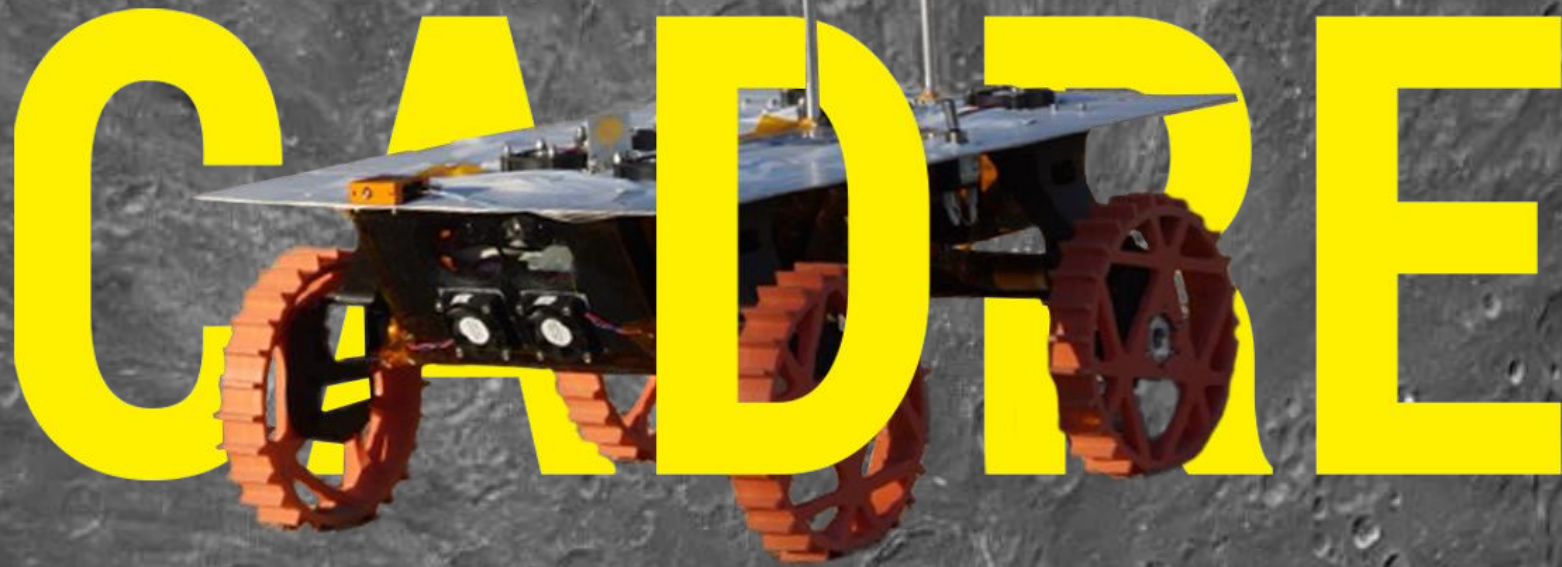




**Maintaining Reliability in a Harsh Environment:
The Design and Delivery of the
CADRE Lunar Rovers and Base station**

Molly Shelton, Power Subsystem Delivery Lead

Kick it off with some questions

In a world of “faster and cheaper” how do you maintain resiliency?

What does “faster and cheaper” really mean, and how will we be impacted by the growing space economy around us?

Do we have to make a trade between fast, cheap and resilient? Or can we optimize our systems around

- A realistic schedule
- A budget that matches our rising costs of operation
- A better understanding of what parts of the system have to be resilient.

The goal for today is to show you what how we tried to optimize on CADRE, and to celebrating what worked while learning from what didn't.

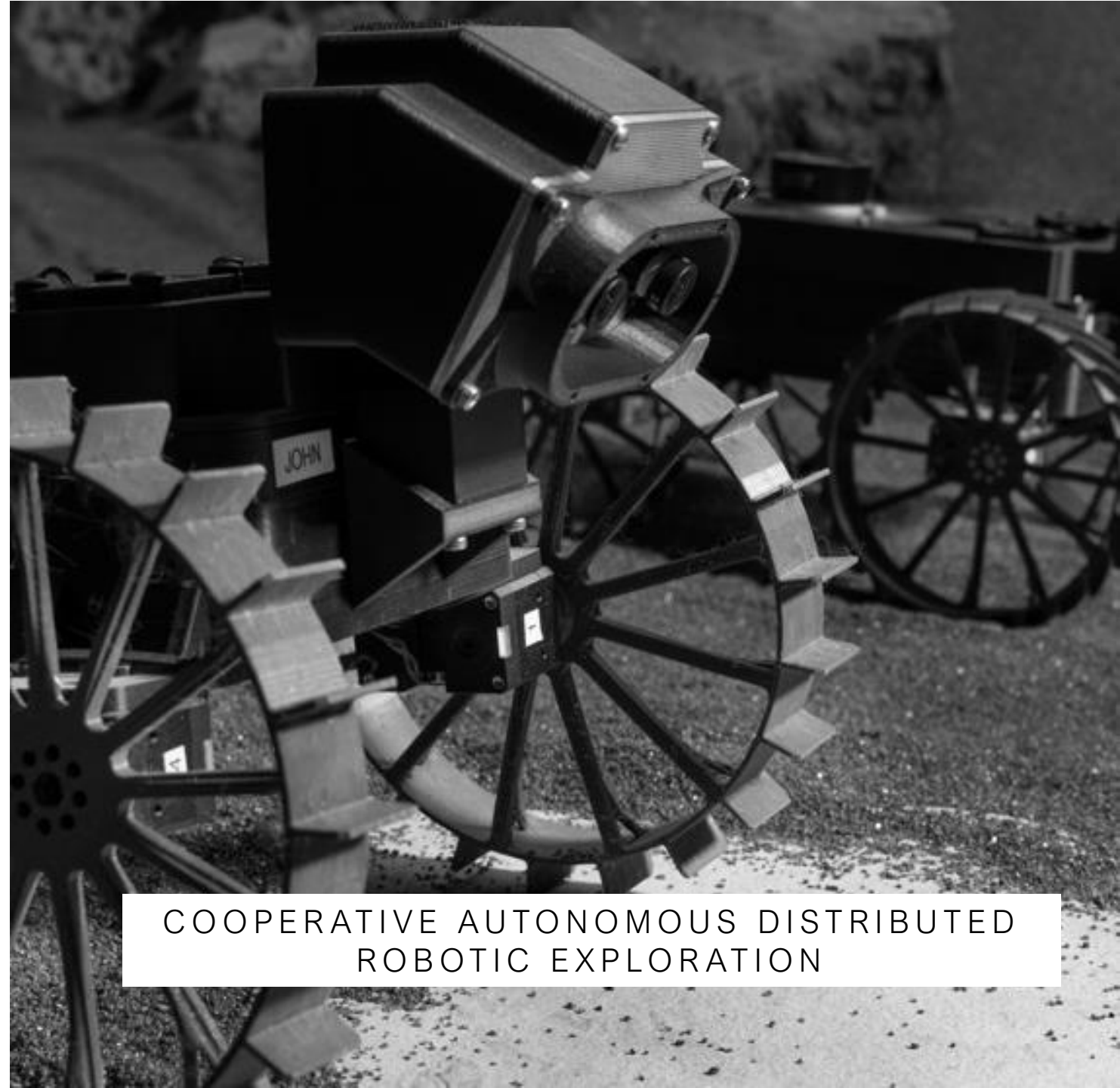
Let's start at the L1, what will CADRE do?



