

Design of High Power Cube Satellite Power System

Paper Number SSC14-WK-26

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Ducommun
Miltec



General Information



- Discussed here is Miltec's first cube satellite Electrical Power System (EPS) design and implementation. This presentation covers the design requirements, problems encountered, mistakes made, some of the work arounds and finally some thoughts and directions towards correcting design flaws and EPS improvements for the next generation.
- This paper is meant to provide a starting point for power designers new to the cube satellite arena.
- Originally, this first hardware implementation was intended for prototype evaluation, but was later elevated to flight unit status to support a flight test
- Also the design was targeted towards possible usage in a larger satellites (provides power overkill for a 3U cubesat)
- Certain items are considered company proprietary and will not be discussed in detail
- Questions and comments should be forwarded to Randy Rice at:
rrice@one.ducommun.com

Large amount of detail is included in Small Satellite Conference Paper SSC14-WK-26
"Design of a High Power Cube Satellite Power System"

Paper should be included within the conference minutes, if not email me for a copy

Design Requirements



Most Important Requirements

Four Battery Charge Regulator (BCR) channels each with independent MPPT
Capability to handle a minimum of 96 Watts throughput power from the solar panels
Support 6, 7 or 8 cell panels over a -50 to 100°C range (BCR input of 11 to 25VDC)
Charge the battery without powering any subsystems and also provide a charge in the event of an over discharged battery
Support Lithium-Ion and Lithium Polymer batteries up to 3 cells in series
Allow use of inexpensive Radio Control (RC) hobby type batteries (~\$75.00) for testing and software development (with potential use as a flight battery)
At a minimum: three output switches connected to the battery each capable of 7 amps; 2 line cutter circuits (for solar panel and line cutter release) each capable of 4 amps; One 45 minute delay switch for radio power
I2C buss for control and telemetry functions
Temperature telemetry for all solar panels and battery

Design Requirements Continued



Additional Requirements

Integrated remove before flight pin and separation switch circuitry

Battery over charge/over discharge protection

Minimize battery current drain for in situ long term battery storage (>1year)

Very quiet (high frequency noise and peak to peak ripple) 3.3 and 5 volt power converters with 4 amp minimum output current for each voltage

12 volt, 2 amp and 28 volt, 1 amp boost converters

Support high power charging from ground support equipment

Low current (1 Amp) 3.3, 5 and raw battery switches, at least one each

Reverse input protections for ground charging, battery and solar panels

Standard PC/104 foot print

Provide a battery heater power switch and control function and a battery temperature measurement function

Research Design Methods/ Performed Market Survey



- Researched design methods:
 - Maximum Power Point Tracking (MPPT)
 - Limiting the battery drain during long time storage
 - Limiting battery over discharge and redundant overcharge protection
 - Meshing the power from the 4 different BCR channels into one power stream for the battery bus
 - I2C bus implementation and I2C telemetry gathering and switch control
 - Temperature measurement
 - Remove before flight and separation switch implementation
- Performed market surveys of components:
 - Battery Charge Regulators
 - Ideal Diode Circuits
 - Power Converters, Buck and Boost
 - Electronic Switches
 - I2C components
 - Components for temperature measurement
 - Components for protection against reverse power connection
 - Transient voltage protection components
 - Timer circuits
 - Pulse Width Modulation circuits for battery heater control

**Conducted extensive research to determine the optimal designs and components
The designs and components are addressed in greater detail in the Paper**

