Flight Performance of the Hybrid Energy Storage System Payload Onboard the CSUNSat1 CubeSat

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2018 Space Power Workshop
Los Angeles, CA

Outline

- Overview of CSUNSat1 Project
- CSUNSat1 launch!
- Primary mission phase
  - Performance testing in flight
- Extended mission phase
  - Life testing in flight
  - Model development and flight validation
- Summary
- Acknowledgements

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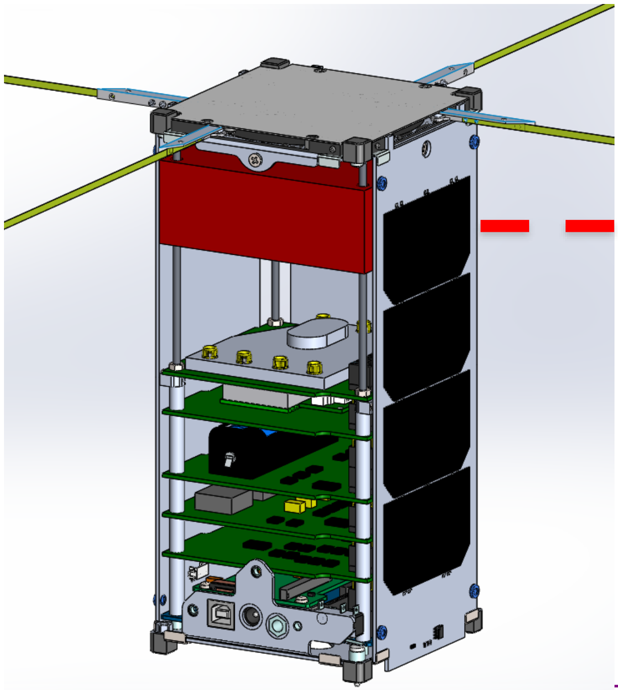
CSUNSat1 Team

- JPL Energy Storage Team
  - Keith Chin
  - Marshall Smart
  - Erik Brandon
  - Joseph Stiles (intern)

- Gary Bolotin – System Engineer
- John Baker – Lunar Flashlight Mission Manager
- Prof. James Flynn – CSUNSat1 Lead

CSUN/JPL Collaboration Program

- **Funded by NASA's 2013 Small Spacecraft Technology Program (only 2 yrs)**
- Time frame: 11/1/2013 – 9/27/2015

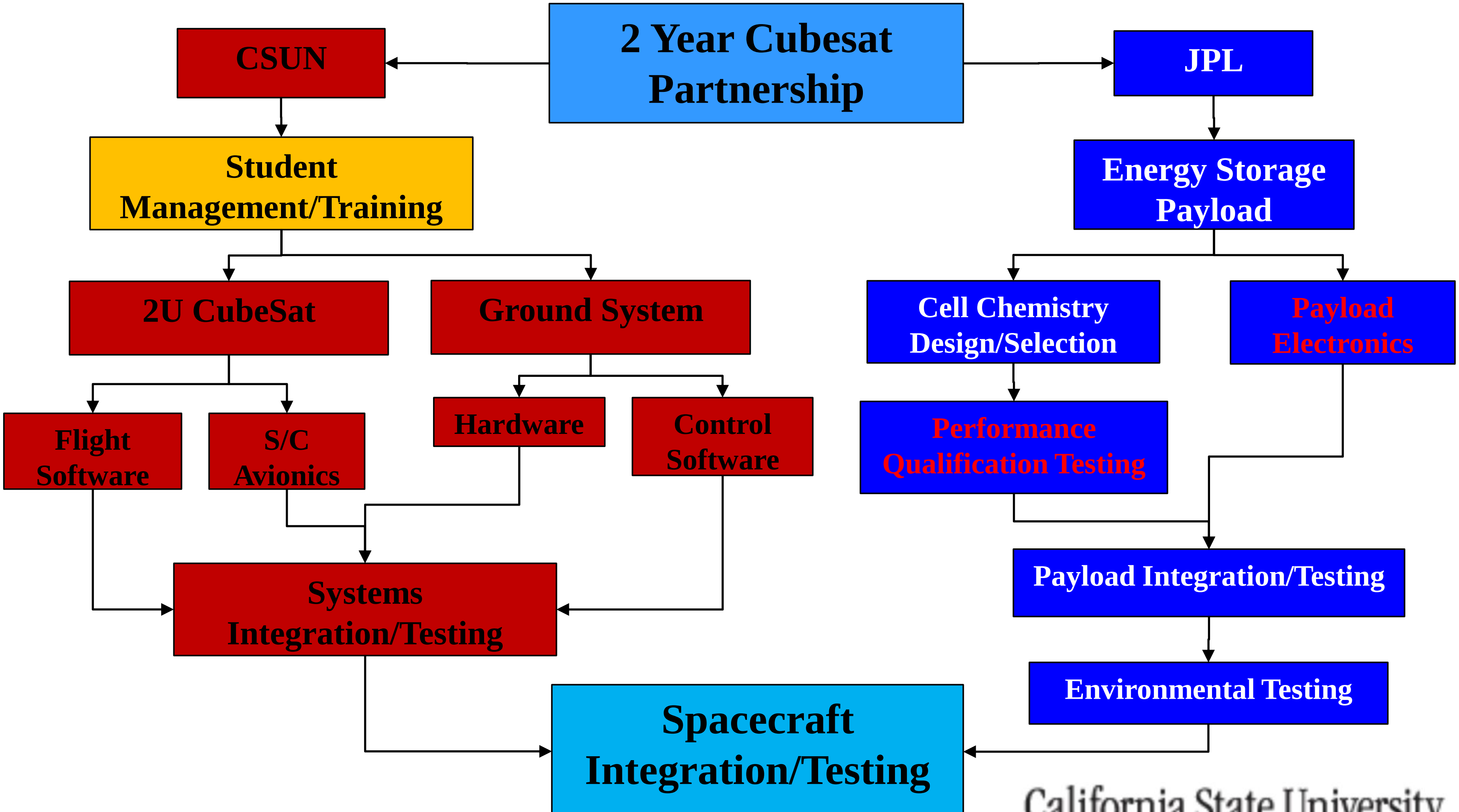


JPL Energy Storage Payload

CSUNSat1: 2U CubeSat

- **Processor**
- **Communications**
- **Power System**

Program Activity Flowchart



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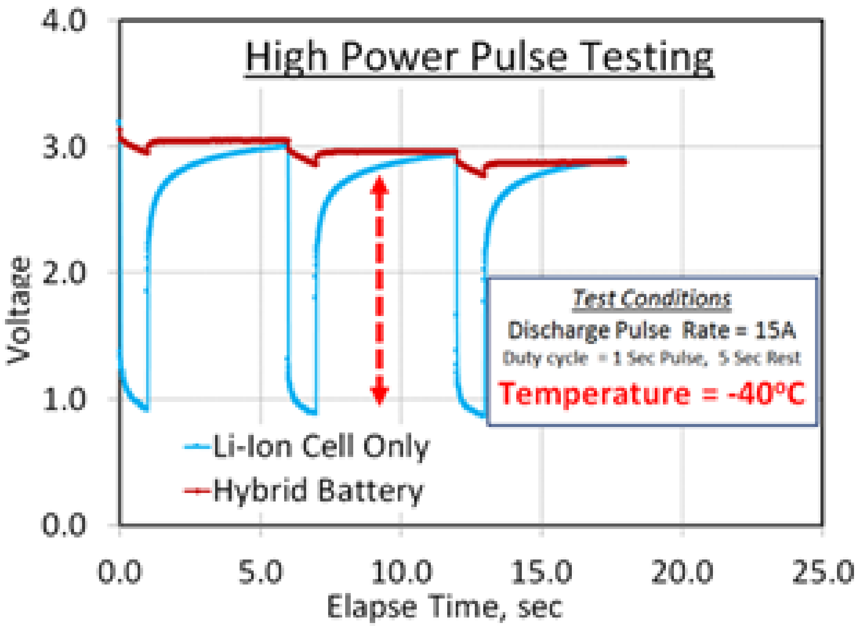
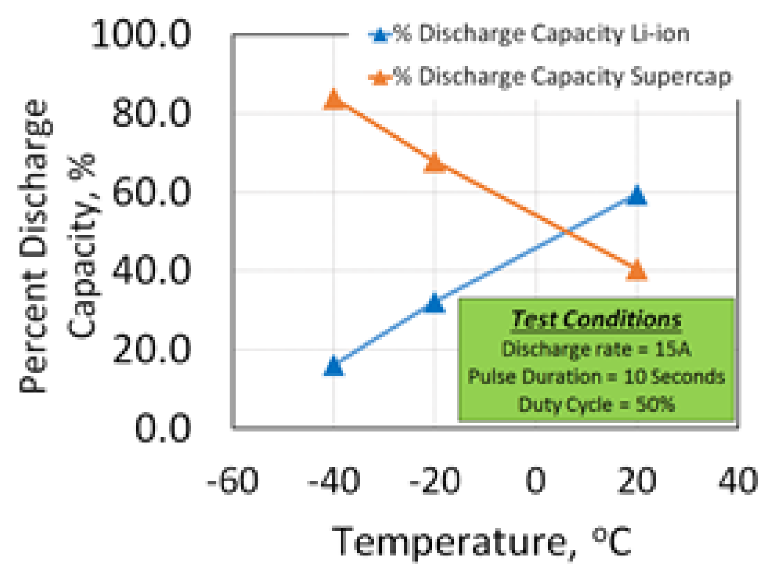
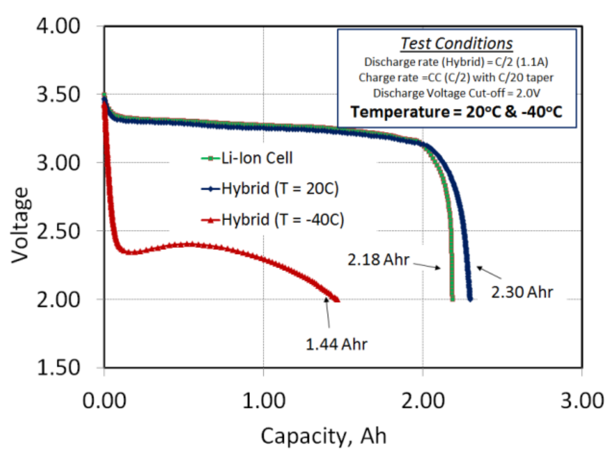
JPL Hybrid Performance Testing







