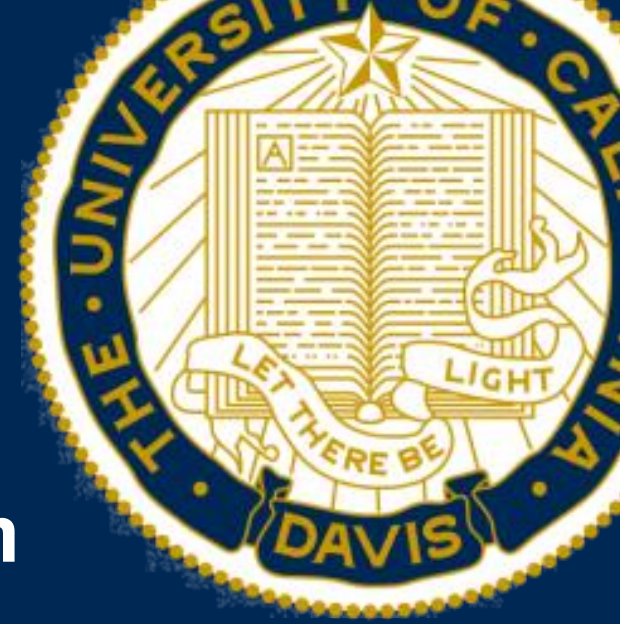


University of California, Davis
Center for Space Exploration Research



Orbital Demonstration of an EKF-based Digital Twin for Lithium-Ion Battery State Monitoring and Prediction

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Introduction

- **Who's in the room?**
 - Private, public, academia?
 - Satellite builders & operators?
 - Component development?
 - Research & development?
- **My background**
 - NASA Ames Systems Engineer, 2017 – 2021
 - Designed, tested, operated three different CubeSat missions
 - UC Davis graduate student, 2021 – present
 - Research on GNC for deployable, autonomous inspection satellite

Demand for Battery Monitoring & Prediction

- **Maintenance of battery health & lifetime**
 - Keep battery within operational limits
 - Track anomalies; find patterns in degradation
 - Perform diagnostics without ground-based intervention
 - Data-limited situations
 - Reduce human workload, esp. with large constellations

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 - Decision: using energy to heat battery or charge battery
 - Charging limits amidst changing temperatures
 - Degradation-aware mission planning

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- **Risk reduction**
 - System knowledge enables higher performance
 - Reduce margin around operational envelope

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- **Improve upon heuristic-based flight rules and ground-based anomaly response**

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DOD Limits for Cyclic Operations

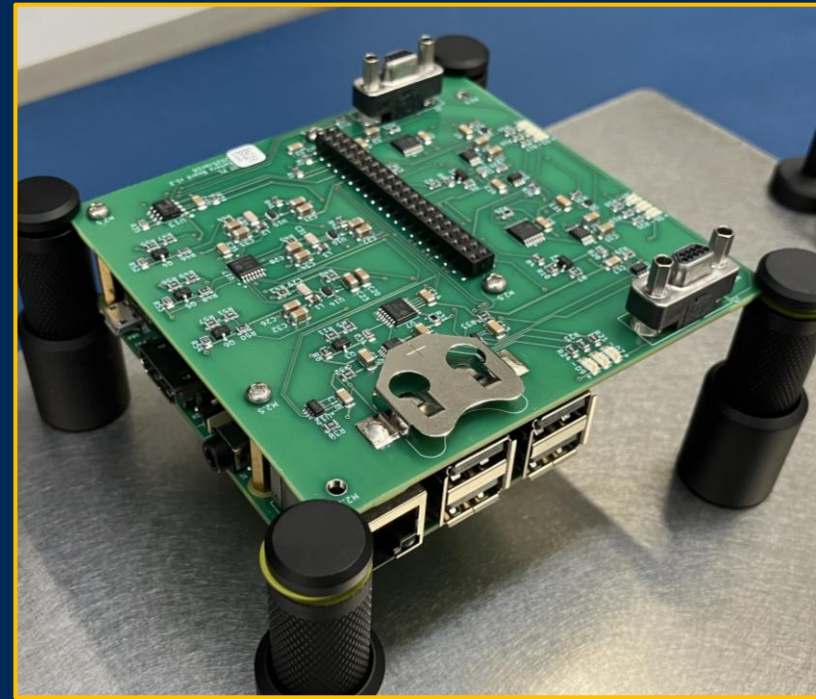
Number of cycles	Allowable DOD
<100	<70%
100 < # cycles < 5,000	<60%
5,000 < # cycles < 30,000	<40%
> 30,000	<20%

Note: A battery cycle is defined as any time the battery is discharged to 50% or more of the allowable DOD and recharged to near full.

From ARC-STD-8070.1, regarding NiH2 and Li-ion batteries

Satellite Payload: Hardware

- **Three independent channels**
- **Batteries:** LIR-2032
 - 45 mAh initial capacity
- **Sensors:** temperature, voltage, current
 - Temperature sensors placed in close physical proximity to cells
- **Charge:** Li-Ion management controller
- **Discharge:** resistor with voltage regulator
 - Two discharge paths for “high” (1C) and “low” (1/10 C) discharge modes
 - Programmable potentiometers for feedback control of charge and discharge
- **Computer:** RPi CM4
 - Typically 3W



Payload Board v1.2 with RPi CM4 attached. Two coin cells on opposite side, not visible.

- **Heater:** 5W resistive (not shown)

Satellite Payload: CONOPS

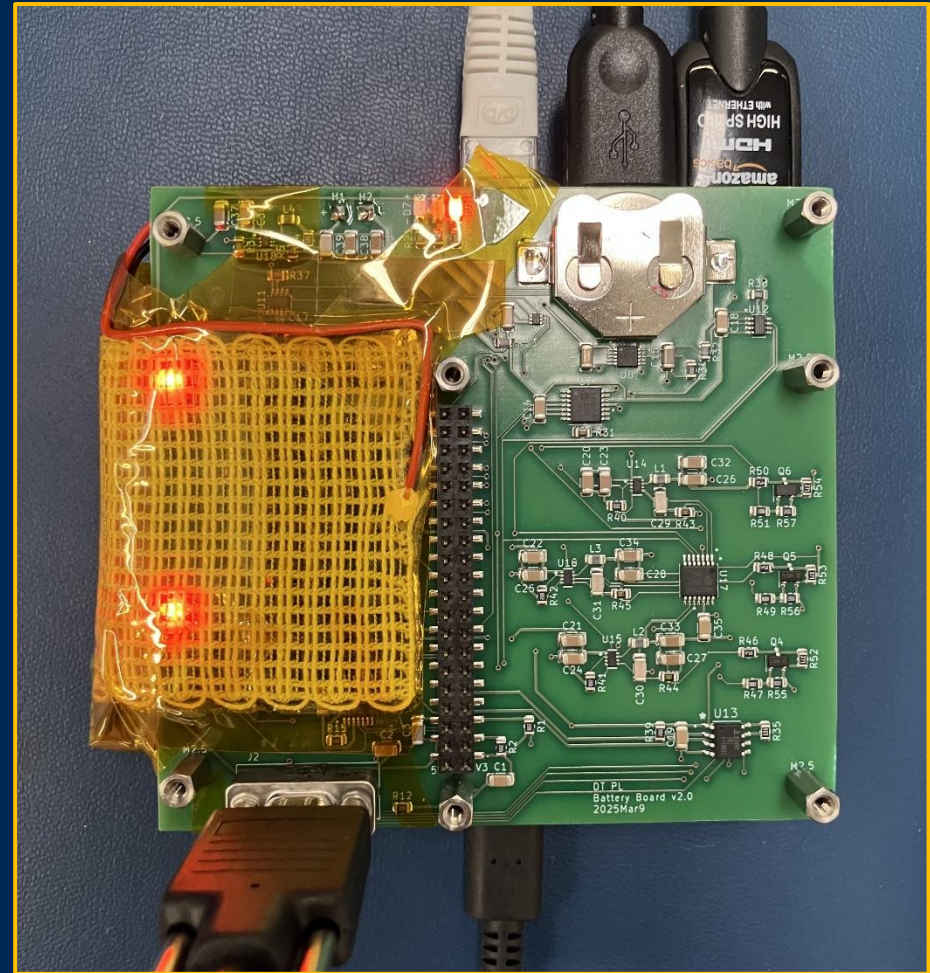
- **Cycle batteries at 1C**
 - Constant current charge up to 4.20 V
 - Constant current discharge down to 2.75 V
 - 5-minute rest between mode switches
- **Log voltage, current, temperature at 1 Hz**