COOPERATIVE AUTONOMOUS DISTRIBUTED
ROBOTIC EXPLORATION
TEAM

WHAT IS CADRE?

A game-changing Technology Demonstration of a network of **multiple robots** working **cooperatively** as a team, to **autonomously** accomplish a task.



COOPERATIVE AUTONOMOUS DISTRIBUTED
ROBOTIC EXPLORATION

MISSION OVERVIEW

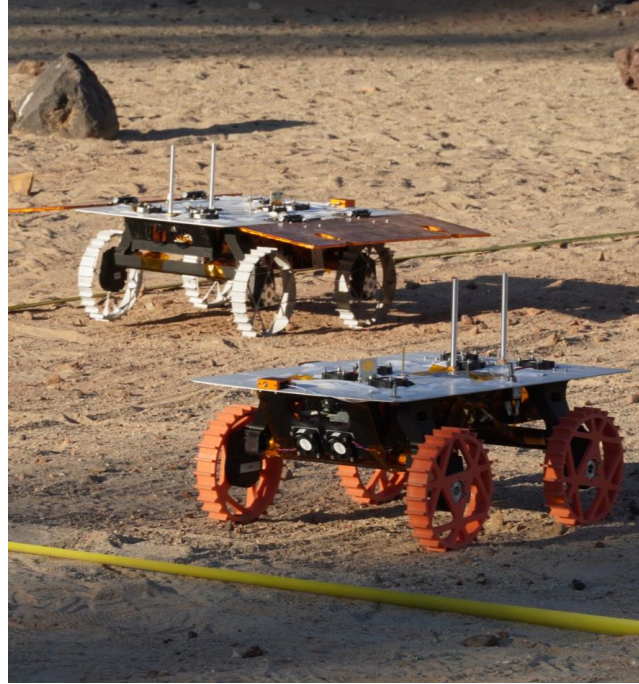
- CADRE will demonstrate these new autonomy advancements on the moon.
- CADRE is manifested as a payload on a commercial lunar payload service (CLPS) Intuitive Machine's IM-3 mission, and is headed to Reiner Gamma (Moon's equatorial region) next year.
- CADRE's technology demonstration will focus on cooperative exploration and distributed measurements using multiple ground penetrating radars (GPRs).



STRONGER TOGETHER.

MULTI-AGENT SYSTEM

CADRE's multi-agent system can achieve new and expanded capabilities



01

Enables new science via the collection of data in different locations at the same time.

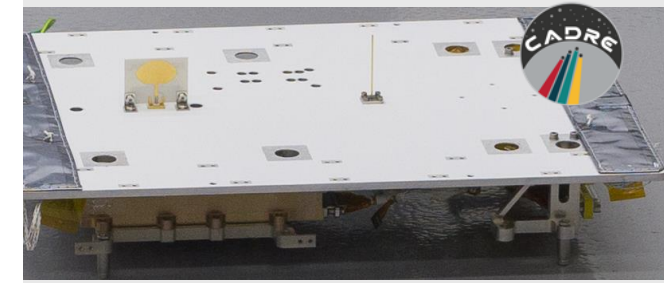
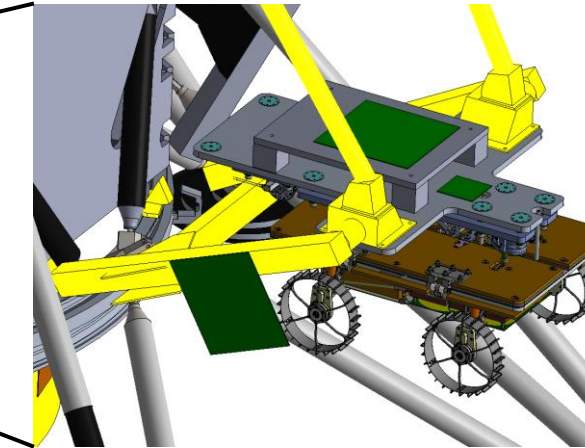
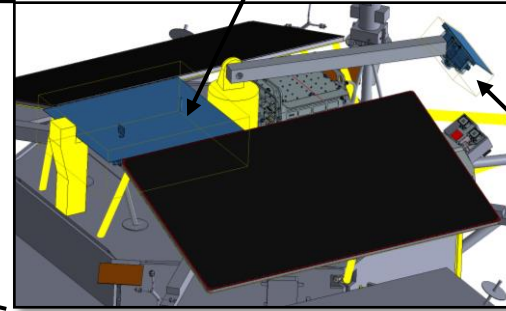
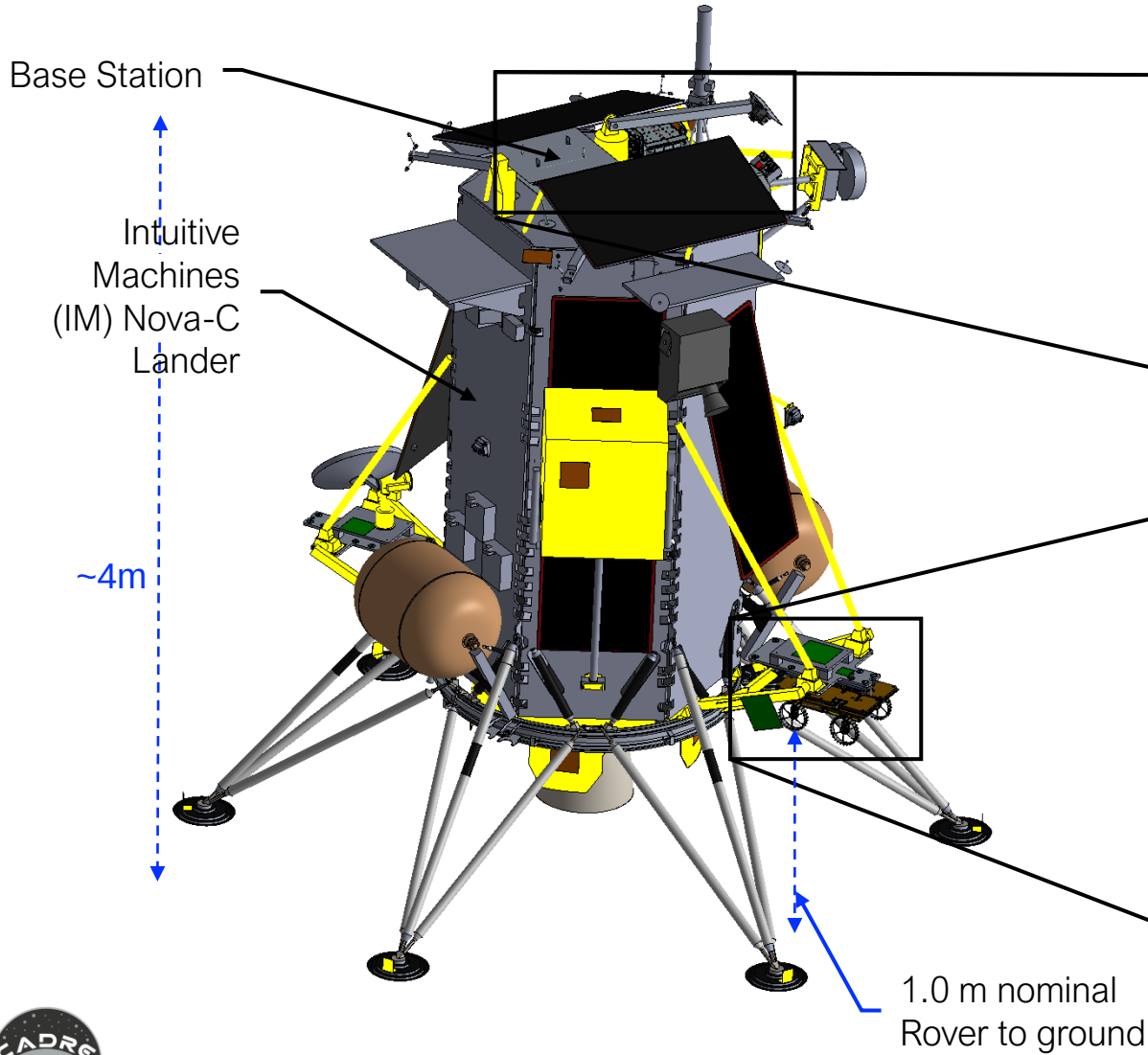
02

