Space Information Laboratories

Engineered for Aerospace

Rad-hard and SEU Immune Power Systems for Cislunar CubeSat Missions

SIL Overview

What we do:

We develop and manufacture space-qualified patented Power Systems and Avionics products for rockets, missiles, strike weapons, small satellites, unmanned aerial vehicles, and aircraft.

For:

NASA

LOCKHEED MARTIN

DARPA

NORTHROP GRUMMAN

Nanoracks

SPACE & MISSILE SYSTEMS CENTER

FIREFLY AEROSPACE

Georgia Tech

SIL's Advanced Technologies

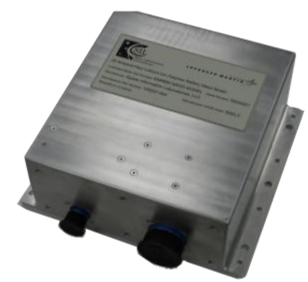
VBITS Autonomous Flight Termination System

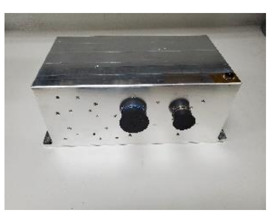
Intelli-Avionics®

Space Based Range

SIL ULA Delta rocket flight heritage.
Image Source: NASA Kennedy Space Center

Intelli-Pack®
High Power Li-Ion Polymer Avionics/Telemetry Battery

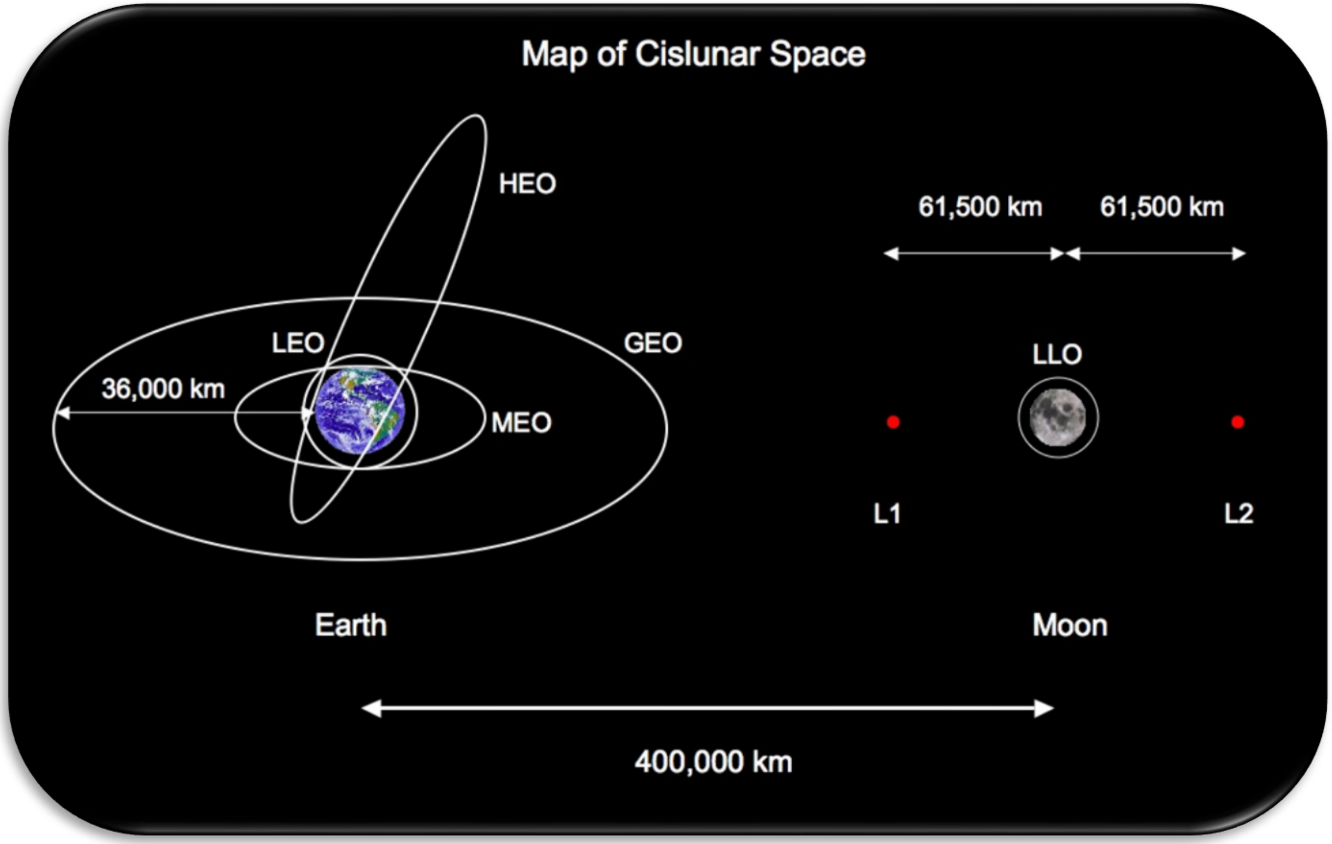




Commercial SmallSat Battery Systems

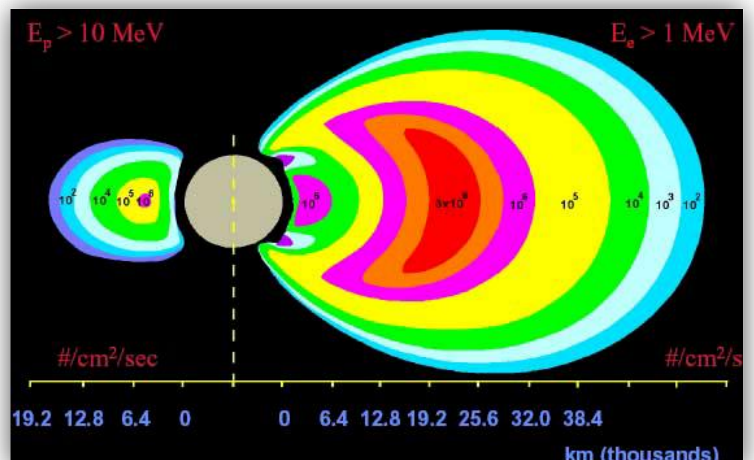
Strike Weapon Li-Ion Polymer FTS

Defining Cislunar