Satellite Payload: CONOPS

- **Cycle batteries at 1C**
 - Constant current charge up to 4.20 V
 - Constant current discharge down to 2.75 V
 - 5-minute rest between mode switches
- **Log voltage, current, temperature at 1 Hz**
- **After 100 cycles, perform Reference Performance Test (RPT)**
 - Approximately weekly while on-orbit
 - 1/10 C discharge, followed by 2 hour rest
 - 1/5 C charge, followed by 2 hour rest
 - 1 C pulses (discharge, charge) for 10 s with 10 minute rest between pulses at 100%, 65% and 30% SOC
 - Log data at 10 Hz during pulses
 - 1 C discharge to reach each SOC
 - 1 C discharge, followed by 2 hour rest
 - Resuming cycling
- **Launched on 28 Nov 2026**

Satellite Payload: CONOPS

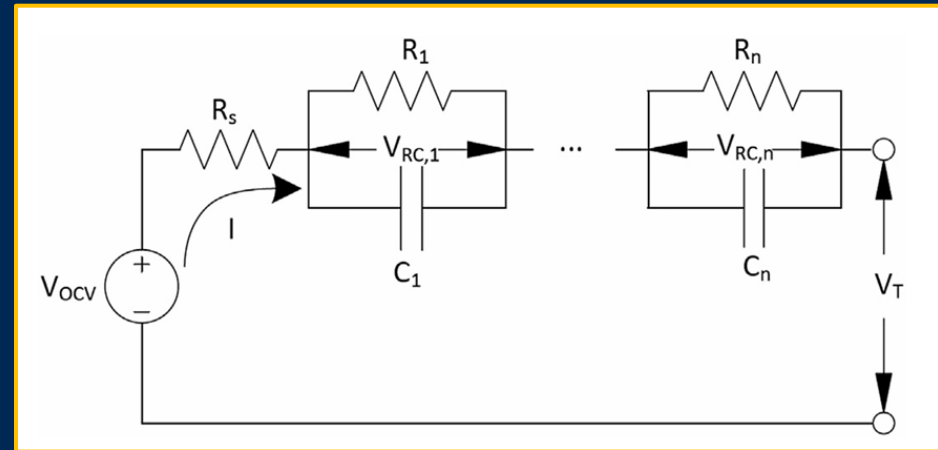
- **Temperature limits**
 - > 65°C, stop all operations
 - > 60°C, stop charging
 - > 30°C, turn heater off
 - < 22°C, turn heater on
 - < 19°C, charge at 0.50 C
 - < 10°C, charge at 0.25 C
 - < 0°C, stop charging
 - < -10°C, stop all operations



*Payload Board v2.0 with heater in place.
LEDs are used to communicate battery mode,
i.e. Charge, Discharge, Rest.*

Battery Model & Estimator

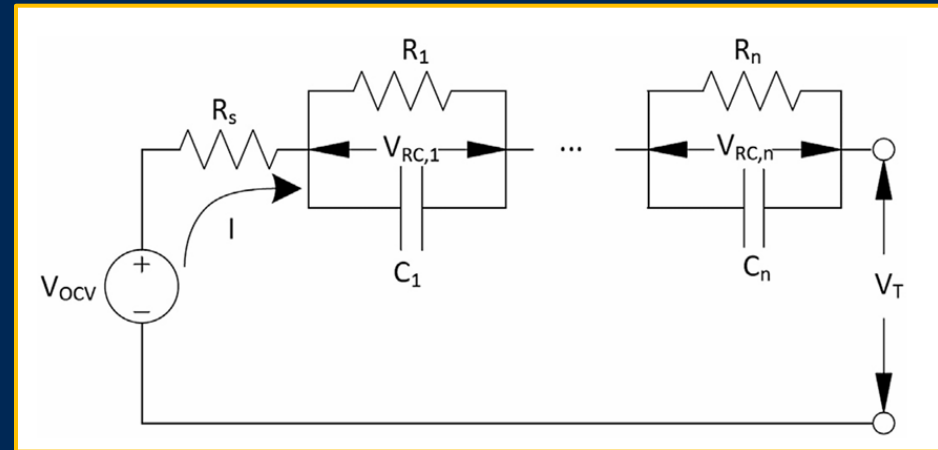
- **Equivalent Circuit Model**
 - Single RC pair
- **Dual Extended Kalman Filter**
 - Fast Loop, 1 s
 - Voltage, SOC
 - Slow Loop, 1000 s
 - Capacity, internal resistance
 - Internal resistance, RC values are functions of SOC, but not temperature



Equivalent Circuit Model for batteries
Source: Cortés, et al

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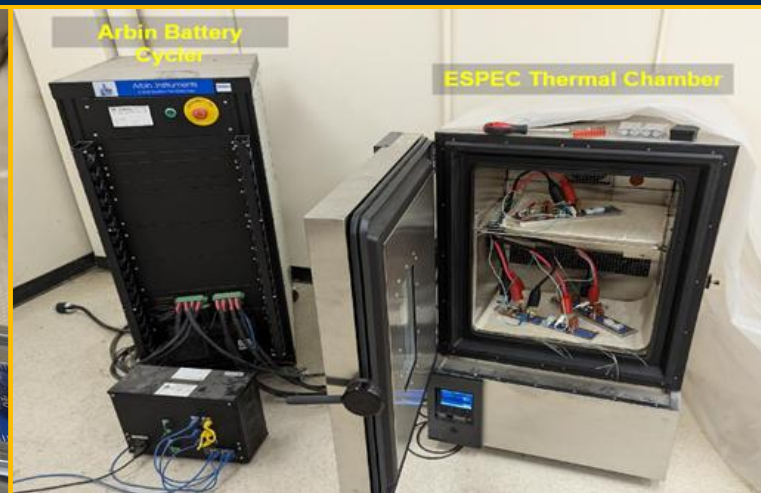
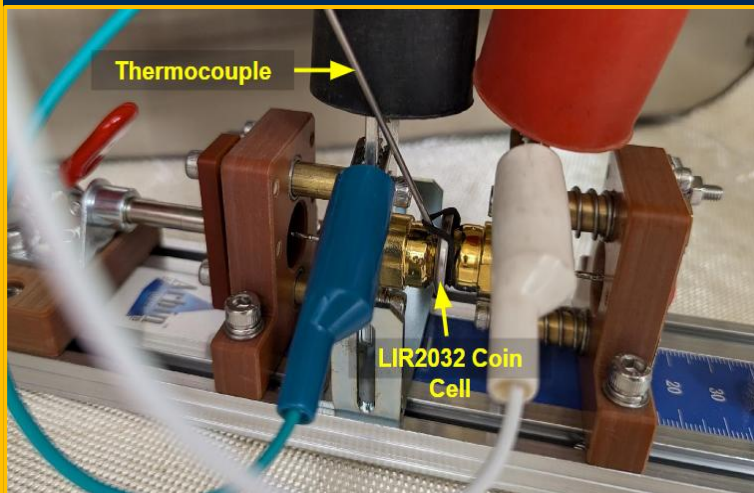
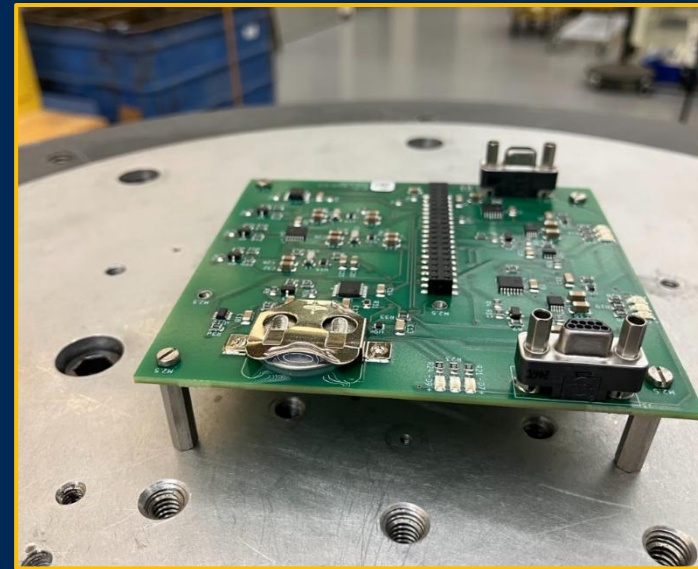


