The most important thing we build is trust

ADVANCED ELECTRONIC SOLUTIONS | AVIATION SERVICES | COMMUNICATIONS AND CONNECTIVITY | MISSION SYSTEMS

Lithium-Ion Cell Balancing Electronics – Benefiting the Satellite Industry

Presenter: Joseph Castaldo
Director of Sales, RF and Power Products
2016 NASA Battery Workshop

Commercial in Confidence

Cell balancing electronics is an essential element for the long term, safe, and optimum performance of Lithium-Ion batteries. Lithium-Ion battery is now the most commonly used technology for all space applications that include all earth orbiting satellites, planetary probes and space transportation systems, etc. While Lithium-Ion batteries have many advantages over more traditional technologies, they need to be carefully managed with regards to charge and discharge, as the cells are sensitive to overcharge and over discharge. Further, depending on the length of the mission and number of charge/discharge cycles, cell voltages within a battery can diverge from each other and need to be balanced for the optimum battery performance. Cobham Semiconductor Solutions (formerly Aeroflex) has developed Lithium-Ion Cell Balancing that is suitable for all space missions and avionics applications. These units are complimentary to the Lithium-Ion battery pack and work with batteries from any of the leading manufacturers. Currently Cobham Lithium-Ion battery cell balancing electronic units (BEUs) are flying on many geosynchronous communication satellites and most importantly on a NASA/JPL planetary probe (Juno) that entered the Jupiter orbit on 4 July 2016 following a 5-year journey. All of these units have demonstrated superior in-orbit performance by balancing the cells within a few millivolts of each other. At least 22 additional BEUs are slated to be launched between now and 2018 on numerous communication satellites. This paper briefly summarizes the development history of this product line, highlights the design features, summarizes the on-going ground tests and documents the flight experience including detailed information on Juno BEU flight performance.

- Introduction
- Overview of Lithium-Ion Battery Cell Balancing Electronics Unit (BEU)
- On-orbit Experience and Future Launches
  - Inter-Planetary (Juno)
  - Geosynchronous Earth Orbit (GEO)
- BEU Ground Testing Experience
- Overview of Battery Interface Electronics (BIE)
- Summary

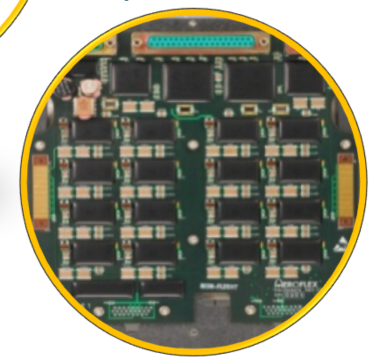
Cobham at a Glance

COBHAM

- US Headquarters in Crystal City, Virginia
  - Founded by Sir Alan Cobham in 1935
- Cobham is a leading technology and services innovator, known for providing solutions to most challenging problems, from deep space to depths of the ocean
- Cobham acquired Aeroflex in September 2014

•Battery Electronics Unit

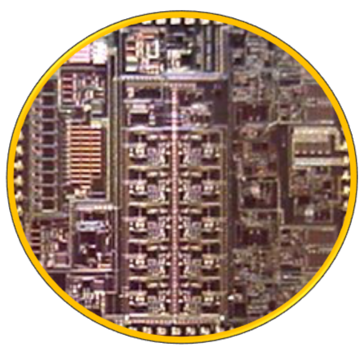
•Heritage Chip On Board



•Space Grade Voltage Regulators

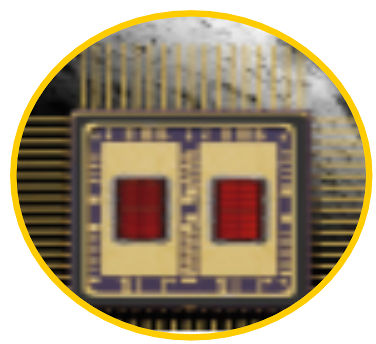
•Flip Chip Packaging

•Rad Hard ASICs



•Rad Hard PWM

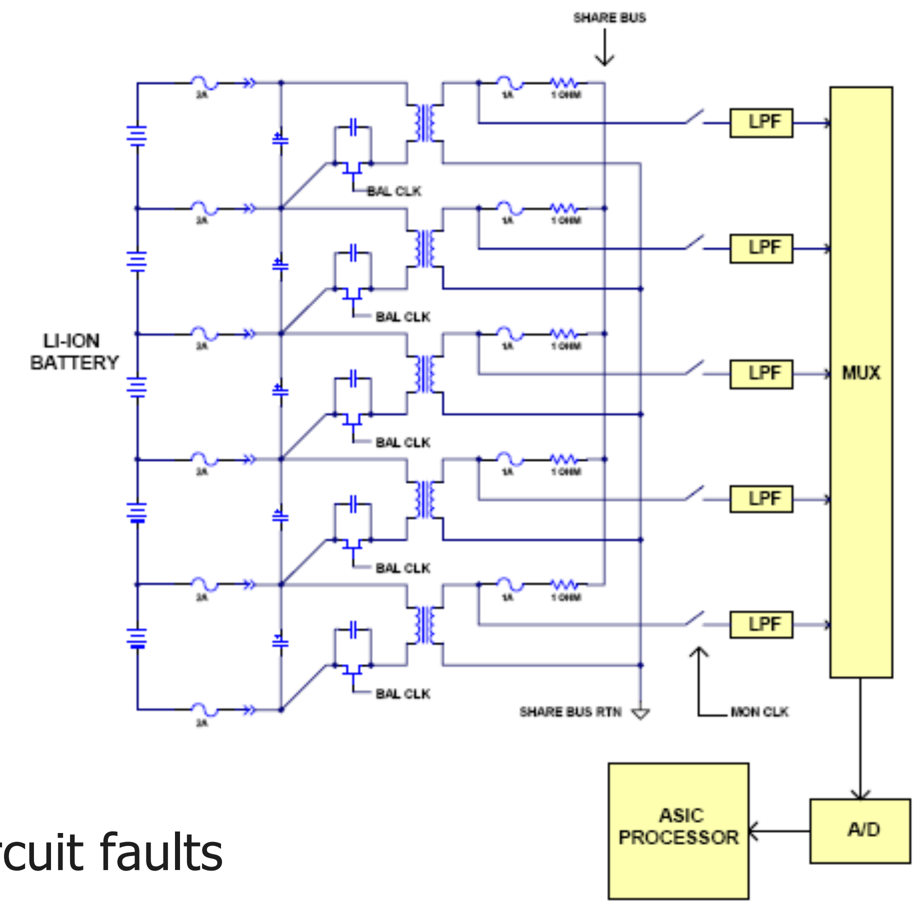
•Quad, Rad Hard Voltage Supervisor



- Lithium-Ion batteries have become prominent in space applications because of their superior performance and lower mass and cost benefits
- However, these batteries require electronic cell balancing to reduce the possibility of cell overcharge
- Further, cell balancing is required to achieve the maximum possible mission life for the battery and the corresponding platform

- The Cobham family of Battery Electronics Units (BEUs) was designed, fabricated and tested to meet specifications from Boeing, Lockheed Martin and Northrop Grumman, for use with Lithium-Ion batteries
- Basic approach for BEU was developed by Boeing, and is described in Patent 6,873,134. This patent covers the transformer-coupled DC-AC converters that transfer charge over a bidirectional Share Bus
- Additional Patents issued to Cobham (Aeroflex) during the development are:
  - Battery Balancing Including Resonant Frequency Compensation, US 7,592,775
  - Compensation for Parasitic Resistance in Battery Monitoring, US 7,786,701
- Cobham completed the electrical and mechanical designs of the original BEU plus multiple derivatives. Engineering Models (EM) and Engineering Qualification Models (EQM) were fabricated and tested
- Multiple Flight units have been delivered & launched
- In addition to cell balancing, the BEU provides the following additional functions:
  - Cell voltage monitoring
  - Battery voltage monitoring
  - Telemetry (MIL-STD-1553)
  - Driver circuits to activate external Battery Cell Bypass Switches

- Autonomous operation –
  turn-on & forget!
- Operate continuously during charge, discharge & standby modes
- Balancing current directly proportional to voltage difference between cells
- Balancing / Monitoring accuracy:
  5.0mV/10mV BOL
  10mV/20.0mV EOL (18 years, GEO)
- Highly efficient resonant Power Converters



- Fault tolerant, for both cell faults and circuit faults
- Negligible degradation due to temperature, life and radiation
- The 24 Cell Unit draws 3W from the battery plus ~9W from the bus

Autonomous Balancing

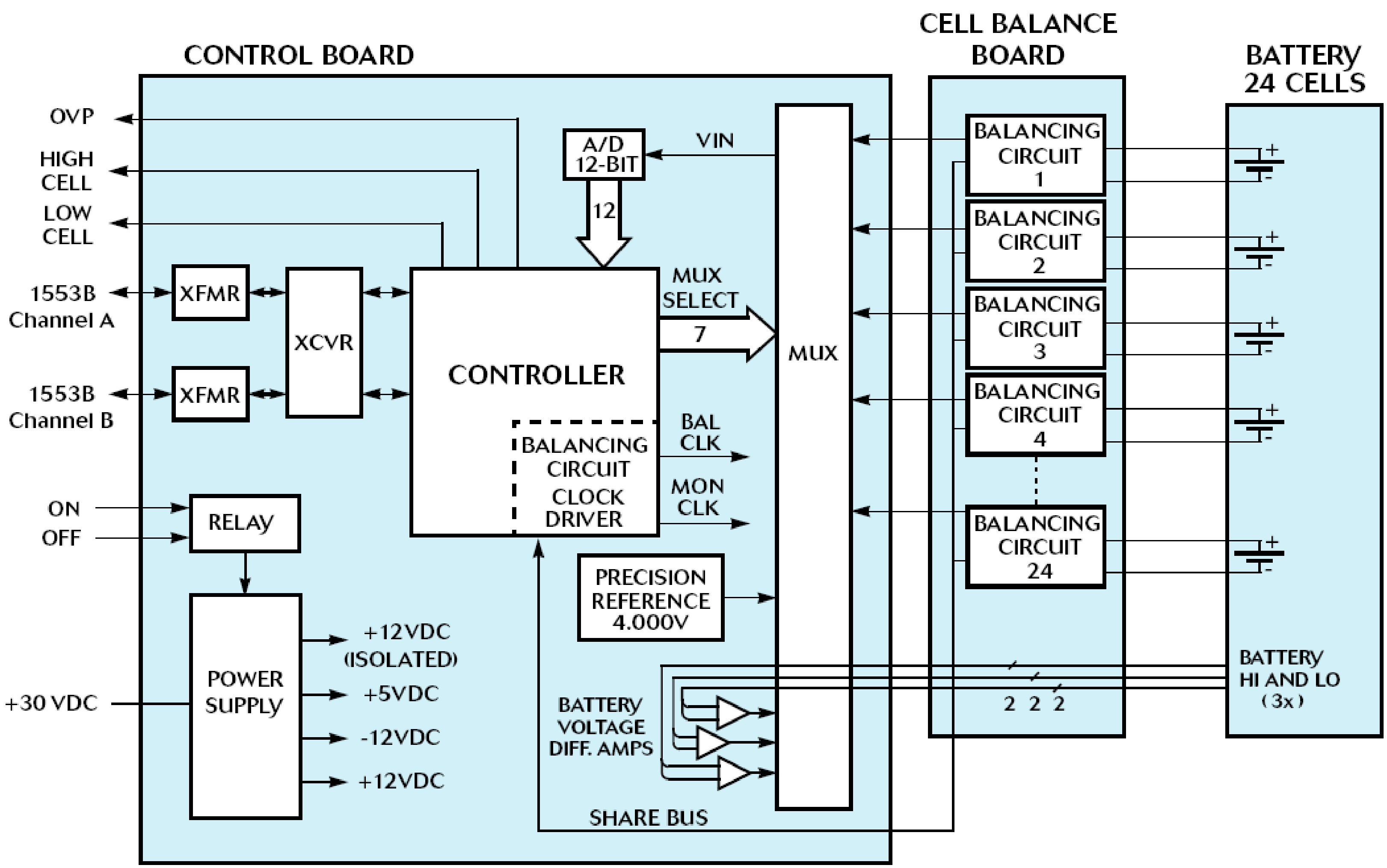
- No need for cell voltage measurement!
- "Share Bus" uses Transformer Coupled Charge Sharing to distribute charge from high voltage cells to low-voltage cells
- Long Term Stability is not affected by environment (temperature cycles, aging, radiation)