Provides freedom of entry to typically inaccessible spaces & extreme environments.

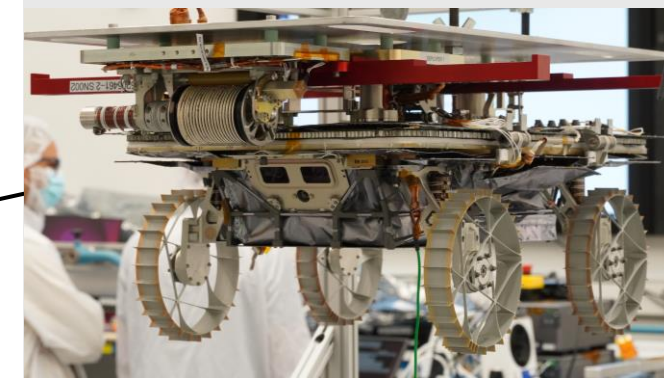
03

Significantly improves efficiency, flexibility, and resiliency.

SYSTEM OVERVIEW



JPL provided SACA
Situational Awareness Camera
Assembly mounted to lander
provided gimbal



JPL provided Rover-
Deployer assembly x3





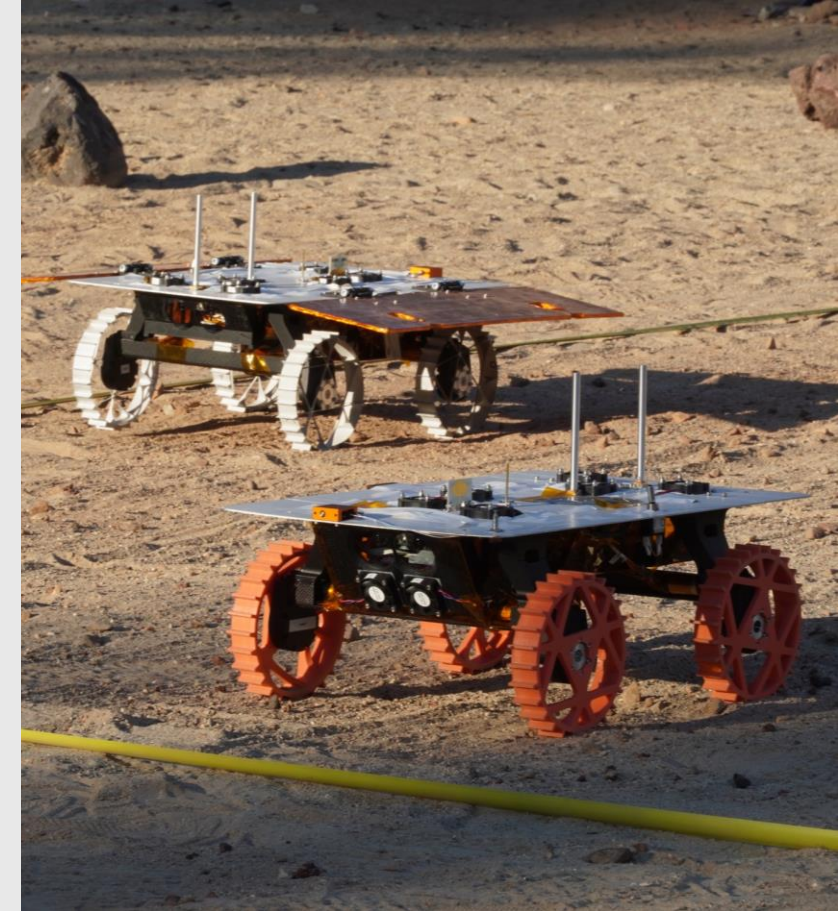
2015-2017

Development of a small rover with
unique mobility capabilities
(PUFFER)



2018-2021

Development of multi-agent autonomy for
cooperative exploration in unmapped
environments
(A-PUFFER)