Equivalent Circuit Model for batteries
Source: Cortés, et al

- **Predictions with 1 week (cycling time) horizon**
 - Due to RPT, 7 days of cycling time is 8 days of real time
 - “Naïve approach”, linear fit to coulomb counting on battery cycles
 - “EKF approach”, linear fit to previous slow loop capacity updates
- **Estimator is not updated by RPT data!**
 - Initialized with single RPT before installed in s/c

Ground Testing

- **Laboratory Testing (not w/ payload HW)**
 - Extensive (multiple weeks) at various temperatures and C rates
- **TVAC (w/ payload HW)**
 - Subsystem at weak vac (~ 1 kPa) at 0°C and 40°C (operational)
 - Full system at strong vac (non-operational)
- **Mission Sim (w/ payload HW)**
 - 48 hours of operations, including communications with s/c bus

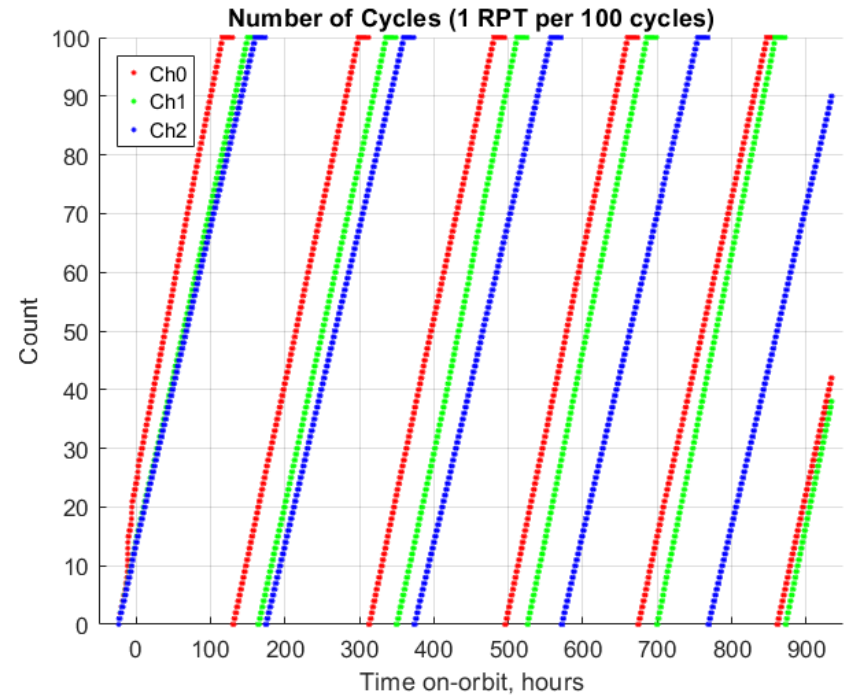
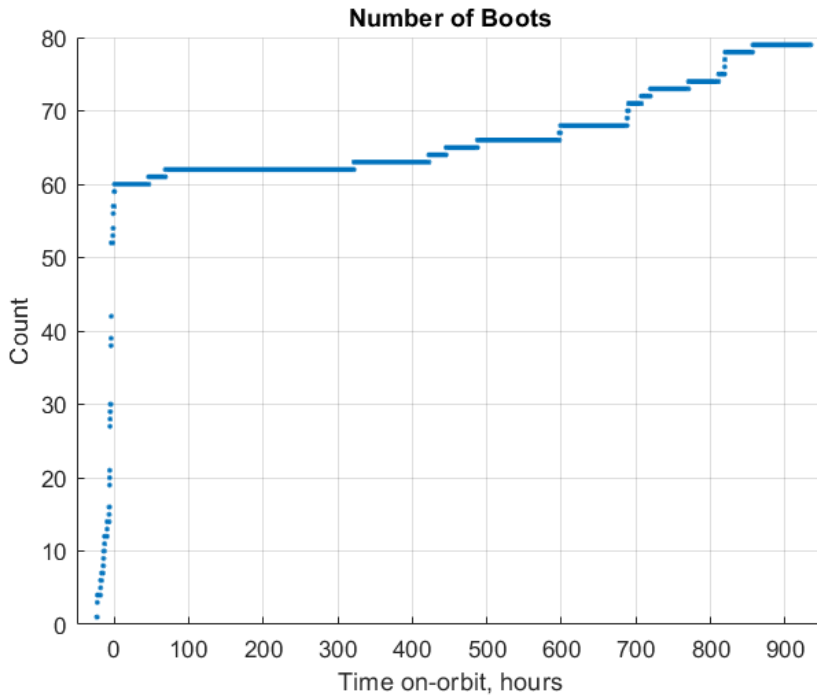


Above: **Subsystem vibration test**

Left: **Cell and probes in test rig**

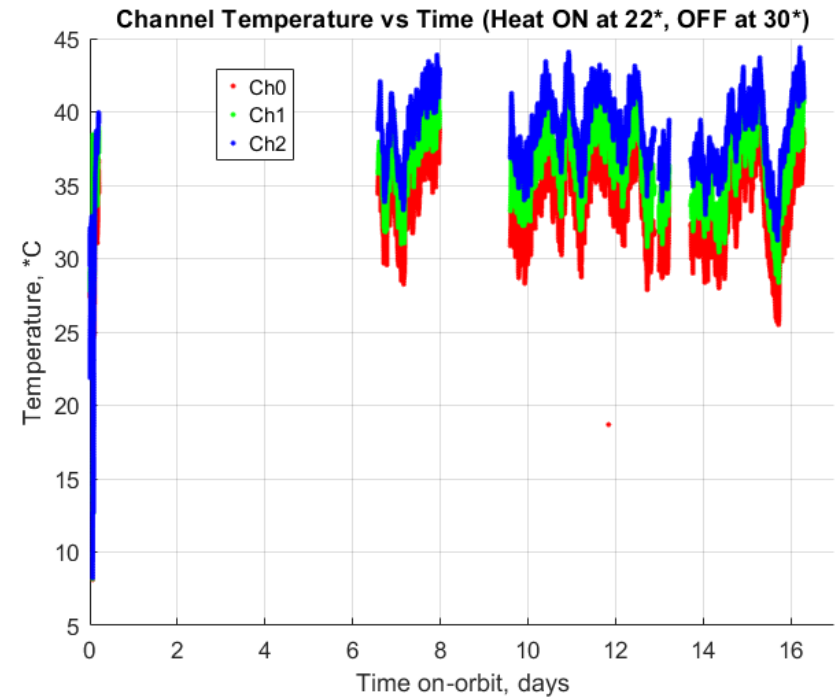
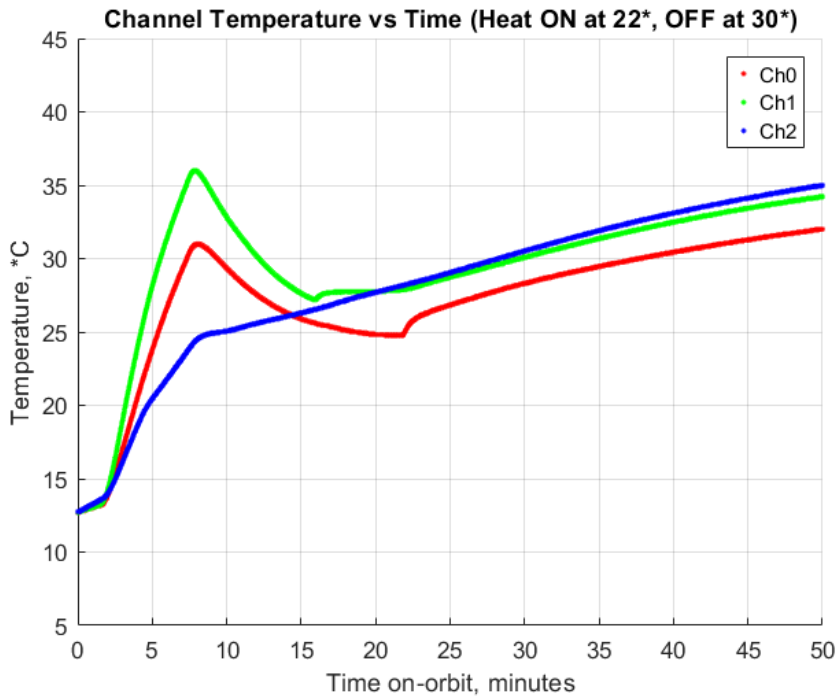
Right: **Battery cycler and thermal chamber**