Power Input Section Design



LTC4365 passes a voltage range and prevents reverse connection

FROM GROUND POWER

LTC4365
VOLTAGE RANGE
PASS
12 – 28V
DUAL
SI7414DN-T1-E3

IDEAL DIODE CONTROLLERS

FROM
SOLAR
ARRAY

SINGLE LTC4357
SI7414DN-T1-E3

SINGLE LTC4357
SI7414DN-T1-E3

SINGLE LTC4357
SI7414DN-T1-E3

FROM
SOLAR
ARRAY

SINGLE LTC4357
SI7414DN-T1-E3

FROM
SOLAR
ARRAY

SINGLE LTC4357
SI7414DN-T1-E3

FROM
SOLAR
ARRAY

SINGLE LTC4357
SI7414DN-T1-E3

BCR
CHANNEL 1
3 LTM8062s IN PARALLEL
BATT FLOAT SET TO 8.1V

MPPT

BCR
CHANNEL 2
3 LTM8062s IN PARALLEL
BATT FLOAT SET TO 8.1V

MPPT

BCR
CHANNEL 3
3 LTM8062s IN PARALLEL
BATT FLOAT SET TO 8.1V

MPPT

BCR
CHANNEL 4
3 LTM8062s IN PARALLEL
BATT FLOAT SET TO 8.1V

MPPT

POWER SUMMING NETWORK

LTC4365
VOLTAGE RANGE
PASS
2.5 - 8.3V
SI7994DP-T1-GE3

LTC4365
VOLTAGE RANGE
PASS
2.5 - 8.3V
SI7994DP-T1-GE3

LTC4365
VOLTAGE RANGE
PASS
2.5 - 8.3V
SI7994DP-T1-GE3

LTC4365
VOLTAGE RANGE
PASS
2.5 - 8.3V
SI7994DP-T1-GE3

BATTERY

Power from all
BCRs summed

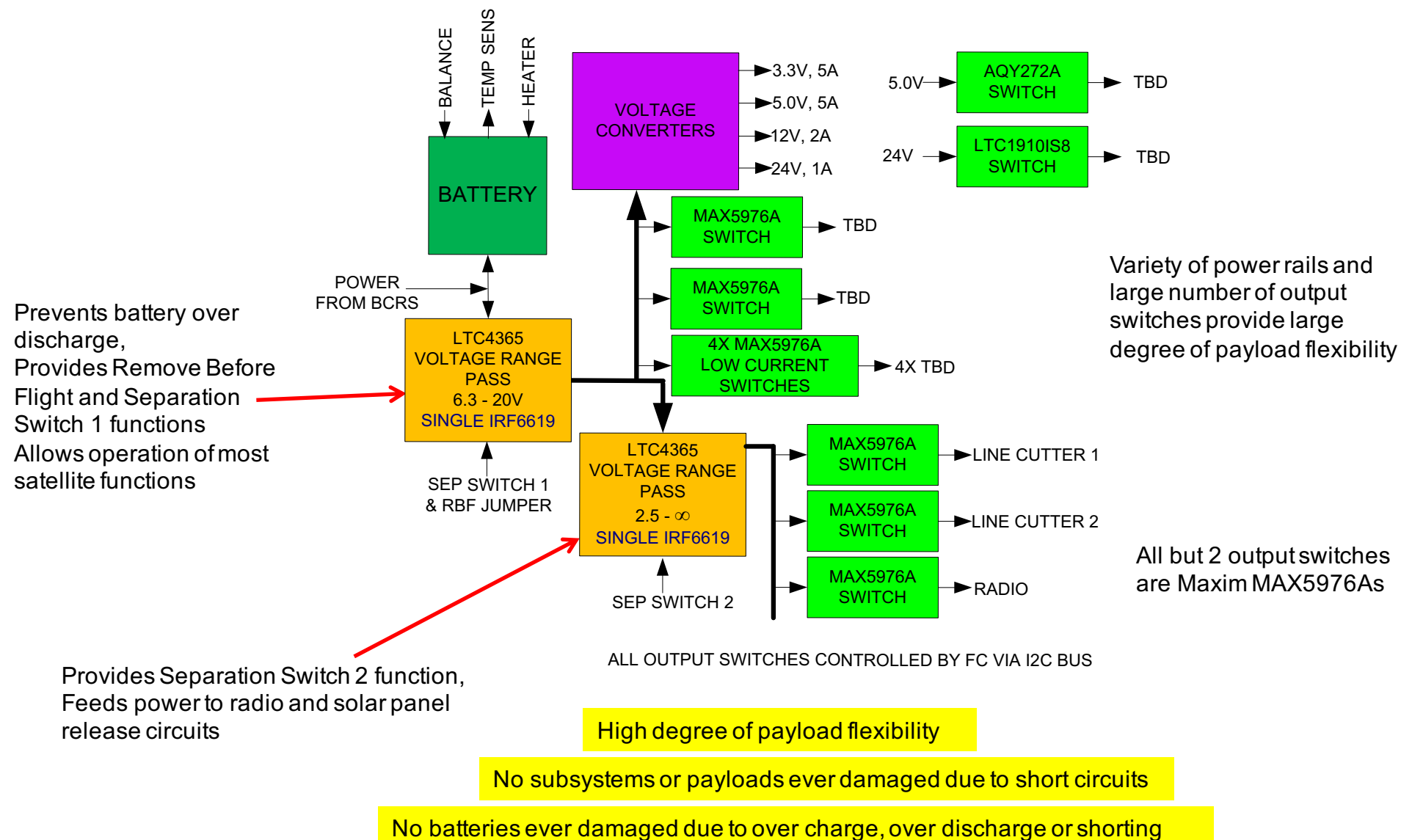
Each BCR channel
capable of placing 5.55A
onto battery bus

Each LTC4365 provides
redundant battery
overcharge protection and
redundant reverse current
prevention

Automatically charges battery with no requirement for internal power (will charge a dead battery)

Uses inexpensive (~\$75.00) RC Hobby batteries for testing and software development

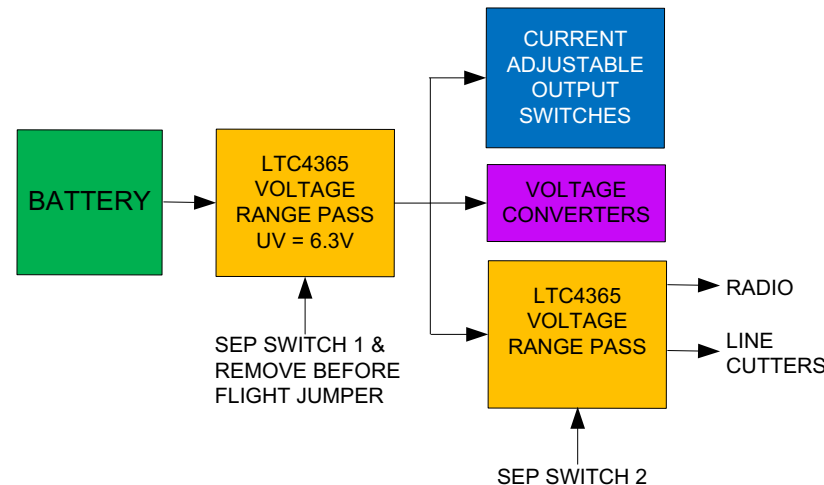
Power Output Section Design



RBF and Separation Switch Detail



- Separation Switch implemented using LTC4365s in a single MOSFET (IRF6619) Configuration
 - LTC4365 shutdown pins pulled to ground by separation switches while stored inside PPOD
 - After ejection from PPOD, shutdown pins pulled high through 50K Ω resistors connected directly to the battery
 - The launch provider required three inhibits to prevent premature release of antennas/solar panels, the separation switches served as two inhibits (the third inhibit required no release or transmission for 45 minutes after ejection and must use onboard sensors to verify satellite is in orbit)
 - Remove before flight jumper pulls first LTC4365 to ground under all conditions and aids in handling/storage outside of a PPOD.



BCRs will charge battery no matter the state of the RBF Jumper and Separation Switches

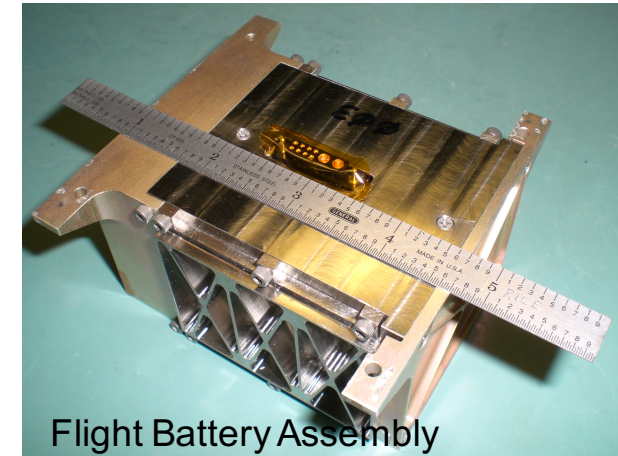
During storage, drain current from battery is < 400 μ A, for a 6AH battery, that provides a storage life of ~1.7 years

Flight Battery



- Flight Battery

- The satellite flight battery was fabricated by connecting two Yardney Technical Products, Inc. part number LiAD7BM-1, 6 Amp-Hour (AH) Lithium-Ion cells in series
- The LiAD7BM-1 was developed specifically for this program
- Assembly is designed by Miltec and assembly contains temperature sensors and heaters
- Also the midpoint connection between the two battery cells is brought out to the battery connector to facilitate battery balance.