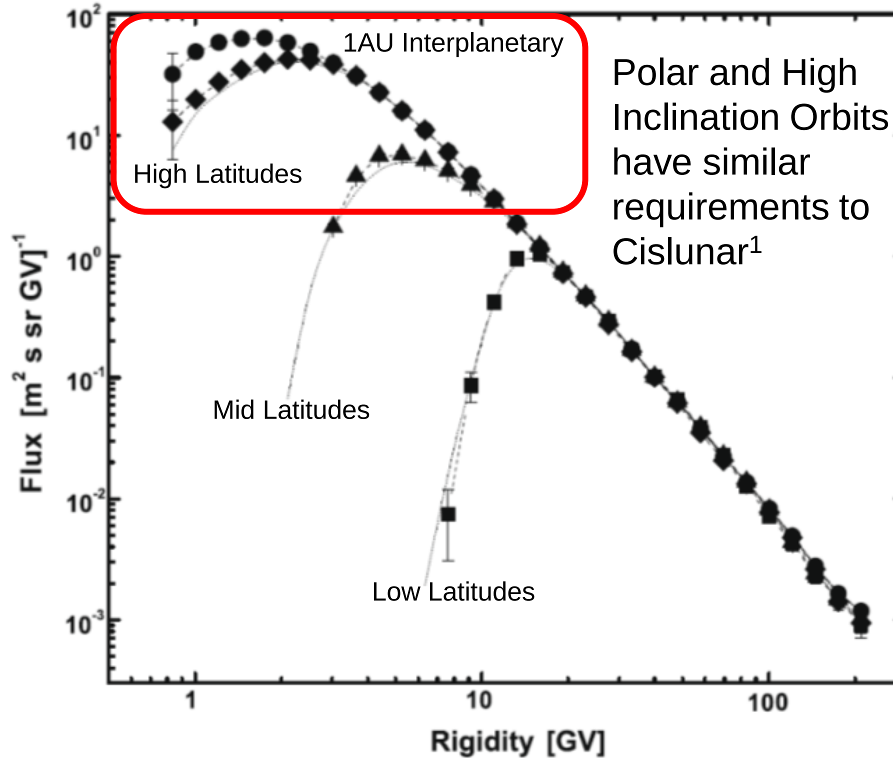
Need to verify: Spudis, Paul D., Develop Cislunar Space Next, Horizons, March/April 2012 (Volume 37, Issue 5), AIAA Hou

Radiation Beyond LEO



Van Allen Belts
Source: Georgia Tech ECE6390 Fall 2012

AMS-01 STS-91
He^{++} GCR Flux



1. If orbit remains outside the Van Allen Belts

Chart adapted from: P. Bobik, G. Boella, M.J. Boschini, M. Gervasi, D. Grandi, K. Kudela, S. Pensotti, P.G. Rancoita; “Fluxes and nuclear abundances of cosmic rays inside the magnetosphere using a transmission function approach”, Advances in Space Research 43 (2009) 385–393

Mitigation Approaches

“Solar Activity Forecast for Next Decade Favorable for Exploration”
– 2019, Bay Area Environmental Research Institute at NASA’s Ames Research Center
(https://www.nasa.gov/feature/ames/solar-activity-forecast-for-next-decade-favorable-for-exploration)

Mission Planning & Design

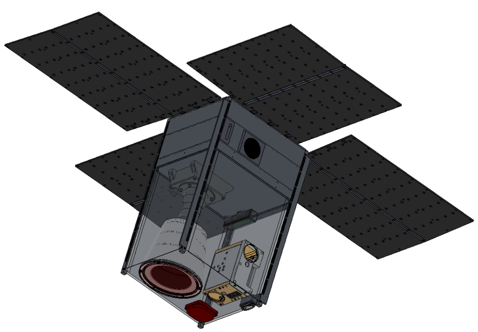
Technology Selection & Design

Hardened by Design (Part or Circuit Levels)