Orbital Data: Operations



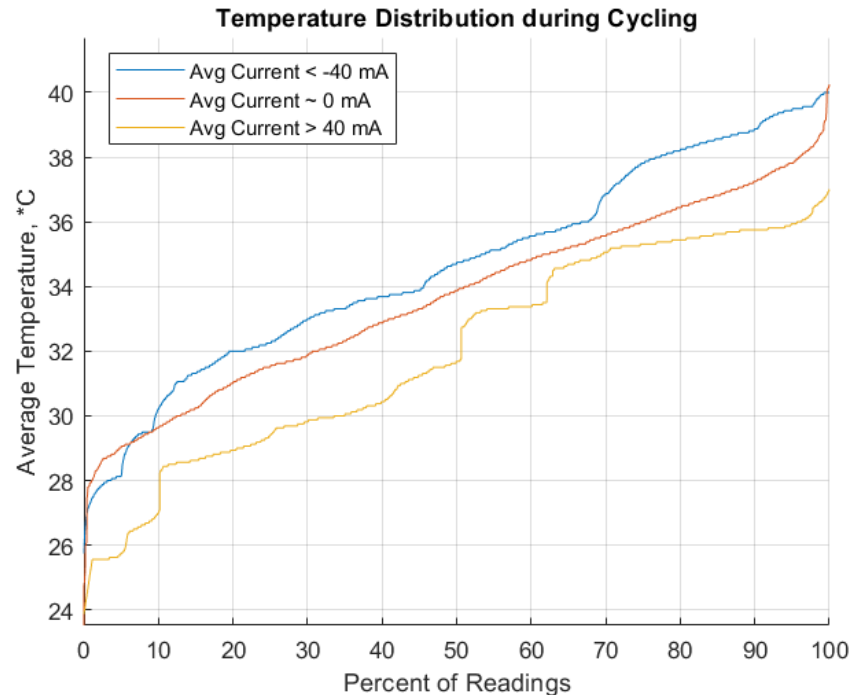
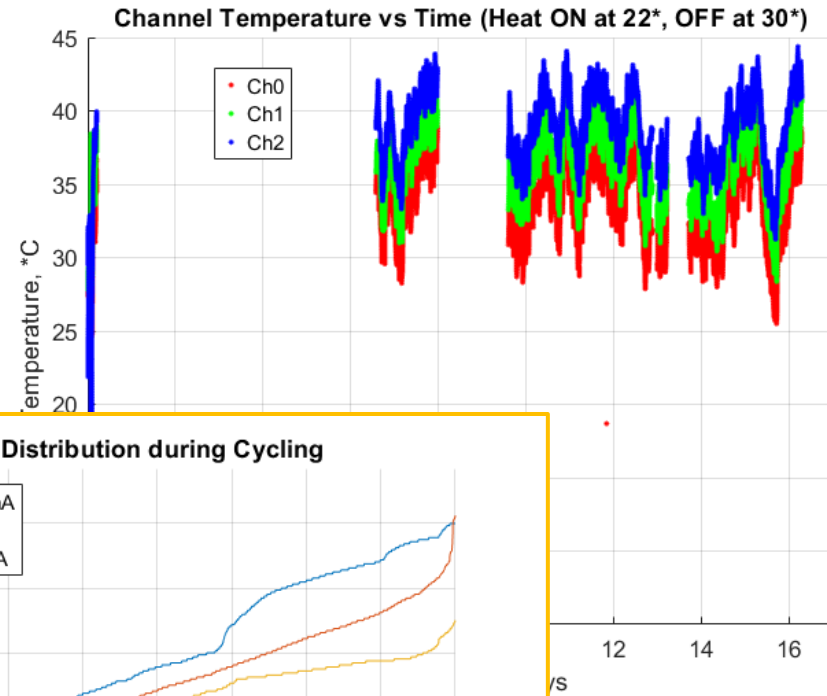
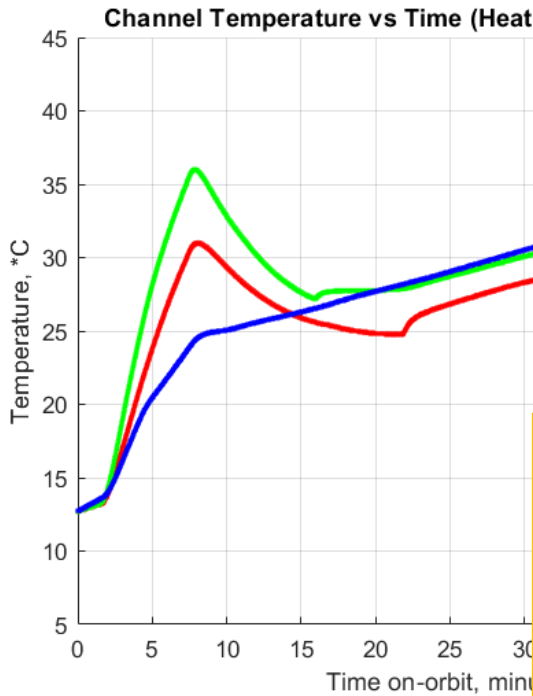
Note some terrestrial data after installation into bus