Active & Continuous

- High voltage cells help charge low voltage cells
- Highly efficient resonant converters draw 1/8 W per cell from battery
- Ideal for any mission life and orbit
- Continuous Balancing is beneficial to LEO Missions
- Easy to use and to interface with existing systems
- Relatively Stable Thermal Loading
- Turn-on and forget!

Continuous Balancing Independent of State-of-Charge
Made Possible by "Share Bus" Technology

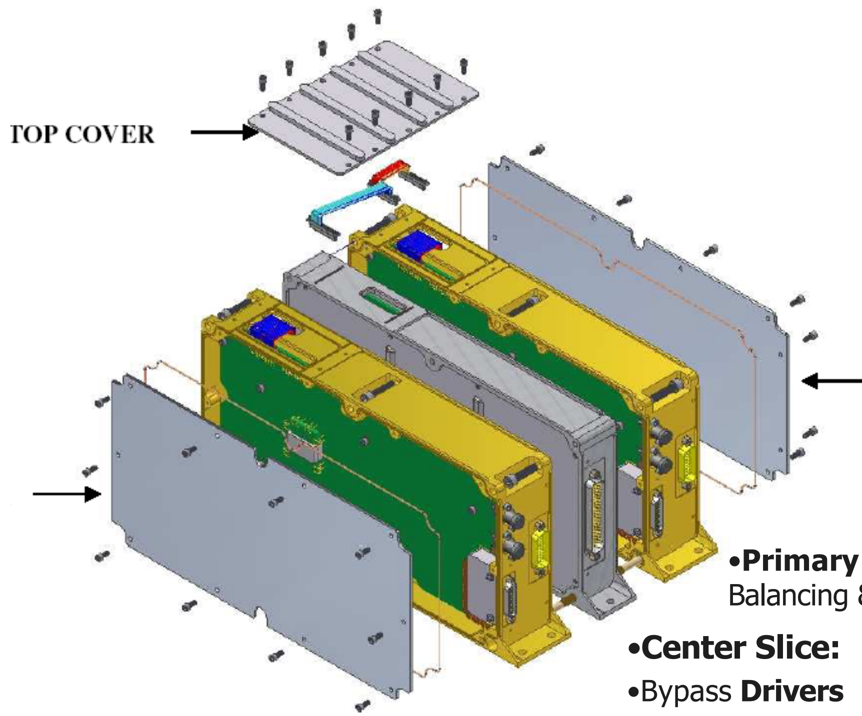
BEU Functional Block Diagram



Can accommodate varying number of cells in series

BEU Physical Construction & Environments

- Temperature Range
  - Operational -24^{o}C to 61^{o}C
  - Qualification -34^{o}C to 71^{o}C
- Pyro-shock
  - 2500G SRS
- Random Vibration
  - Peak Spectrum 28G2/Hz X, 17G2/Hz Y & Z ~50 to 400Hz
- Compliant with MIL-STD-461E
  - CE01, CE02, CS01, CS02, RE02, RS03 (5V/m and 20V/m)
- FMECA
- Reliability (Excludes Bypass Slice)
  - Failure Rate: 186.79 FITS
  - MTBF: 5,353,605 hours
  - Probability of Success: 0.999158, (18 years, GEO)
- More than 100 WCAs performed
  - Power Supply
  - Balancing Circuits
  - 12 Bit A/D Conversion
  - Monitoring Accuracy +/-10mV BOL, (+/-20mV 18 years, GEO)



•**Primary Slice (R):** Balancing & Telemetry

•**Center Slice:**

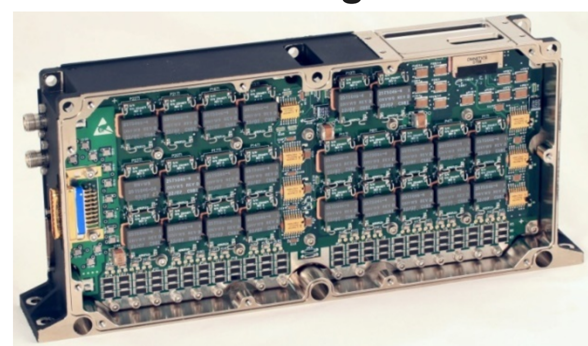
•Bypass **Drivers**

•**Redundant Slice (L):** Balancing & Telemetry

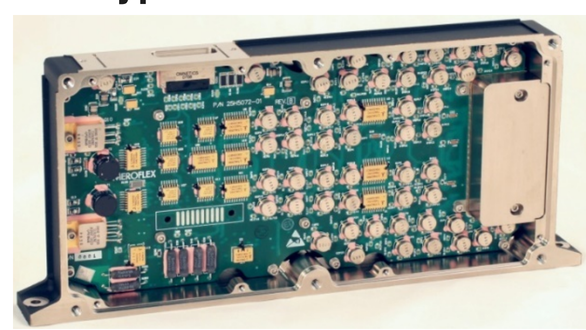
- Size: 11.5″L x 5.25″W x 5.25″H
- Weight: 8.20 lbs. (3.75 Kg)
- Analyzed, tested and qualified for pyro-shock, vibration and thermal vacuum
- 3 machined housings (slices), fastened with twelve 10-32 bolts
- Nickel-plated aluminum housing, painted black for emissivity
- Includes 2 Balancing Cards, 2 Control Cards, 1 Bypass Device Driver Card
- Fully redundant for balancing / telemetry

•Control Card

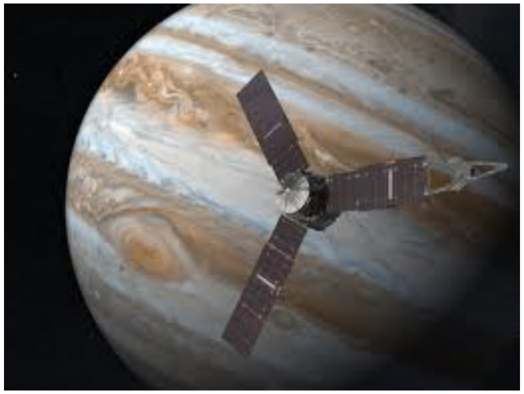
•Balancing Card



•Bypass Device Driver Card



BEU On-Orbit Experience
&
Ground Test Results



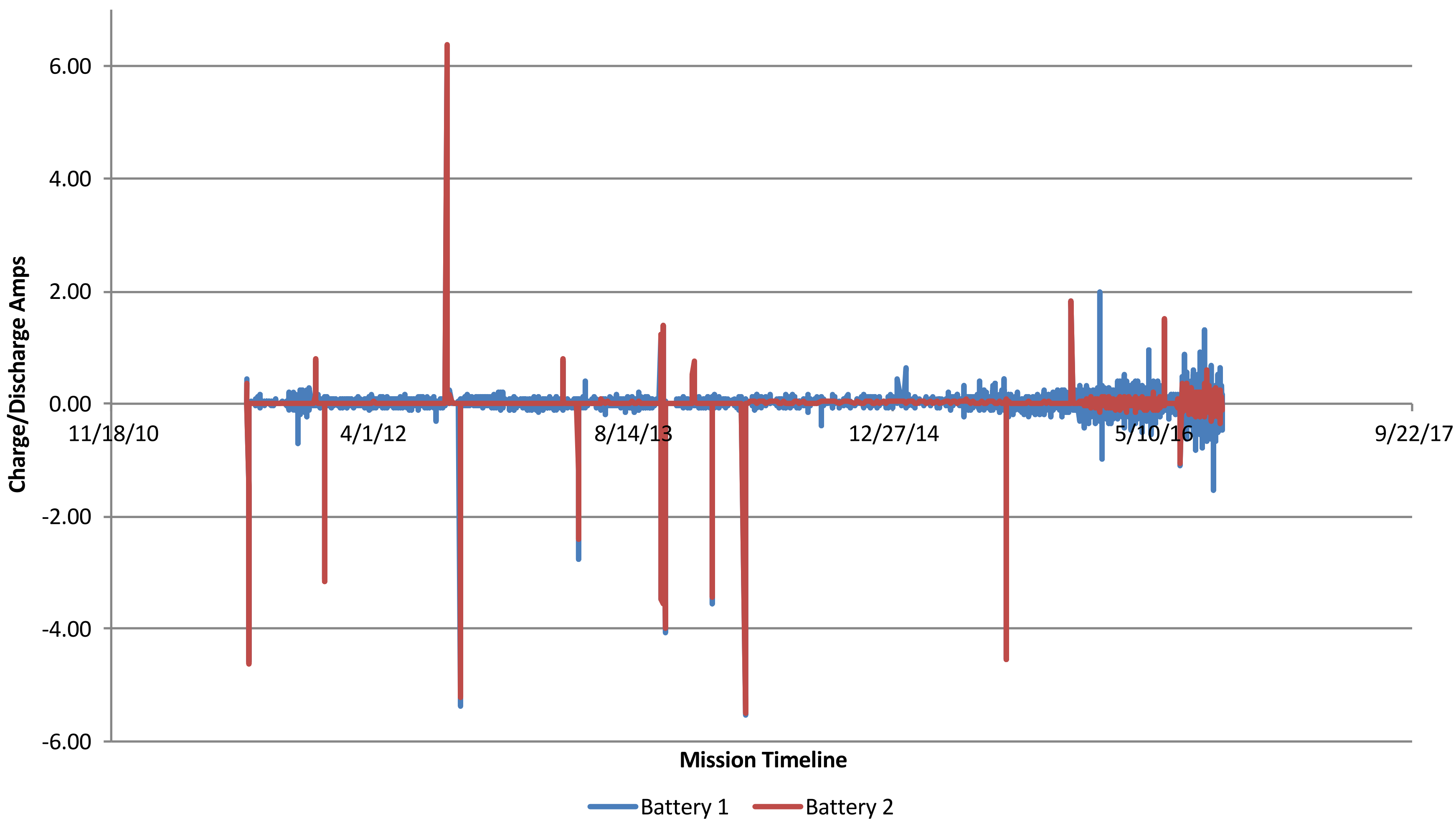
Juno Flight Performance

Includes two 8-cell 50 AH Li-Ion Batteries and corresponding Cell Management Electronics (BEUs)

