CAPITOL
Technology University

CACTUS-1

The CubeSat Power Bus Design Project is a product by Erik Schroen.

Acknowledgements: The Cactus-1 mission is Capitol Technology University's first CubeSat mission. Our launch opportunity was provided via the NASA CubeSat Launch Initiative. The Cactus-1 mission is supported by grants from the Maryland Space Grant Consortium (MDSGC).

Common Electrical Power System for Small Satellites

Erik Schroen

Capitol Technology University

Dr. Alex Antunes

Department of Astronautical Engineering

AE - 458

Senior Design Project 2

Last Edited by Author: 10 April 2019

Last Edited:

By:

Contents

Acknowledgements

I would like to thank Capitol Technology University for providing connections and support that allows other students and I to participate in high altitude balloon flights, RockSat and other sub orbital flights, and orbital launches. Faculty support has allowed these missions to come to fruition and succeed in accomplishing their goals.

I would also like to thank the RockSat-X, RockSat-XN, and the entire RockSat program and Colorado Space Grant Consortium as well as the supporting members for the great opportunity to fly payloads on their launches. The experience gained from these flights has proven invaluable in the development of this guide as well as providing flight heritage for the designs.

Lastly, I would like to thank the Maryland Space Grant Consortium for their continued support to our university, without which none of these missions would be possible.

www.captechu.edu

spacegrant.colorado.edu

md.spacegrant.org

Purpose

The purpose of this document is to discuss a process that an electrical engineer could take to create an Electronic Power System (EPS). This process was determined through my experience gained from multiple orbital, suborbital, and high-altitude balloon (HAB) small satellite missions. The design process will be discussed for each section of the EPS and recommendations will be made. Lessons learned will be provided in relevant sections to discuss any successes, failures, or what could have been done better. The main goal of this document is to speed up the design process of an EPS for a custom small satellite, which is usually the last subsystem to be designed due to changing electrical requirements by other subsystems. This will allow for more testing of the EPS separately and when integrated with the satellite. This documentation assumes a novice level of understanding in electronics, that is at least a circuit theory or equivalent course, an electronic devices course will aid the reader as well.

Biography

I am an Astronautical Engineering major (Graduating May 2019) at Capitol Technology University (CapTechU). At the time of writing this I have flown two successful EPS (Project Hermes 3.0 & Project Aether) and have one EPS waiting for flight that was tested successfully (CACTUS – Hermes) as well as one successful High-Altitude Balloon (HAB) flight for Project Aether. All these projects will be discussed when applicable to apply lessons learned to my designs and techniques. I have worked at U.S. Army Research Laboratory (ARL) for three years in the Sensors and Electron Devices Directorate (SEDD), Power Conditioning Branch, designing (electrically & mechanically), building, and testing/evaluating power systems for multiple purposes.

If you have any questions or need clarifications I can be reached at eschroen2@gmail.com.

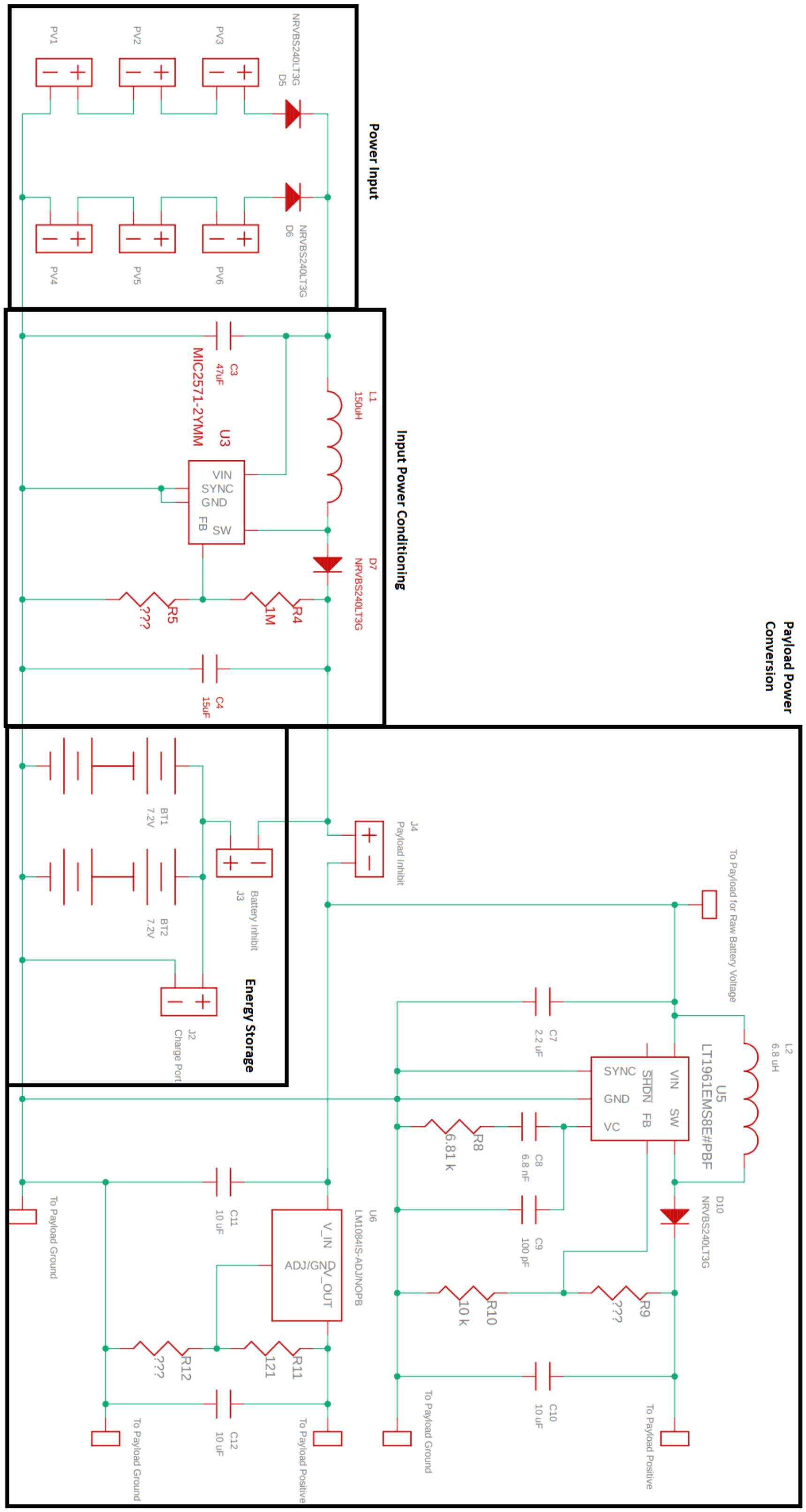

Figure 1 - Sections of an EPS discussed in this document; Power Input, Input Power Conditioning, Energy Storage, and Payload Power Conversion