2021-2024*

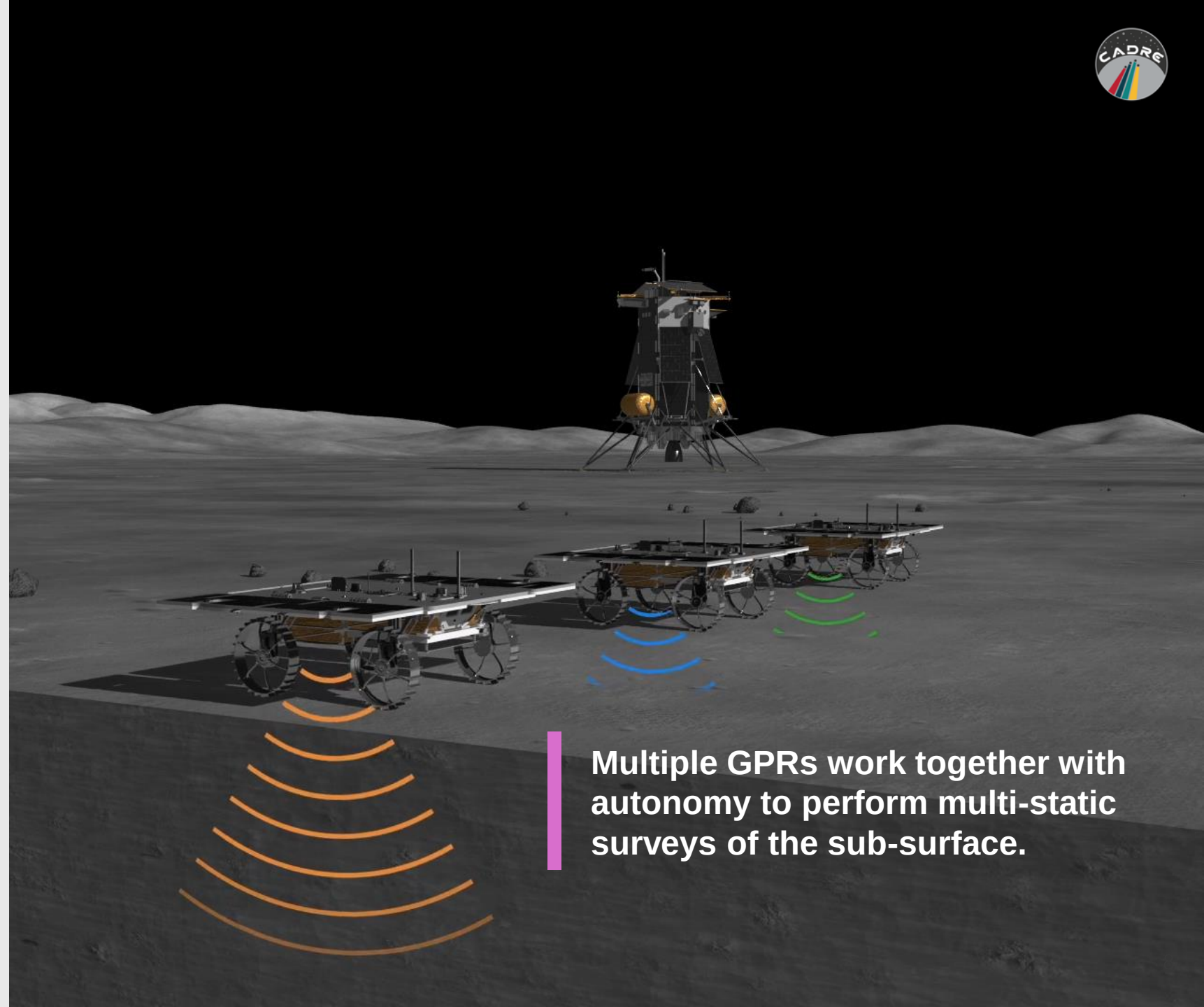
Demonstration of multi-agent autonomy and
multi-static GPR on the Moon
(CADRE)





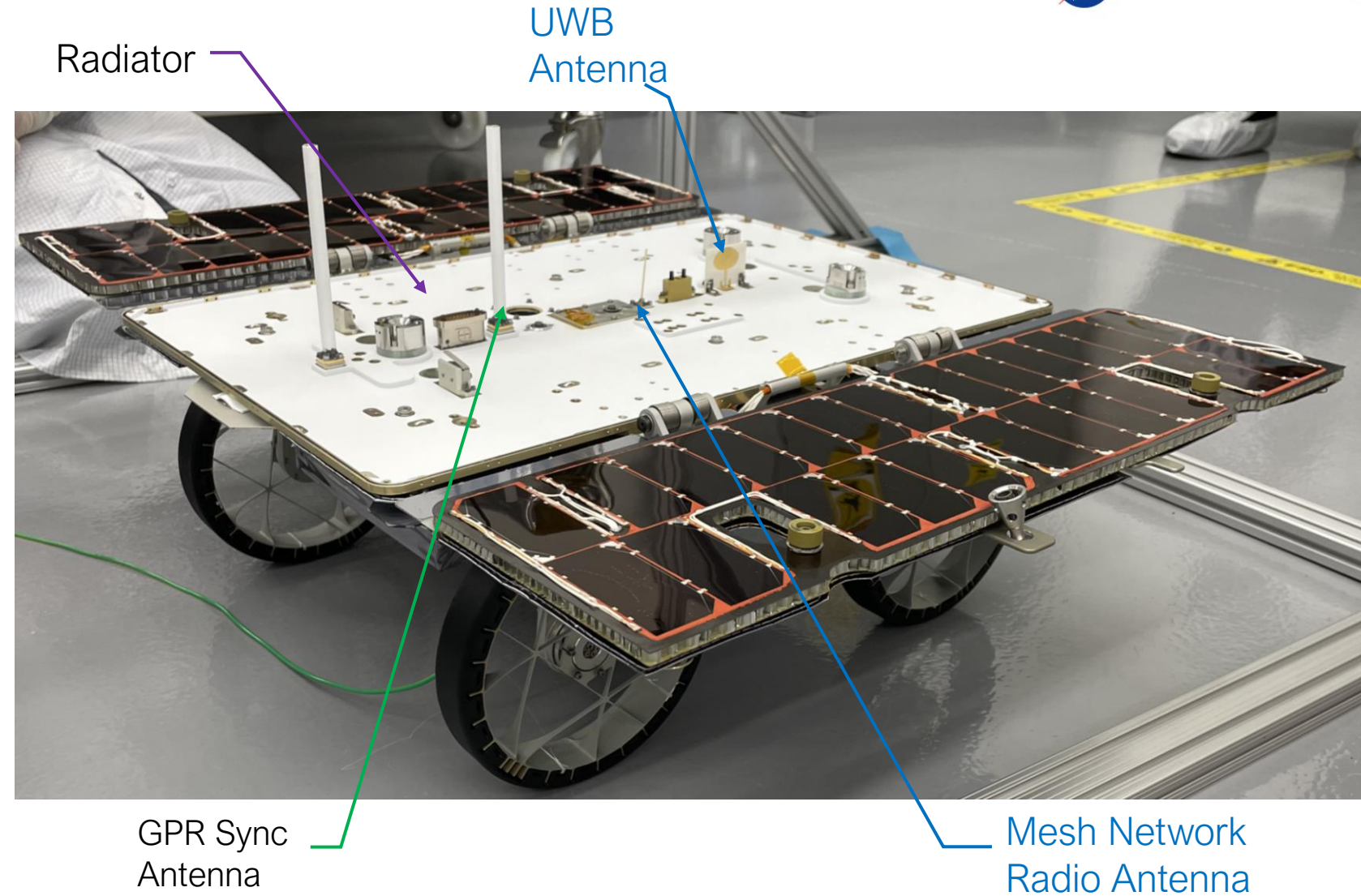
New Technology we will Demonstrate

- High efficiency, light weight solar cells
- High temperature batteries
- GaN FETs on both of our power electronics board designs



Multiple GPRs work together with autonomy to perform multi-static surveys of the sub-surface.