Flight Battery Assembly

- Battery Testing Requirements/Range Safety

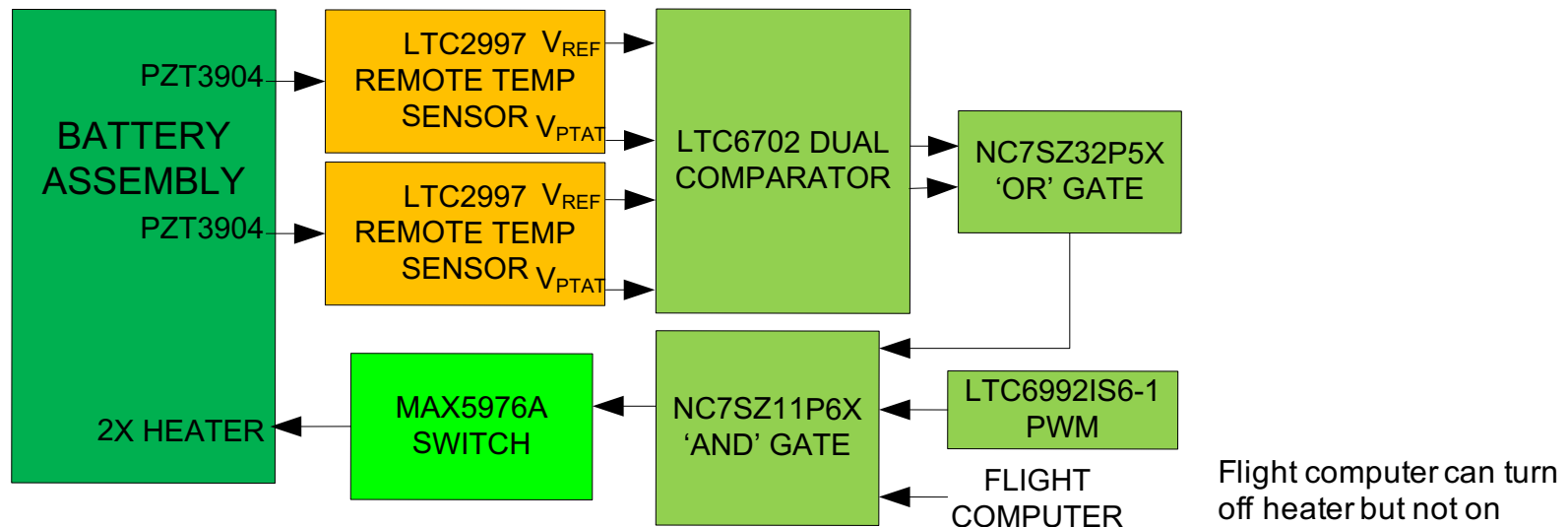
- Range safety indicated testing requirements would be minimized for cells/batteries with existing UL or Mine Safety Administration (MSA) approval, no prior approvals existed for the new Yardney cells
- Batteries required testing for prevention of over charge, over discharge and reverse charge also one cell would need to be short circuit tested
- Since the battery is not meant to be used separately from its protection electronics on the EPS, Range safety agreed that they could be tested as a unit
- Testing for over charge and over discharge was performed in-house, data was collected, a report was generated and submitted, no problems encountered
- The battery is reverse connection protected by an in series N channel MOSFET placed in the Anode battery connection on the EPS and by the connector design, such that it is impossible to reverse connect the battery
- Yardney Technical Products, Inc. performed the short circuit testing, requirement was no rupture or out gassing of the cell could occur, no problems were encountered and a test report was provided to range safety

Battery/cells approved for flight, however, your LV provider may have different requirements, communicate with range safety early

Battery Heater



- Battery Heater Control (battery operating range of -10 to 40C)
 - Temperature measured by two LTC2997s with PZT3904 transistors used as sensors
 - LTC2997 V_{PTAT} pin outputs a linear 4 mV per degree Kelvin and is compared to a V_{REF} powered voltage divider set to 1.09V (0°C), This set point is adjustable.
 - As either sensor goes below 0°C, the dual comparator outputs a high to an 'OR' gate, the 'OR' gate feeds a 3 input 'AND' gate
 - The 2 other 'AND' gate inputs are controlled by the flight computer (which can keep the heater turned off only) and a PWM signal (PWM is set to 10Hz at a 20% duty cycle and is adjustable)
 - The MAX5976A is the final switch feeding two heaters inside the battery assembly, whenever a sensor drops below 0°C, the switch cycles on/off as per the PWM signal (unless the flight computer keeps it's 'AND' gate input low)



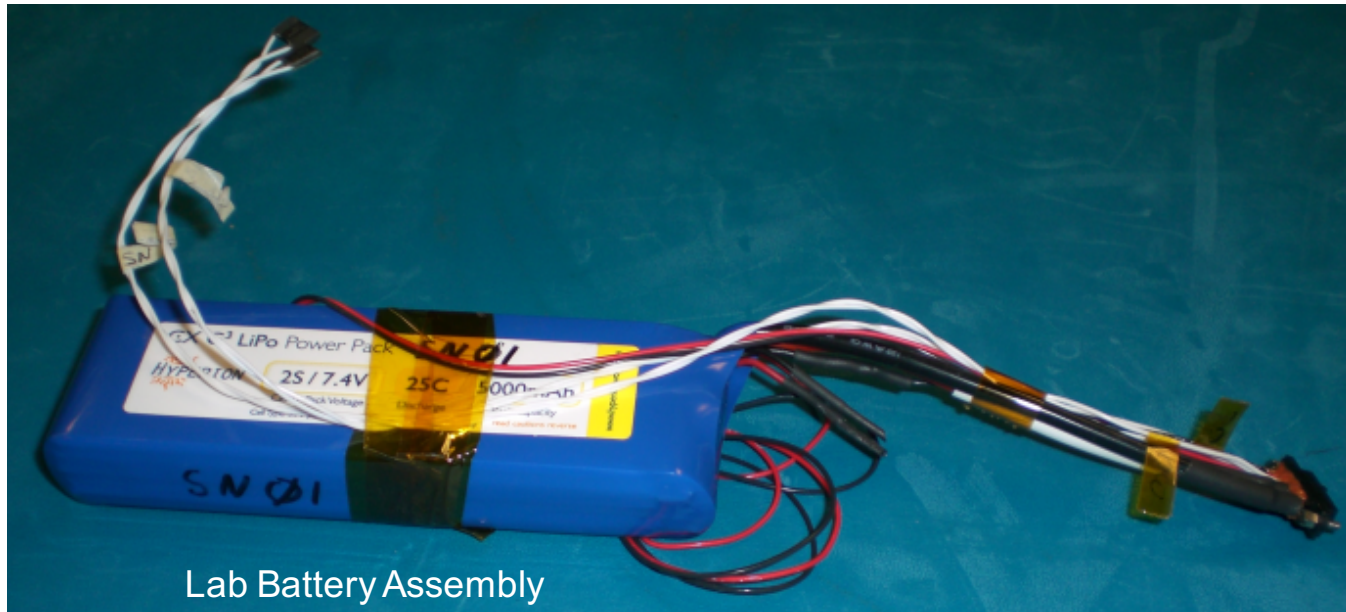
Heater temperature "trip" point and PWM frequency/duty cycle all adjustable