System Level Hardening

Mission Requirements

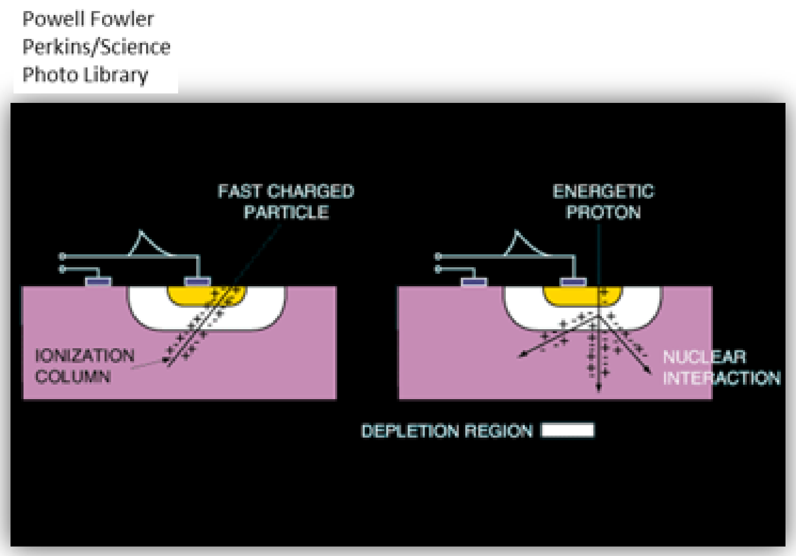
Our Solution…



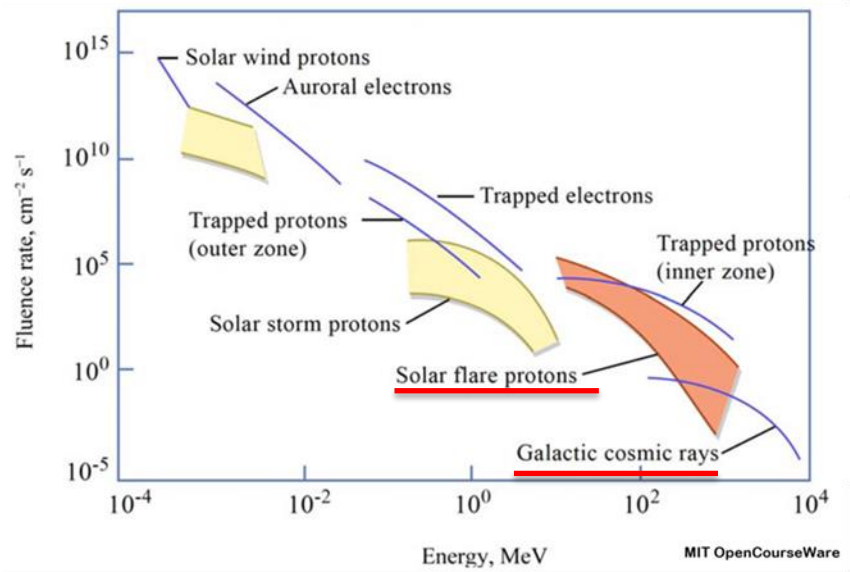
Source: R.L. Ladbury, IEEE NSREC Short Course. July 2007

Radiation Overview

Types	Source	Failure Modes
Galactic Cosmic Rays (GCR)	The Universe	Digital circuit upsets
Solar Particle Events (SPE)	The Sun	Solar array degradation
Trapped Radiation	Van Allen Belts	Thermal surface degradation



Single Event Upset (SEU) in a MOS/CMOS Field effect transistor



Synoptic view of integral particle fluence rate of space radiation versus upper boundary of particle energy (Wilson, J.W., 1978. Environmental geophysics and SPS shielding. Lawrence Berkeley Laboratory Report LBL-8581, pp 33-116).

Radiation is not isotropic or deterministic. Particles are random.