LET'S CELEBRATE WHAT WORKED



Sensors for rovers to estimate “Where am I” and “what is near me”

GOOD THINGS COME IN SMALL PACKAGES



Voxl High Brain (Snapdragon)



Modal AI Interposer



Omnivision Cameras



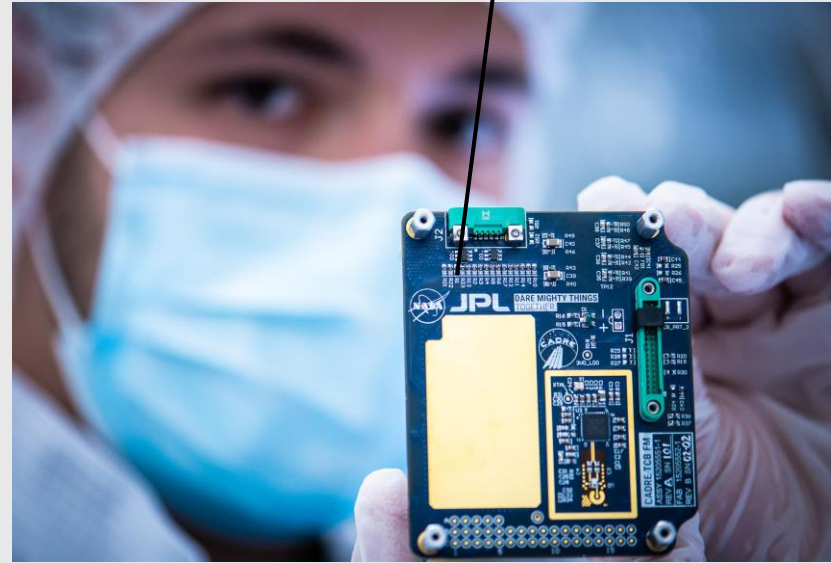
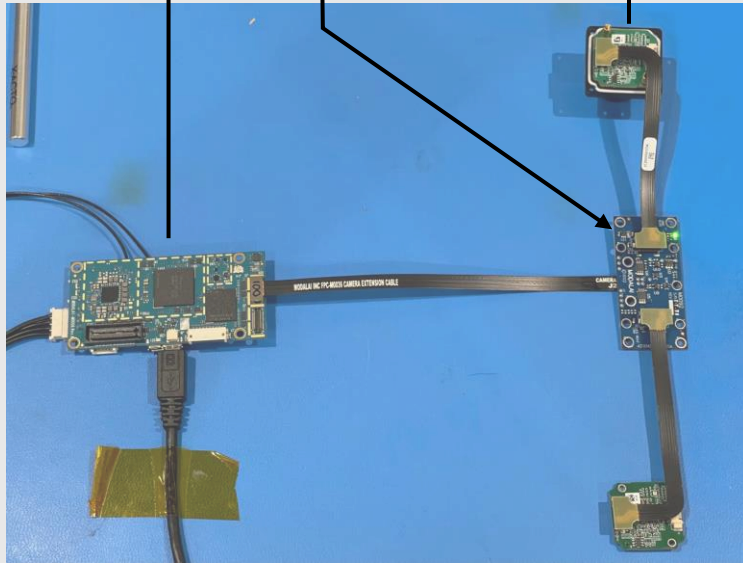
Motor Control Board



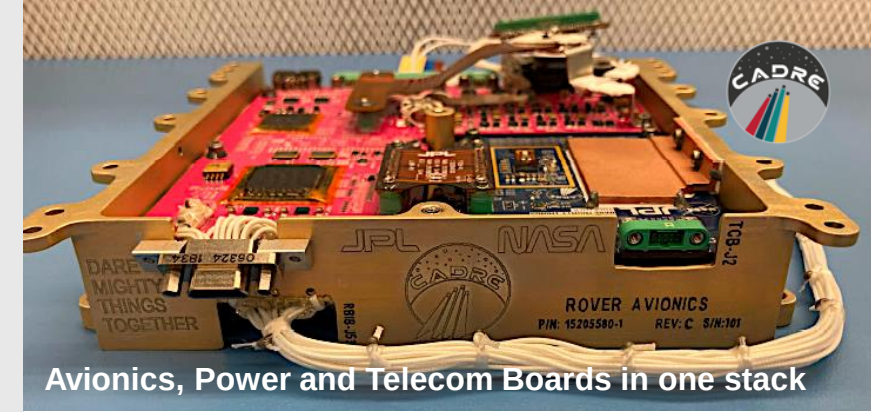
Microhard mesh network radio



Zynq software defined radio

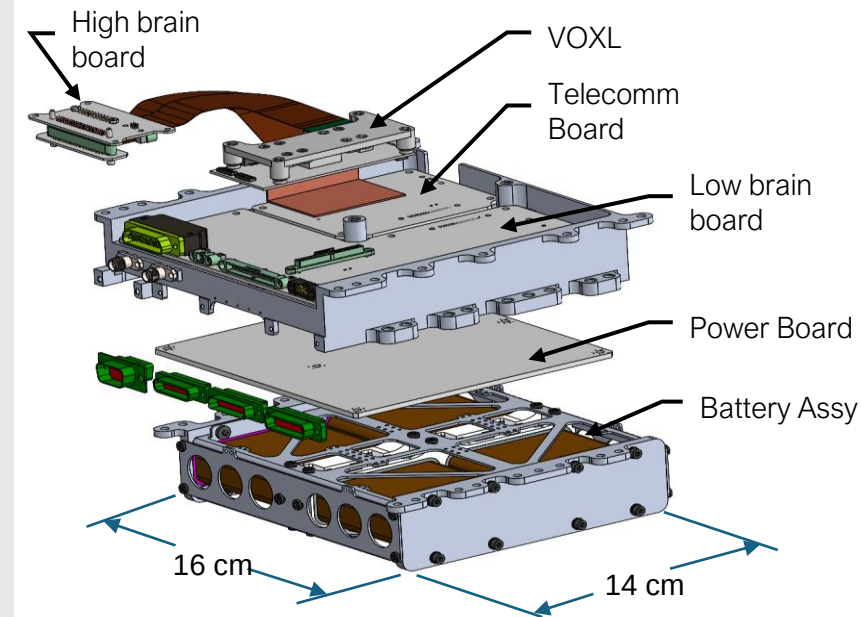


Telecom board with mesh network radio



Avionics, Power and Telecom Boards in one stack

Buy many spares and thermally screen flight parts. Build good relationships with engineers at vendors for critical support.