Lab/Development Battery



- AKA “Throwaway Battery”

- The EPS was also designed to use inexpensive RC hobby type Lithium Polymer (<\$75) batteries during testing and software development
- Hyperion G3 CX 5000 MAH 2S 7.4V 25C/45C LIPOLY Pack, part number HP25C50002S
- Temperature sensors, leads for heater connections and the same interface connector used for the flight battery were added to the Hyperion battery (if you make your own, make sure the cable is at least 16 inches)
- Several of these lab batteries were fabricated and used throughout development and testing with no problems.



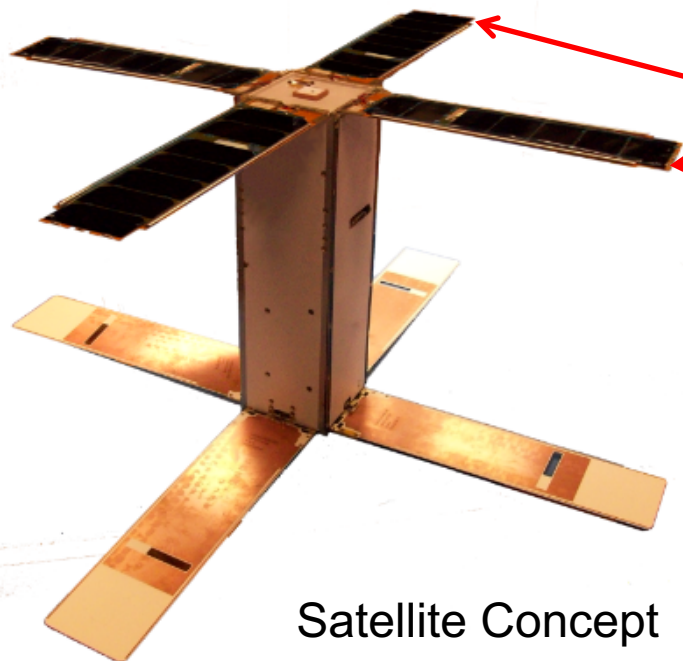
Lab Battery Assembly

Expensive flight batteries not required for testing or software development

Solar Panels



- The solar panels are Miltec custom-designed and were fabricated by Pumpkin, Inc
- All panels are identical
- 7 Spectrolab, Inc. UTJ solar cells per panel (~1 Watt per cell)
- Temperature sensors are MMBT3904 transistors which work in conjunction with Linear Technology Corporation part number LTC2997
- Refer to the LTC2997 specification sheet, figure 8, for the design method
- The outputs of the Temperature Sensors were fed into an I2C ADC for telemetry purposes.



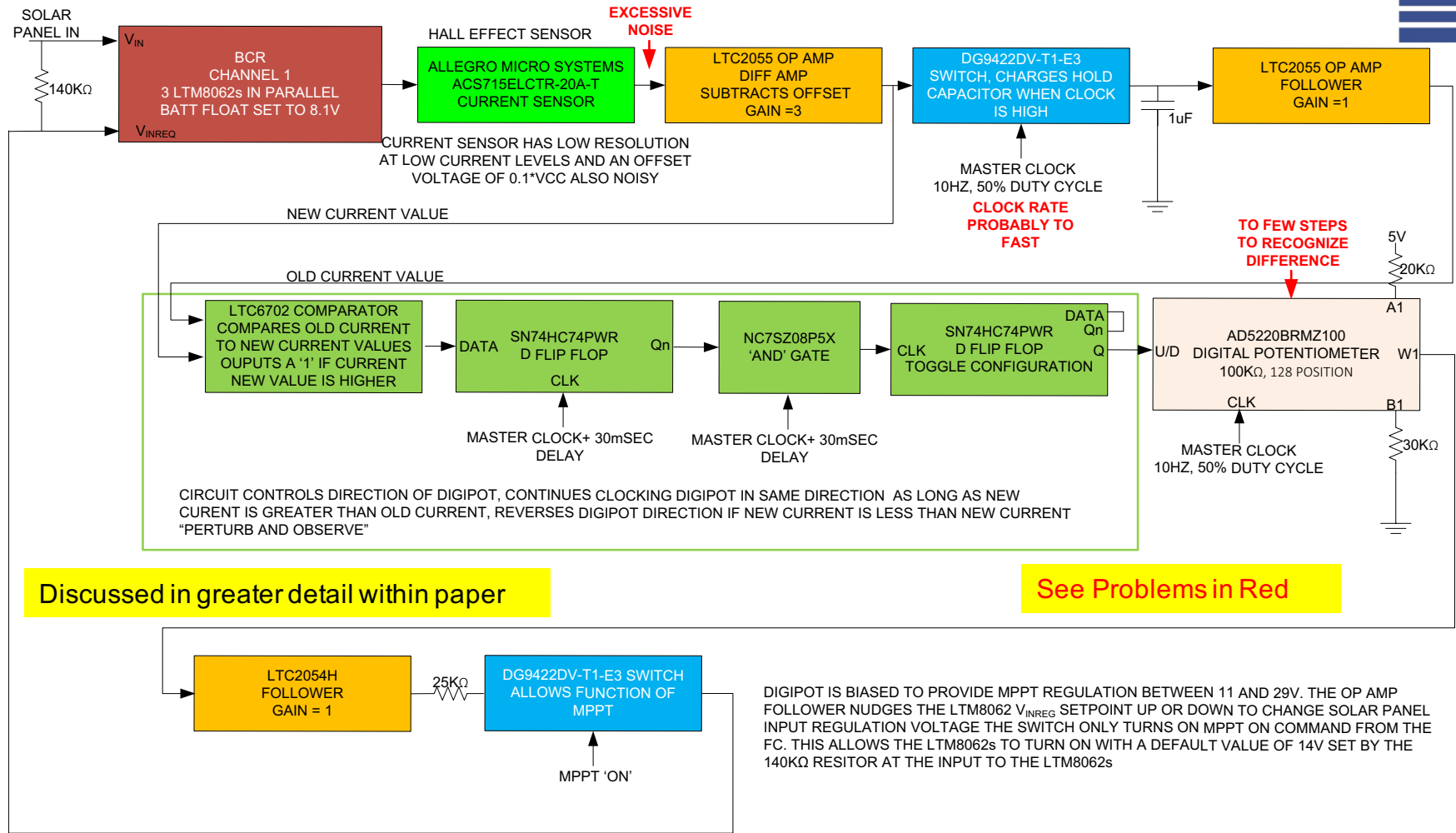
Four solar panels deploy after PPOD ejection, 28 Spectrolab UTJ cells in a single plane

