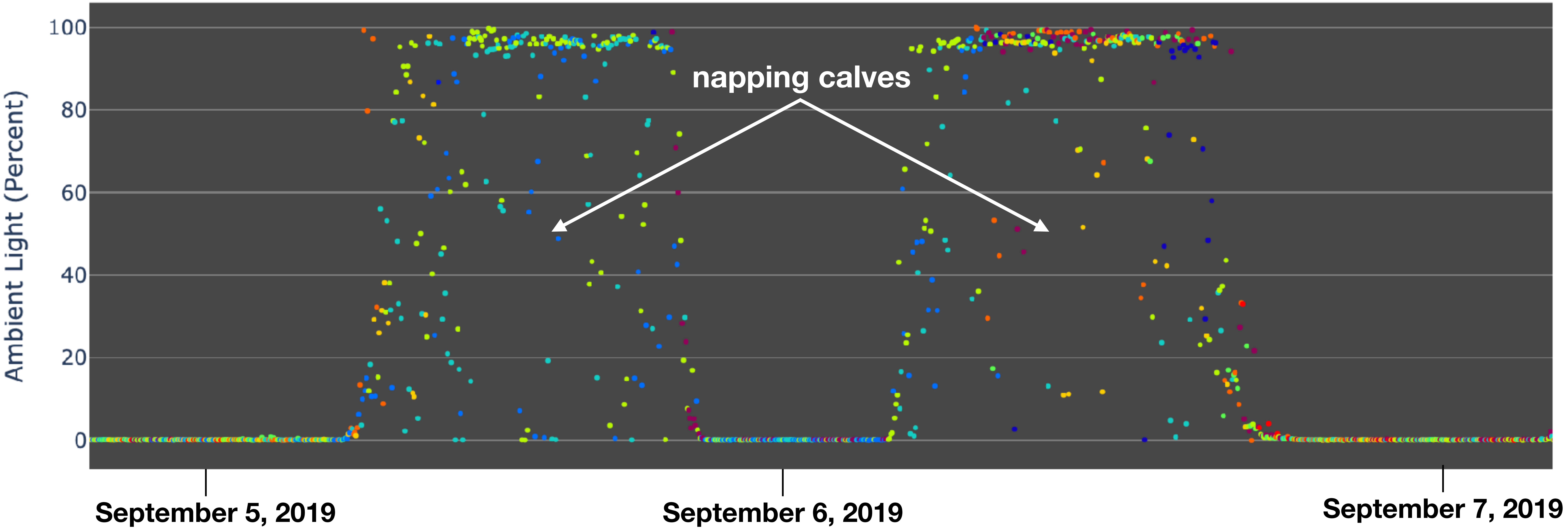
Night of 8/25 - 8/26/2019

Sunnyside Farms, Scipio Center, NY


38669

27
003 209 855 551
38684


September 4-23, 2019



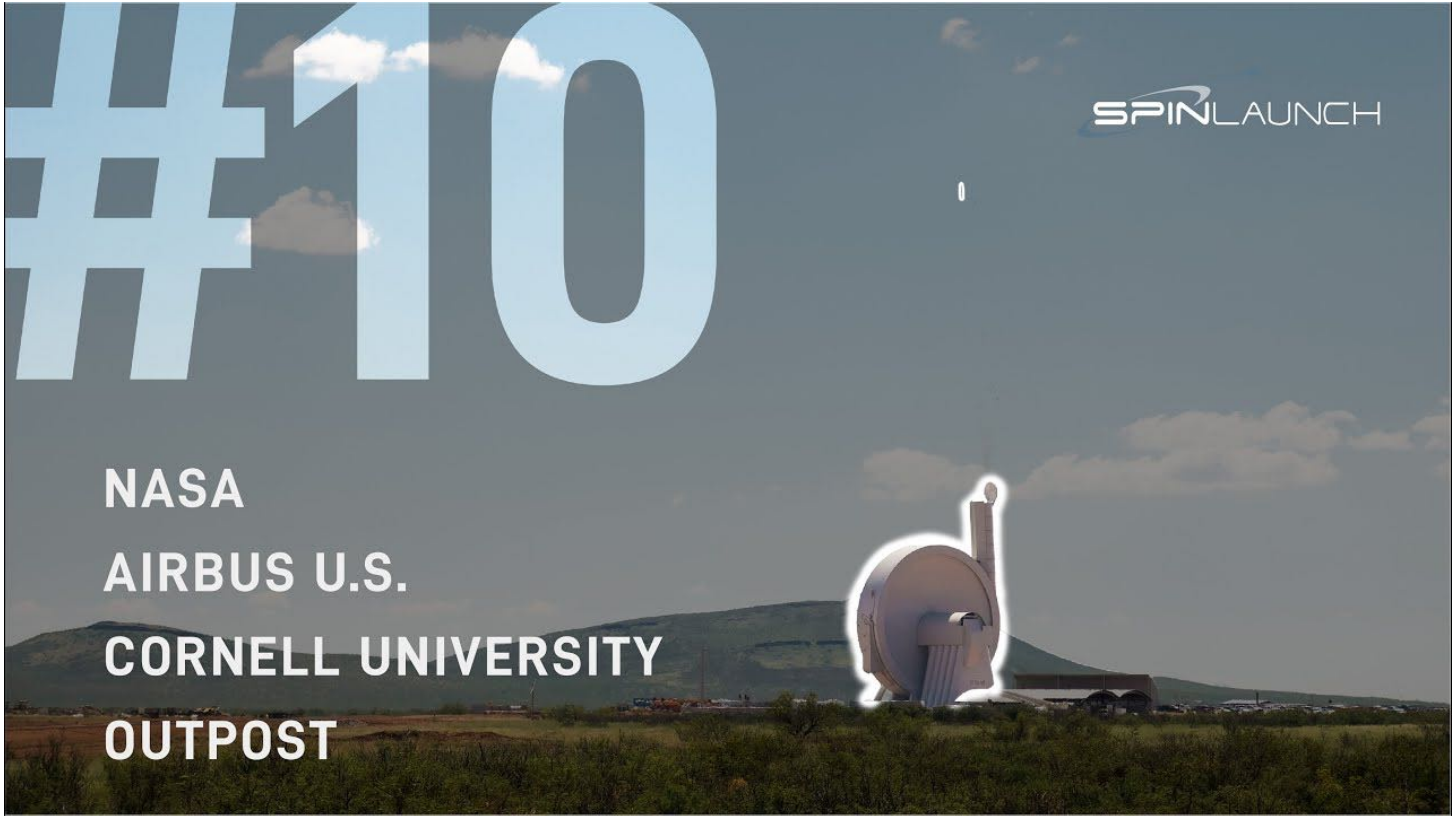
Ambient Light (Percent)
100
80
60
40
20
0
napping calves
September 5, 2019
September 6, 2019
September 7, 2019

1. What are chipsats?
2. Why are they interesting?
3. What are they good for?

1. A new field of study within aerospace engineering: R-selected spacecraft
2. Advancement of the state of the art for chipsats.
3. An algorithm that optimally routes data through a planar swarm of spacecraft.
4. First translational research application for chipsats in digital agriculture.
5. First multi-body optical navigation algorithm that recovers absolute time in addition to trajectory.

There have been some more recent developments . . .


Getting off planet . . .
JCB



[YouTube Link]