8 Cell Dual Redundant

Battery Charge/Discharge Current Profile

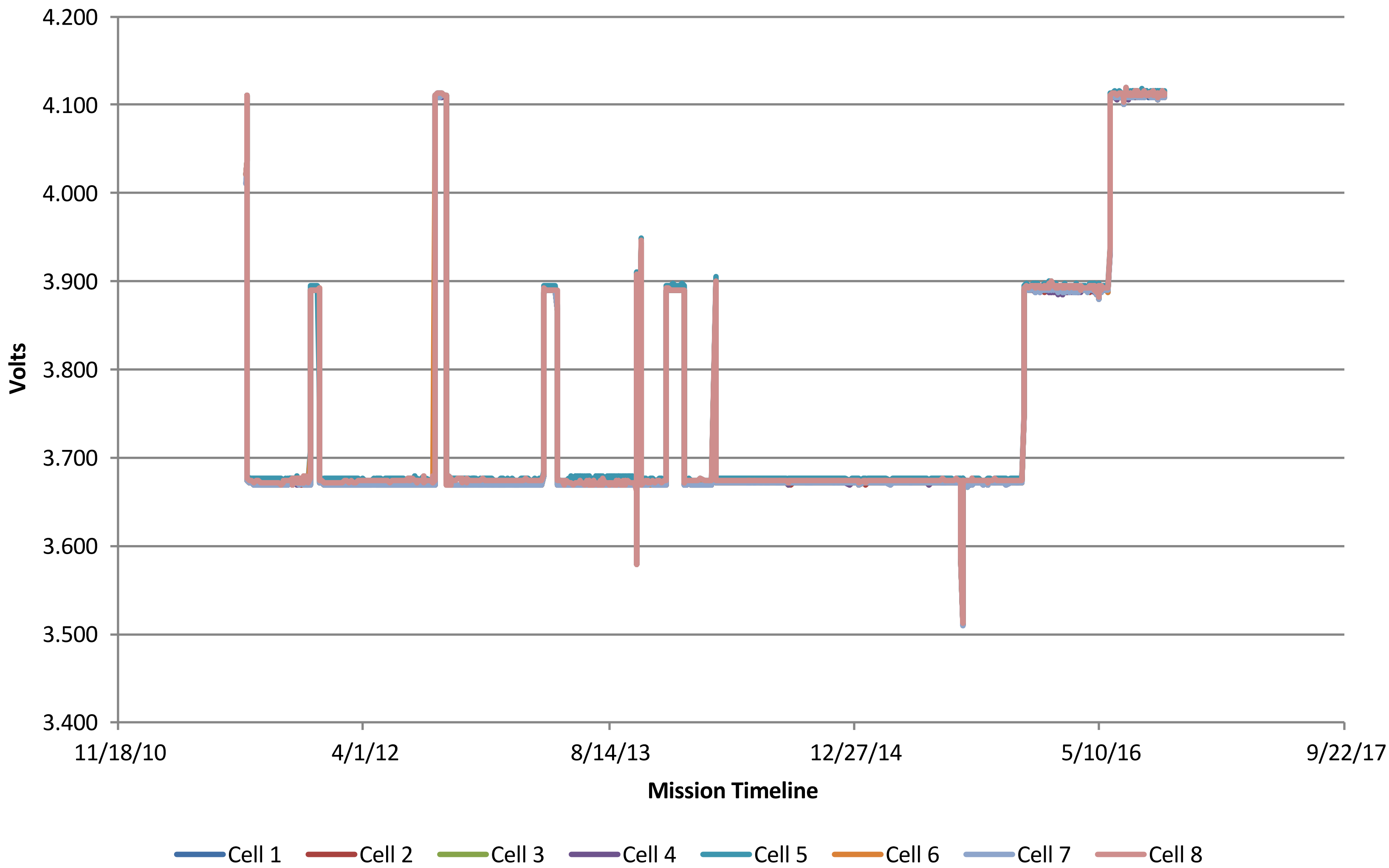
Launch to Post Jupiter Orbit Insertion



Battery 1 Cell Voltage Performance

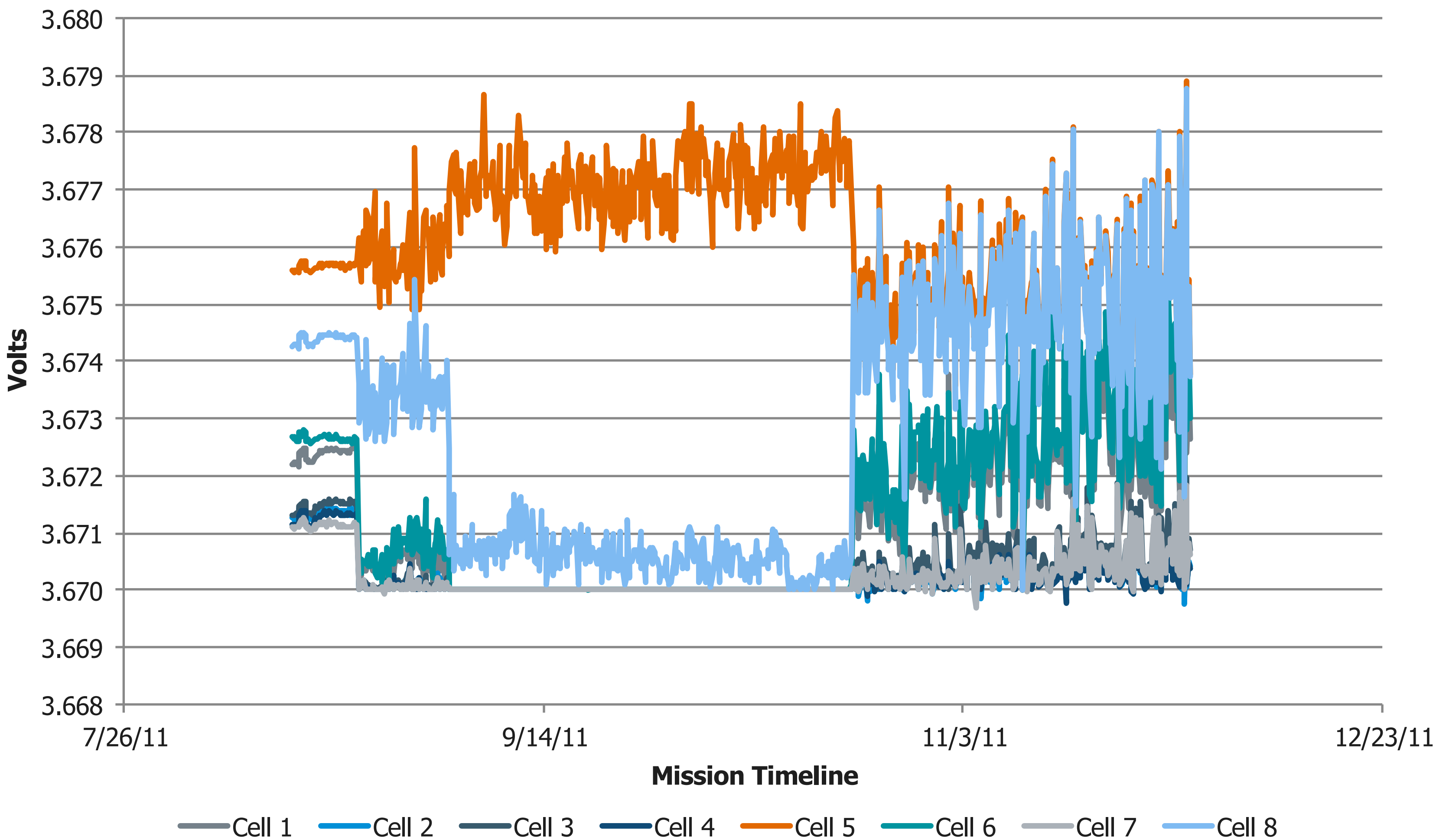
COBHAM

Launch – Post Jupiter Orbit Insertion



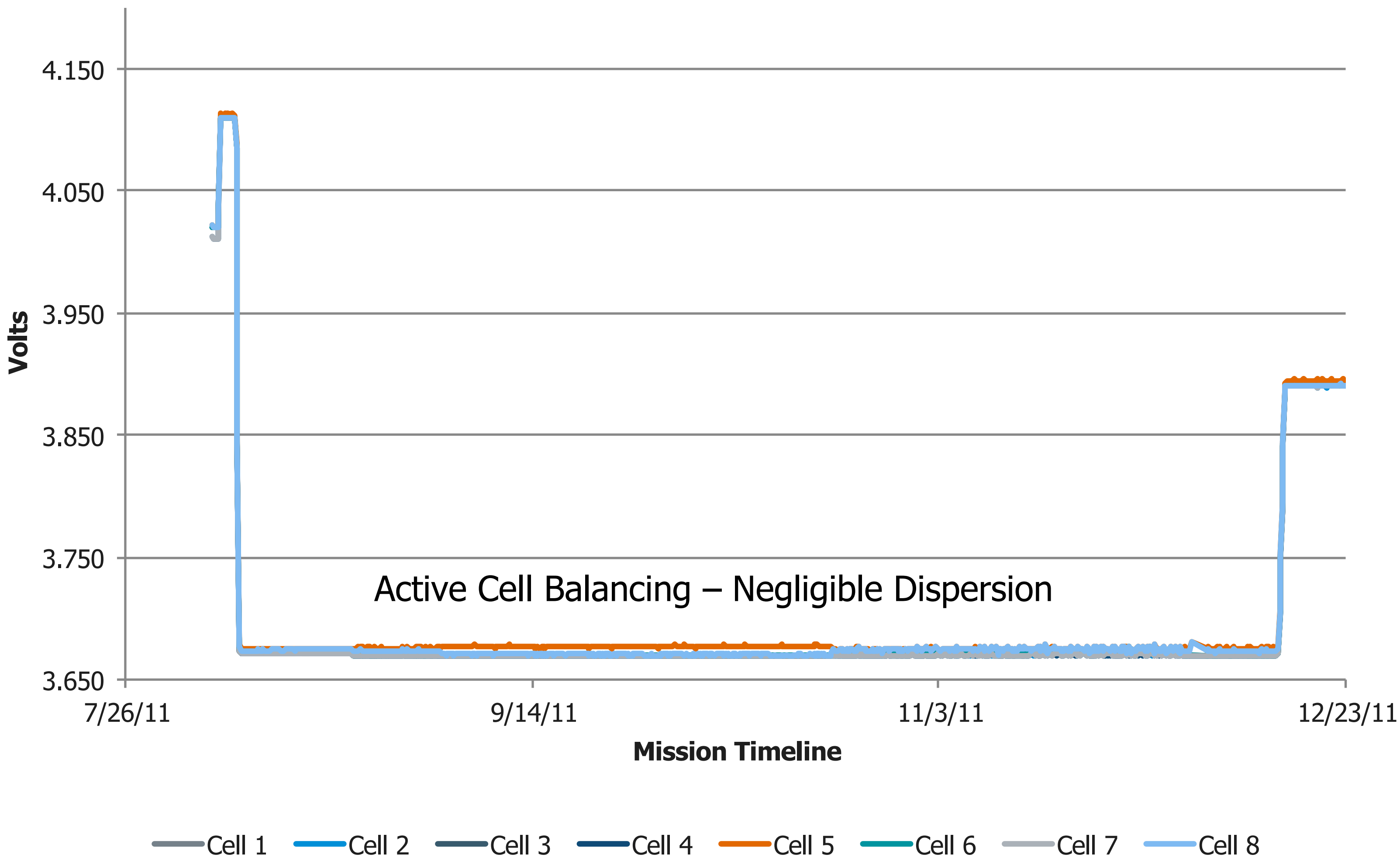
Battery 1 Cell Voltage Dispersion

- Balancer performance during no battery activity phases (BOL)
- Majority of cells were balanced within 8mV of each other