All Panels are identical

Panels will charge battery while folded

Satellite Concept

Maximum Power Point Tracker (Perturb and Observe)

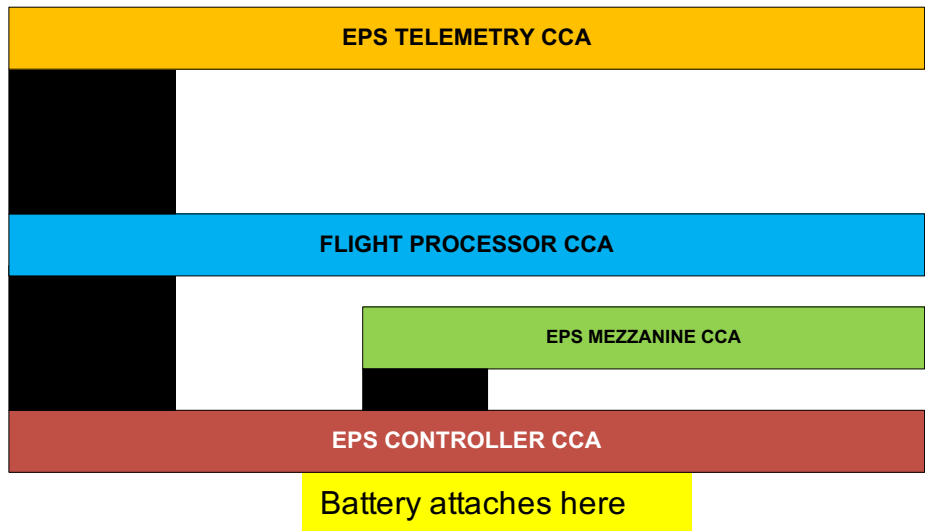


Current measurement noise issue, used backup plan of setting input regulation to a fixed voltage of 14V for a maximum input power of ~24W. Note the MPPT design might have worked at higher input power levels (more solar panels) or if the number of digipot steps per "perturb" could be adjusted. The next revision will use an overall simpler design with an improved more flexible current measurement design, a digipot connected directly to the BCR to manipulate the input voltage set point and the feedback loop controlled by a micro controller. This new design has already been bread boarded and tested