Power Budget

The first thing that should be accomplished is developing a rough power budget for the payload. This can be updated later as systems become more solidified and numbers become more concrete, but you need a basic idea of how much power each system is going to require before you can really get started. This information will determine almost everything hereafter. This initial document should consider the **worst-case scenarios**, it is always easier to overdesign early and lower the requirements later then to have to increase your requirements after a preliminary design. The most common systems you will have to consider for a university mission are your computer/processing (typ. Raspberry Pi or Arduino), scientific/engineering payload, and communications, though others may apply depending on the specifics of the mission. You should attempt to gather as many datasheets as possible for each component that is likely to fly to help you generate worst case scenarios for each system.

Table 1 - Early power budget for Project Aether

Component	**Quantity**	**Maximum Current (A)**	**Nominal Voltage (V)**	**Power (W)**	**Total Current (A)**	**Total Power (W)**
Raspberry Pi 3	1	1.3	5	6.5	1.3	6.5
Iridium Modem	2	1.3	5	6.5	2.6	13
Amplifier	2	0.001	7.2	0.01	0.003	0.02
Spectral Camera	1	0.25	5	1.25	0.25	1.25
VIPE Transformer	1	3	7.2	21.6	3	21.6

Voltage and Current: Table 1 shows the power budget used for Project Aether. Early on the team knew these components would be flying, all the information for maximum current and nominal voltage were taken from datasheets for the devices. The amplifiers and VIPE Transformer could run directly from the batteries so the nominal voltage was the value of the nominal voltage for the batteries, discussed later. The maximum current that each system will draw is important because the components that are selected for the power board must be able to handle the required currents. The other systems would need regulation to achieve 5 V.

Power: Power was a simple calculation from current and voltage ($P = I * V$). Total current and total power are there to account for the quantity of each device. The total current for all devices can be calculated (7.153 A) and the total power can be calculated (42.37 W) to aid with battery selection later. If the flight time of the payload for suborbital missions or HAB flights or the desired-on time for orbital missions is known, then the Amp-hour (Ah) required can also be calculated to aid in battery selection by $Ah = t * I$ where t is in hours. Project Aether was a suborbital sounding rocket mission with a flight time of 15 minutes, so the battery capacity required was 1.79 Ah. Note, this is an estimate because the current draw of the devices may not be the same as the current draw from the batteries.

Energy Storage

After the power budget you can select the batteries that will be flown. The most common battery type and the one that will be used throughout this document is a **Lithium-Ion 18650 rechargeable cell**. Lithium-polymer cells may also be flown and should be interchangeable in this design so long as the cell voltages are not too low or high. **Whichever chemistry is chosen, this should be communicated in your design reviews so it is clear that you are flying batteries and will need time and access to charge them during testing and preflight.**

Cell Chemistry: An 18650 cell's nominal voltage is 3.7 V and the peak voltage at a full charge is 4.2 V. The nominal voltage is where most of the battery's capacity is, so as the battery discharges it will stay at this voltage for longer, shown in Figure 2. The capacity axis can be taken as discharge over time. With a load applied the battery voltage strarts droping until the nominal voltage, where is very slowly decreases until reaching a point where the voltage quicly drops. At the knee point where the battery voltage drops off the battery is fully discharged. The different curves are different discharge currents, 1C being the lowest and 18C being the highest.