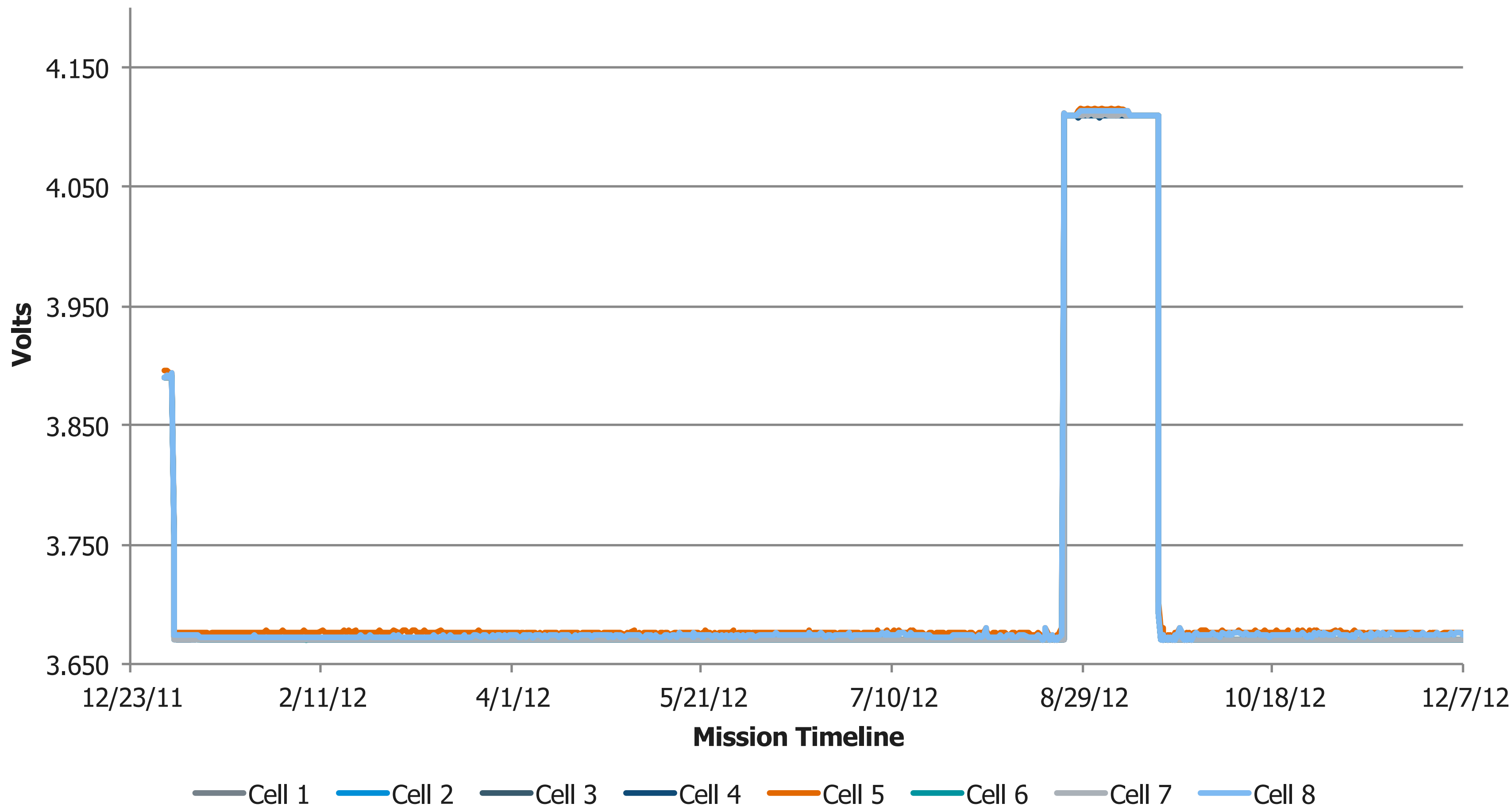
Battery 1 Voltage Performance

Year 1 – All Cells Balanced to within 5mV



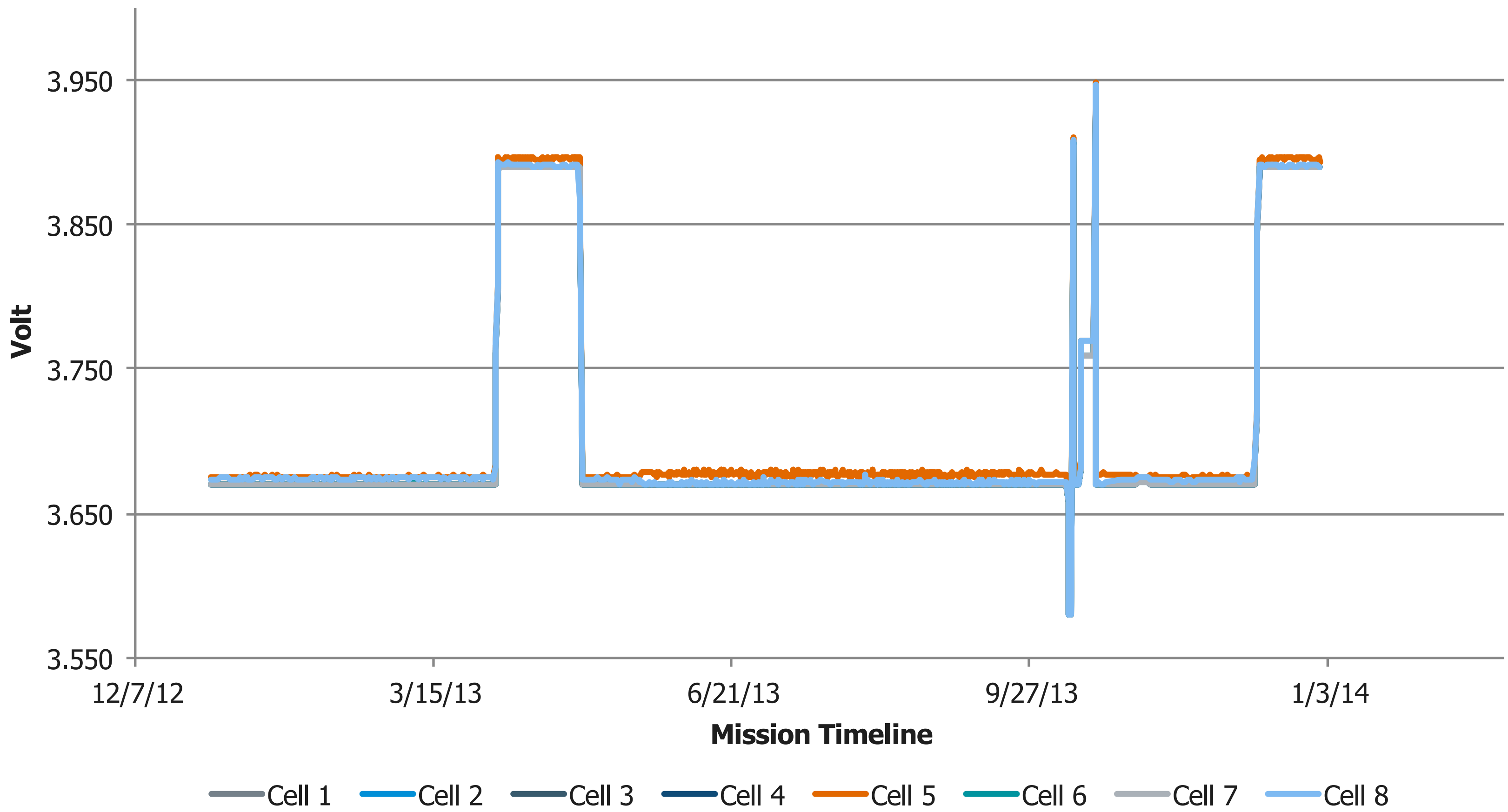
Battery 1 Voltage Performance

Year 2 - All Cells Remain Balanced to within 5mV



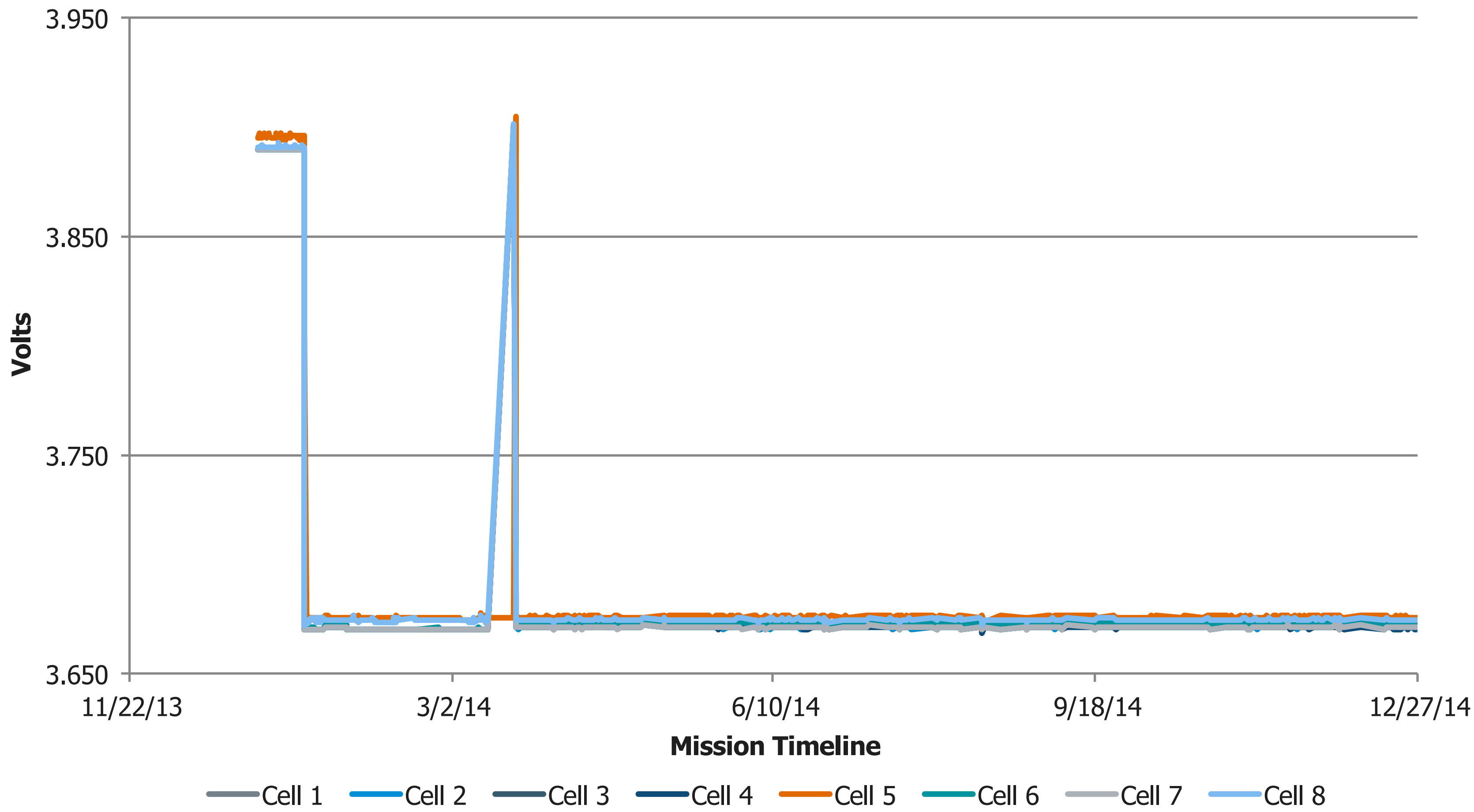
Battery 1 Voltage Performance

Year 3 - All Cells Remain Balanced to within 5mV EOC/EOD



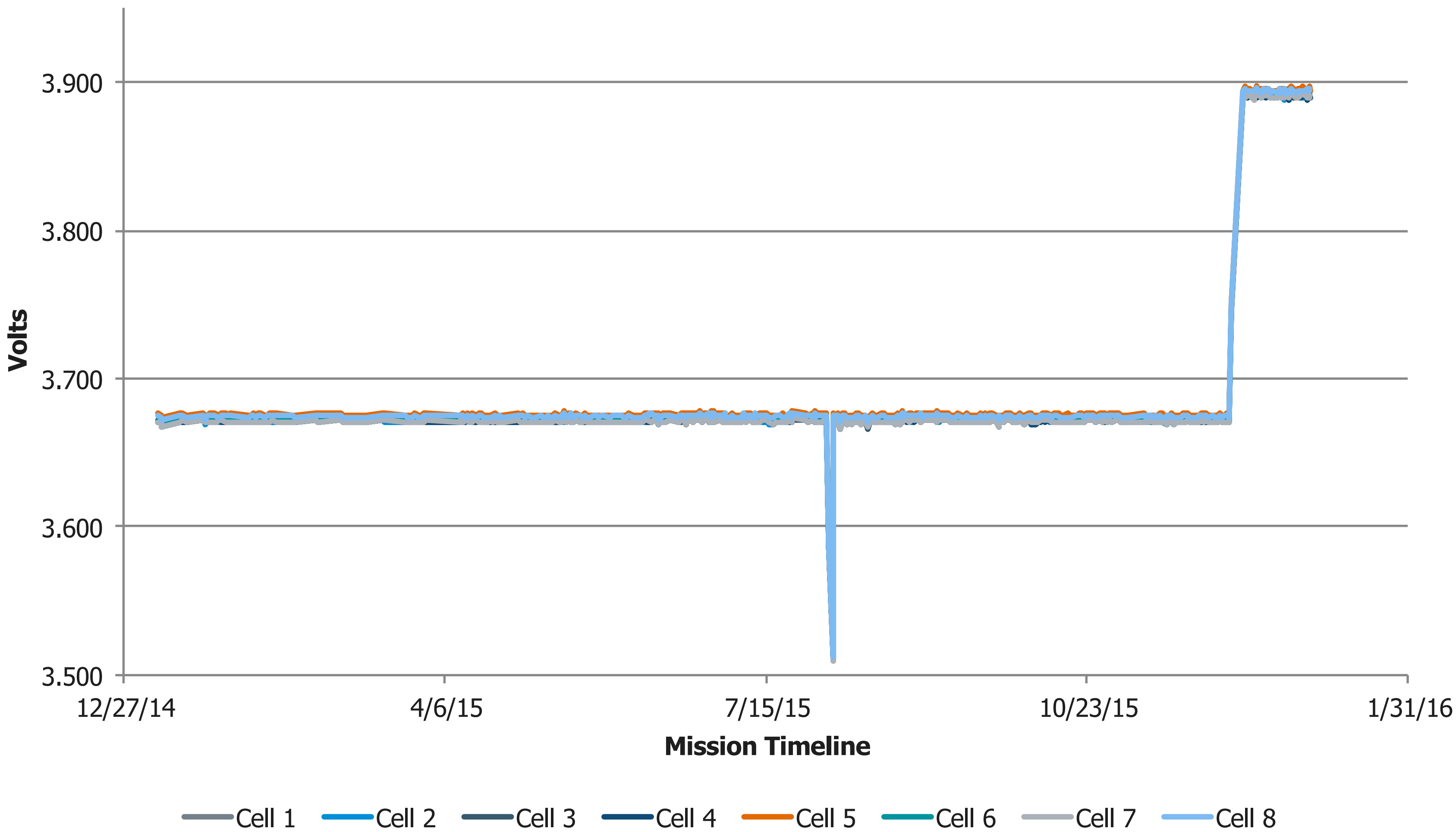
Battery 1 Voltage Performance

Year 4 - All Cells Remain Balanced to within 5mV



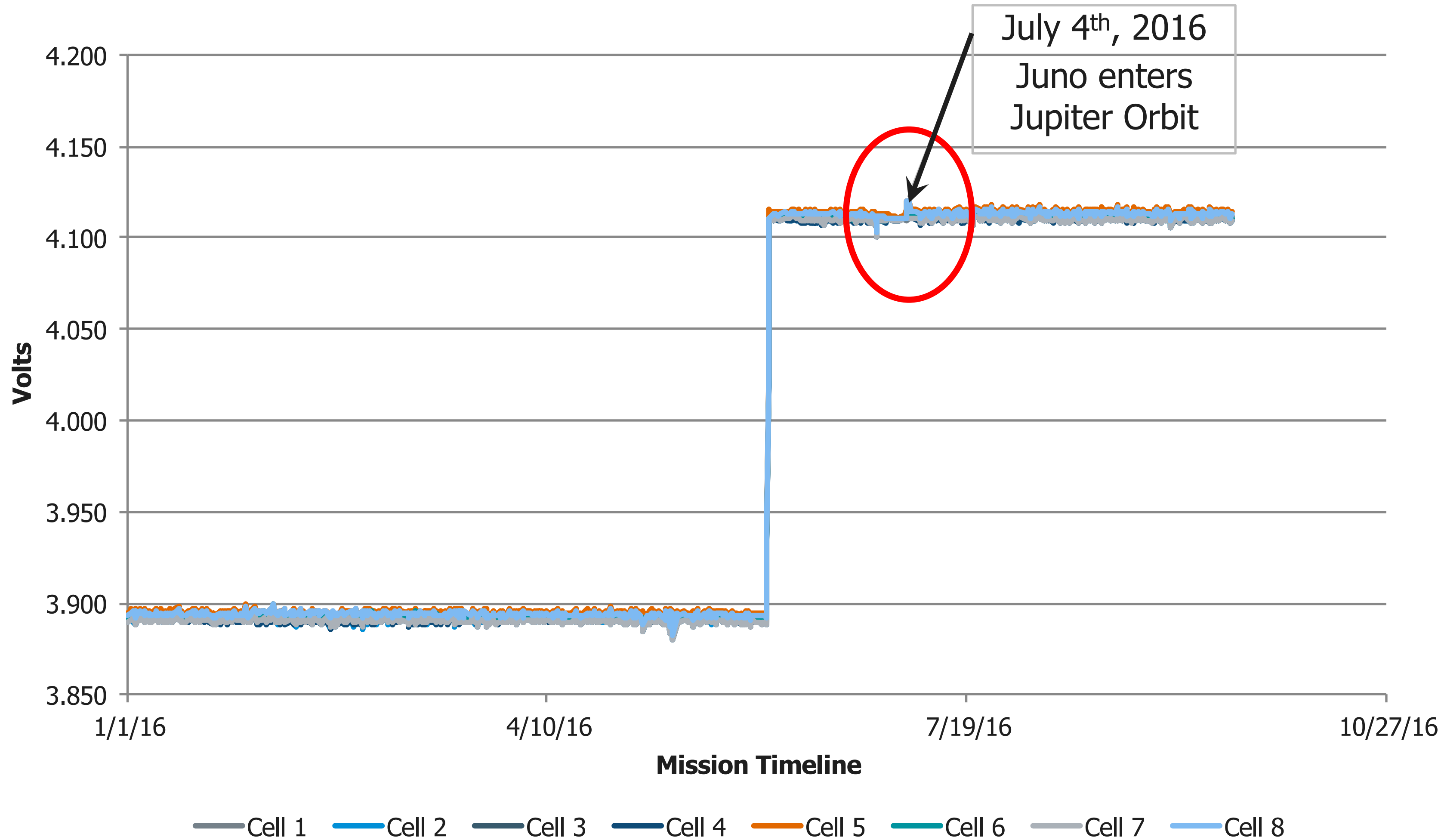
Battery 1 Voltage Performance

Year 5 - All Cells Remain Balanced to within 5mV



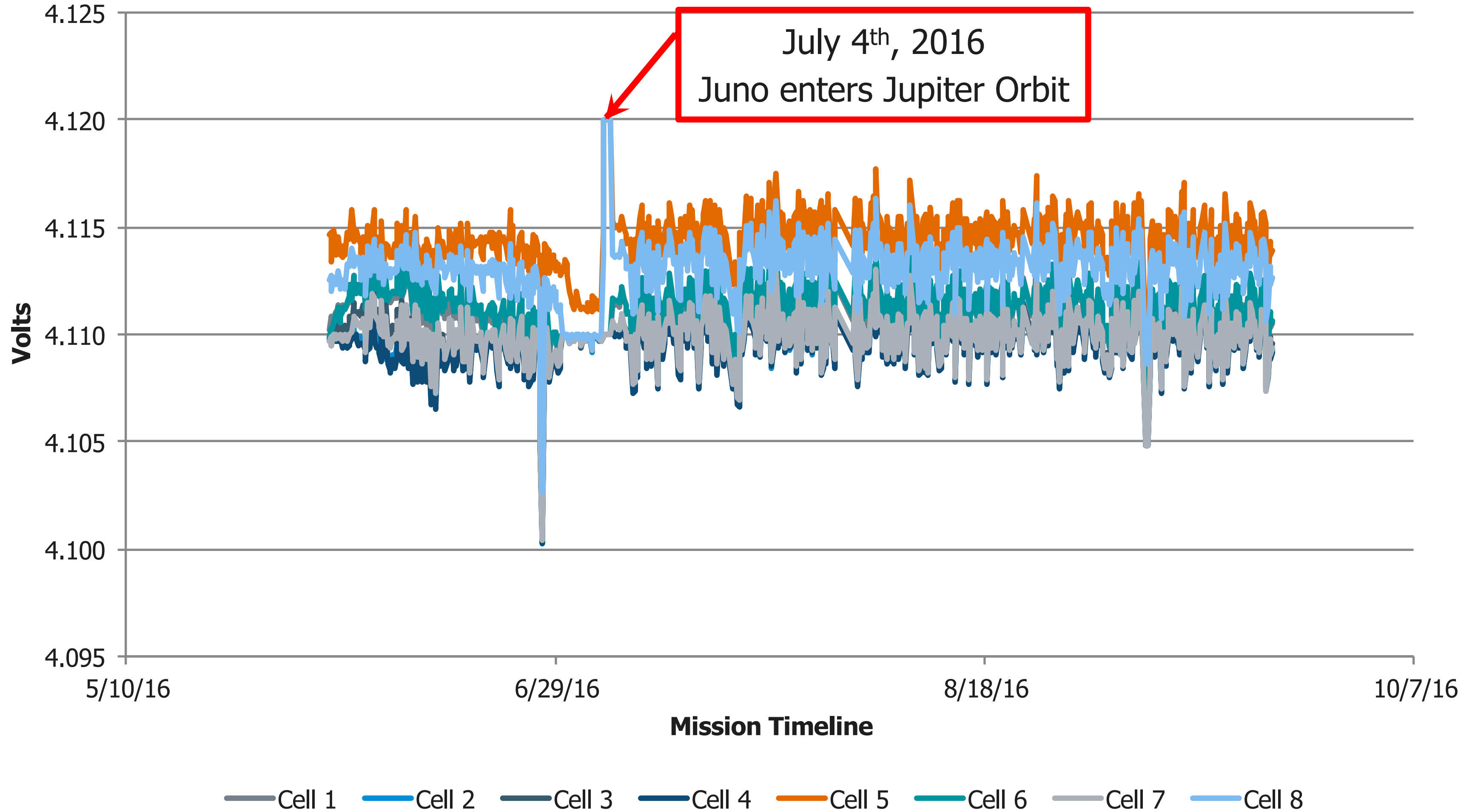