Circuit Card Assembly (CCA) Implementation

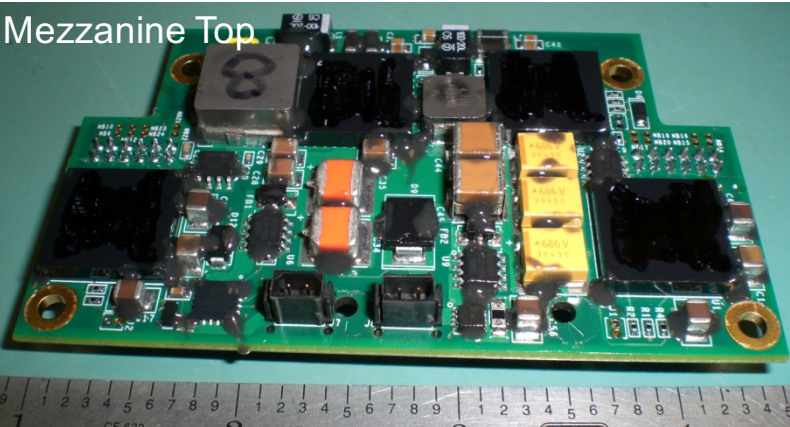
Standard PC/104 foot print



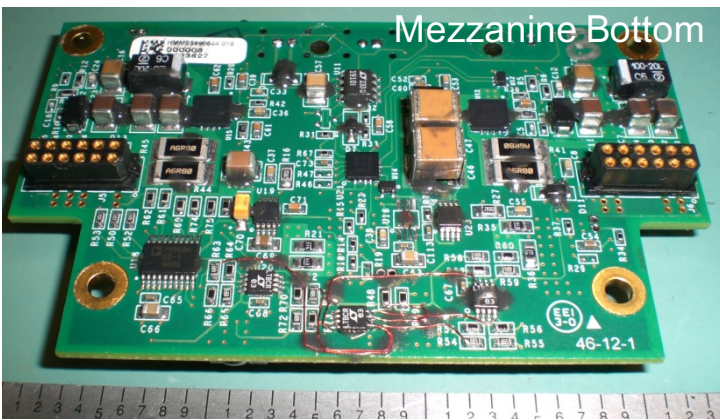
Flight Stack



Mezzanine Top



Mezzanine Bottom

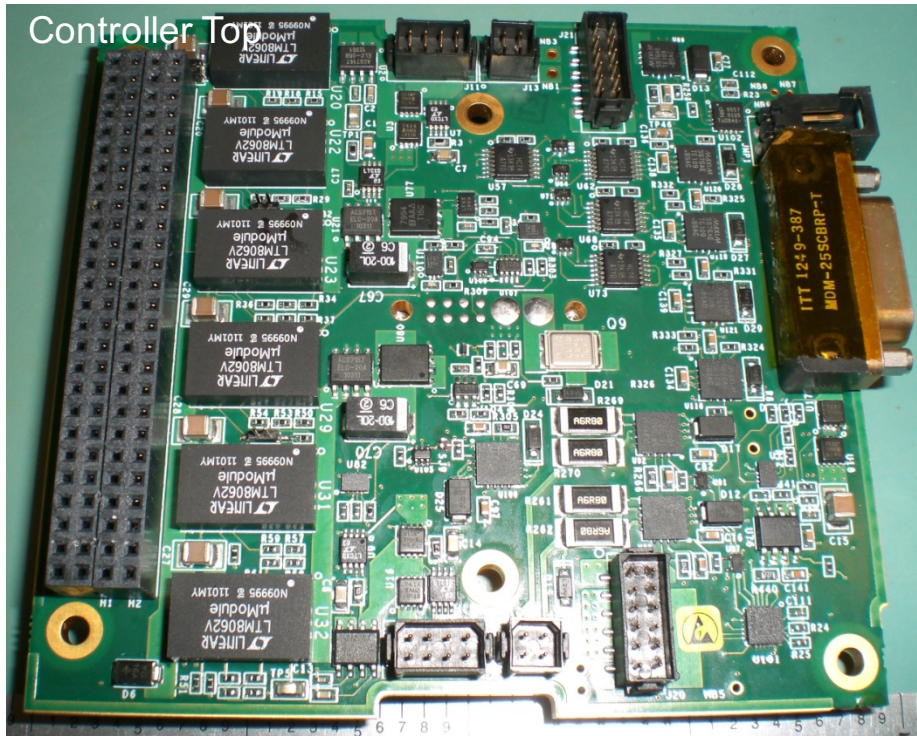


Mezzanine contains all power converters, can be quickly customized to accommodate specific power requirements

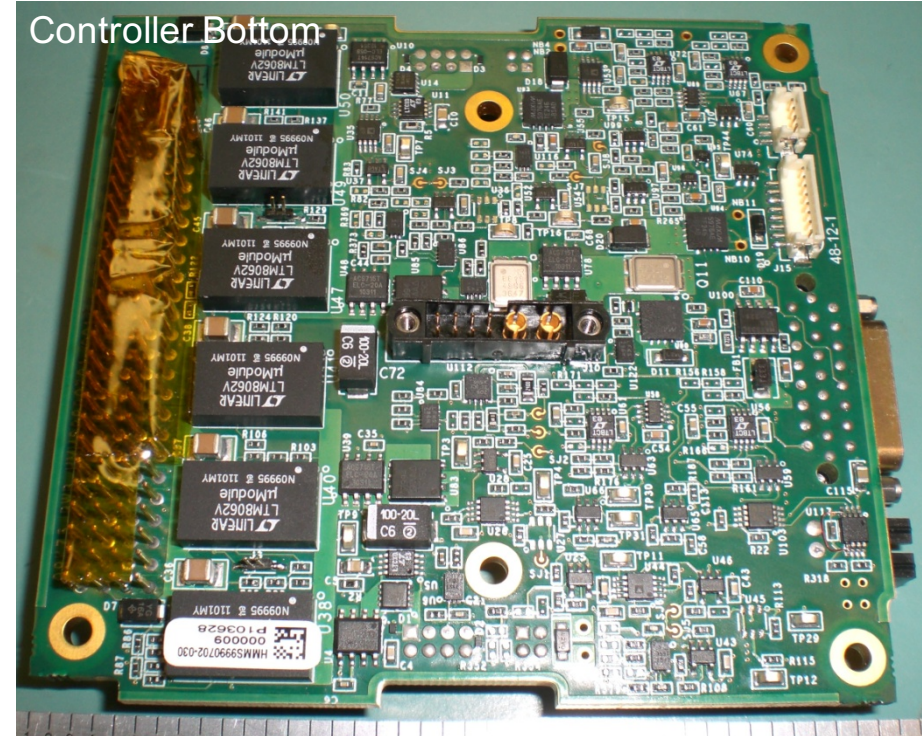
Circuit Card Assembly (CCA) Implementation Continued, EPS Controller Card



Controller Top



Controller Bottom

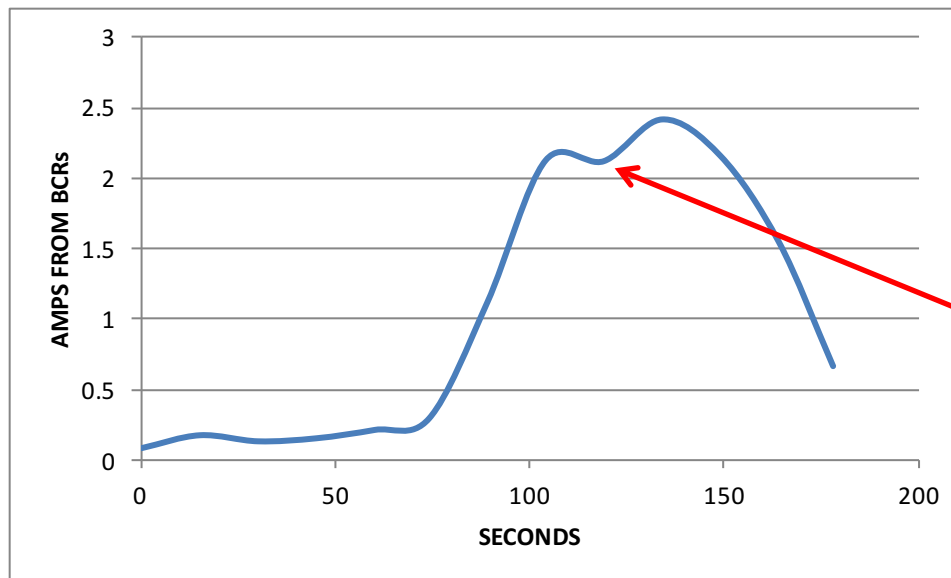


- Controller performs all other functions except telemetry
- Due to large throughput current design, the PWB was ~0.15 inches thick
 - Large thermal mass of the ground plane led to challenges in soldering through hole connectors to the PWB, this was overcome by preheating the PWBs
 - Also this large PWB thickness caused defective vias between layers causing some PWB rejections

PWBs/CCAs that made it through testing are very reliable

Next revision PWBs are designed to decrease PWB thickness

Orbit Power Data Sample



Unknown Shadow Event
(occurs repeatedly)

- 178 Second block, 15 second interval samples
 - The satellite is rotating the solar panels towards and away from the sun, the period of rotation is approximately 4 minutes
 - At the 134 second point, the combined BCR output current peaks out at 2.42 Amps at a battery voltage of 8V or 19.84W
 - The maximum theoretical power available from the solar panels is 24.13 Watts (BCR input regulated to 14V and 0.431A from each of the 4 panels) since BCR efficiency is ~82%, the Max theoretical power on the battery bus is 19.78W
 - **Ratio of maximum orbit power to maximum theoretical power is 19.84/19.78 = ~1**
 - There is of course some measurement error in the telemetry data but overall the correlation is good