CADRE rovers use modern COTS parts to provide the capabilities needed (smaller footprint, higher computing power, mass savings, low cost).

These parts were not designed with the intention to be used in the lunar environment



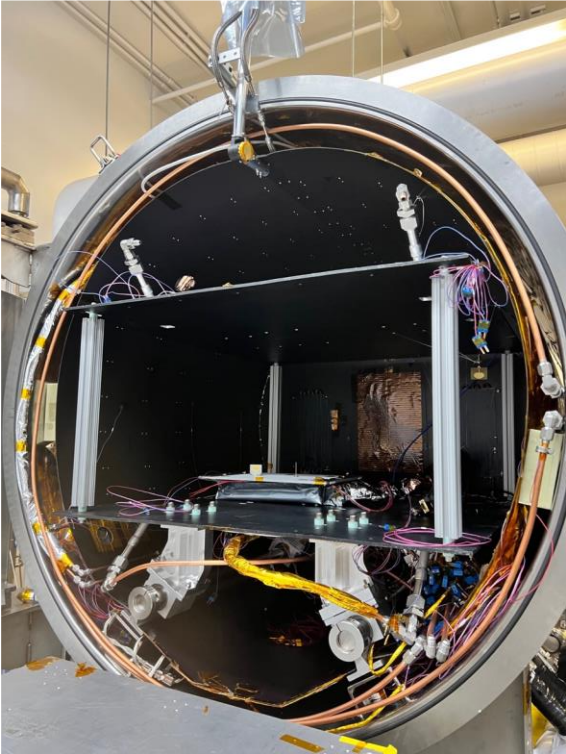
MULTI-AGENT AUTONOMY TEST

- December 22, 2023, JPL Cleanroom
- “Super Test” of Multi-Agent Autonomy on Flight Hardware (3 FM rovers and FM Base station)

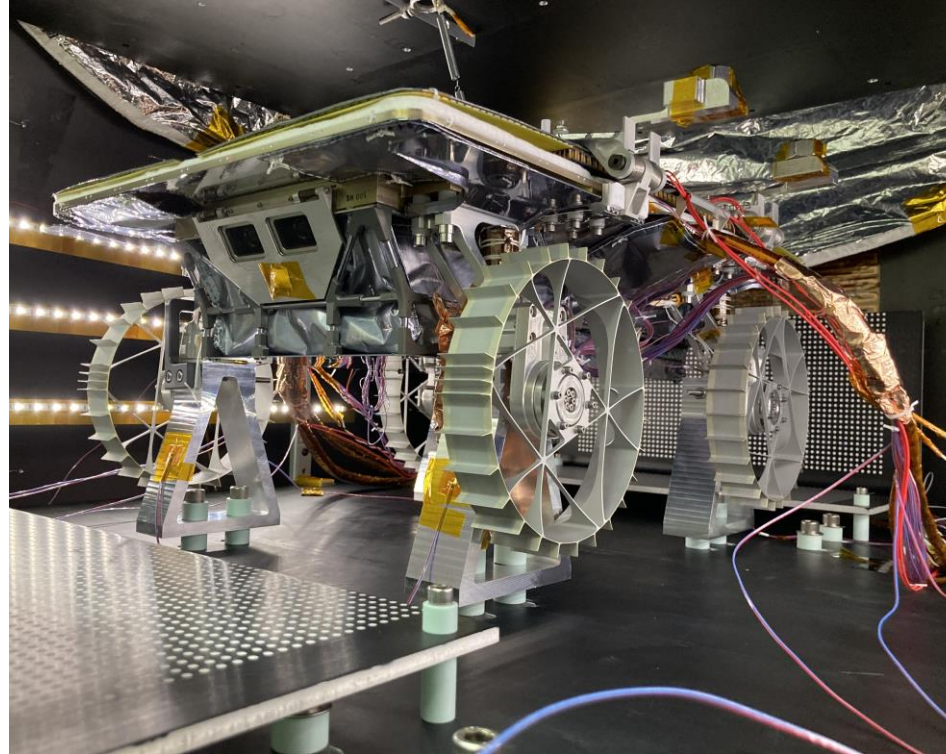
Integrated Flight Hardware and Software tested to verify capabilities required for successful Autonomy Threshold experiment on the moon.



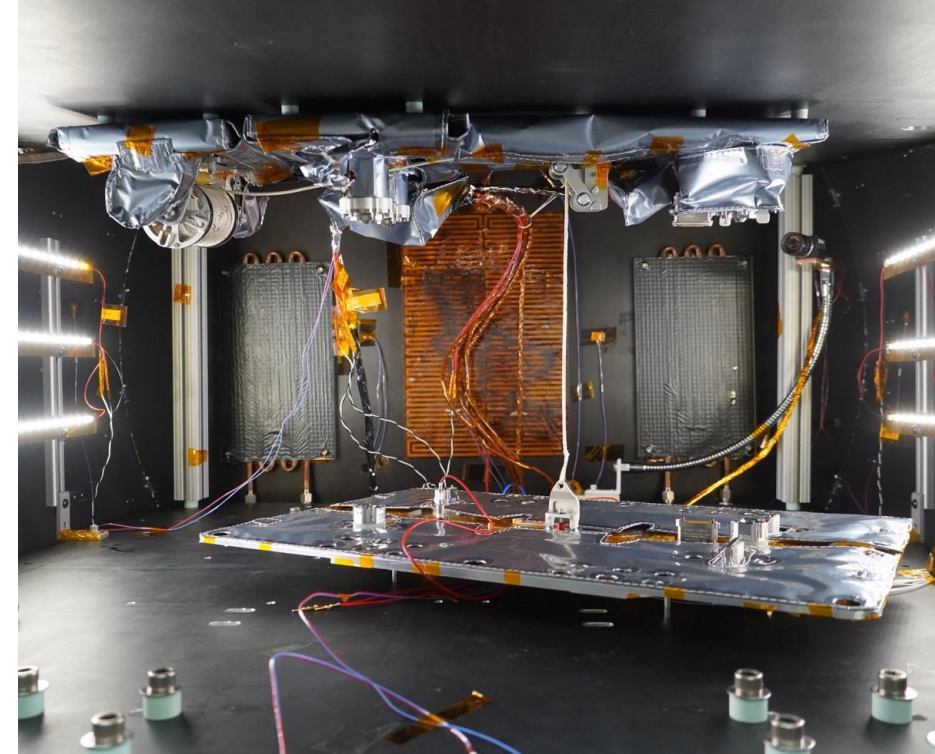
COMPLETED THERMAL VACUUM TESTS



Base station in TVAC Test Dec '23



FM Rover 1 TVAC Test Oct '23



Deployer with Lunar Mass Sim Rover in TVAC Test Nov '23

A radiator keeps the rover (and its avionics) as cool as possible, but the Moon is hot and the rovers sleep automatically (i.e., turn off computer) to cool off efficiently before waking up on the half-hour mark.