Battery 1 Voltage Performance

Year 6 - All Cells Remain Balanced to within 5mV



Battery 1 Voltage Performance

Year 6 – Improved Cell Balancing, Cells Balanced well within 5mV

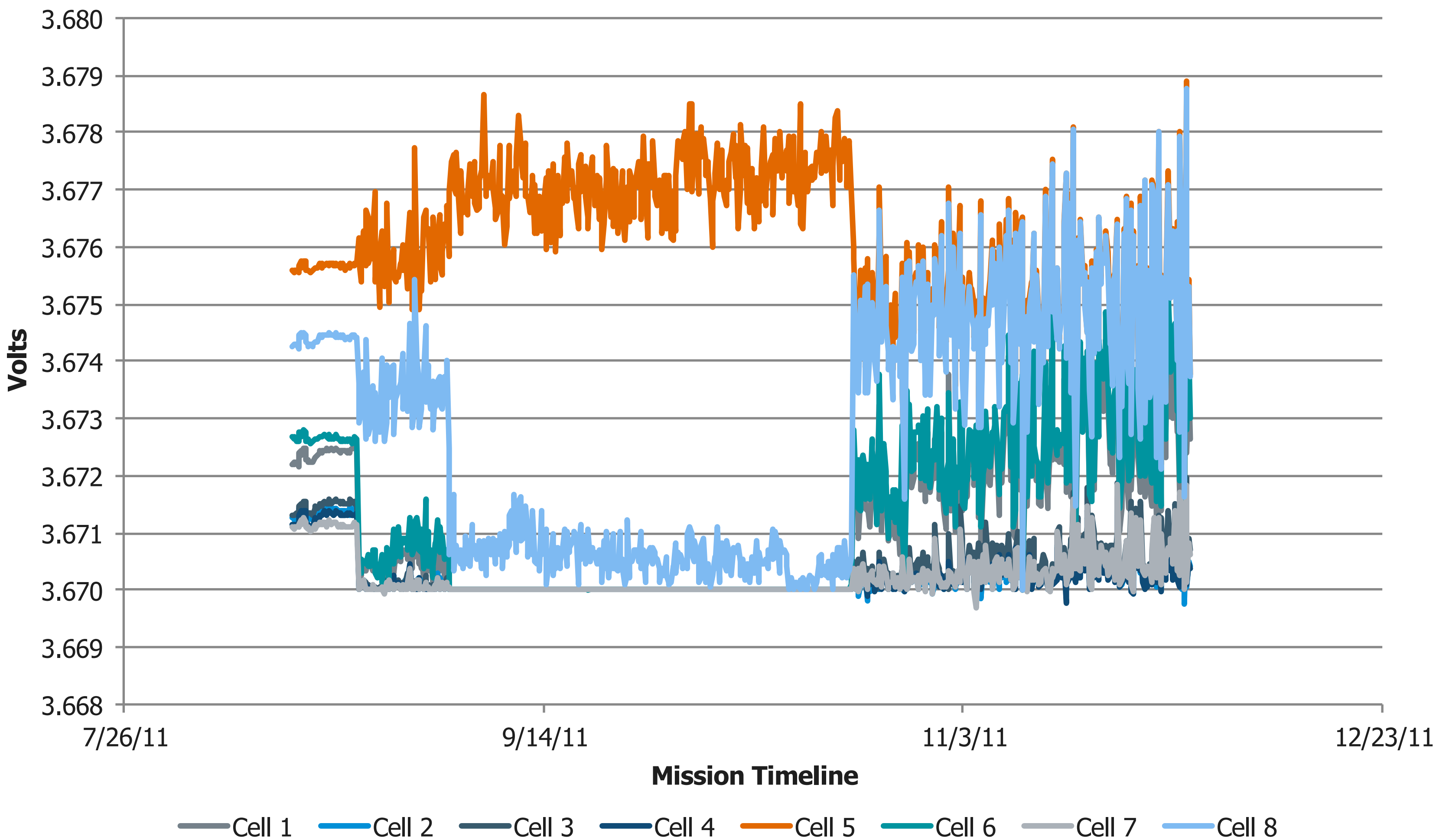


Superior BEU Performance Demonstrated on a Critical Planetary Mission

Battery 1 Cell Voltage Dispersion

Balancer performance at Beginning of Life

- Majority of cells balanced within 8mV of each other



BEU Legacy

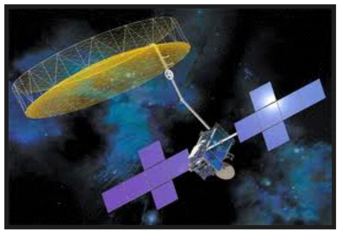
Over 40 units supplied to Boeing

- All Boeing commercial and non-commercial spacecraft with Li-Ion batteries use Cobham BEUs for cell balancing
- 1st set of BEUs launched on a GEO commercial spacecraft in 2010