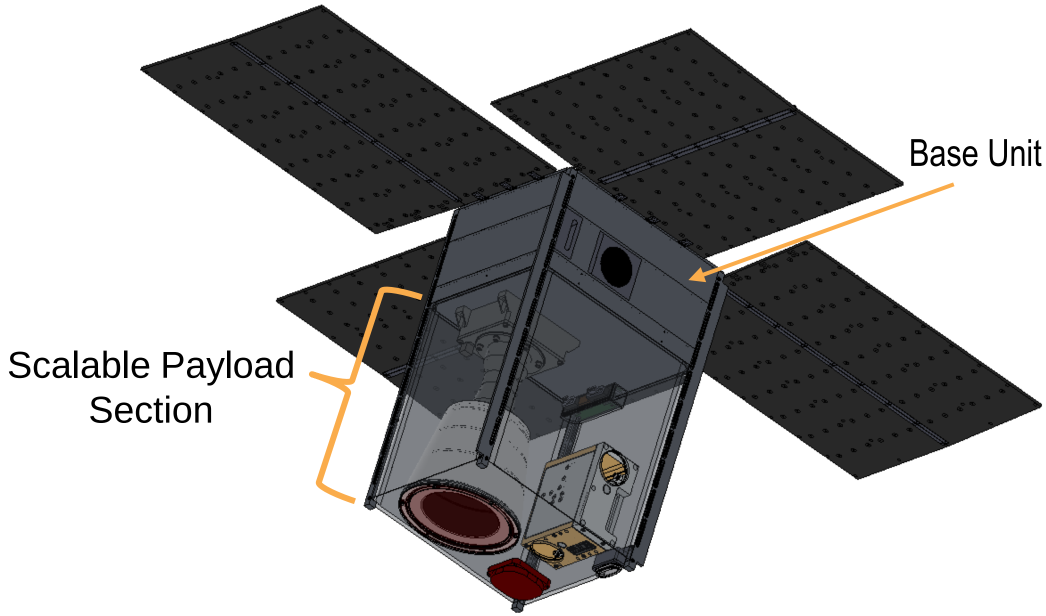
Shielding

Shielding [mm Aluminium]	High particle fluences from the Sun ("Max" or confidence level=95%)		Low particle fluences from the Sun ("Min" or confidence level=50%)	
	Dose over 2h (on the Moon) [mSv]	(Travel) Dose over 180h (7.5d) [mSv]	Dose over 2h (on the Moon) [mSv]	(Travel) Dose over 180h (7.5d) [mSv]
0.2	215.86	19'410.7	30.07	2'704.3
0.3	150.10	13'496.9	18.21	1'638.0
0.4	113.83	10'236.1 (1 krad)	12.51	1'125.3 (110 rad)
0.5	90.46	8'135.5	9.16	823.6
0.6	74.29	6'681.7	7.00	629.0
0.8	54.64	4'913.8	4.63	416.4
1	43.24	3'889.1	3.41	306.4
1.5	27.93	2'509.2	1.92	172.8
2	20.14	1'810.9	1.27	114.3
2.5	15.42	1'386.9	0.91	81.7
3	12.20	1'097.3 (110 rad)	0.68	60.8
4	8.43	757.7	0.43	38.3
5	6.24	561.6	0.30	26.5
6	4.96	446.2	0.22	20.0
7	4.01	360.8	0.17	15.5
8	3.34	300.4	0.14	12.5
9	2.86	257.5	0.12	10.4
10	2.45	220.7	0.10	8.7
12	1.91	171.5	0.07	6.5
14	1.51	135.5	0.05	4.9
16	1.23	110.6	0.04	3.9
18	1.03	92.9	0.04	3.2
20	0.87	77.9	0.03	2.6

Chameleon SmallSat

OMSR Bus

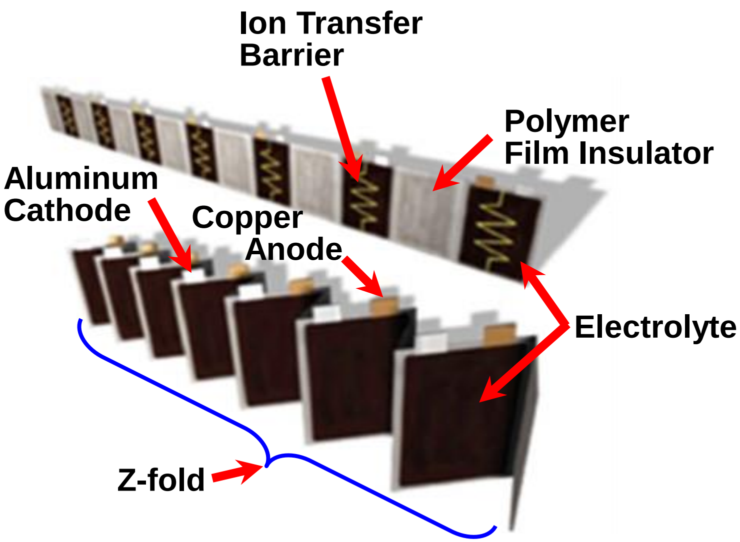
- 12U to 27U Open, Modular, Scalable, Reconfigurable (OMSR) Flexible Bus
- Designed for EMI/EMC protection of advanced payloads
  - **LEO:** ISR, SAR, PNT, SIGINT
  - **Cislunar:** PNT, Exploration, *Your Vision*
- Built on a collection of USAF-funded TRL-9 Small Business Technology subsystems
- Shielded from every angle



SIL Power Storage

Li-Ion Polymer Intelli-Pack® Battery Products	Discharge Current	Cycle Life	Thermal Cycle
8S1P, **2 Ah** 5.7"L x 3.25"W x 3"H, 2.7 lbs	30A Continuous 60A Pulse, < 1 Sec	1000 cycles @ 1C to 80% capacity, 100% DOD	-10 to +60°C no heater, -40 to +60°C w/ heater
8S1P, **2.1 Ah** 6.36"L x 3.75"W x 1.5"H, 1.95 lbs	2.1A Continuous 6A Pulse, < 1 Sec	1000 cycles @ 1C to 80% capacity, 100% DOD	-10 to +71°C no heater, -40 to +71°C w/ heater
8S1P, **3.3 Ah** 6.75"L x 4"W x 2.8"H, 3.25 lbs	6.6A Continuous 16.5A Pulse, < 1 Sec	1000 cycles @ 1C to 80% capacity, 100% DOD	-10 to +60°C no heater, -40 to +60°C w/ heater
8S1P, **5 Ah** 8.7"L x 3.3"W x 4.3"H, 5.75 lbs	30A Continuous 60A Pulse, < 1 Sec	1000 cycles @ 1C to 80% capacity, 100% DOD	-10 to +60°C no heater, -40 to +60°C w/ heater
8S2P, **6.6 Ah** 6.75"L x 4"W x 4.2"H, 5.5 lbs	13.2A Continuous 33A Pulse, < 1 Sec	1000 cycles @ 1C to 80% capacity, 100% DOD	-10 to +60°C no heater, -40 to +60°C w/ heater
8S1P x 2, **20 Ah** 9"L x 9"W x 3.75"H, 14.5 lbs	30A Continuous 100A Pulse, < 1 Sec	500 cycles @ 1C to 80% capacity, 100% DOD	-10 to +60°C no heater
8S2P, **52 Ah** 14"L x 7"W x 5.5"H, 26.2 lbs	104A Continuous 208A Pulse, < 10 Sec	22,000 cycles @ C/2 to 80% capacity, 20-30% DOD	-10 to +60°C no heater, -40 to +60°C w/ heater