Orbital Data: Temperature



Heater only active for 5 ~ 10 minutes after boot

Orbital Data: Temperature



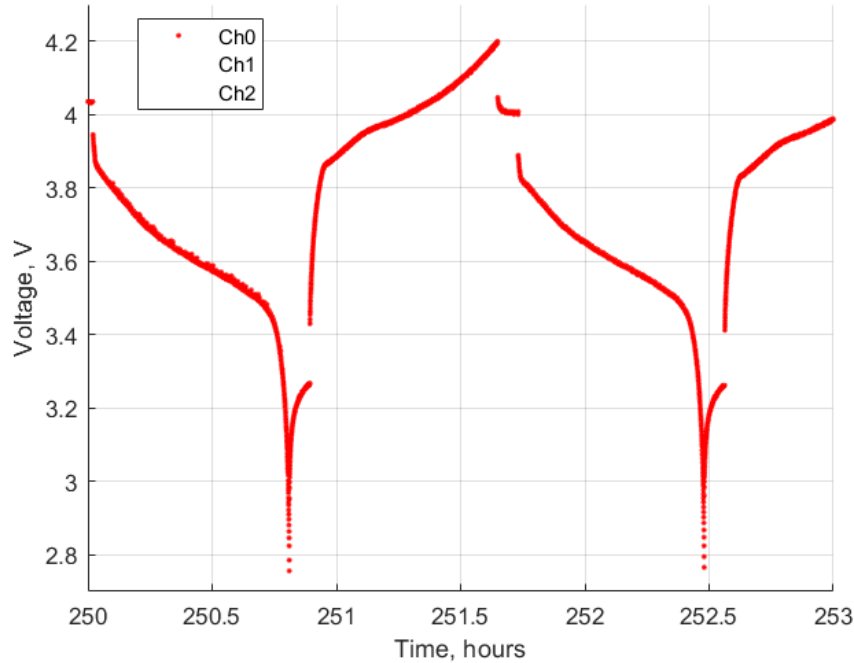
Variation due to activity: 4°C

Variation due to environment: 10°C

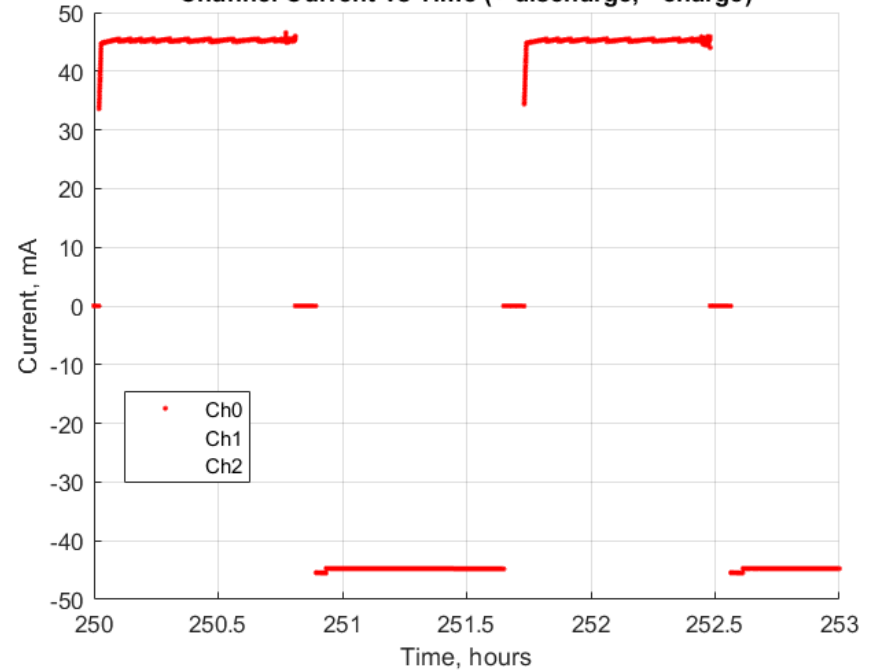
**+ discharge
- charge**

Orbital Data: Voltage, Current

Channel Voltage vs Time

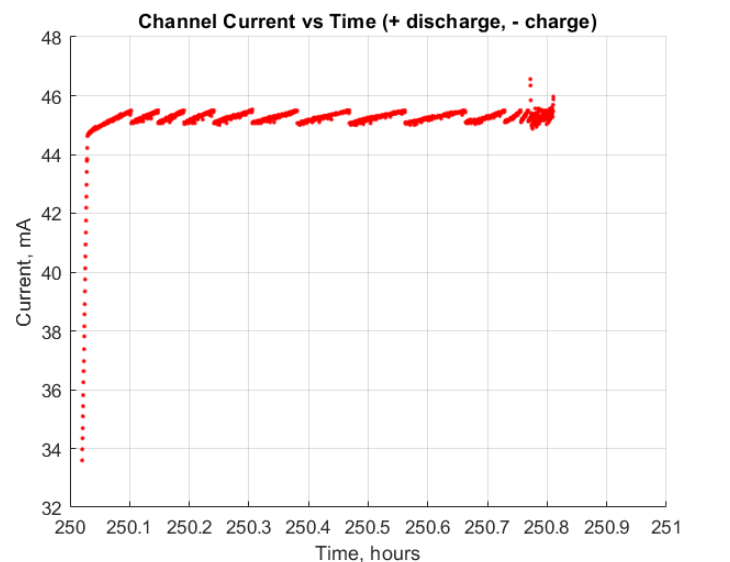
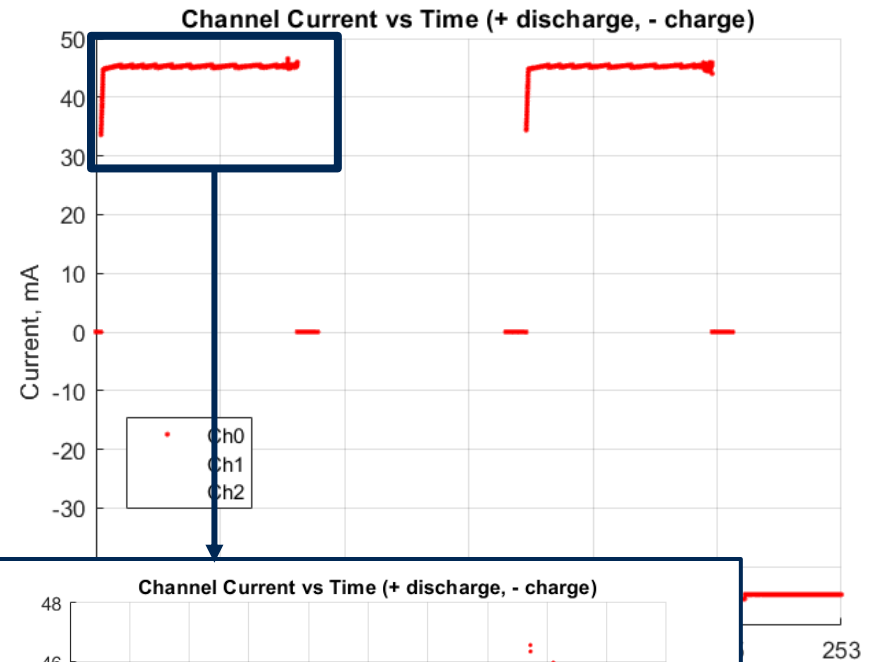
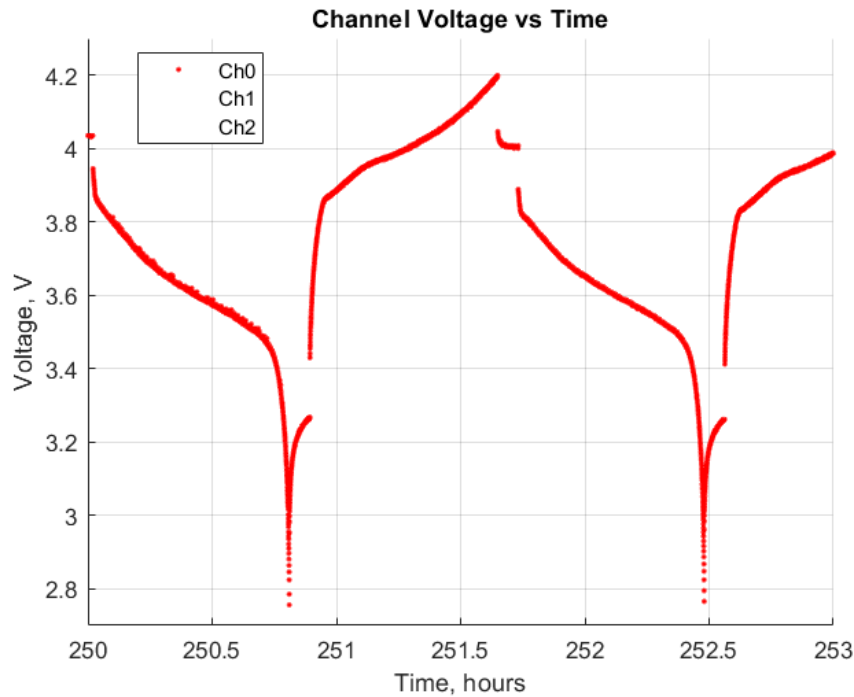


Channel Current vs Time (+ discharge, - charge)