- BEUs performing as expected

24 Cell Dual Redundant BEU

Boeing BEU Launches at a glance

COBHAM

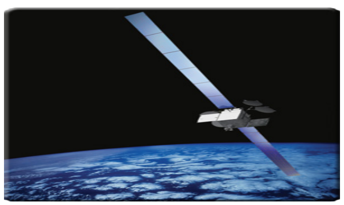


HS-702HP
SkyTerra 1
Nov 2010

HS-702MP
Intelsat 22, 21
Mar 2012,
Aug 2012

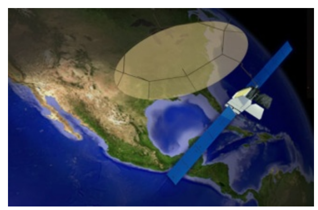
HS-702SP
ABS-3A
Mar 2015

HS-702HP
Eutelsat 117
Jun 2016



HS-702HP
SES 9
Mar 2016

HS-702HP
Inmarsat 5
F1 – Dec 2013
F2 – Feb 2015
F3 – Aug 2015



HS-702HP
MexSat 2
Oct 2015

HS-702MP
Intelsat 33e
Aug 2016

SkyTerra	2 BEU
Intelsat 22	2 BEU
Intelsat 21	2 BEU
Eutelsat 115	2 BEU
ABS-3A	1 BEU
Intelsat 29e	2 BEU
Eutelsat 117	2 BEU
Intelsat 33e	2 BEU
Inmarsat5	2 BEU
SES 9	2 BEU
MexSat	2 BEU