Very good comparison of maximum orbit telemetry power to maximum theoretical power

Summary/Path Forward



- Summary

- Miltec's first Cube Satellite Electrical Power System
 - Originally intended to be a prototype only (next iteration corrects all problems)
 - Maximum Power Point Tracking was the only requirement not met
 - Some problems caused by Controller PWB thickness
 - Design deemed “good enough” for flight and units are now operating on orbit

Units now functioning in LEO with no failures

- Path Forward

- Next generation schematic and layout already completed
 - MPPT design already breadboarded and tested using Demo cards
 - Microcontroller added to control the MPPT loop (software provides adaptability)
 - Microcontroller also eliminates Telemetry CCA
 - To alleviate PWB thickness problems, current design places the BCRs onto separate distributed PWBs and sums them at the battery

All problems alleviated, design ready to complete build process.
Design can support a large variety of payload requirements
At this stage, additional design requirements could easily be accommodated.

Suggested Student Project - Solar Panel Simulator



- The testing of Maximum Power Point Trackers requires either a real solar panel and actual sunlight or a solar panel simulator.
- Possible to construct a low-cost simulator using a lab power supply (in our case an Agilent E3236A), notebook processor and a software program.
- Software Engineers wrote a program that monitored the lab supply output voltage as it was being changed by a Maximum Power Point Tracker and modified the lab supply output current limit according to a programmed solar panel current/voltage curve.
- A GUI allows for changing the simulated panel open circuit voltage and short circuit current and also displays the power supplies output. The operator can observe the “Percentage of Maximum” voltage and easily determine how well the Maximum Power Point Tracker is working. This proved to be a very useful tool during testing of new Maximum Power Point Tracker designs.

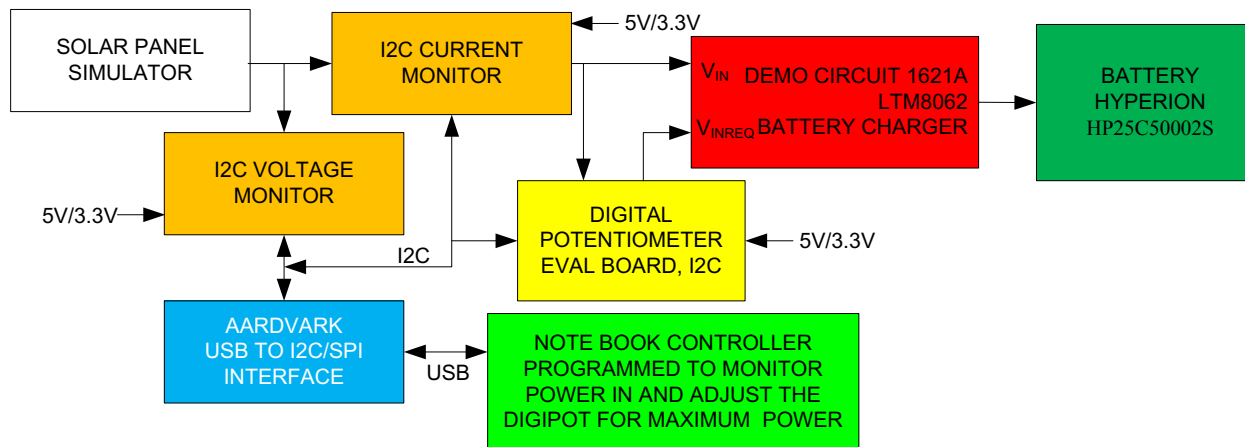


Solar Panel Simulator is a useful tool for MPPT testing. Trying to get the software released as a free product, if you are interested in a copy please email me

Suggested Student Project - Maximum Power Point Tracker



- Utilize available low-cost demo cards for quick MMPT circuit implementation/testing
- Cost of demo cards and other miscellaneous parts < \$1000
- The demo cards, Aardvark and battery attached to a plywood board
- Prototyping the design using low cost demo boards allows the designer to identify design flaws and evolve the design



- Refer to the paper for some additional cautions/suggestions for this project
- Please feel free to contact me with any questions

This method verified our next generation design



Thank you

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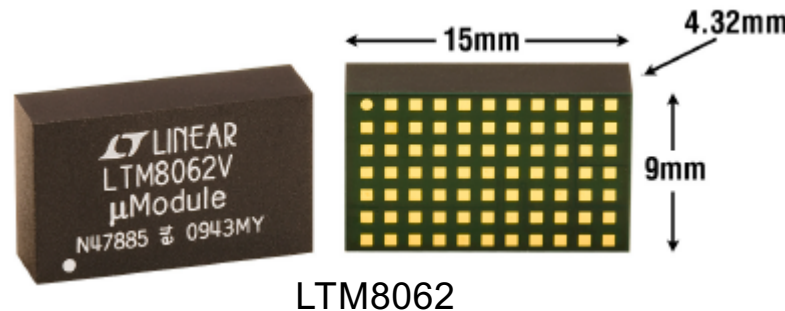


Back Up Charts

Input Section Components



- Battery Charge Regulator (BCR)
 - Linear Technology Corporation's LTM8062 (9x15mm foot print)
 - Near complete BCR, needs only resistors for float and input voltage programming, small capacitors and TVS, can charge Lithium Ion and Lithium Polymer batteries
 - Input voltage range, 5 to 32V, max output current of 1.85A, can be paralleled for additional current
 - Its efficiency is typically **81 to 83% (not so great, but you get a lot of components in pkg)**
 - Pulls maximum current at a fixed input voltage point, set by a resistor at the V_{INREG} pin, was thought the V_{INREG} pin could be used to track the solar panel Maximum Power Point
 - Used three LTM8062s in parallel per BCR channel. So each BCR channel would be capable of providing a maximum of 5.55 amps onto the battery bus.
 - The maximum theoretical current onto the battery bus from all four BCR channels is 22.2 amps. (large overdesign considering available 6AH battery capacity)
 - The amount of waste heat generated by the BCRs at a full 22.2 amps (162 Watts) output would be approximately 35 Watts.
 - Even though each BCR channel is only connected to a single 7 cell panel, during acceptance testing each BCR channel was tested to 27 Watts throughput or a total of 108 Watts for all 4 channels