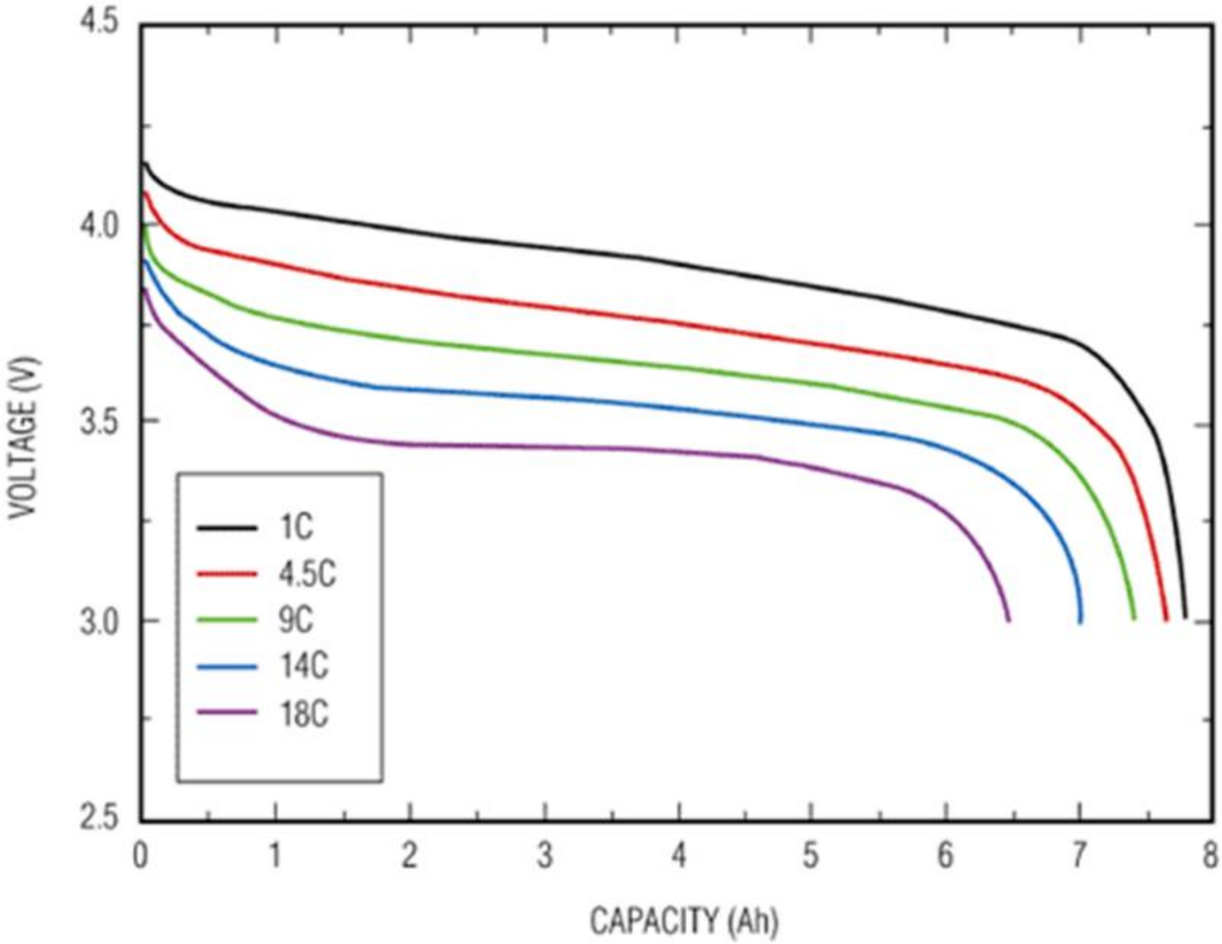

Figure 2 – Lithium-Ion 18650 battery voltage vs. capacity - Electrical Engineering Stack Exchange

Maintenance: The main thing to be careful of is to **not over charge or over discharge the cells**, these will destroy them and render them inoperable. Generally, the charger will not allow the cells to be overcharged. However, the cells can be charged directly from a power supply or a custom charger (Appendix), in this case the voltage setpoint should be the peak voltage of the cell and the current should be limited to 1 A maximum or lower. Peak voltages are listed in Table 2. The batteries should be left on the power supply until the current flowing into them is close to zero at the voltage setpoint. Initially when the battery is put on the power supply the battery voltage will 'float' up, and once disconnected will also 'float' down, therefore the current flow into the battery is the best indicator of state of charge. Over discharge is accomplished by monitoring the battery or cutoff circuitry, **when the cell voltage gets too low the battery should be fully charged before continuing use**. **During charging batteries should never be left alone and should constantly be monitored.** As shown in Figure 2, 18650 cells should not be discharged lower than 3 V.

Battery Selection

Creating a Pack: By placing multiple battery cells in series, you create a 'pack' with a higher voltage, shown in Table 2 and Figure 3. If multiple cells are used the positive terminal of a battery should always be connected to the negative terminal of another. There will be an overall positive and overall negative terminal which are the power connections to the circuit.

Table 2 – 1 - 4 Lithium-Ion cell battery pack voltages

Number of Cells	Minimum Voltage (V)	Nominal Voltage (V)	Peak Voltage (V)
1	3	3.7	4.2
2	6	7.4	8.4
3	9	11.1	12.6
4	12	14.8	16.8

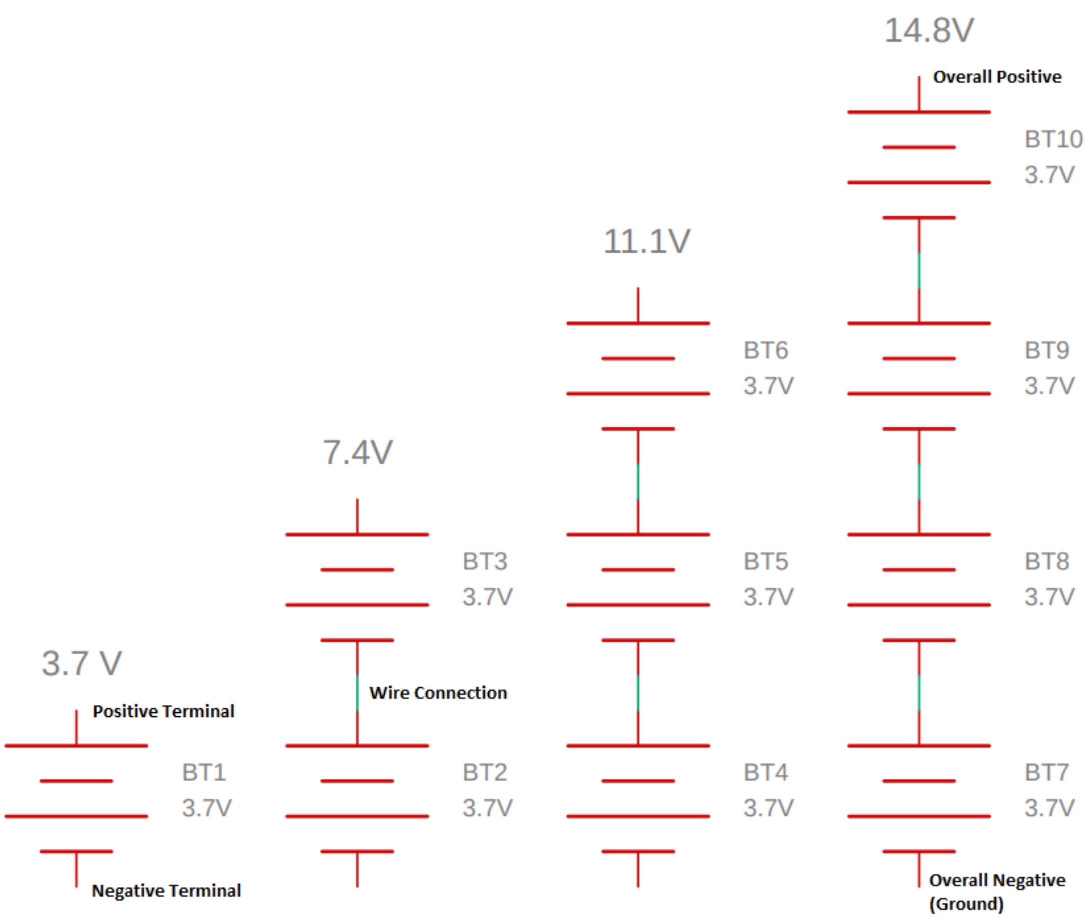

Figure 3 – 1 - 4 Lithium-Ion 18650 cell battery pack configuration

Voltage: The number of battery cells that you use for a mission comes down to the volume and mass constraints of the EPS and satellite as well as the needed capacity of the EPS, discussed next. A good rule of thumb is to keep the nominal voltage of the battery pack close to the voltage that requires the most current, favoring a slightly higher voltage over a lower voltage. As an example, if the payload has many 5 V devices drawing current, 2 cells in series may be a good choice for the payload.