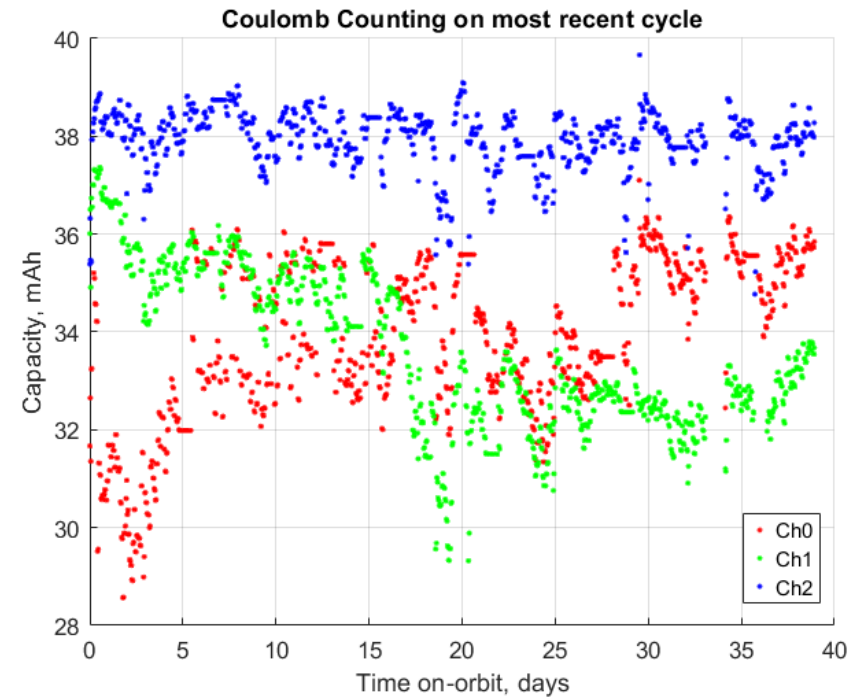
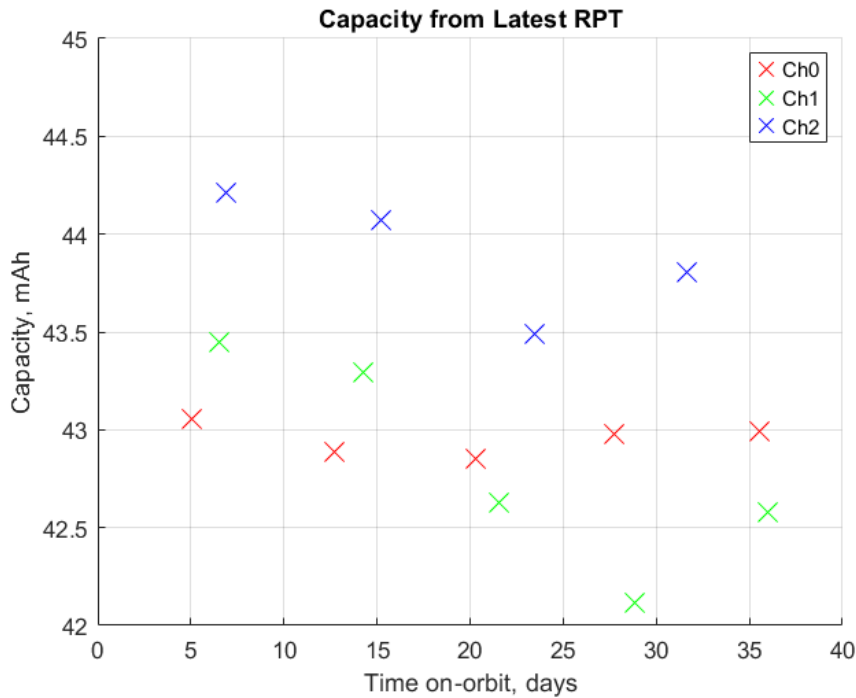
Typical voltage and current curve during charge/discharge cycles

Orbital Data: Voltage, Current



Artifacts from constant current controller

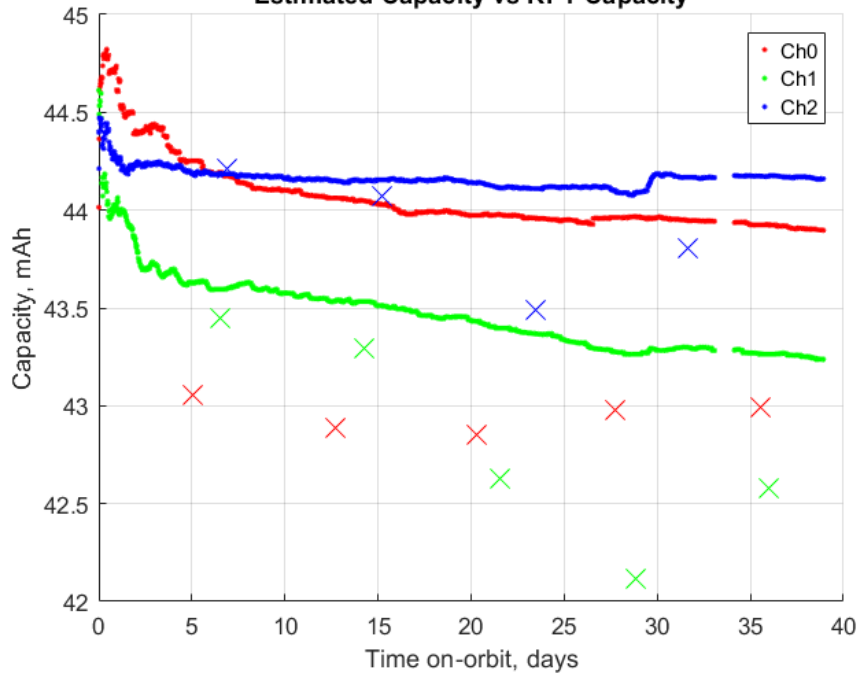
Orbital Data: Capacity



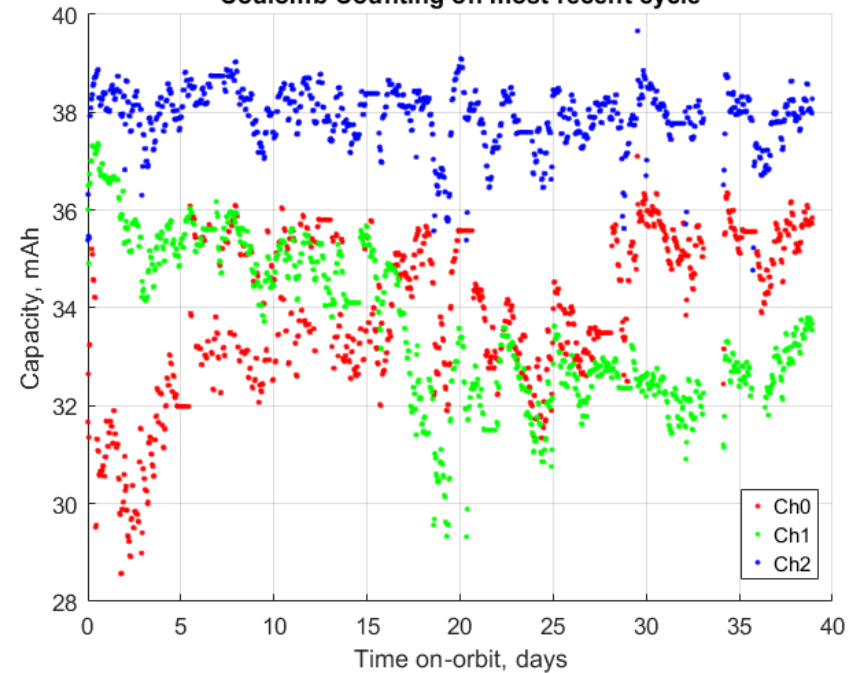
RPT is at 1/5 C, while cycling is at 1 C

Orbital Data: Capacity

Estimated Capacity vs RPT Capacity



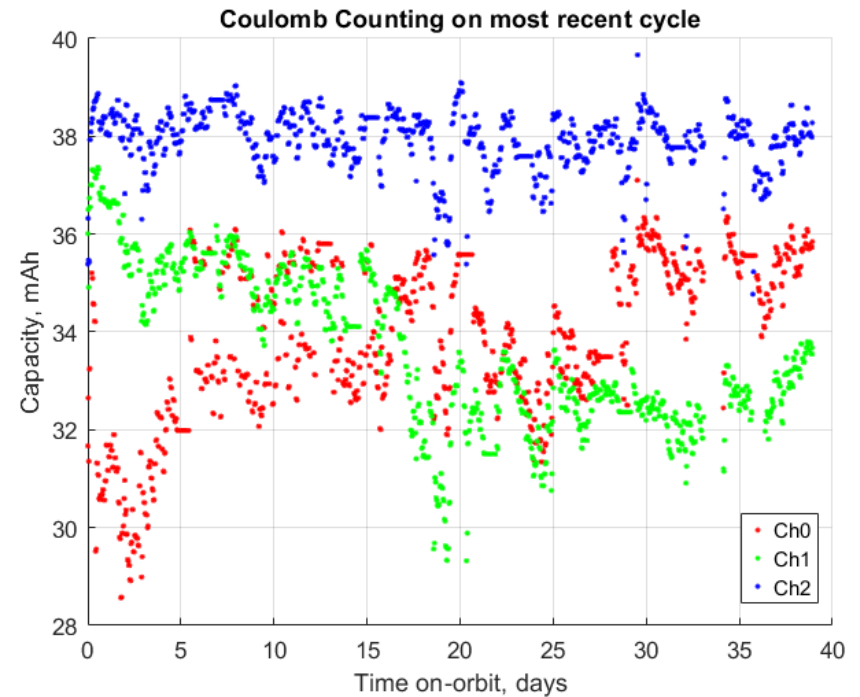
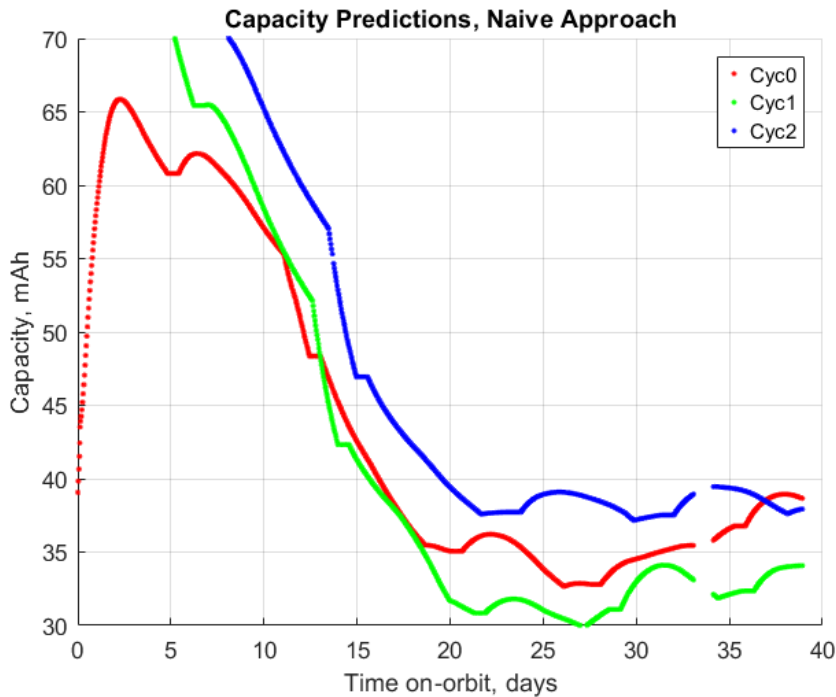
Coulomb Counting on most recent cycle