- Excellent performance down to -40°C.
- Li-ion provides high energy output.
- Supercaps provide high power output.
- Enhanced usage life from load-sharing.

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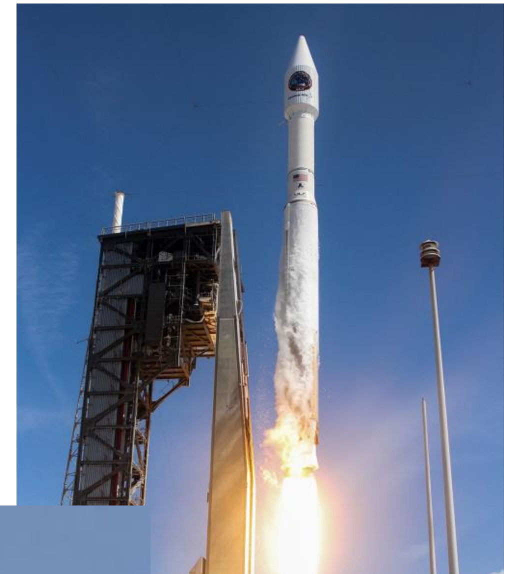
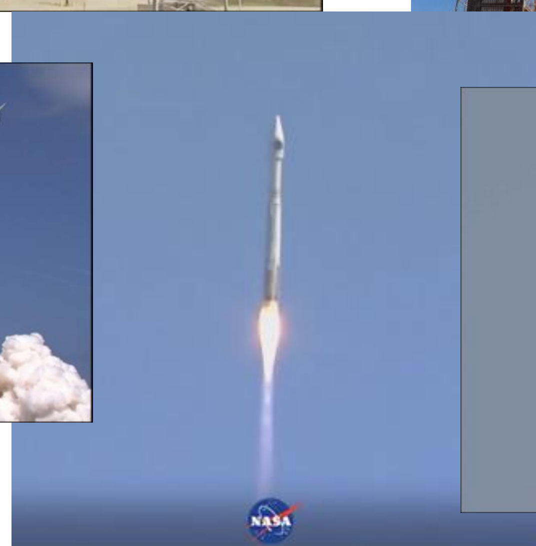
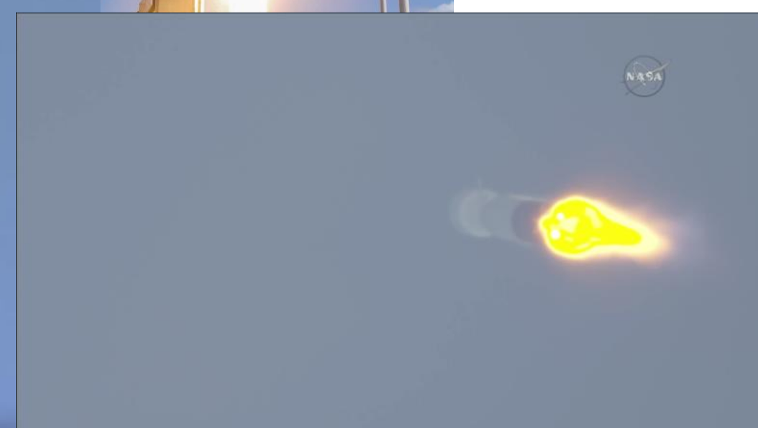
CSUNSat1 Launch from Cape on April 18th, 2017!!







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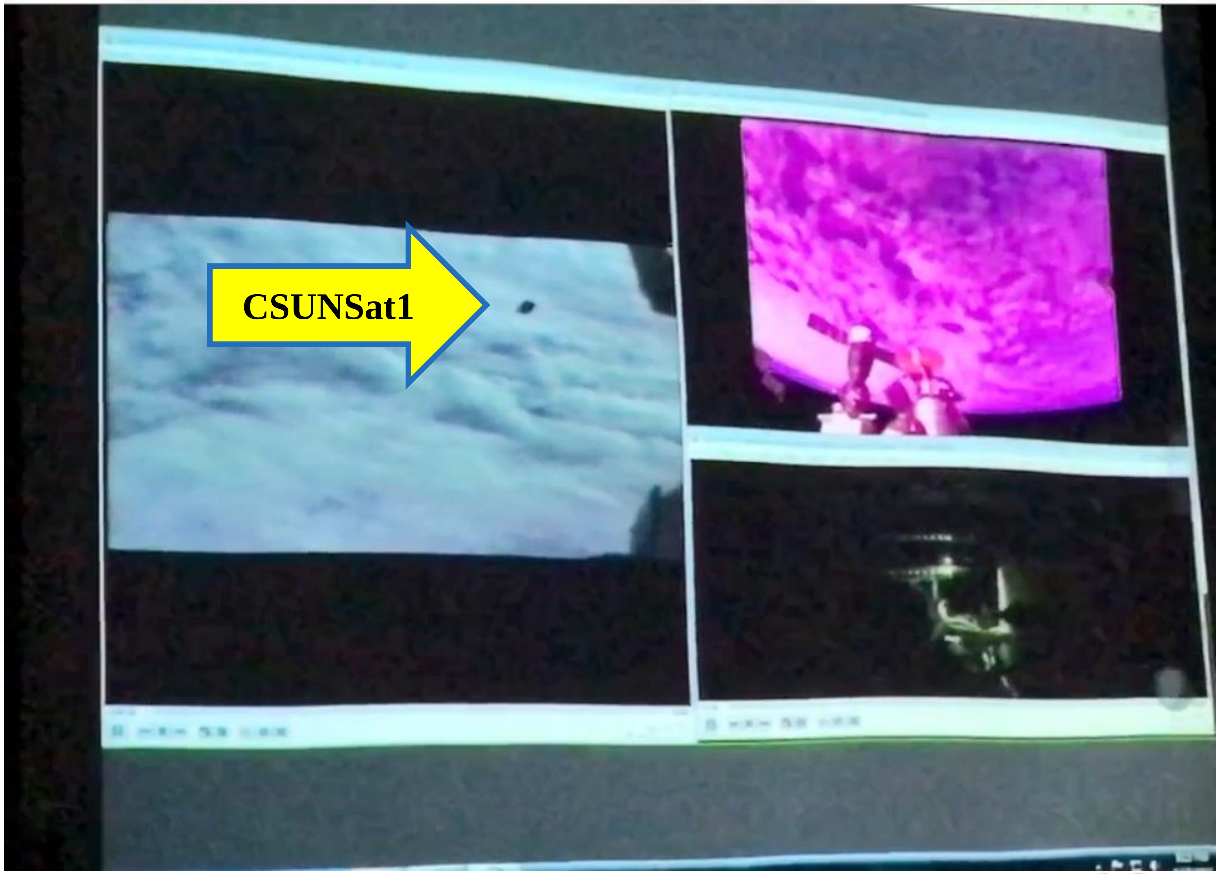
CSUNSat1 Launch from ISS on May 17, 2017, 041500 GMT!!



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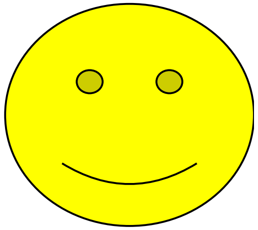
Primary Mission

- CSUNSat1flight system checkout
  - Payload battery functional test.
  - Charge/discharge of battery, supercapacitor, and hybrid mode.
- Payload thermal performance characterization
  - High power (>5C-rate) tests @ nominal temperatures $> 0^{o}$C
  - High power (>5C-rate) tests @ low temperature $< 0^{o}$C.
- *Pass/fail Criteria:*
  - *Both battery and supercapacitor functional.*
  - *Hybrid system is functional.*
  - *Capacity loss on the battery is < 10%.*



100% success!