Current and Capacity: Current and capacity is the next consideration. The maximum possible current draw and required capacity should be obtained from the power budget. Battery cells have a maximum discharge rate, and while adding cells in series increases the batter pack voltage, it does not increase the maximum current discharge rate of the pack. To do this packs must be added in parallel such as in Figure 4. This will not increase the pack voltage but will increase the total capacity and maximum discharge current. Typically, the maximum discharge rate is around 5 - 10 A for 18650 cells, however exact number can be obtained from the data sheets of the cells once they are chosen/purchased. The typical capacity is around 1,500 – 3,600 mAh depending on the quality of the cell. The total number of cells in the packs determines the capacity, so in the case of Figure 4 there are 4 cells total, if each has a capacity of 2,000 mAh that gives the pack a total capacity of 8,000 mAh or 8 Ah. Meanwhile the maximum discharge current will be determined by the number of parallel branches, in the case of Figure 4 there are 2 branches, if each cell has a maximum discharge current of 5 A, that will give the pack a maximum discharge current of 10 A. Any number of branches can be added to meet the design requirements of the EPS, however, keep volume in consideration when selecting the number of cells. Common dimensions for 18650 cells are given in Figure 5 for planning.

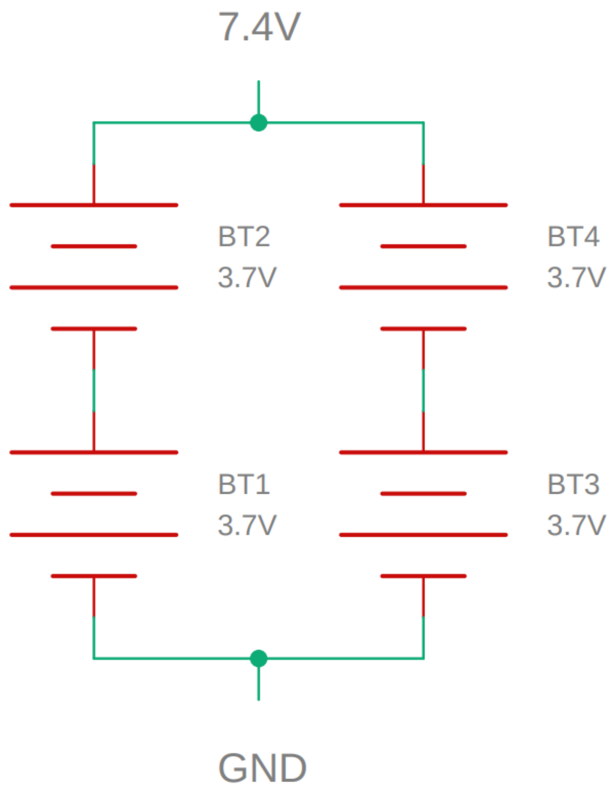

Figure 4 – 2 branches of 2 Lithium-Ion 18650 cells creating a 'pack'.

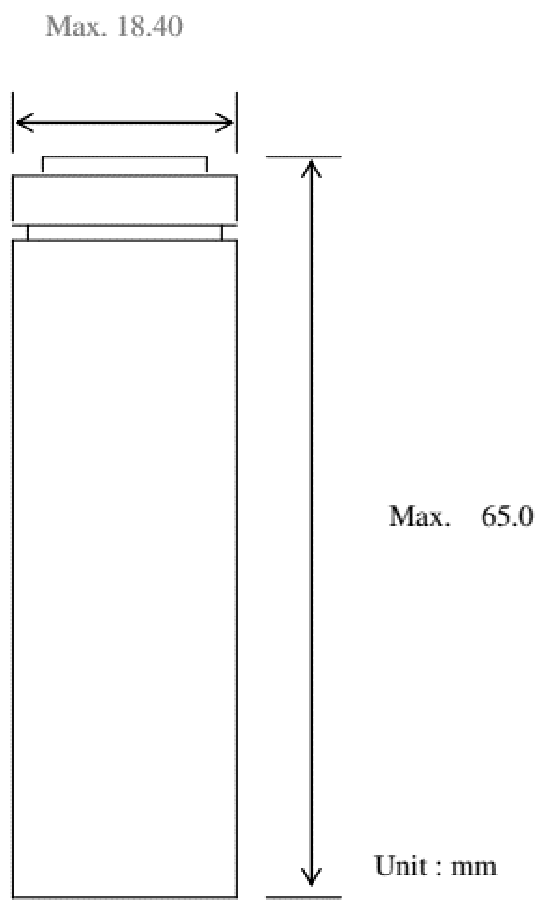

Figure 5 – Common Lithium-Ion 18650 cell dimensions – batteryspace.com

Purchasing: I have bought 18650 cells from Amazon, DigiKey, and BatterySpace and have had no issues with the cells I received. When looking for cells you must be cautious of **outrageous claims on capacity level**. Some will claim capacities of 5,000 mAh which is impossible with our current technology. The following are cells I have found:

- Amazon (www.amazon.com): Search for 18650 Lithium Batteries, I have used **EBL**, but any with reasonable claims and good review should suffice, currently $3.25 per cell ($12.99 4 pack)
- DigiKey (www.digikey.com): Search 18650 and select Batteries Rechargeable (Secondary), there will be a few options, you most likely want to use a single cell, (3.6 or 3.7 V voltage rated). SparkFun Electronics has single cells for $5.95.

- BatterySpace (www.batteryspace.com): Select Lithium Ion Batteries, Li-Ion/Polymer Single Cells, 3.6V/3.7V Li-Ion Cylindrical Cell Series, 18650/20700/21700 Rechargeable Batteries, large selection of 18650 cells, \$5.15 - \$13.95 (Ensure they are 18650 cells, there are other cell types listed), choice can be made based on capacity and price considerations.