RPT is at 1/5 C, while cycling is at 1 C

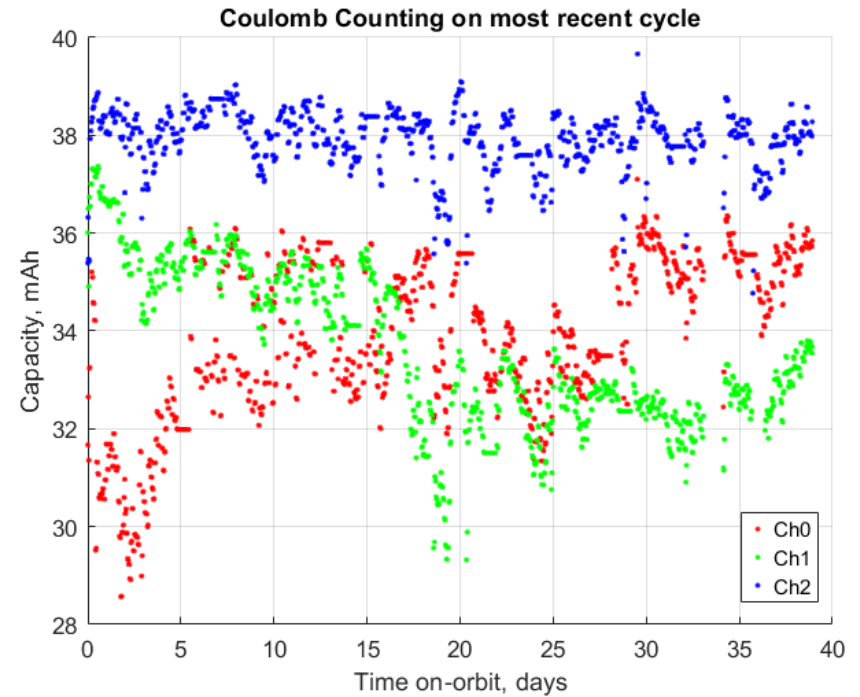
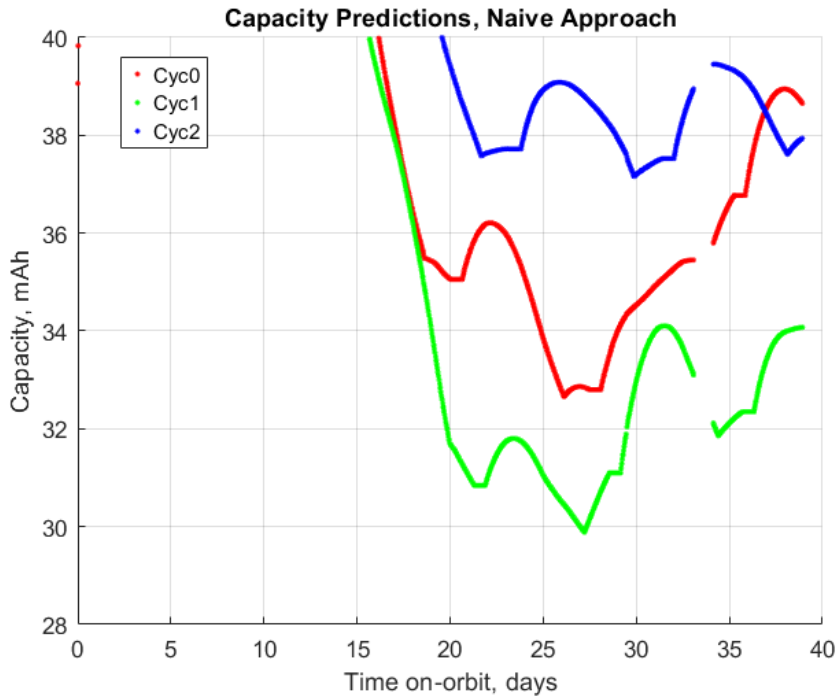
EKF does not have access to RPT data, aside from initialization prior to installation