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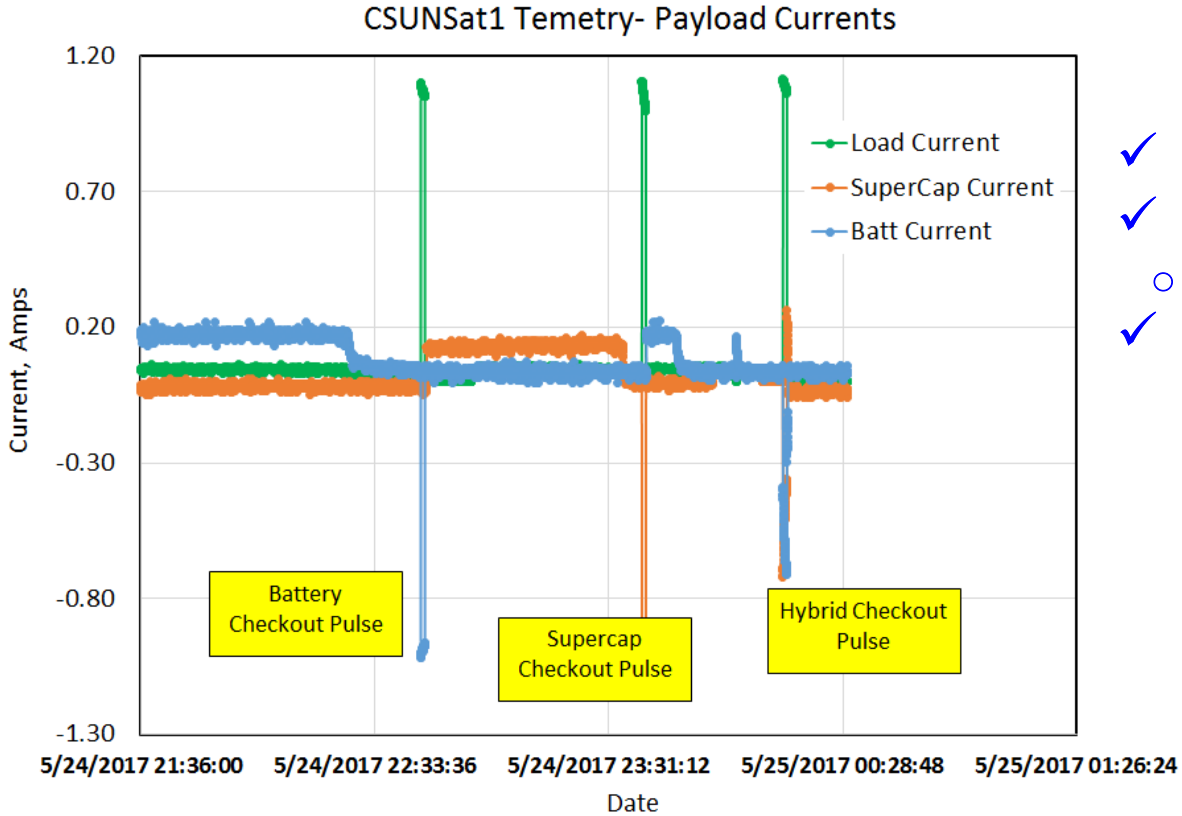
CSUNSat1 flight test data

Payload system checkout



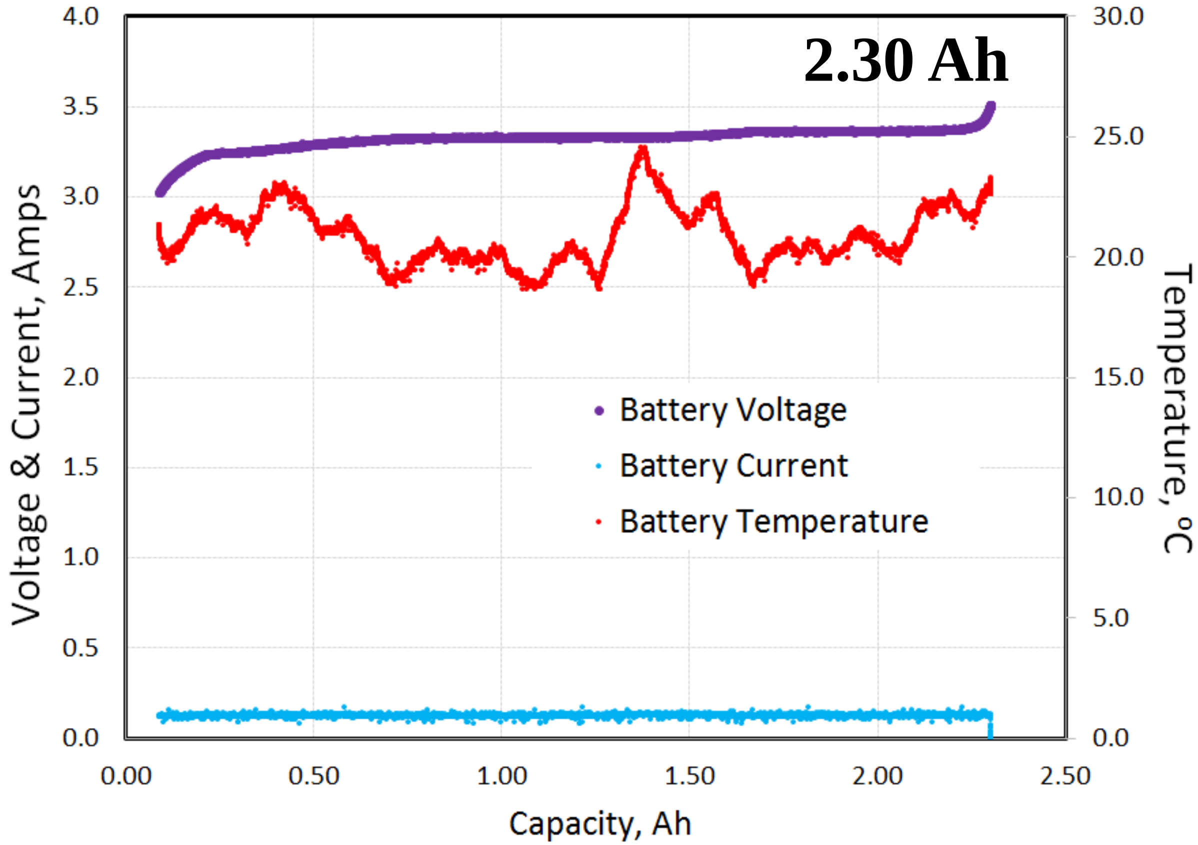
- ✓ **CSUNSat1 all systems go!**
- ✓ **Battery is in good health**
  - **Battery voltage > 3.0V (3.3 BOL)**
- ✓ **SuperCaps are in good health**
  - **Capacitances** **(310F nominal)**