Verified in TVAC that the stereo camera calibration holds and rovers can sense properly when it is hot.

Lessons We Learned:

How it started:



How it's going:



“When CBE becomes NTE”: CADRE initially had 4 rovers, now there are three.

“Continuous Optimization of Compromises” – Kevin Barltrop



Our (Summarized) Lessons

The scope problem:

If you focus on your L6 requirements before worrying about the L3s, you will be in pain when the L3s change. But if you wait for a final set of L3s, you will never have hardware.

The lesson for budget, schedule, and technical:

- 1, Capture all major functions early in the hardware design – communication types, critical functions, major power interfaces – then be open to system design changes as they come.
- 2, Understand your risk posture and write it in a way that you can reference as team members change.
- 3, Test in accordance with your risk posture, +10%.

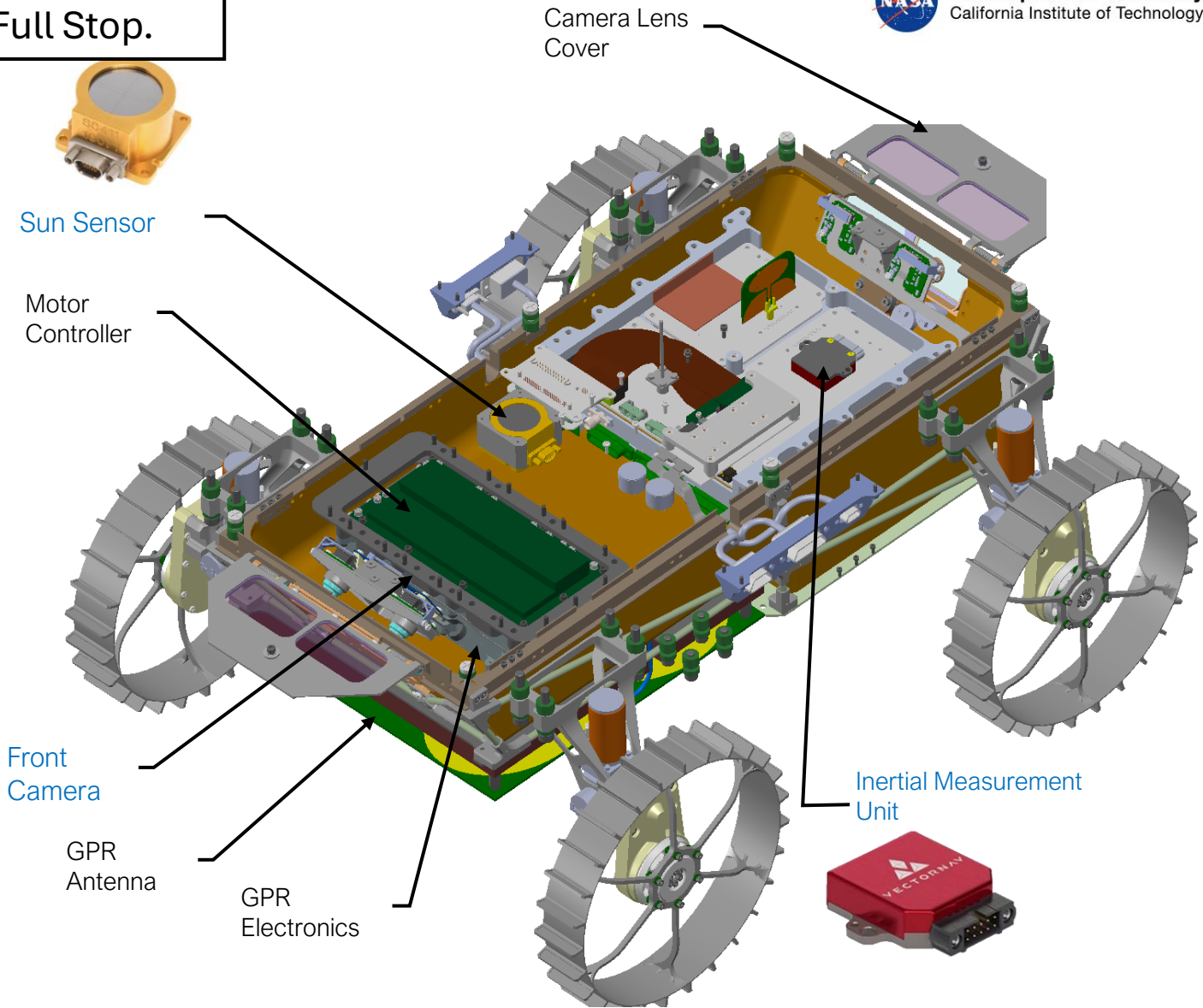
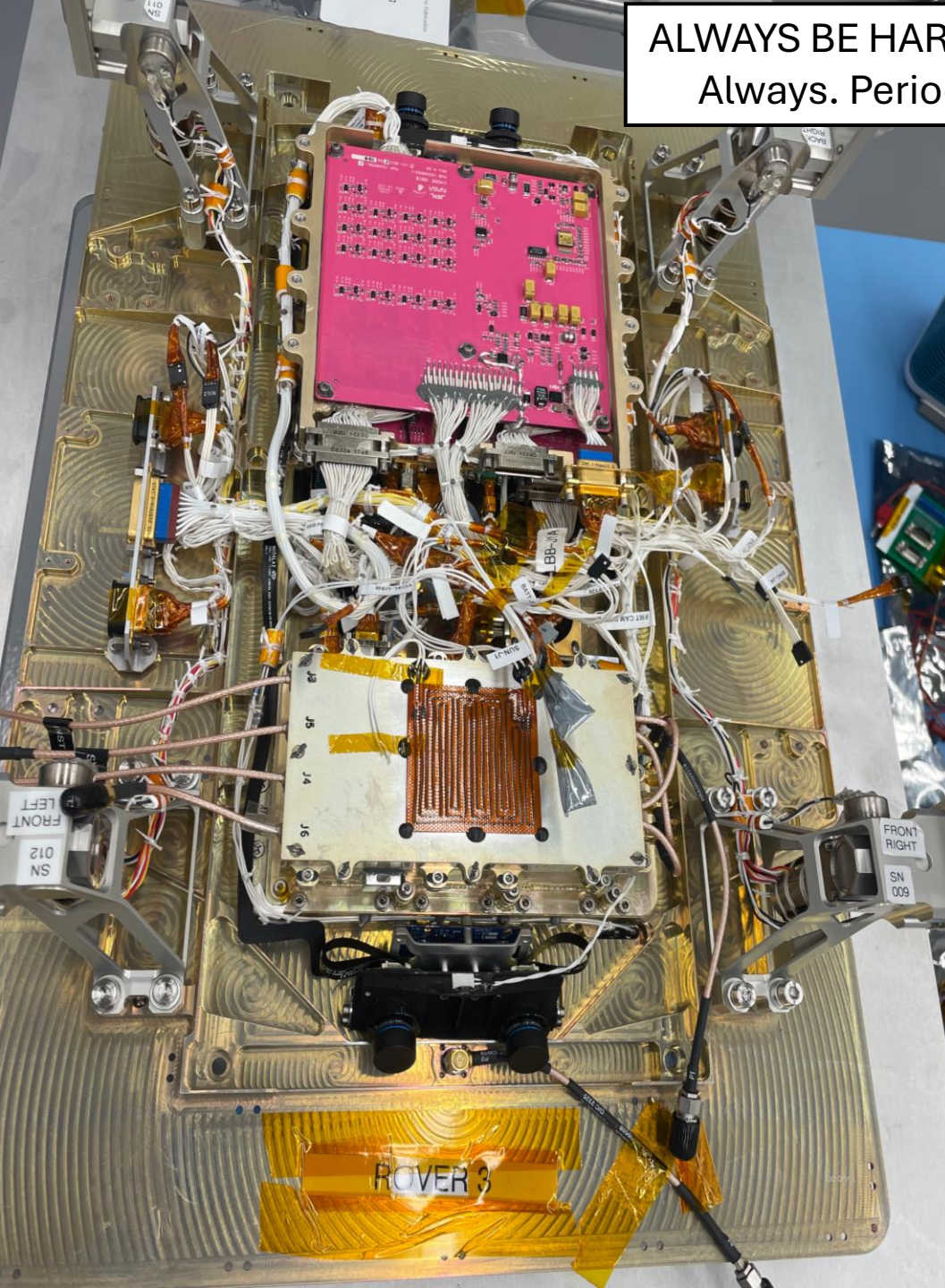
And the final lesson...