For chargers most will be for single cell chargers, so once the battery pack is made it will not be able to be charged from a single cell charger without disassembly. Instead, charge from a power supply which was discussed in the Maintenance section. I have found the following chargers:

- Amazon: These are tricky to find, searching for 18650 chargers will result in many single cell chargers (EBL has packs that come with these, great if you need cells as well). **Tenergy TLP-2000** is a fantastic charger and I highly recommend this, it can select charge from 1 – 4 Lithium cells and has alligator clips which can be directly connected to the overall positive and negative terminals of the pack.
- DigiKey: Search 18650, Click Battery Chargers, not many and they are single cell chargers.
- BatterySpace: Some single cell chargers in the same place the cells were located.

Electrical Input

RockSat

For a RockSat mission, you will want to tell the reviewers that you require a input pulse from the rocket, most of the time for my missions this was at T – 0 (launch), but this pulse could be whenever during the launch you prefer your payload to activate (stage separation, second stage ignition, skirt separation, etc. or any specific time interval). Keep in mind the time it will take for the payload to initialize (Pi/Arduino boot time, etc.). This input pulse will be a 28 V pulse, with a selectable duration (1 second was used for my payloads and was more than enough). Figure 6 shows a circuit which was flown multiple times with constant success, each part will be evaluated after the image. The part numbers I used are listed and can be rebought and used again for any mission using 1 – 4 18650 cells, however, new, improved, and cheaper parts are always surfacing, I will explain what is required to select your own parts as well.

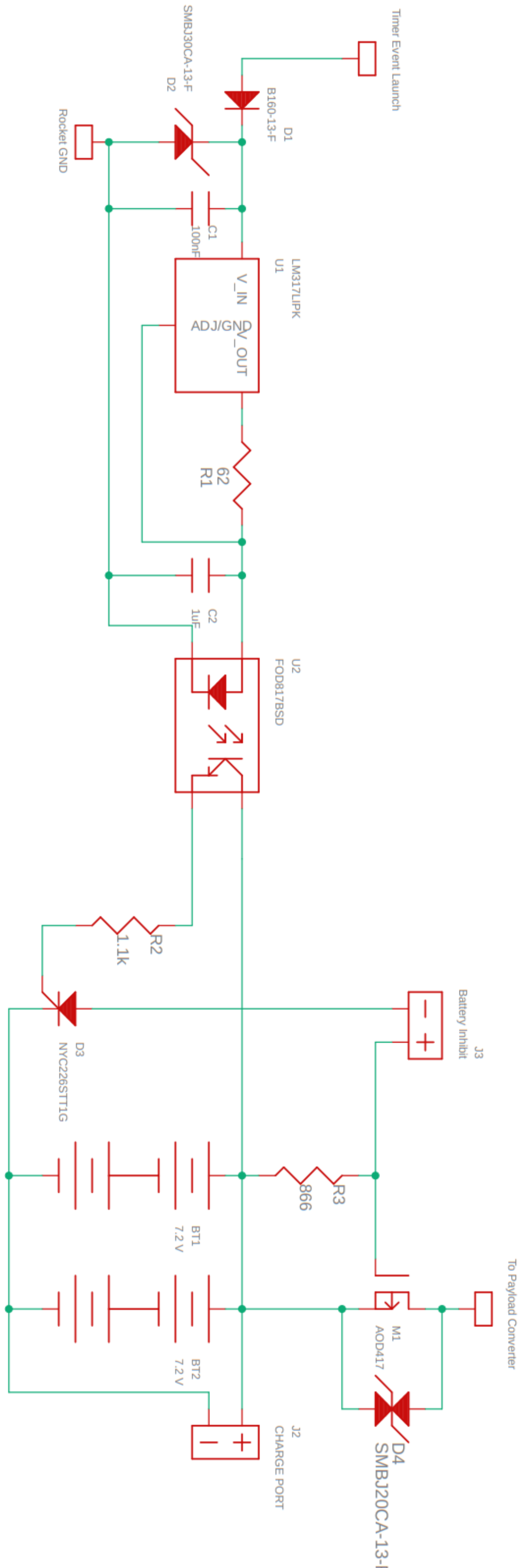

Figure 6 - Electrical input used for RockSat launches, successful on Hermes 3.0, Aether, and HAB flights.

Component Breakdown: This circuit takes an input from the rocket timer event line, protects against unexpected transients, creates a constant current source from the signal to turn on an optoisolator, which isolates the onboard battery power from the rocket's power system. The optoisolator then activates an SCR which turns on a MOSFET to allow the battery power to begin flowing into the system. Each part's role in the design is described below and the process for which I selected them is outlined.

- **Timer Event Launch & Rocket GND** –These connections are to the connector to the rocket. These should just be through hole connections that wires (typ. 18 or 20 gauge) can be soldered into to make a connection with the external connector to the rocket. This is not the 28 V rocket power connection, it is the timer event pin which should only enable for a limited amount of time after launch or whenever you decide to activate your payload, the other connection is to the rocket's ground.
- **D1** – This is a protection diode which prevents a reverse current (either transient or from incorrect polarity) from destroying the circuit. Search for diode on DigiKey and select Diodes – Rectifiers – Single then use the following filters:
    - Packaging: Cut Tape (CT)
    - Part Status: Active
    - Stock Status: In Stock
    - Mounting Type: Surface Mount
    - Voltage – DC Reverse (Vr) (Max): This is the voltage that the diode can hold off if applied in the reverse direction, this must be equal to or greater than 28 V, 35 V or greater will provide plenty of headroom.
    - Current – Average Rectified (Io): This is the average forward current the diode can conduct constantly without damage, this needs to be equal to or greater than the output of the constant current source U1 (20 mA in this case), overhead is good as always.
    - At this point you could sort by ascending unit price and these parts should work for you, however for ease of soldering I would suggest the following filter (The part I used is an SMA, extremely small package and difficult to solder, lesson learned):
        - Supplier Device Package: SMB & SMC
    - These parts will be large enough to easily solder, just check to make sure the parameters all work for your conditions and the operating temperature is within range for mission/space setting, and again sort by unit price ascending.