Li-Ion Z-Fold Battery



- 170 to 250 Wh/Kg Energy Density (LCO & NMC Li-Ion Cells)
- Capacities in .5 to 200 Amp-Hours and 10 Year Life
- Used in Chevy Bolt, Electric Vehicles, UAS, Launch Vehicles, Missiles, SmallSats, etc.
- Very low cell internal resistance (10Amp-Hr Cell, < 3 mΩ) allowing high current discharge (5-30C) and rapid recharge (< 1 hour, 1C Charge) and minimal heat rise

Protect, Prevent, and Enclose

Certain technologies are employed to stop cell failure propagation, limit cell-to-cell thermal transport, and safely contain flames and debris.

Protect with SIL's advanced RadTol BMS housed within each Li-Ion Intelli-Pack® battery

- Real-time monitoring and balancing of all cells
- Protects cells against Overvoltage, Undervoltage, Over Current, Short Circuit, and OOT Thermal
- Temperature sensing

Prevent with semi-active Thermal Isolating Phase-change (TIP) material for large format batteries

- TIP between each cell pair and around the cell pack
- Phase change characteristics absorb heat energy if a cell-pair goes into thermal runaway
- Prevents cascading cell failures

Enclose with SIL's robust and flight proven battery housing

Cell pack is further insulated with UL 94 V-0 fire resistant foam to smother any cell expulsion

RadTol BMS

Battery telemetry at 1 Hz rate

- Voltages: 1 mV resolution, pack & cells
- Current: 1 mA resolution, battery level
- Temperature: 1°C resolution, arrayed on cells
- SOC and SOH, Diagnostics flags

Protection Features

- Charge: Over voltage, over current, Lockout, cell voltage equalization,
- Discharge: Under voltage, over current, short circuit, lockout, pulse programmable
- Temperature: Over/under protection for all operations, Autonomous heaters for cold operations

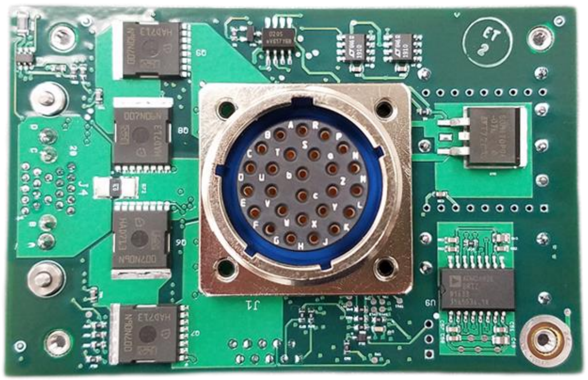
Autonomous Built-In-Test

Verifies battery is functional, periodically updates SOC, SOH

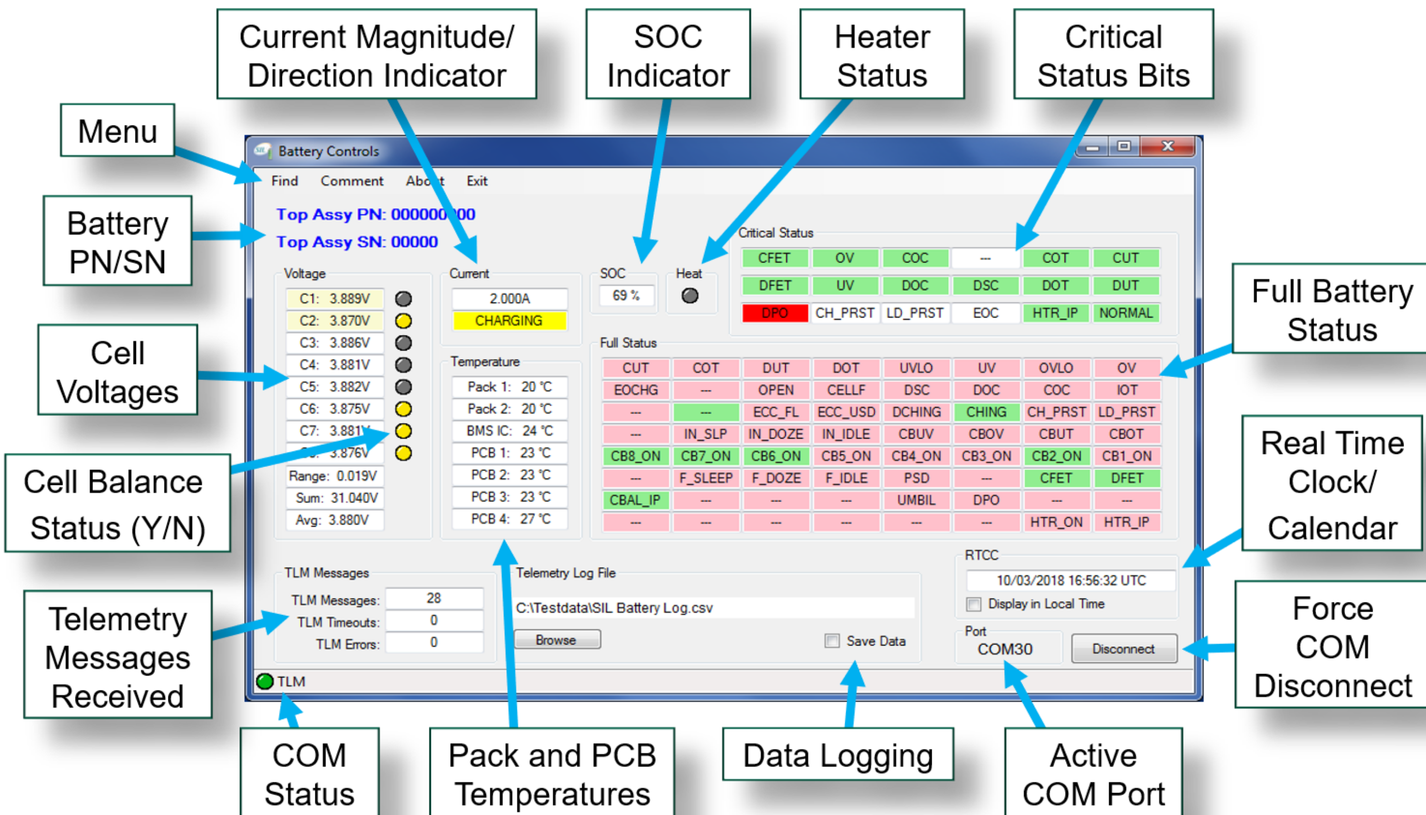
Min/Max Data Recorder (Black Box), Saves battery data in event of fault or failure