Nighttime testing with spotlights to emulate lunar lighting conditions and verify vision-based capabilities (i.e., state estimation + mapping)



ALWAYS BE HARDWARE RICH!
Always. Period. Full Stop.



CADRE rovers host enough compute and sensing for on-board autonomous surface mobility and multi-agent planning.

SUMMARY

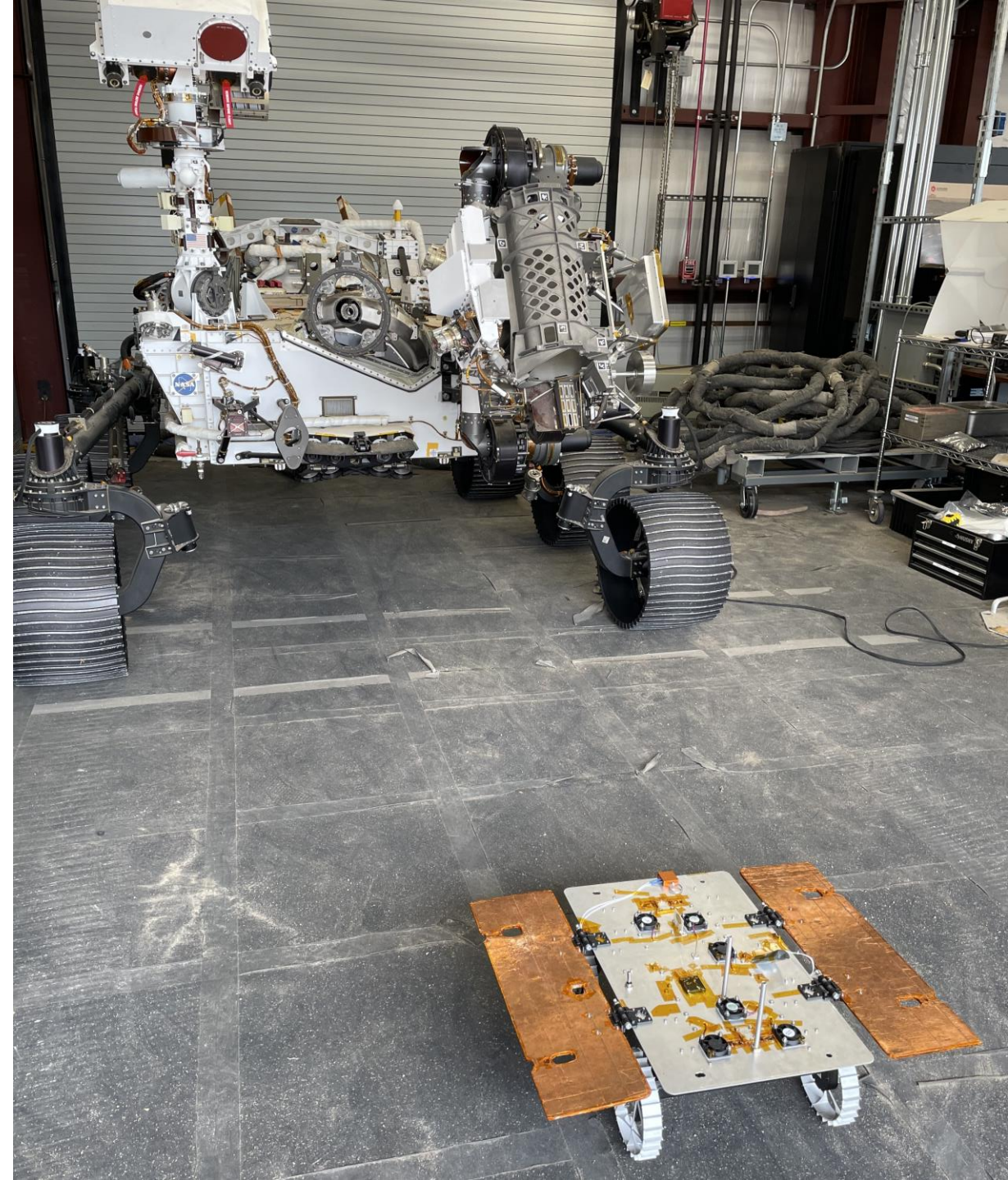
How do you maintain reliability in the age of faster and cheaper?

Define your problem early and update it only when you must.

Optimize systems around a realistic schedule, work to 90% of the budget that you have, and understand your risk posture inside and out.

For the boots on the ground, work hard, but don't push beyond your bounds. Unsustainable work practices make flawed budget tools.

For those setting the course, guide your team and identify the functions needed to complete your mission, then trust your team to implement the right engineering solution.



THANK YOU