- **D2** – This is a transient voltage protector, protecting from overvoltages to the system, this will clamp the voltage applied to the system to the breakdown voltage of the diode. Search for diode on DigiKey and select TVS - Diodes then use the following filters:
    - Packaging: Cut Tape (CT)
    - Part Status: Active
    - Stock Status: In Stock
    - Mounting Type: Surface Mount
    - Voltage – Breakdown (Min): This is the minimum voltage the diode will break down and begin to clamp at, so this needs to be higher than the input pulse voltage (28 V) but lower than the U1 maximum allowed voltage (38 V for the example U1). 30 V – 35 V is a good starting range (33.3 V for the example D2).
    - At this point you could sort by ascending unit price and these parts should work for you, however for ease of soldering I would suggest the following filter:
        - Supplier Device Package: SMB & SMC
    - These parts will be large enough to easily solder, just check to make sure the parameters all work for your conditions and the operating temperature is within range for mission/space setting, and again sort by unit price ascending.
    - Note: Some of the parts are unidirectional and some are bidirectional, both will work perfectly fine. Bidirectional is essentially two diodes in opposite directions back to back and will clamp in both directions, while unidirectional is only a single diode. With bidirectional the orientation will not matter when soldering, with unidirectional you must ensure that the cathode is on the positive rail and the anode is on the negative rail/ground such as in the example circuit.

- **U1** – This is a linear regulator which typically provides a fixed output voltage so long as the input voltage is a certain voltage above it (typ. 1.25 V), however this one is set up in a constant current supply configuration. This provides a constant current that is safe and guaranteed to turn the optoisolator on. Search for Linear Regulator on DigiKey and select PMIC – Voltage Regulators - Linear then use the following filters:
    - Packaging: Bulk, Cut Tape (CT), and Tube
    - Part Status: Active
    - Stock Status: In Stock
    - Mounting Type: Surface Mount
    - Output Configuration: Positive
    - Output Type: Adjustable
    - Number of Regulators: 1
    - Voltage – Input (Max): This must be equal to or greater than 28 V, 35 V will provide plenty of headroom (38 V for the example U1).
    - Current – Output: This must be equal to or greater then what's required to turn the optoisolator on (typ. ~20 mA, and ~50 mA is typically their max). Greater than or 50 mA will provide headroom.
    - Sort by price ascending and check the operating temperature is within acceptable range. Anything with LM317 will work great, I would suggest not going with a complicated package (such as 8-SOIC) as only 3 pins are required for this part, a DPAK or SOT-223 will work great.

- **R1** – This resistor sets the output current of the constant current regulator, there will be a formula for this in the linear regulator datasheet under a section labeled Current Limiter or Current Regulator, which is typically $I = \frac{1.25\,V}{R1}$, check the part datasheet to confirm this. So, if ~20 mA is needed to turn the optoisolator on a 62.5-Ω resistor is needed. Next you need to find the power that the resistor will use, which can be found using $P = I^2 * R$, this will be used to select the package, the power for the 20-mA case is 25 mW. Search for resistor on DigiKey and select Chip Resistor – Surface Mount then use the following filters:
  - Packaging: Cut Tape (CT)
  - Part Status: Active
  - Stock Status: In Stock
  - Resistance: Use a 1% standard resistor value chart, Figure 7, and select the closest 1% value resistor to the needed value (I would recommend going with the next lower value, so the linear regulator creates slightly more current). In the 20-mA case I would select 61.9 **Ω**.
  - Supplier Device Package: From this point I would limit the package, 0805 is the most common package and relatively easy to solder, this is the smallest I would go. Power needs to be taken into consideration, each common package has a maximum power of:
    - 0805: 125 mW
    - 1206: 250 mW
  - Sort by price ascending and check the operating temperature is within acceptable range.

- **C1 & C2** – These are suggested capacitors for stable operation of the linear regulator which can be found in the linear regulator datasheet under the Typical Application section. 100 nF is typical for the input capacitor to most Integrated Circuits (IC), and 1 μF is typical for the output of a LM317, however this may change depending on the chosen chip. Search for capacitor on DigiKey and select Ceramic Capacitors then use the following filters:
  - Packaging: Cut Tape (CT)
  - Part Status: Active
  - Stock Status: In Stock
  - Capacitance: Select the required capacitance value as described in the datasheet.
  - Voltage – Rated: This needs to be equal to or greater than 28 V, headroom is always good (typ. 50 V).
  - Temperature Coefficient: X7R, this is a rating of how much the capacitance value will change with temperature, X7R is one of the best and I would recommend selecting this.
  - Mounting Type: Surface Mount, MLCC
  - Package/Case: I would recommend 0805 or 1206
  - Sort by price ascending and check the operating temperature is within acceptable range.

- **U2** – This is the optoisolator or optocoupler, this device electrically isolates the rocket from your payload through an optical medium. When current is applied to the LED on the left side in the diagram, it activates a phototransistor on the right side of the diagram which then allows current to flow through it, with no light, no current flows (except for a very small leakage current). Search for optoisolator on DigiKey and select Optoisolator – Transistor, Photovoltaic Output then use the following filters:
  - Packaging: Cut Tape (CT)
  - Part Status: Active
  - Stock Status: In Stock
  - Mounting Type: Surface Mount
  - Number of Channels: 1
  - Output Type: Transistor
  - Current – Output/Channel: This value must be large enough to turn D3 on, which is typically quite low, I would still suggest selecting greater than or 30 mA at least.
  - Sort by price ascending and check the operating temperature is within acceptable range. There will be a chart in the datasheet that will have Collector Current vs. Collector-Emitter Voltage with different Forward Currents (I_F). This chart is used to determine the forward current you need. For the part chosen in my design you can see a 20 mA forward current provides enough collector current at around 7.2 V (your nominal battery pack voltage) of Collector-Emitter Voltage (~18 mA) to activate D3. Selecting a target forward current will then allow you to select U1 and R1, just ensure the selected value is within safe operating conditions located in the Electrical Characteristics chart.
- **R2** – This is a current limiting resistor to protect D3. The value depends on the SCR (D3) chosen but allowing around 5 mA of current should work for most. Use the nominal battery voltage from your battery pack to select this value and the gate voltage drop of D3 (800 mV for an estimate), $R = \frac{V_{nominal} - V_{SCR}}{I}$. The 1.1 kΩ in the diagram permits 8 mA of current. Follow the R1 guide and select the required 1% value resistance for this case.