Programmable BMS

Agnostic to Cell Chemistry



Control Interface



Testing Standards

NAVSEA 9310-AQ-SAF-010

Technical Manual for Navy Lithium Battery Safety Program Responsibilities and Procedures

SMC-S-018, Li-Ion Battery Design Guideline for Launch Vehicle Applications

SMC-S-016, Test Requirements for Launch, Upper-Stage and Space Vehicles

RCC 319, Section 4.26 - Li-Ion FTS Batteries

Cell Screening requirements and Range Safety Space Qual for launch vehicle applications

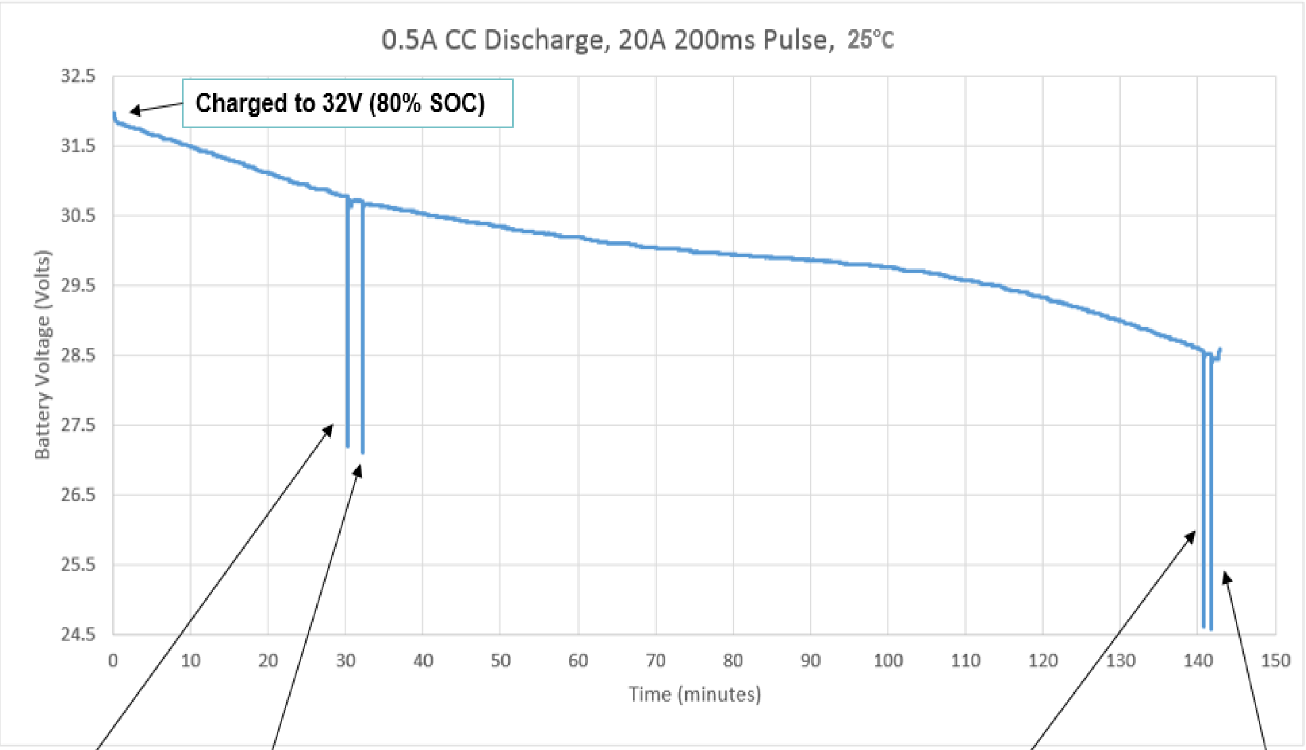
RCC 324-01, Li-Ion Batteries for Avionics and Telemetry Systems