SuperCap1 = 317.8 F

SuperCap2 = 302.1 F

CSUNSat1 flight test data

Initial 24 hr charge cycle



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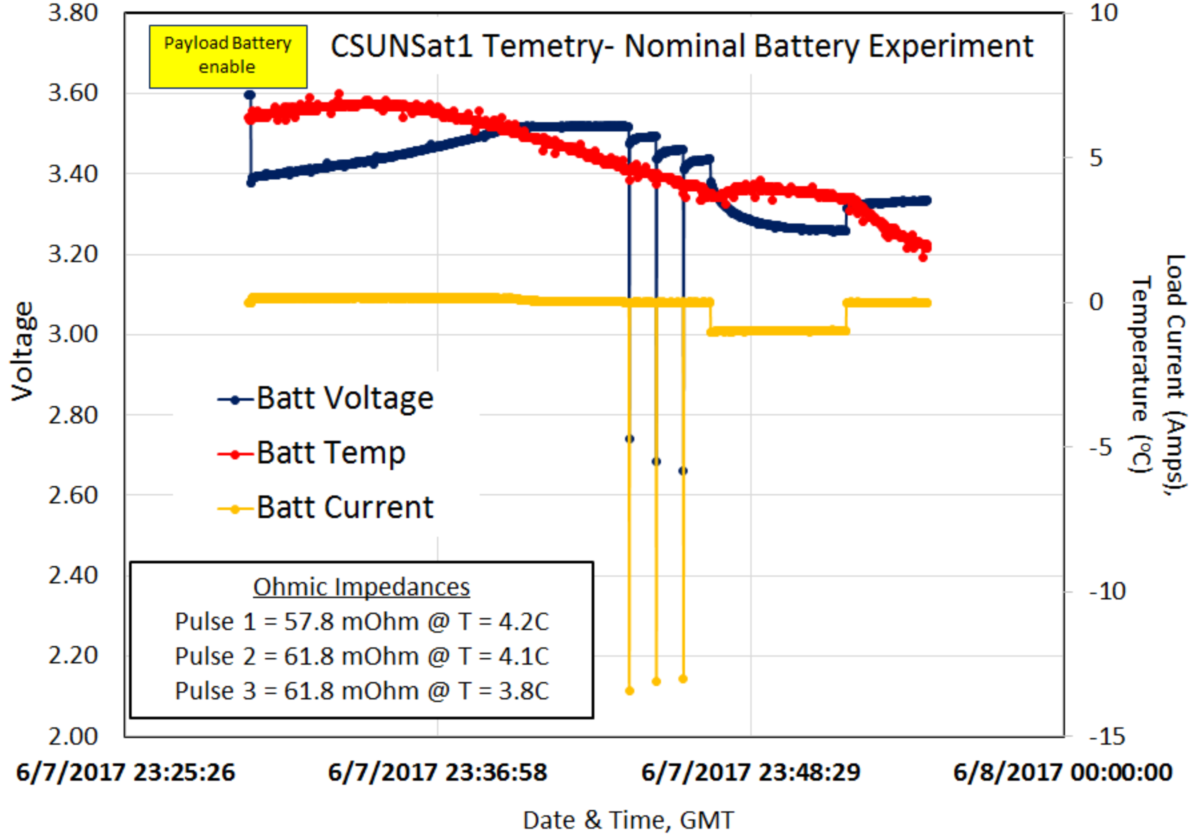
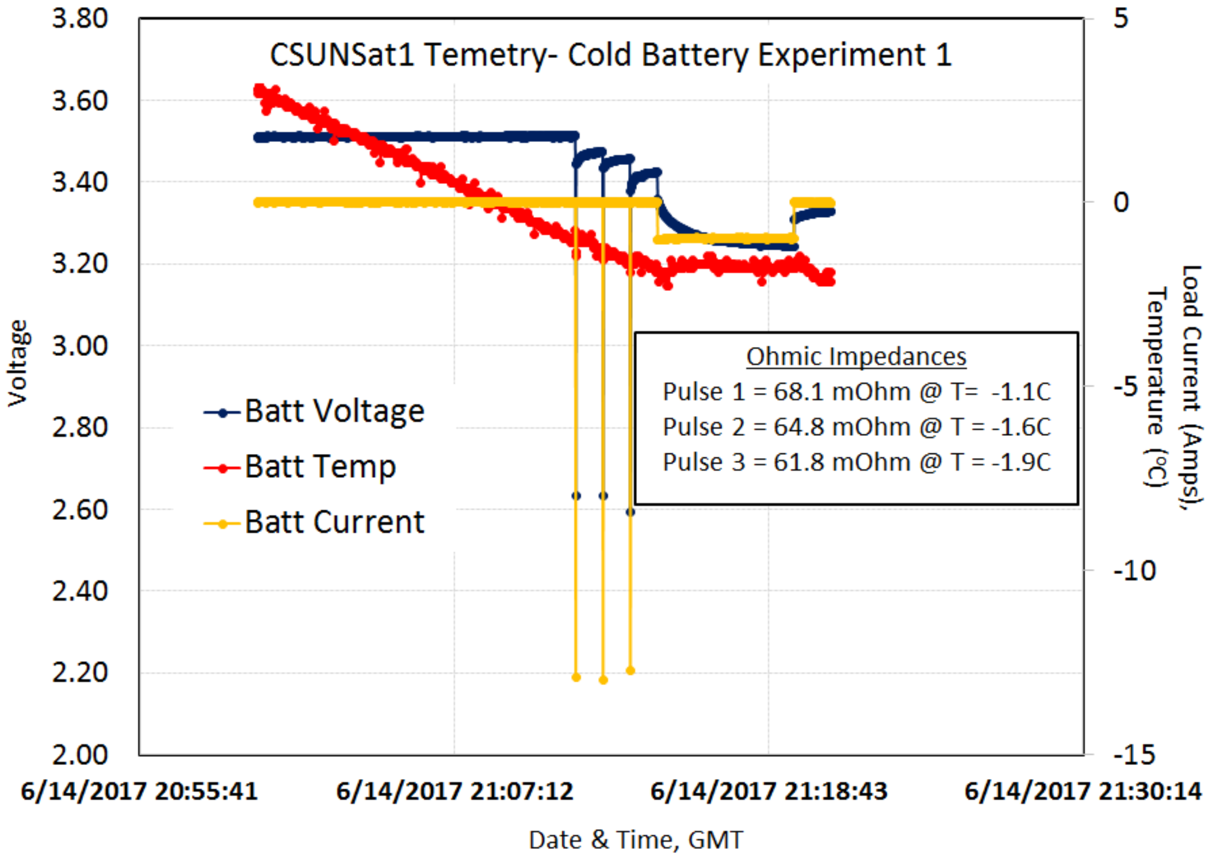
CSUNSat1 flight test data

Nominal temperatures



CSUNSat1 flight test data

Low temperatures



- **CubeSat thermal environment posed significant challenges in achieving low payload temperatures.**

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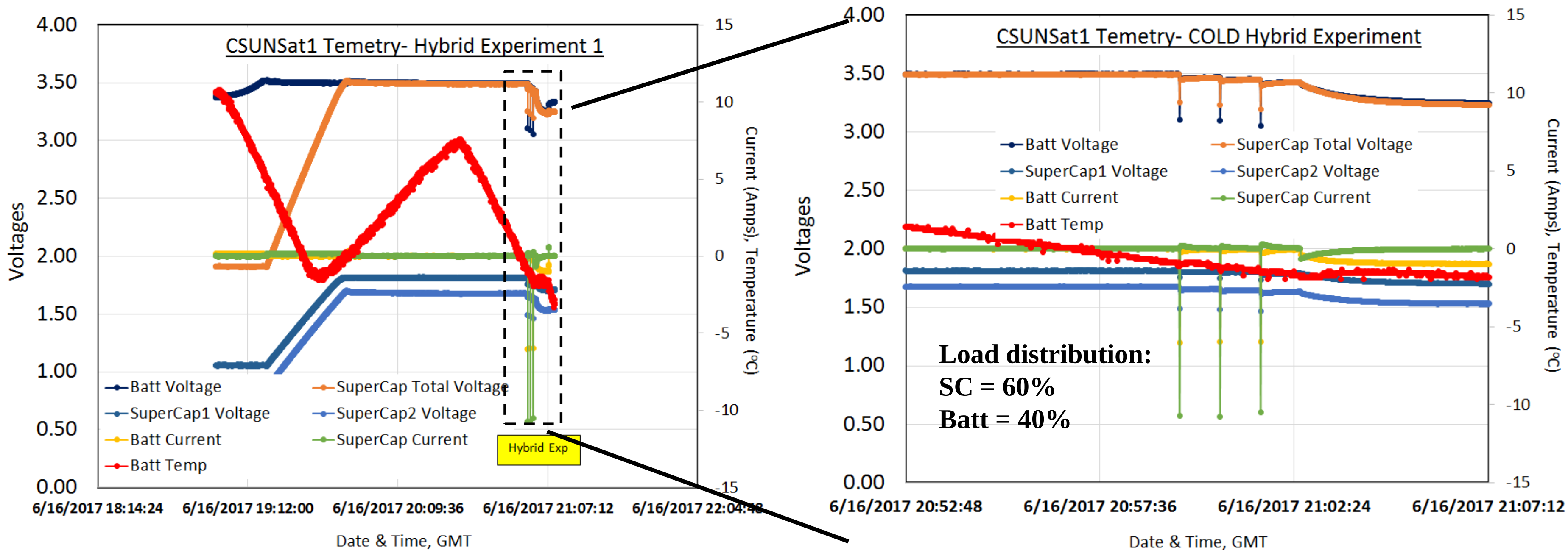
CSUNSat1 flight test data

Low temperatures



Pulse #	Batt Imp (mOhm)	SC Tot Imp (mOhm)	SC2 Imp (mOhm)	SC1 Imp (mOhm)	Temp (°C)
1	64.89	22.35	17.44	4.91	-1.10
2	62.83	21.19	16.07	5.12	-1.33
3	66.70	23.88	17.43	6.46	-1.57

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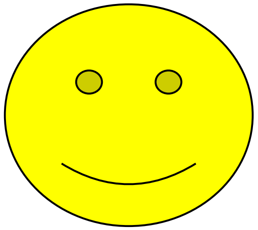
Extended Mission

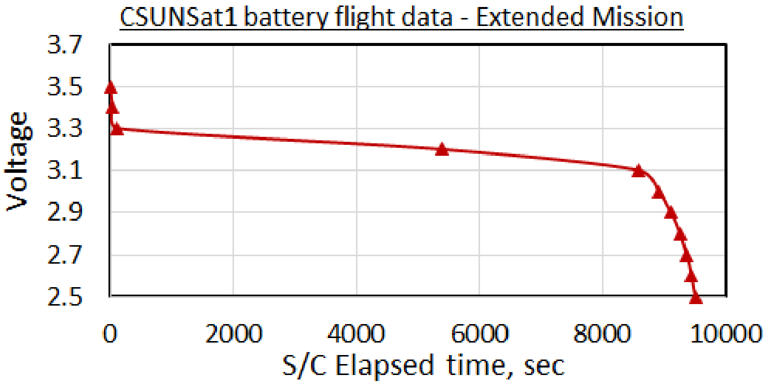
- Enable payload battery as primary energy storage
- Perform battery life characterization
- Battery performance model development
  - Model validation from CSUNSat1 flight data
- *Pass/fail Criteria:*
  - *Minimum of 10 full charge/discharge cycles.*
  - *Functional predictive model capabilities.*
  - *Model fidelity < 5% error.*



100% success!