BEU Ground Testing & Evaluation

8 Cell BEU Evaluation Unit

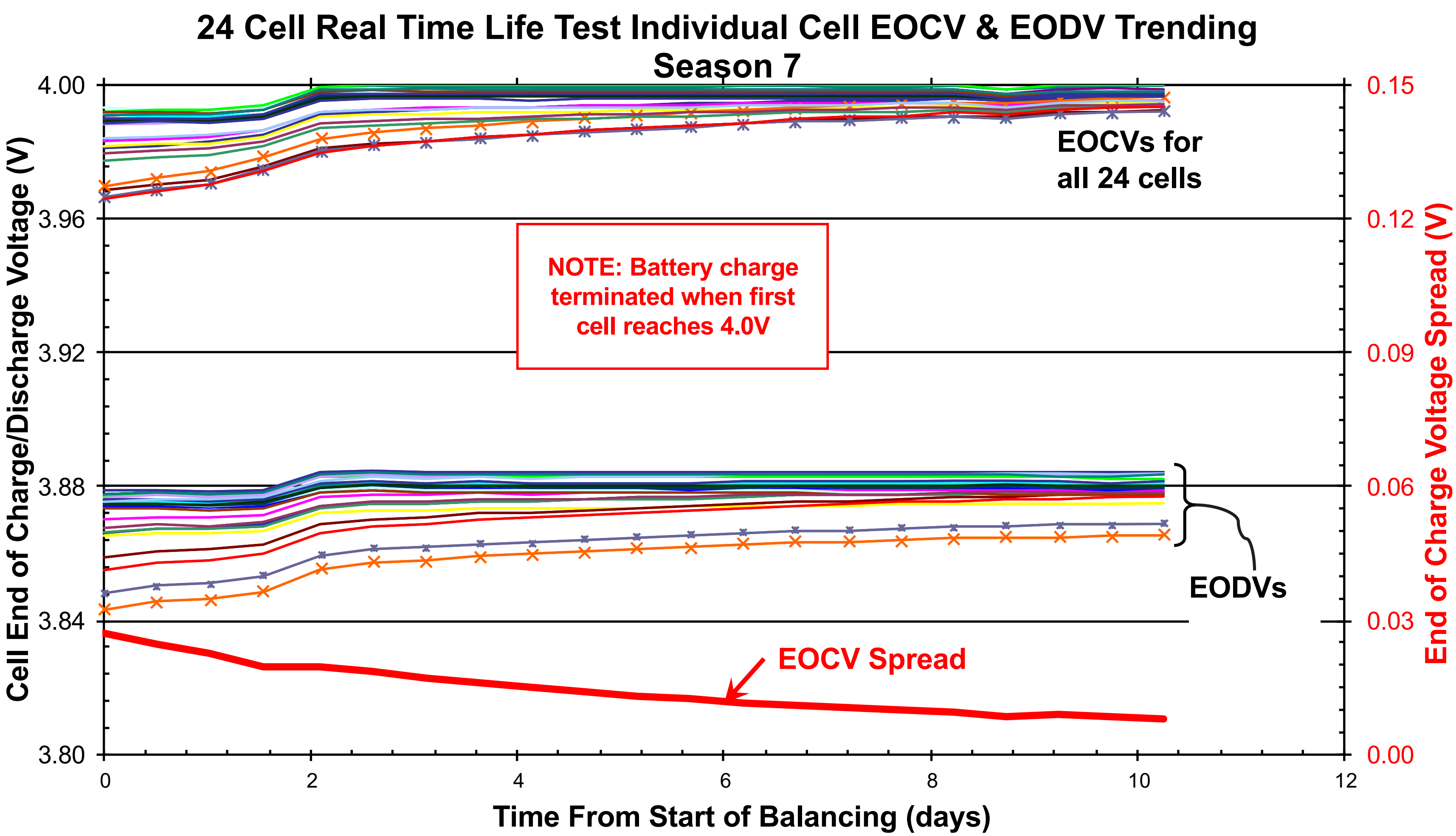
12"L x 9"W x 2.65"H

Organization	Test	Test Duration	Status	Remarks
SSL	GEO cycle life	>6 years to date	Completed	Performed as expected
Naval Surface Warfare Center	Comparison of 3 cell balancing designs	Multiple Years	Completed	Superior Performance demonstrated - LEO
Boeing	GEO cycle life	Various	Completed >13 seasons	Performing as expected (dispersion <20mV)
Aerospace Corp	Cycle life	Multiple Years	Delivered	
NASA JPL	Planetary cycle life	Multiple Years	Delivered	
Northrop Grumman	LEO cycle life	910 Cycles	Completed	Performed as expected

BEU Ground Testing Results

Season 7

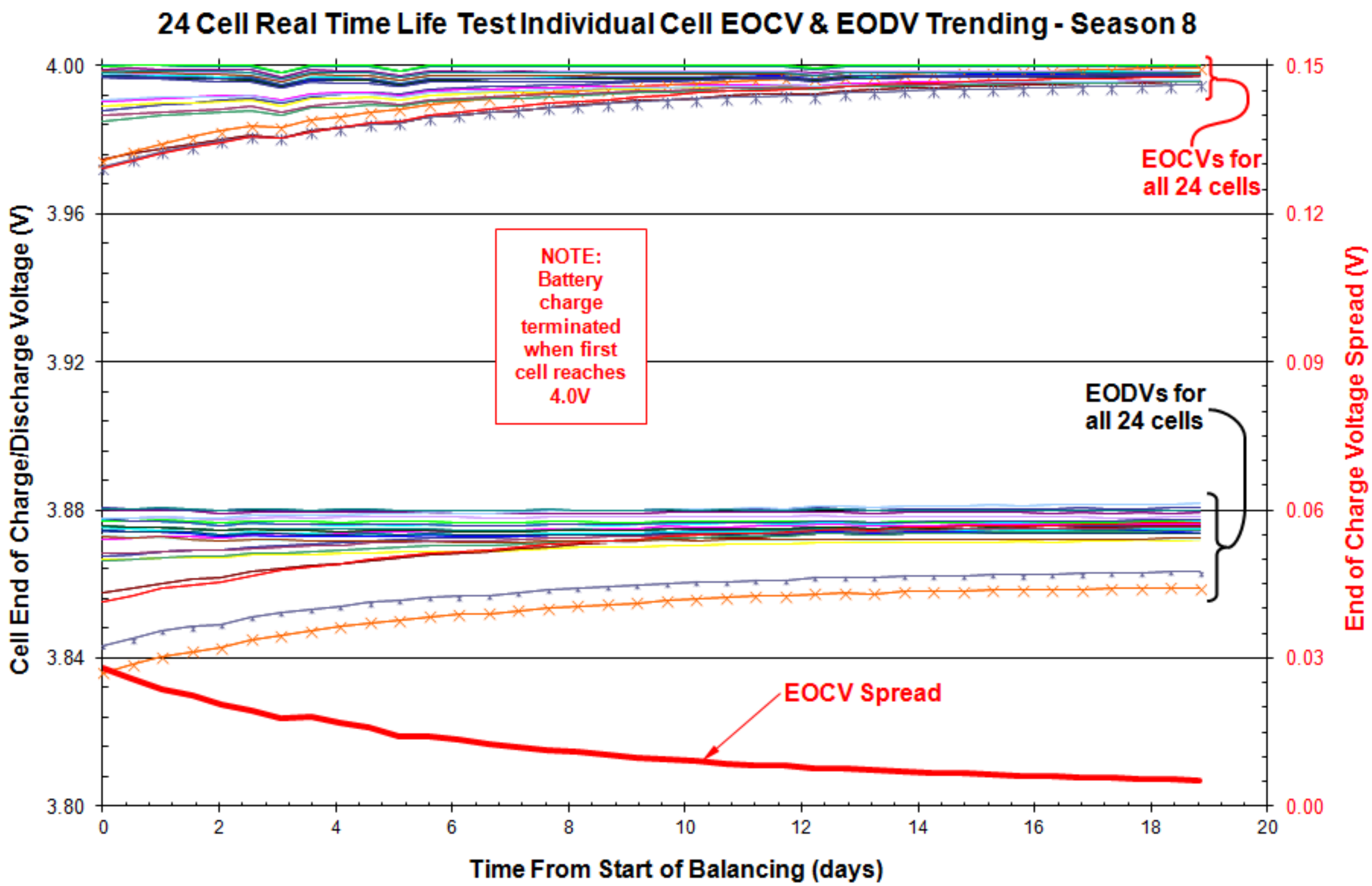
- *A Cobham BEU was used on a 24 cell battery in real time life test at SSL. The six year test consistently balanced the cells to within a 4mV.*



BEU Ground Testing Results

Season 8

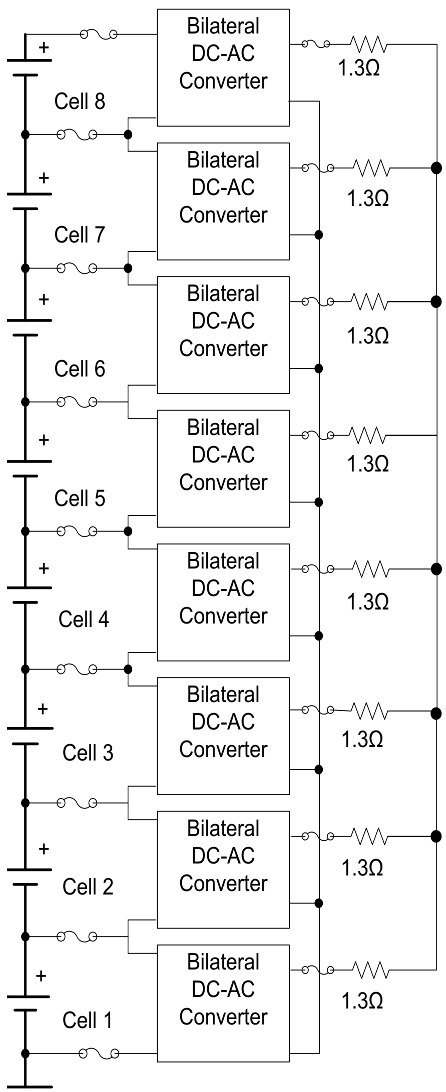
- *A Cobham BEU was used on a 24 cell battery in real time life test at SSL. The six year test consistently balanced the cells to within a 4mV.*



Modification of BEU for LEO Lithium-Ion Batteries

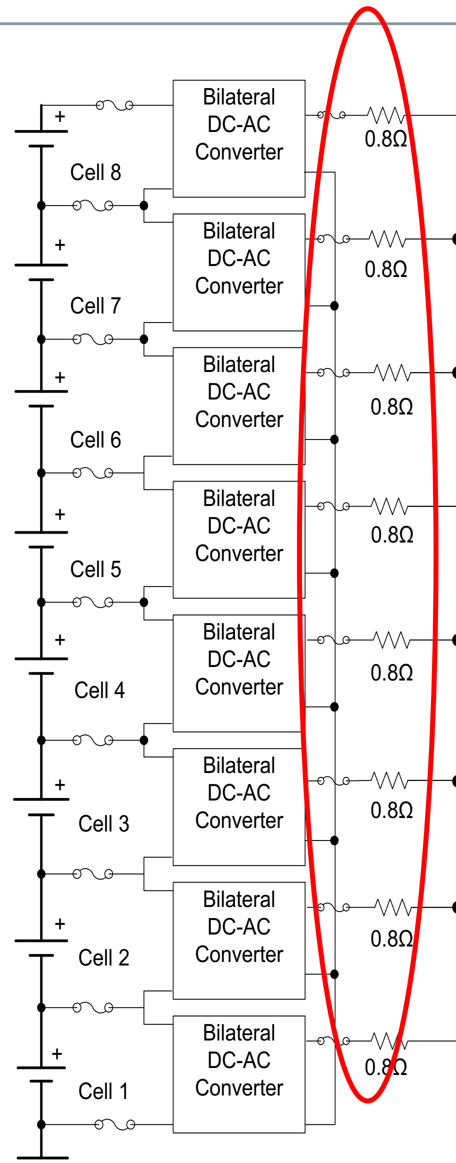
COBHAM

To accelerate balancing on a Government Funded LEO Ground Test



- Original (GEO)
- 1.3Ω transfer resistance includes the fuse resistance

$$I_{cell} = \frac{V_{Cell} - V_{Ave}}{x\Omega}$$



- Modified (LEO)
- Reduced the share bus resistance. Kept the same fuses and changed series resistance to 0.5Ω for an effective of 0.8Ω transfer resistance.