- **D3** – This is an SCR which, once activated through a gate signal (current through R2) will allow current flow through it so long as it is above a certain holding current. When it falls below this value it will no longer conduct and will require another gate pulse to activate. We will use this to disconnect the batteries from our payload normally until activated by the rocket, then the batteries will supply power to the payload until the battery voltage falls too low. Search for SCR on DigiKey and select Thyristor - SCRs then use the following filters:
  - Packaging: Cut Tape (CT)
  - Part Status: Active
  - Stock Status: In Stock
  - Mounting Type: Surface Mount
  - Voltage – Off State: Ensure these values are greater than the maximum battery voltage (8.4 V in the example case).
  - To limit the remaining parts down will take some trial and error. Ideally you want to select the lowest Current – Hold (Ih) (Max) for the least amount of waste power, however you need to ensure the Voltage – Gate Trigger (Vgt) (Max) and Current – Gate Trigger (Igt) (Max) are sufficiently low that U2 can supply the necessary current with the selected forward current, and the battery nominal voltage. I would recommend using the example part as a guide at the very least to compare values.
  - Sort by price ascending and check the operating temperature is within acceptable range, also paying attention to the package type and size for solderability and size considerations on the Printed Circuit Board (PCB).
- **R3** – This resistor will set up the holding current for the SCR. To calculate this value, take the Current – Hold (Ih) (Max) of the selected SCR, the Voltage - On State (Vtm) (Max) of the SCR, and the minimum voltage of the battery pack which is 6 V in the example circuit. Then calculate $R = \frac{V_{min} - V_F}{I_H}$, where V_{min} is the minimum voltage of the battery pack, V_F is the on state voltage of the SCR, and I_H is the holding current of the SCR. This gives us 860 **Ω** or 866 **Ω** for a standard 1% value. Follow the R1 guide and select the required 1% value resistance for this case.
- **J3** – This is an inhibit connector which is just 2 through holes to solder wire into on the PCB. The wires should be connected to a locking switch or a jumper that is accessible to a user on the outside of the payload. This inhibit ensures the system does not activate inadvertently and allows the payload to be switched off if switched on during testing.

- **J2** – This should be an accessible connector to the outside of the payload which connects to the battery overall positive and negative for charging. This connector should be covered when not in use to prevent accidental short circuits.
    - A protection diode could also be added to prevent a reverse charging current to be applied (this would destroy the batteries and/or charger) which would be added on the positive line with the anode facing the port. With this in the forward drop of the protection diode must be accounted for when charging (charging voltage will be the maximum voltage of the battery pack plus the forward drop). This can be minimized by using a low drop Schottky diode which can be found on DigiKey by searching for Diode and then selecting Diodes – Rectifiers – Single and following the same selection process as D1. The Voltage - DC Reverse (Vr) (Max) must be greater than your maximum battery pack voltage and the Current - Average Rectified (Io) must be greater than your charging current.
    - The alternative to this is ensuring the charging connector is a one-way connector, that is, it cannot be plugged in backwards (we used a Dean Connector for this).

- **M1** – This is the p-type MOSFET which functions as an electronic switch. This blocks the battery voltage from the payload until the activation signal is received, where it then connects the battery voltage to the payload and converters. When the voltage on the gate is equal or close to the voltage on the source, the MOSFET is closed, no current flows. When the voltage on the gate is much lower than the voltage on the source the MOSFET is open, current flows relatively unimpeded (small on-state resistance). Search for MOSFET on DigiKey and select Transistor – FETs, MOSFETs - Single then use the following filters:
    - Packaging: Cut Tape (CT)
    - Part Status: Active
    - Stock Status: In Stock
    - FET Type: P-Channel
    - Mounting Type: Surface Mount
    - Drive Voltage (Max Rds On, Min Rds On): This device needs to be 'Logic Level' since the forward drop of D3 will apply a voltage on the gate when we need the MOSFET to be on. Selecting 4.5V, 10V will give a large selection of Logic Level devices that will work in this application.
    - Drain to Source Voltage (Vdss): This must be greater than or equal to the maximum battery voltage, with overhead.
    - Current – Continuous Drain: This must be greater than the maximum current determined in the worst case for your power budget. In the example case 25 A was selected.
    - Vgs (Max): This value must be equal to or greater than the maximum battery pack voltage, again with overhead.
    - The parts can now be sorted by price ascending.
        - The lower the value of Rds On (Max) @ Id, Vgs the better, this is the resistance of the device when it is on, higher values lead to excess heat generation and inefficiencies.
        - For the package, D-PAK, TO – 252, and D^2-PAK will work fine.
        - Ensure operating temperature is within range
- **D4** – This is a protection diode for the MOSFET. When the inhibit is pulled and the MOSFET is conducting current and attempts to turn off, the inductance in the PCB traces can slam the MOSFET with a high voltage spike, this diode clamps this voltage spike below the Drain to Source Voltage (Vdss) to protect the diode. The process for selecting this is the same as D2, however the Voltage – Breakdown (Min) should be less than the Drain to Source Voltage (Vdss) of the MOSFET but greater than the maximum battery voltage, for the example I selected 22.2 V while the Drain to Source Voltage (Vdss) was 30 V and the maximum battery voltage was 8.4 V.

This concludes the design breakdown for the example, this circuit can be used by any payload with 1 – 4 18650 cells so long as the current required by the payloads is within range of M1. The number of batteries in series will determine R2 and R3, all other parts are usable with any amount of batteries so long as current limits are not exceeded for your payload.

		(5%)		(1%)	
E6	E12	E24	E48	E96	E192*
100	100	100	100	100	100
					101
				102	102
					104
			105	105	105
					106
				107	107
					109
		110	110	110	110
					111
				113	113
					114
			115	115	115
					117
				118	118
	120	120			120
			121	121	121
					123
				124	124
					126
			127	127	127
					129
		130		130	130
					132
			133	133	133
					135
				137	137
					138
			140	140	140
					142
				143	143
					145
			147	147	147
					149
150	150	150		150	150
					152
			154	154	154
					156
				158	158
		160			160
			162	162	162
					164
				165	165
					167
			169	169	169
					172
				174	174
					176
			178	178	178
	180	180			180
				182	182
					184
			187	187	187
					189
				191	191
					193
			196	196	196
					198
		200		200	200
					203
			205	205	205
					208
				210	210
					213
			215	215	215
					218
220	220	220			
				221	221
					223
			226	226	226
					229
				232	232
					234
			237	237	237
		240			240
				243	
					244
					246
			249	249	249
					252
				255	255
					258
			261	261	261
					264
				267	267
	270	270			
					271
			274	274	274
					277
				280	280
					284
			287	287	287
					291
				294	294
					298
		300			
			301	301	301
					305
				309	309
					312
			316	316	316
					320
				324	324
					328
330	330	330			
			332	332	332
					336
				340	340
					344
			348	348	348
					352
				357	357
		360			
					361
			365	365	365
					370
				374	374
					379
			383	383	383
					388
	390	390			
				392	392
					397
			402	402	402
					407
				412	412
					417
			422	422	422
					427
		430			
				432	432
					437
			442	442	442
					448
				453	453
					458
			464	464	464
470	470	470			470
				475	475
					481
			487	487	487
					493
				499	499
					505
		510			
			511	511	511
					517
				523	523
					530
			536	536	536
					542
				549	549
					556
	560	560			
			562	562	562
					569
				576	576
					583
			590	590	590
					597
				604	604
					612
			619	619	619
		620			
					626
				634	634
					642
			649	649	649
					657
				665	665
					673
680	680	680			
			681	681	681
					690
				698	698
					706
			715	715	715
					723
				732	732
					741
		750	750	750	750
					759
				768	768
					777
			787	787	787
					796
				806	806
					816
	820	820			
			825	825	825
					835
				845	845
					856
			866	866	866
					876
				887	887
					898
			909	909	909
		910			
					920
				931	931
					942
			953	953	953
					965
				976	976
					988