CSUNSat1 Operational challenges

- Telemetry SD card failed during extended mission phase
- Thermal limitations of payload electronics board from dissipation due to prolonged high rate discharge.



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Battery Model Basics

$$\boldsymbol{Capacity(t) = \int_{sim\_t_o}^{sim\_t_f} i * dt}$$

$$\boldsymbol{SOC} = \frac{\boldsymbol{Capacity(t)}}{\boldsymbol{100\%Cap(Temp, usage)}}$$

$$V(t) = V_o + \eta$$

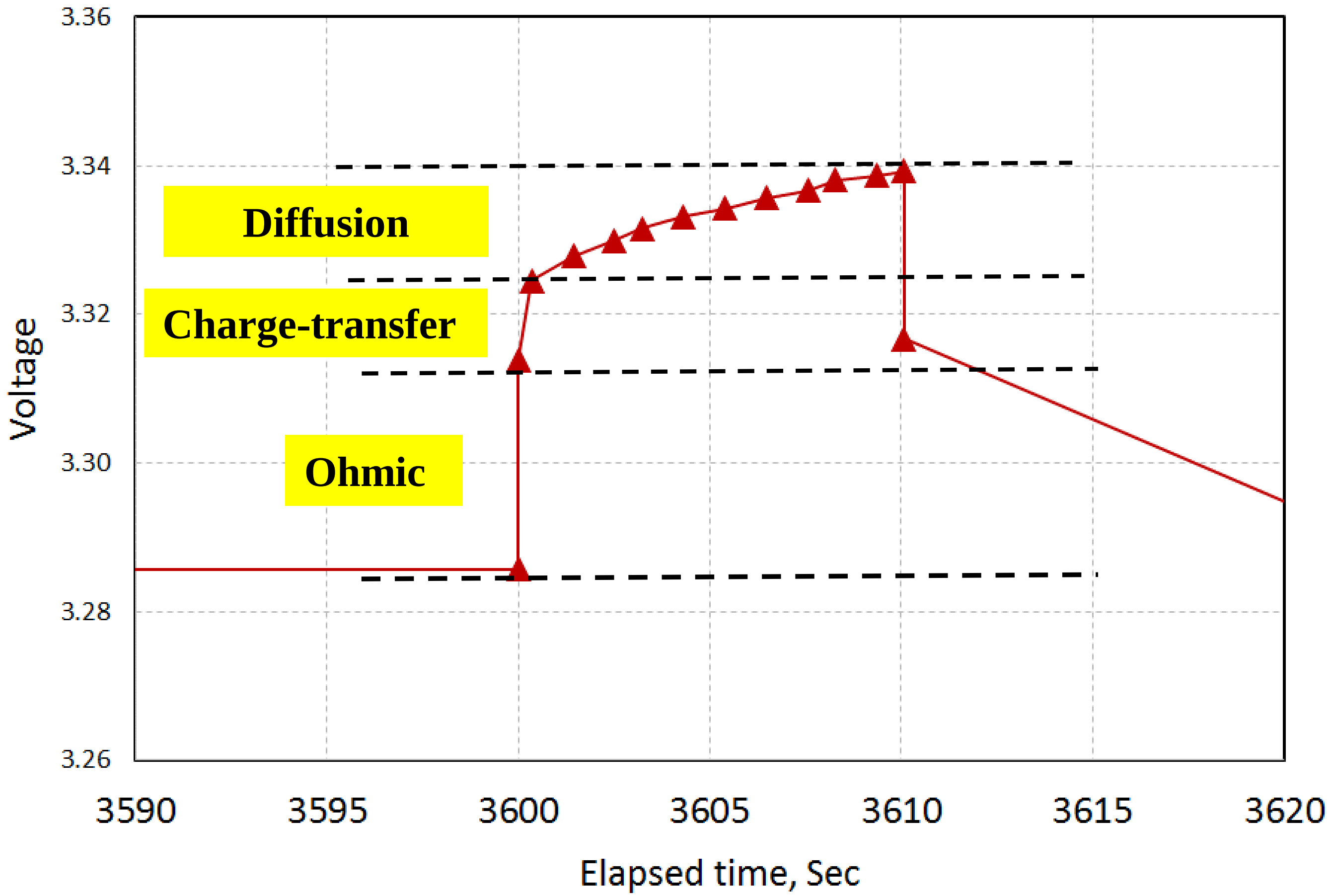
Over-potential

$$\eta = Load \; * Impedance\boldsymbol{s}$$

$$\boldsymbol{Impedance} = f(Ohmic, ChargeTransfer, MassTransfer)$$

$$\boldsymbol{Parameterization} = Impedance(Temp, SOC, time)$$

DC Impedance perspective



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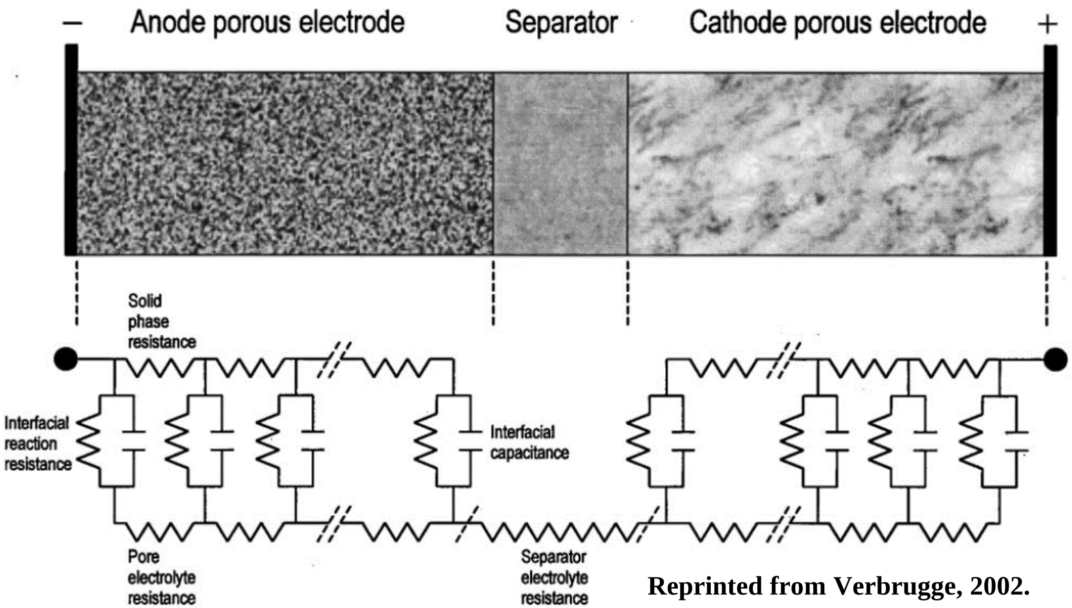
Battery physics from ac impedance



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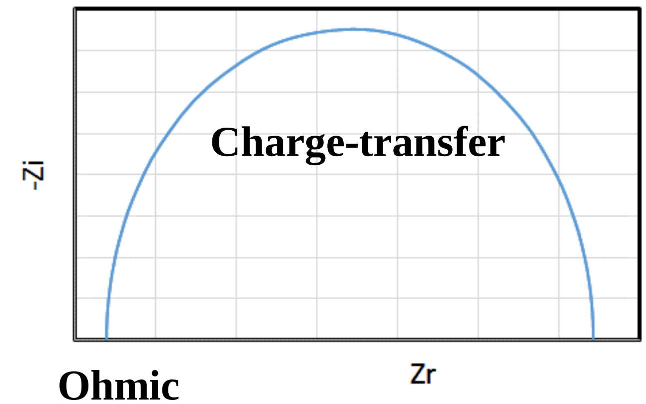

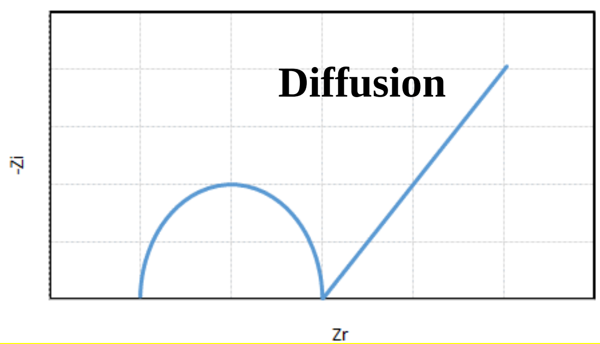

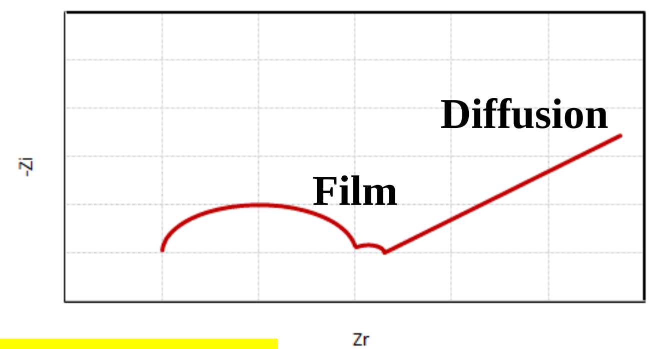

- **Basis for battery model: ohmic, charge-transfer, film, & mass-transfer impedances. It has physical basis, easily measurable, and representable mathematically for modeling purposes.**