BMS designed to pass UN38.3 Tests 1 thru 5, and 7

SIL

Discharge Testing

2Ah FTS Li-Ion Battery Continuous and Pulse Current Performance



First set of (4) 20A pulses at 30 minutes

Second set of (4) 20A pulses at 30 minutes

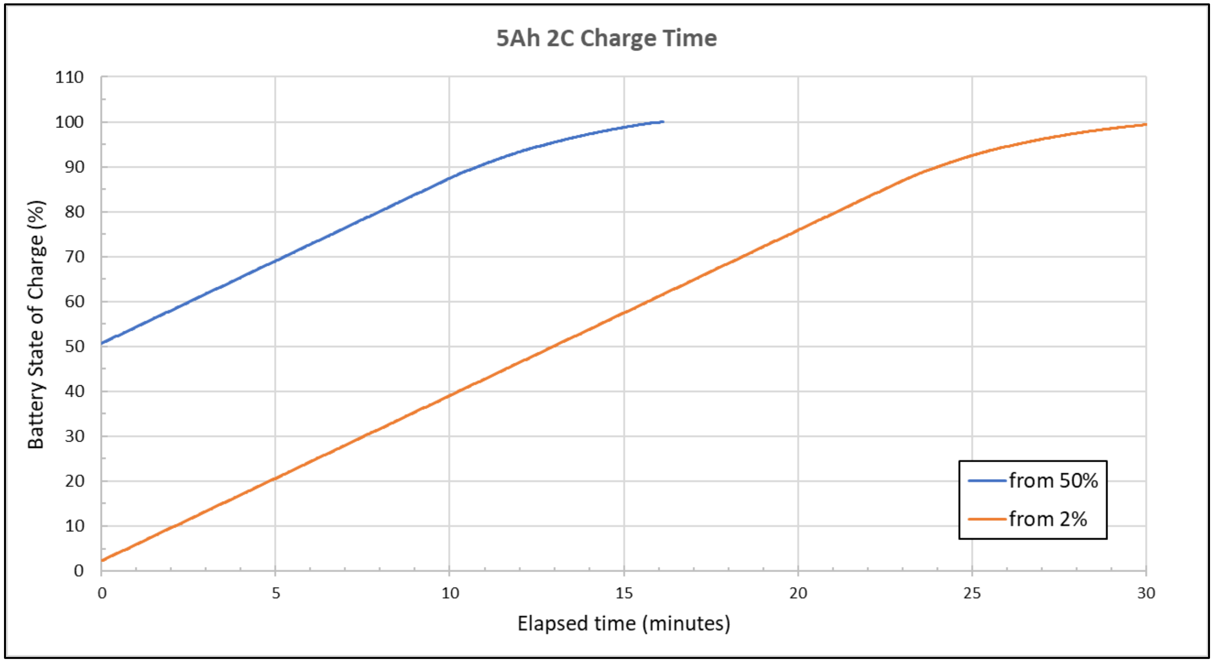
Supplied a 0.5A CC for 140+ minutes with (4) sets of (4) 20A pulses. Voltage remained above 24.5V during all pulses.

First set of (4) 20A pulses to reach minimum voltage droop

Second set of (4) 20A pulses to reach minimum voltage droop

Charge Testing

5Ah FTS Li-Ion Battery 2C Fast Charge Performance



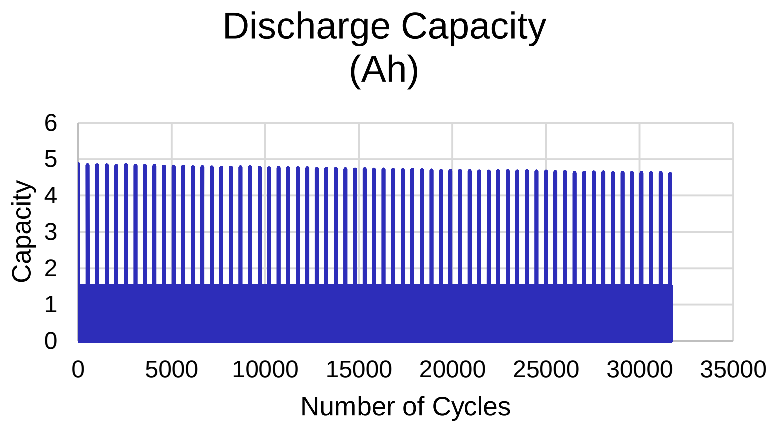
- Battery traditionally charged at C/2 per cell spec sheet and manufacturer recommendation
- Tested 2C "fast" charging with high current capability 5 Ah battery
- BMS includes autonomous charge cut-off functionality so man-in-the-loop is not required

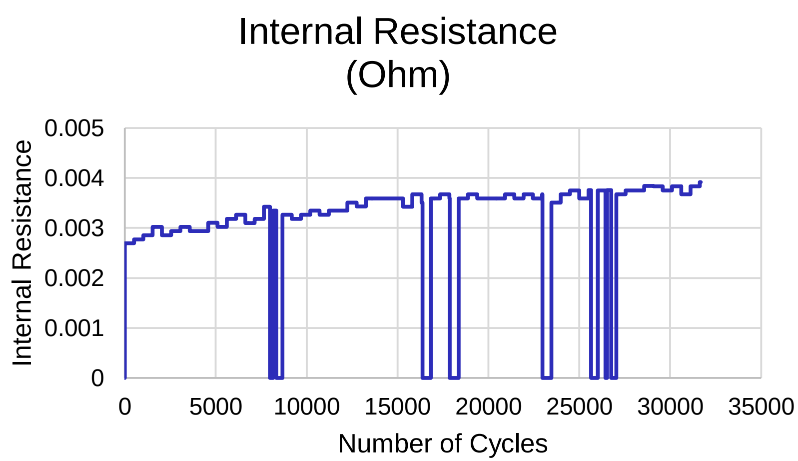
5Ah battery reached 100% SoC from 50% SoC in 16 minutes