For more information, please visit:

http://ams.aeroflex.com/pagesproduct/prods-power-beu.cfm

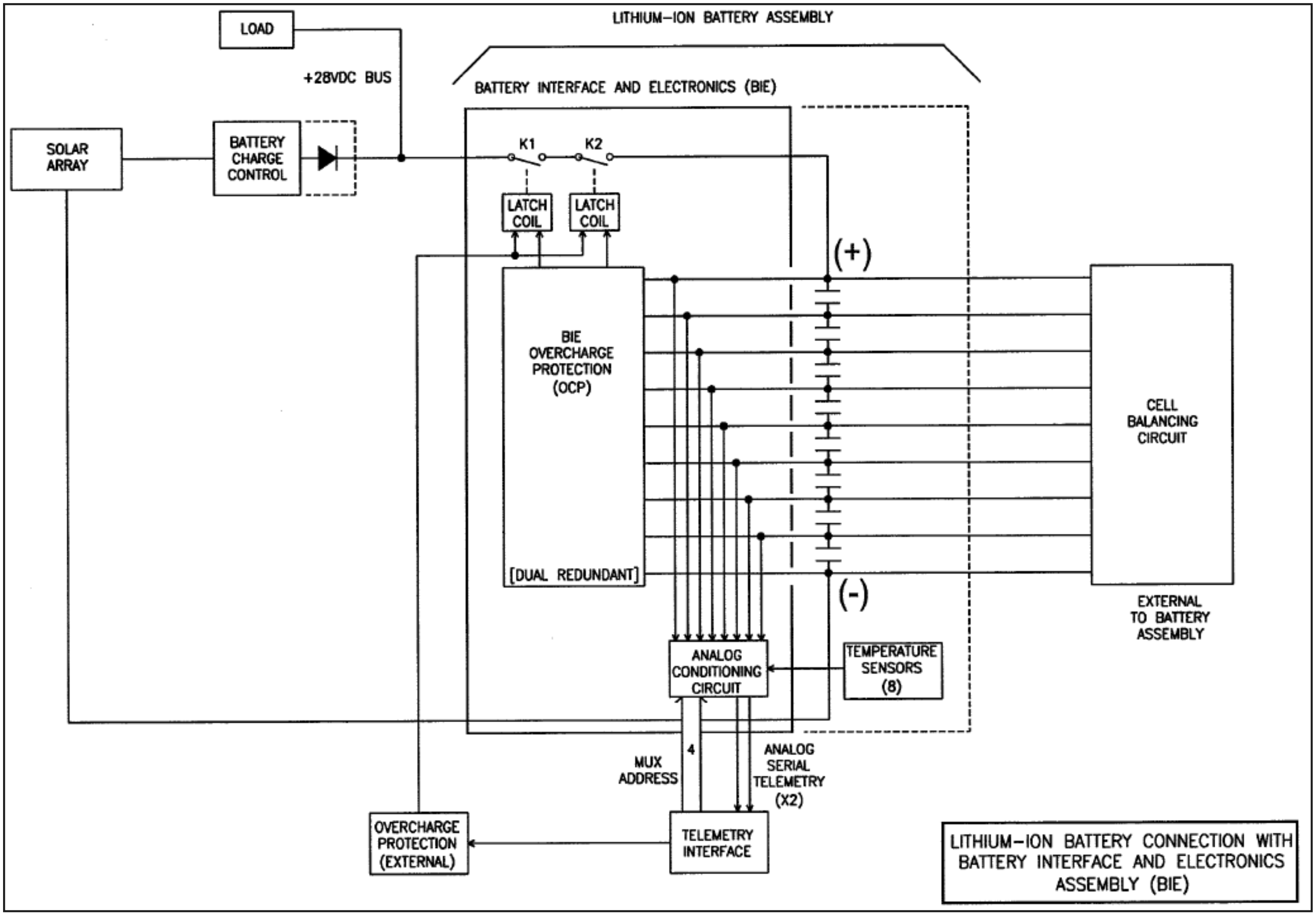
Other Lithium-Ion Battery Interface Electronics From Cobham

Battery Interface Electronics

Battery Interface Electronics (BIE)

- The Cobham BIE was designed, fabricated and tested to meet specifications provided by Orbital Sciences Corp. for use with Lithium-Ion batteries in the Commercial Orbital Transportation System (COTS) to deliver cargo to the International Space Station at low earth orbit (LEO)
- Cobham has completed the electrical and mechanical design of the BIE. Engineering Models (EM), Engineering Qualification Models (EQM) and flight units have been fabricated, tested, qualified and delivered to Orbital
- The BIE includes the following features:
  - Analog telemetry for monitoring of cell voltages, battery voltage and cell temperatures
  - Independent Overvoltage Protection (OVP) / Overcharge Protection(OCP)
  - Battery on/off control through two series 50A contactors
  - Access port for connection to external cell balancing circuit

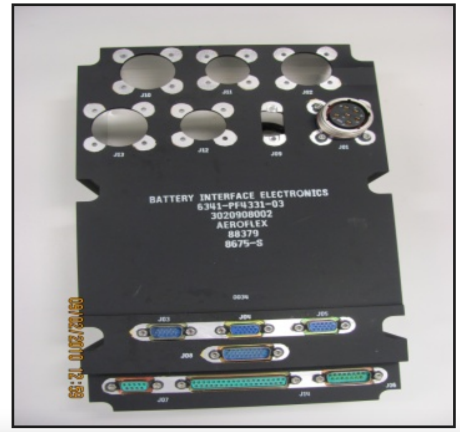
BIE Functional Block Diagram & External Interfaces



Battery Interface Electronics (BIE) Application

COBHAM

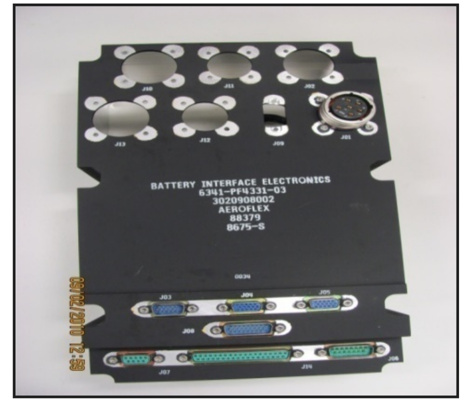
- Provides electrical interface between battery and spacecraft
- Analog Conditioning circuits, provide 0 - 5V conditioned telemetry outputs for each cell, for the total battery, and for 8 thermistor temperature sensors
- OVP circuits monitor each cell voltage. If any cell voltage exceeds 4.5 V, isolation relays open, disconnecting battery from charger. Circuit is dual redundant, and no single point failure can cause relays to open inadvertently
- Isolation relays can be controlled from external sources, to provide on/off control of the battery
- A connector port provides access for an external balancing circuit



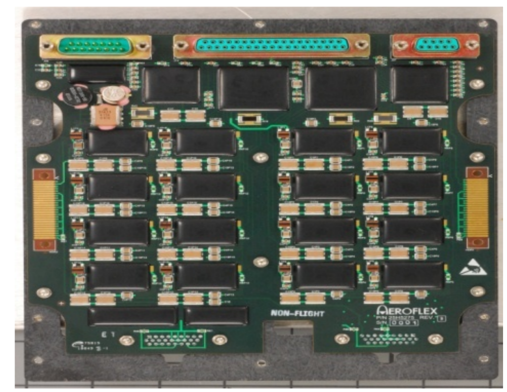
- Orbital/ATK Cygnus Spacecraft, 28V Bus
- Commercial Orbit Transportation System
- Launched September 2013, Multiple Units

- Size: 11.7" L x 6.95" W x 3.63" H (excluding connectors)
- Weight (Complete BIE Unit): 6.6 lbs (3.0 Kg)
  - BIE OVP Slice: 0.46 lbs (0.21 Kg)
  - BIE VTAC Slice: 0.51 lbs (0.23 Kg)
- Analyzed & tested: pyro-shock, vibration & TVAC
- Fastened to Battery Assembly with 8, 8-32 bolts
- Nickel-plated aluminum housing, painted black for emissivity

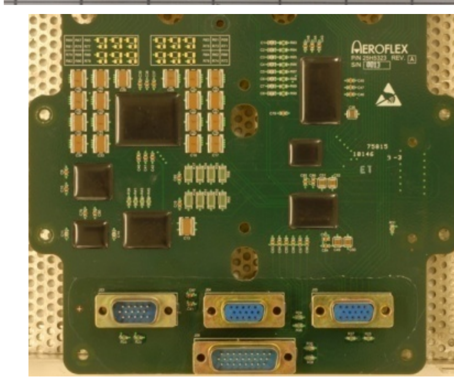
Battery Interface Electronics



Over Voltage Protection Slice



Voltage, Temperature, Analog Conditioning Slice



3 Units per Launch – 21 Units Launched to Date

Launch Date	Status
Sep-13	Demo launch
Jan-14	First commercial cargo supply
Jul-14	Second commercial cargo supply
Oct-14	Failure at launch
Dec-15	First enhanced Cygnus mission
Mar-16	Second enhanced Cygnus mission
Oct-16	Third enhanced Cygnus mission
Mar-17	Planned
2017	Multiple Launches Planned
2017	Multiple Launches Planned
2018	Multiple Launches Planned

- The Battery Electronics Unit (BEU) is an elegant, fully autonomous and continuous, Lithium-Ion cell balancing system with very low heat dissipation and current consumption
- Available to serve multiple missions on an immediate basis
- The Battery Interface Electronics (BIE) is a lower cost Lithium-Ion battery management system that facilitates monitoring of cell voltages, temperatures and provides overcharge/overvoltage protection. Suitable for missions where balancing is not used or necessary
- Both products can be tailored to customer needs and can be supplied at slice levels to be housed in other spacecraft avionics enclosures.
- Large number of units delivered and in orbit with flawless performance

Our Space proven Lithium-Ion Cell Balancing and Battery Interface Electronics coupled with your batteries, is the Ultimate Solution!
Turn On and Forget!