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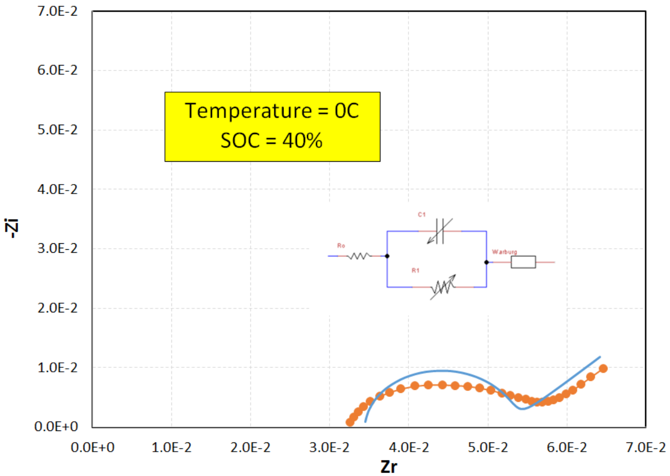
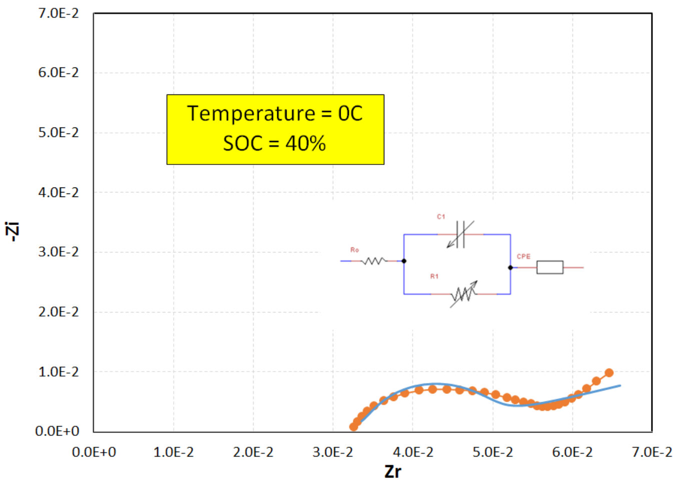
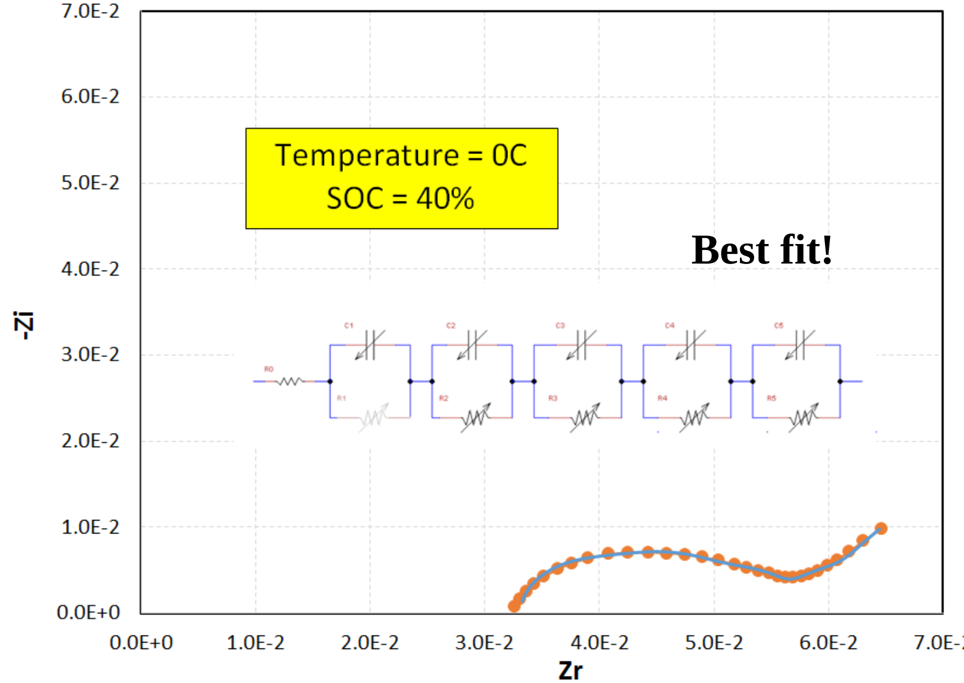
Circuit Modeling Fitting







- **Add RC-units provide substantially improved fit over Warburg & CPE.**

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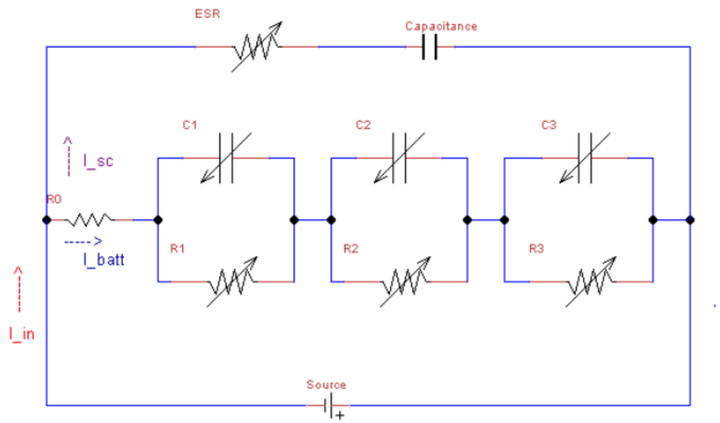
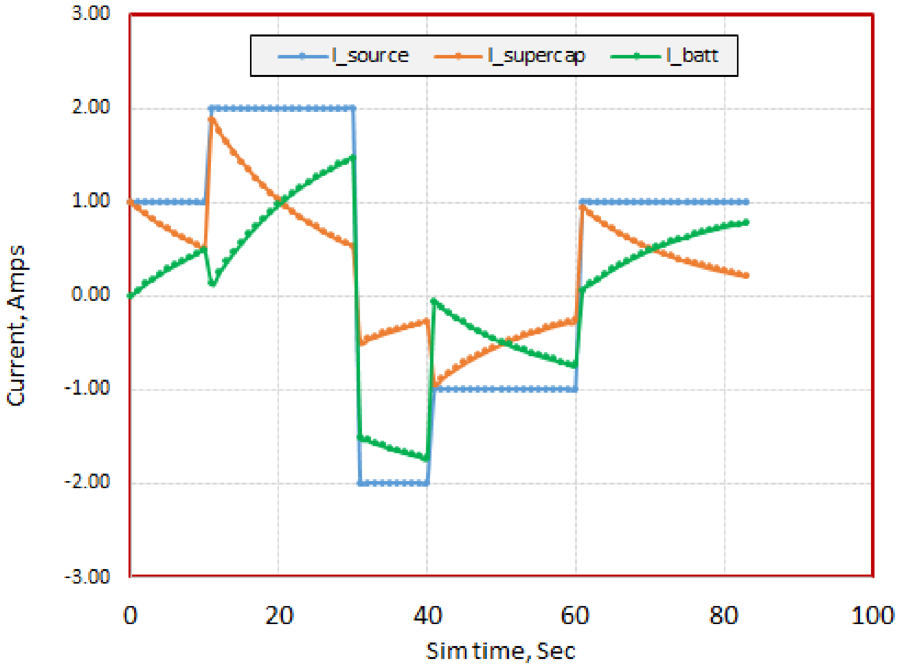
Hybrid Battery Model



Example of hybrid load distribution model:



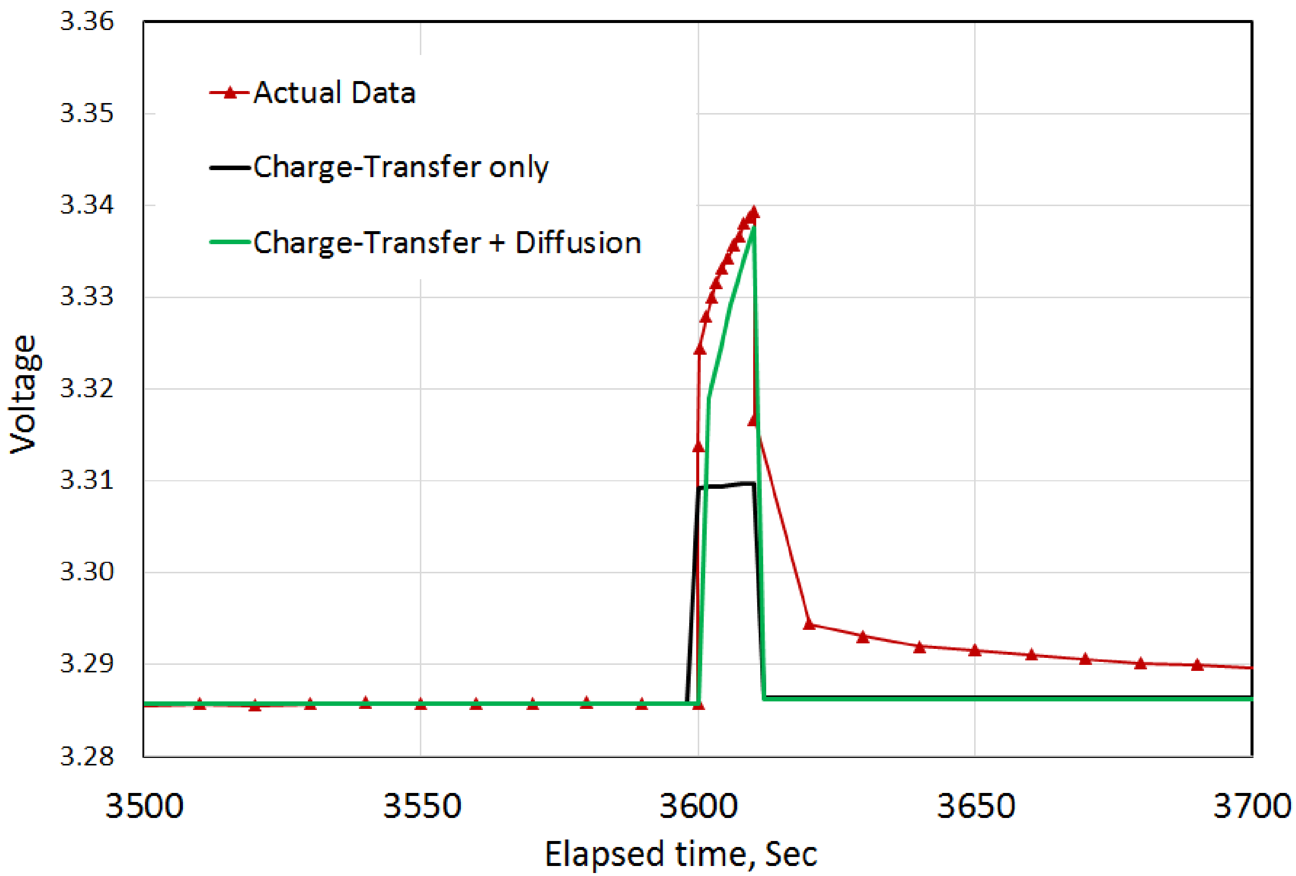
Apply Kirchhoff's current and voltage laws:

$$I_{in} = I_{sc} + I_{batt}$$

$$\xi_{source} = I_o * R_{ESR} + \frac{q}{C_{supercap}}$$

Voltage Model Validation:

Transients



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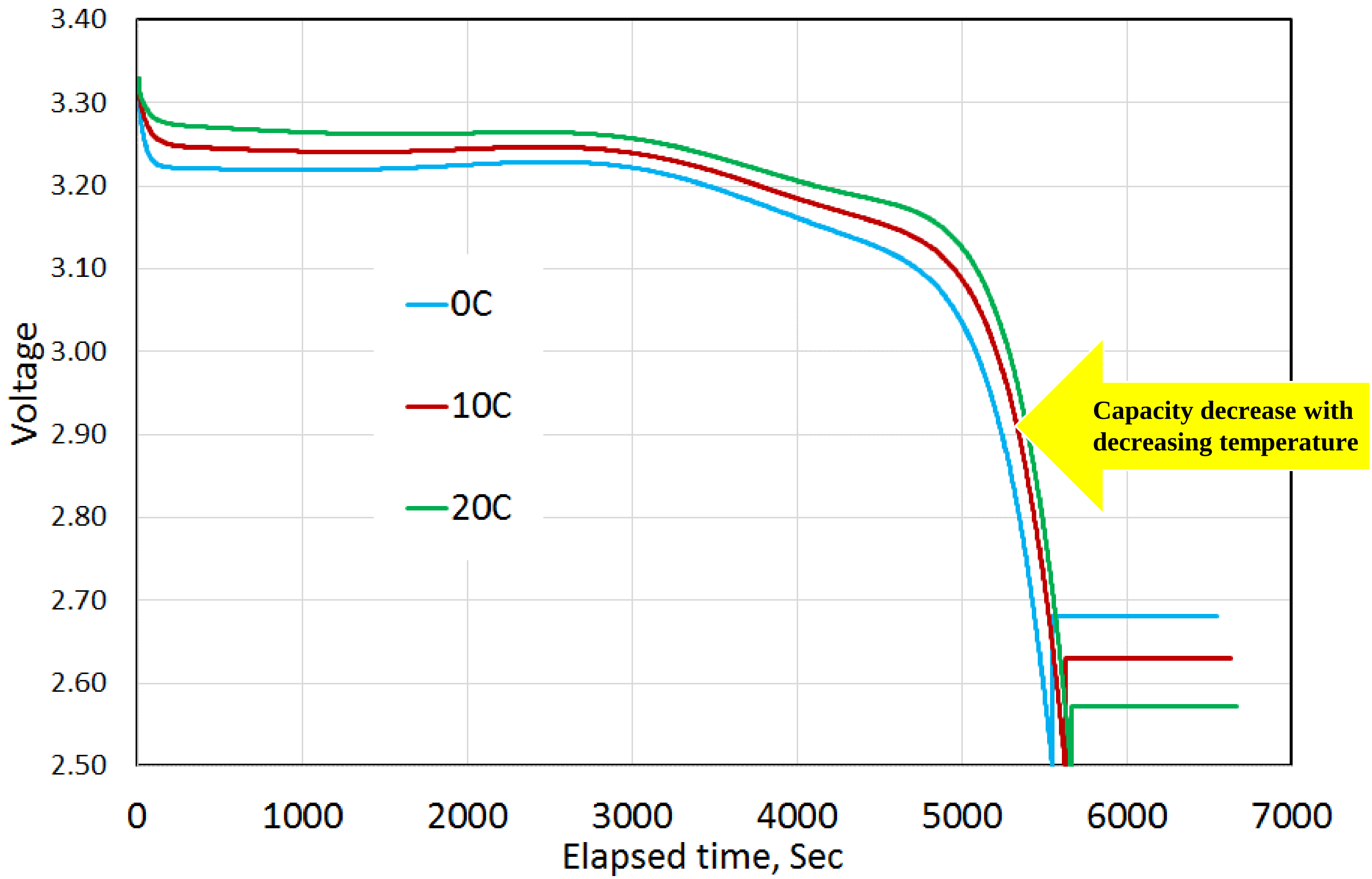
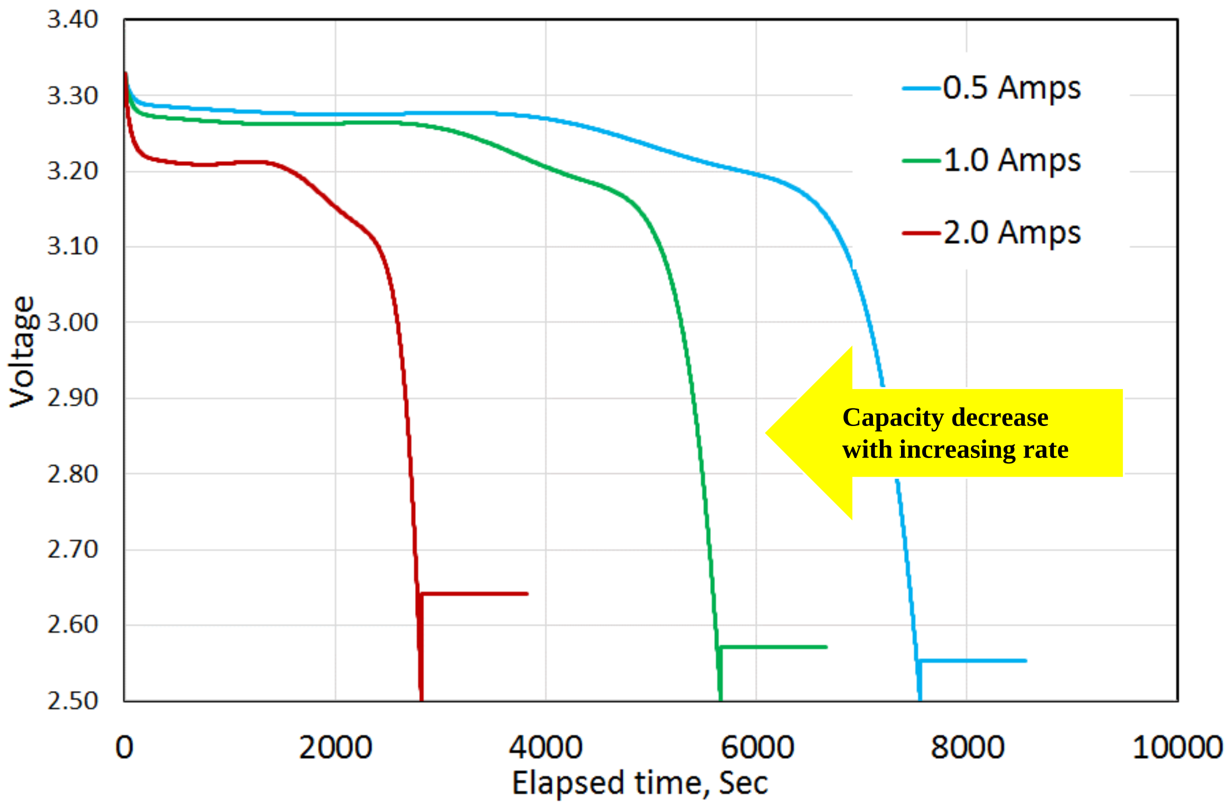
Voltage Model Validation:

Temperatures



Voltage Model Validation:

Current Rates



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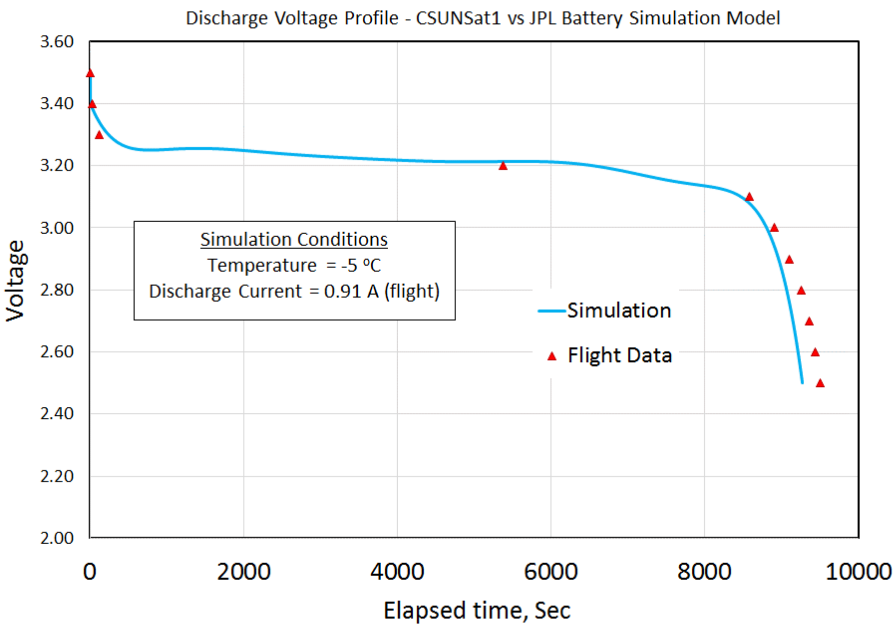
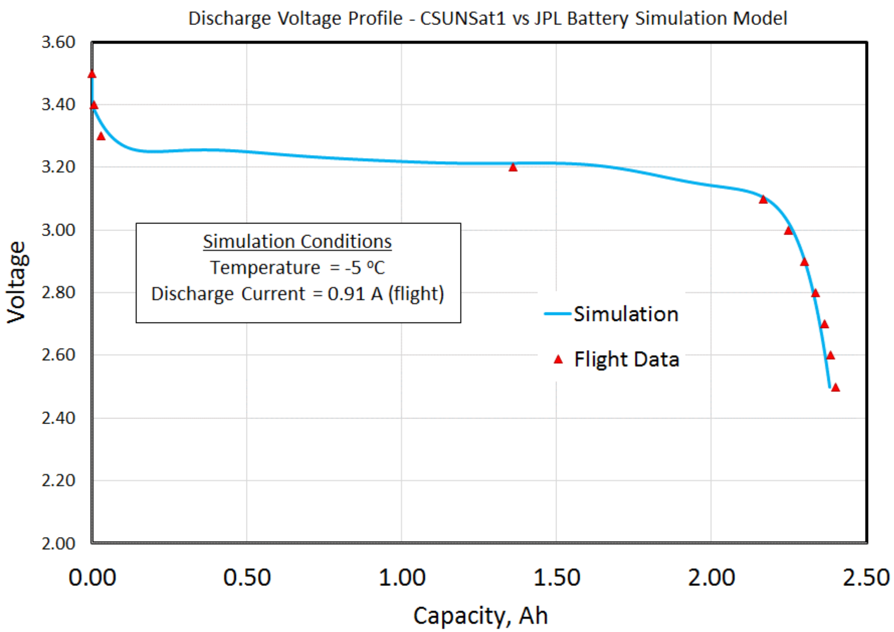
Flight Simulation Test Case:

CSUNSat1 payload telemetry





JPL simulated battery model successfully predicted CSUNSat1 hybrid battery performance on flight.

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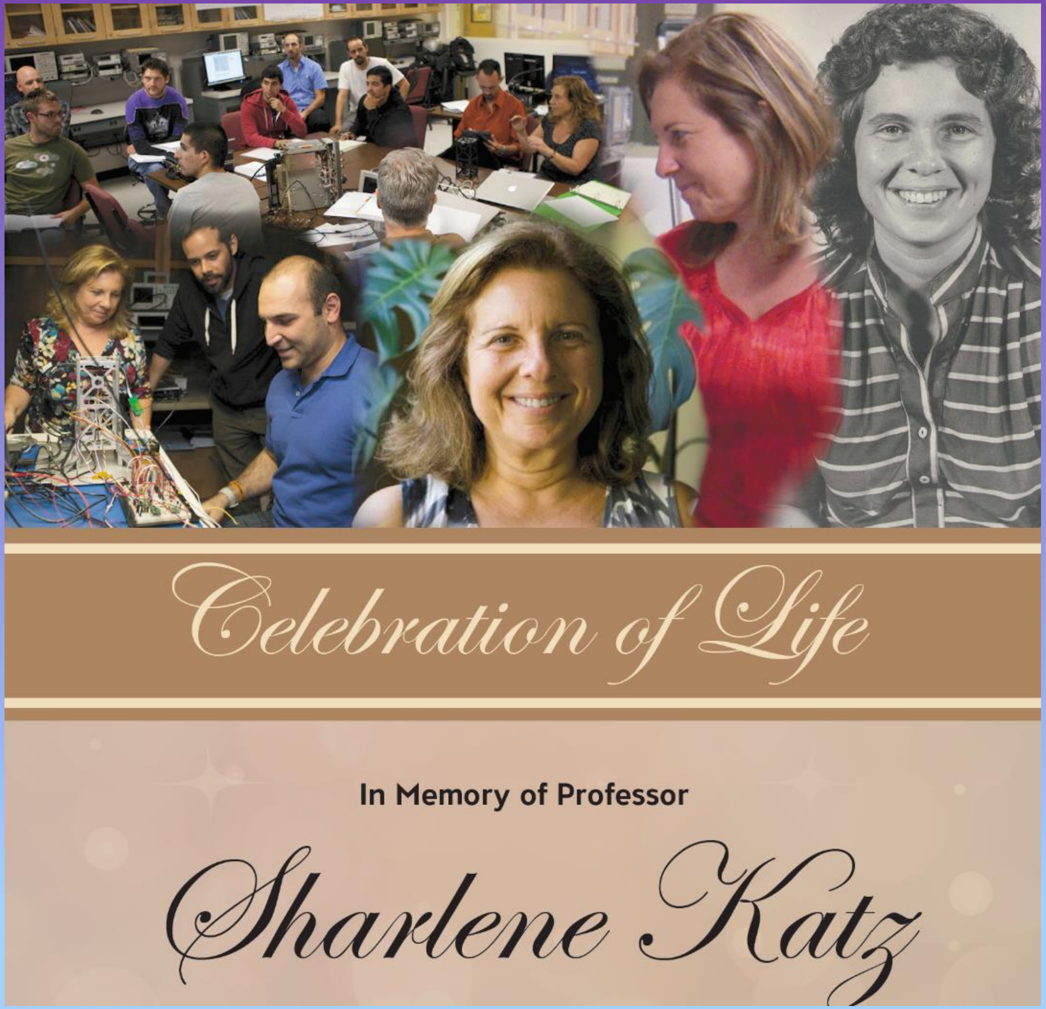
Summary

- CSUNSat1 project is **100% successful** in completing both primary and extended mission phases.
- CSUNSat1 operations provided flight heritage on an enhanced low-temperature high power capable hybrid energy storage system designed for deep space applications.
- CSUNSat1 flight battery telemetry provided validation of an impedance-based battery modeling technique for generic flight applications.
- Future work
  - ❖ Development of CSUNSat2 for science applications.

CSUNSat1 project is dedicated to the Life & Memory of <u>Dr. Sharlene Katz</u>, 1954 - 2017

-In honor of her excellence in engineering & education.



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NASA Acknowledgement

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA) and supported by the NASA STMD 2013 SmallSat Technology Partnerships Cooperative Agreement Notice. JPL CIF (Center of Innovation Funding) for CSUNSat1 operational phase. Lunar Flashlight project for CSUNSat1 extended mission phase.

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