5Ah battery reached 100% SoC from 2% SoC in 30 minutes

Life Cycle Testing

5Ah Li-Ion Battery 1-Year Vacuum Test



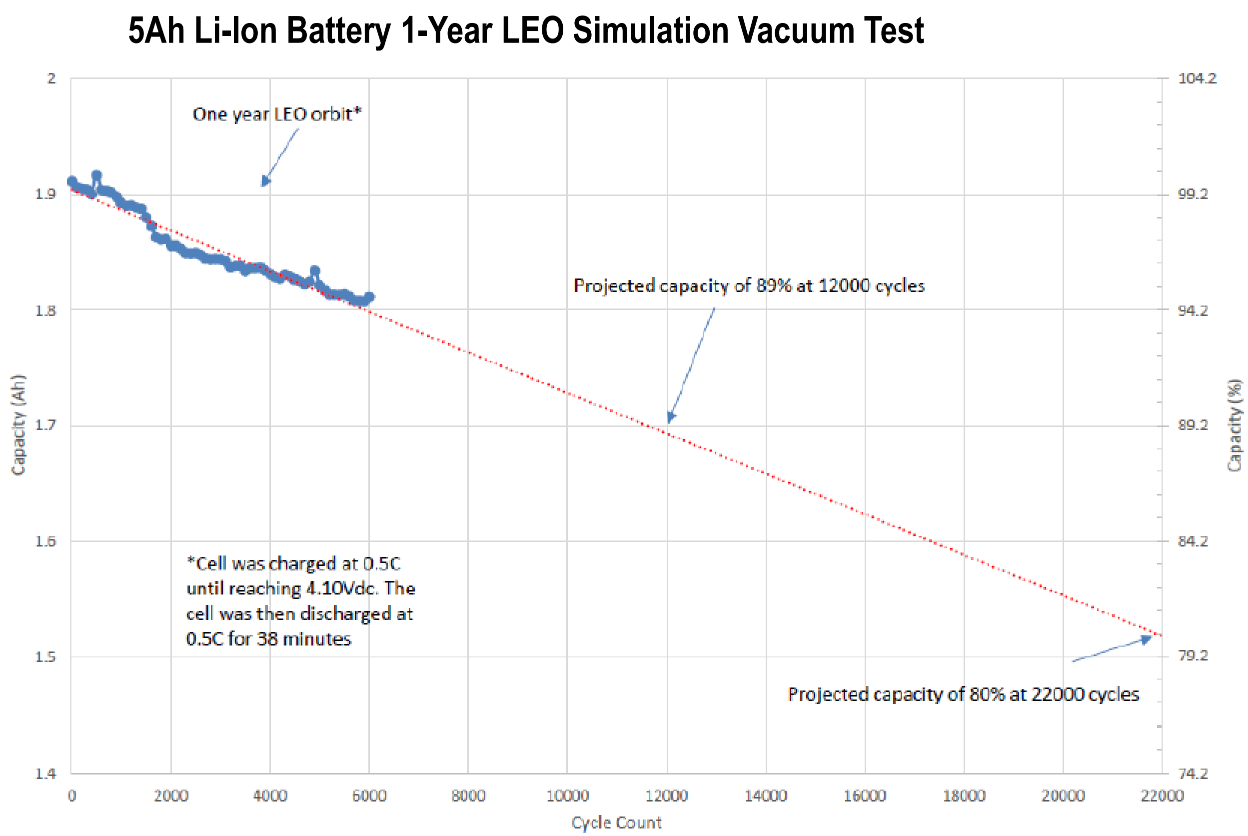


- 30% Depth of Discharge (DOD)
- Cells charged at .5C (2.5 Amps) until reaching 4.1 Vdc
- Cells discharged at .5C (2.5 Amps) for 38 minutes
- Every 100 cycles, the cells internal Resistance was measured and full Capacity test performed from 4.2Vdc to 2.8Vdc

LEO Cycle Life Data Conclusion:

- Li-Ion Polymer NMC Cells have 3X Cycle Life of 18650 and ½ recharge time on-orbit that is a game changer for 6U to 27U CubeSat missions
- Low internal resistance of < 4mohm compared to ~ 60mohm for 18650
- 5Ah Cell is rated for 30C (150 Amps) continuous current and 50C (250 Amps, 1 sec) pulse current that if require high power on-orbit for payloads (SAR, etc.)

Life Cycle Testing



2Ah / 5 Ah Cells performed identically in Vacuum and in ambient conditions

Extrapolation cycle life estimate of 22,000 cycles prior to End of Life (80% Capacity)

Contacts

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Sources

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- Koontz, Steven. (2017). *Space Radiation Environments.* NESC Academy
- Pellish, Jonathan. *Radiation Engineering for Designers 04: Component Selection & Radiation Effects Mitigation*. NESC Academy