Orbital Data: Predictions

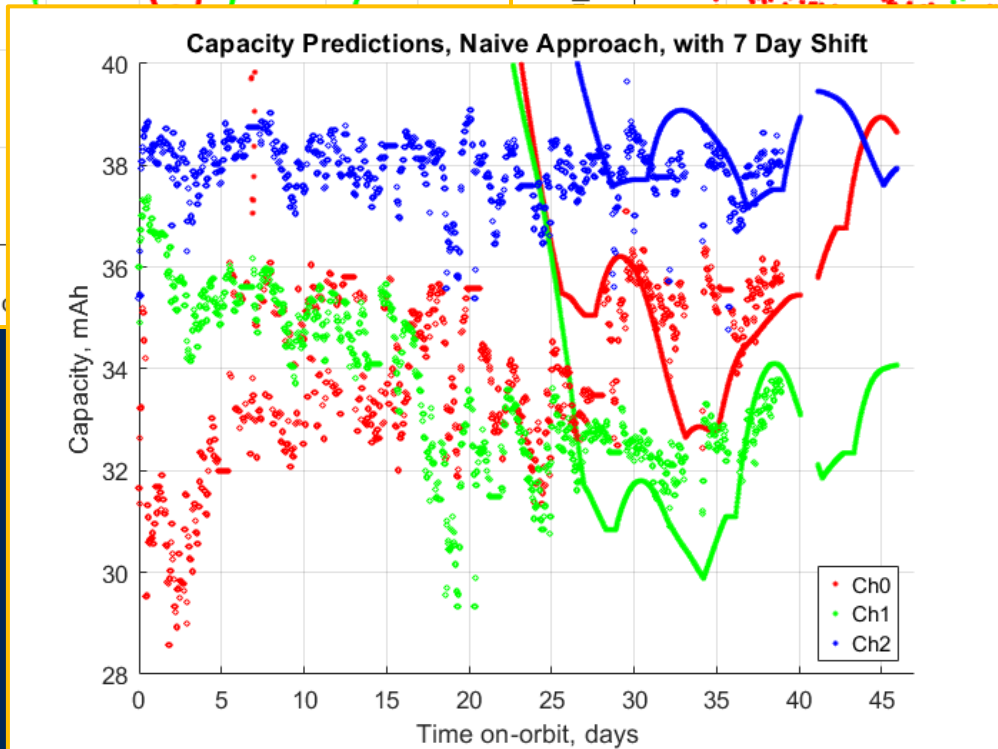
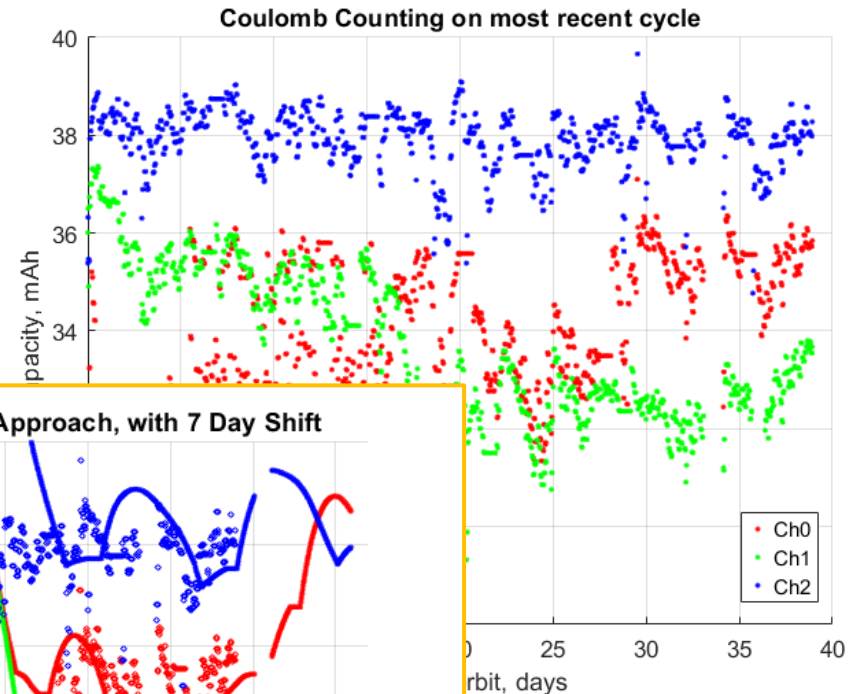
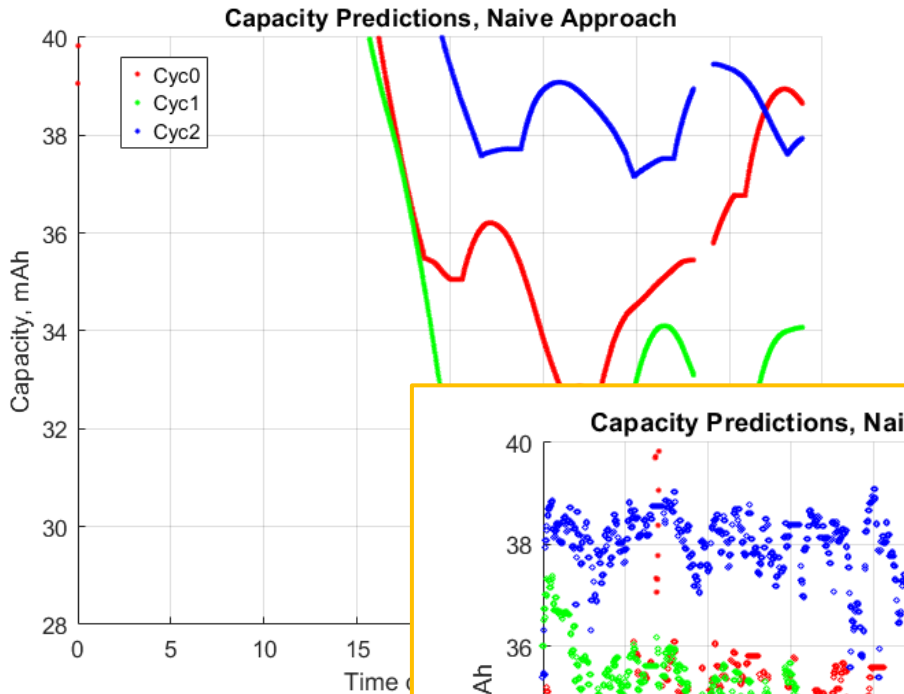


Abundance of resets during terrestrial system-level testing created error in cycle tracking

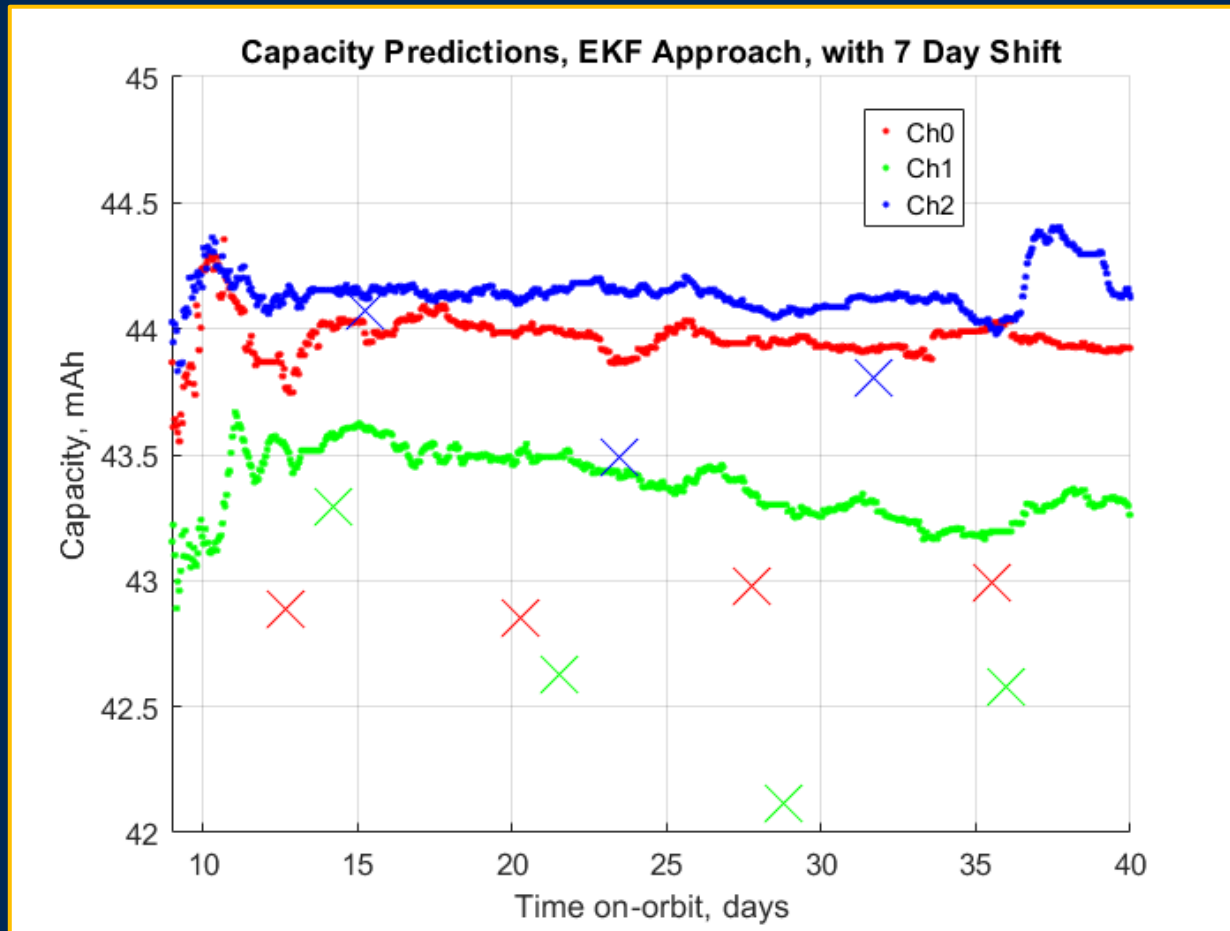
Orbital Data: Predictions



Orbital Data: Predictions



Orbital Data: Predictions



*Hampered by slow degradation, limited data,
accuracy of EKF capacity estimate*

Continuing Work

- Orbital operations
- Degradation research, esp. Lithium plating
 - dQ/dV spikes above 4V
 - Better understanding of temperature, cell variation (electrolyte)
 - Verification with cell deconstruction

Questions?

“Orbital Demonstration of an EKF-based Digital Twin for Lithium-Ion Battery State Monitoring and Prediction”

- Adam Zufall, admzufall@ucdavis.edu

More information in upcoming papers,

“Machine Learning Detection of Lithium Plating in Lithium-Ion Cells: A Gaussian Process Approach” - American Control Conference 2026

“On-Orbit Digital Twin for Spacecraft Battery State and Health Estimation”- AIAA ASCEND 2026

Videos hosted on YouTube,

“Thermal Response of a Raspberry Pi Compute Module 4 in Low Earth Orbit”

“Low-cost thermal vacuum testing for small satellite and high-altitude balloon payloads”