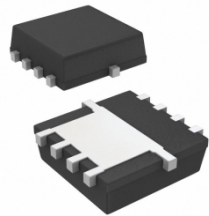


Input Section Components Continued

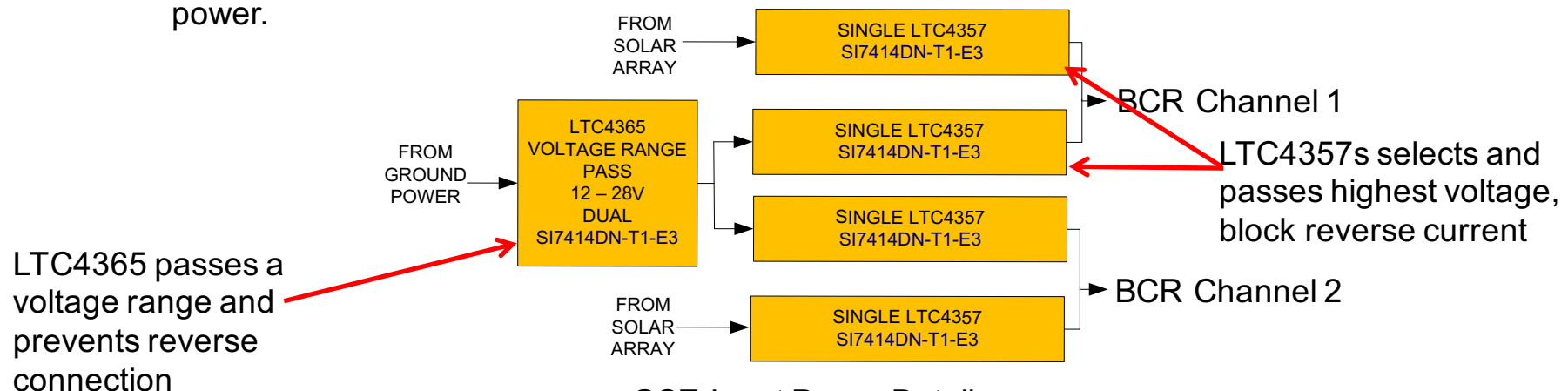
- Ideal Diode Circuit Controllers, Ideal diode circuits were used rather than diodes in order to increase overall system efficiency

- Linear Technology Corporation's LTC4357 (2x3mm foot print)

- Uses a single external N-channel MOSFET
- Throughput voltage range of 9 to 80V
- Does not protect against transients or reverse voltage connections, reverse connection protection diodes and transient voltage suppressor's were added to the circuit
- MOSFETs chosen was Vishay SI7414DN which has a 3.3x3.3mm package capable of greater than 4 amps continuous throughput and a maximum drain source voltage of 60 VDC and a drain to source resistance (R_{DS}) of 25 milli-Ohms at a gate source voltage (V_{GS}) of 10 volts
- This controller was used to feed the power from the solar panels to the BCRs. It also prevents a back feed of current from the battery to solar panels when they are not illuminated.
- Additional LTC4357s are connected to BCR channels 1 and 2 to allow feed from ground power.



SI7414DN MOSFET



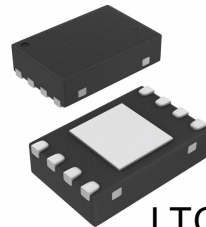
GSE Input Power Detail

Input Section Components Continued



- Programmable Voltage Range Pass controller
 - Linear Technology Corporation's LTC4365 (3x2mm foot print)
 - It will pass a voltage range set by resistive divider circuits at the under voltage and over voltage pins
 - Passes voltages between 2.5 and 34 volts and protects against input voltages between -40 to 60 volts
 - However, if the output is reverse connected, the controller will be destroyed
 - Also once device is operating in the set voltage range, if the input is turned off and the output connection is within the set voltage range, current will flow from output to input unless the shut down pin is pulled low.
 - Uses dual source connected N-channel MOSFETs (employed several different MOSFETs depending on function, refer to the paper for more details)
 - The Input Section functions implemented using the LTC4365 include:
 - GSE power voltage pass through limitation
 - Power summing at the output of the BCRs
 - Redundant protection against battery over charge

Each of the LTC4365 functions is discussed in greater detail within the paper



LTC4365

Output Section Components



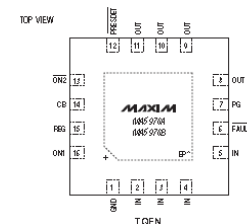
- Ideal Diode Circuit Controllers

- Linear Technology Corporation's LTC4365 , Discussed in the Input Section Components
 - The Output Section functions implemented using the LTC4365 include:
 - Remove before flight jumper implementation
 - Separation switches/inhibits implementation
 - Protection of the battery against over discharge (lower cutoff is 6.3V)

No batteries ever damaged due to over charge or over discharge

- Output Switches

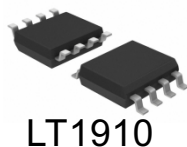
- Maxim Integrated Products MAX5976A (5x5mm footprint)
 - They operate from 2.7 to 18 volts with resistor adjustable current limit up to 7A
 - The 'A' version has an automatic retry after an over current condition.



MAX5976A

- Linear Technology Corporation's part LT1910 Protected High Side MOSFET Driver (8-SOIC PKG)

- Only used for 24V Propulsion Valve control
- Used in conjunction with a Vishay Siliconix SI7414DN MOSFET
- 8 to 48 volt range, adjustable over current protection and automatic restart in the event of an over current event



LT1910

- Panasonic AQY272A, solid state relay, 60 volt operation, 2A max (8.8x9.3 footprint)
 - Used only to switch 5V to the ADACS



AQY272A

No subsystems ever damaged due to short circuits

Battery Balance (not a requirement)



- There are articles, papers and conjecture indicating that 2 cell in series Lithium-Ion batteries do not require battery balancing (Based on my experience this appears correct)
- Desired to include this capability in our design and also gain more experience in designing cell balance circuits.
- The Texas Instruments, Inc. part number bq29200 was the only identified cell balance IC designed specifically for balancing 2 cell in series Lithium-Ion batteries, this seemed like a low risk solution
- The bq29200 was designed in the circuit so that it could be easily connected/disconnected using solder junctions
- Prior to bq29200 connection, the drain current with all systems off was measured in the 300 to 400 micro amp range
- After connection of the bq29200, the drain current with all systems off doubled to 600 to 900 micro amp range
- This amount of current would have caused the PPOD storage time to be cut in half
- The bq29200 was then isolated from the battery cells and the decision was made that battery balance was not required. No attempt at troubleshooting the bq29200 circuit was made.

Battery balance (not a requirement) not available due to excess current draw of bq29200 IC