Figure 7 - Standard resistor values (Use the 1% column). When using calculations, it is inevitable the exact resistance value will be a common value. This chart lists the common resistance values that are manufactured. 1% resistors are common and cheap with good resistance resolution. Using this you can select the closest resistor value to what was calculated (multiply or divide by 10 as much as needed, e.g. 182 is 182 Ω, 18.2 Ω, 1.82 kΩ, etc.). – Venkel

CubeSat/Small Satellite

<u>Solar Panels</u>

Solar Panel Basics: Solar panels are Photovoltaic (PV) junctions which convert light into energy. Solar panels primarily function as current sources up to a certain voltage. Figure 8 shows the typical shape of a Current vs. Voltage curve for a solar panel. The power output of the cell will be the area of a rectangle under the curve with on corner on the origin and the other at some point on the curve. The maximum power will be produced at some point on the knee (2.33 V and 14.6 mA for this curve, producing 34 mW) which is the ideal operating point. Two other useful numbers are the Open Circuit Voltage, which is the highest voltage the cell can produce under no load and under full illumination (2.62 V for the example cell) and the Short Circuit Current, which is the maximum current produced when the cell is shorted and under full illumination.

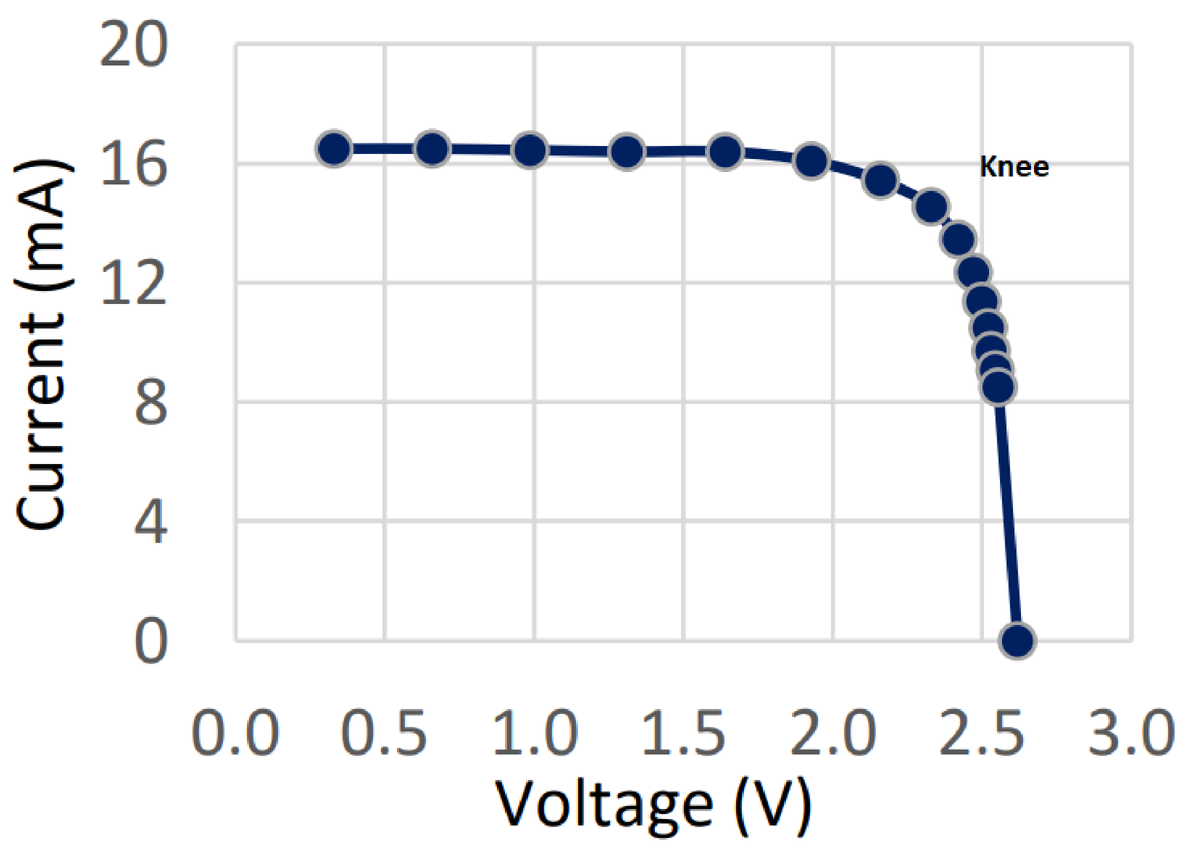

Figure 8 - TrisolX Solar Wing I-V curve - TrisolX

Solar panels were used on the CACTUS – Hermes 3.0 payload, however the panels were supplied to us by the CACTUS team. Solar panel discussion on the panels that were used can be found in the document by Smith, R. P. found in the Reference/Additional Reading section. Here I will discuss what you should consider when selecting solar panels for your mission and summarize lessons learned from the CACTUS team.

Solar Panel Consideration: There are two main considerations when deciding on what solar panel to use for your mission, these are the efficiency of the cell and the packing efficiency of the cells. With a very limited amount of surface area on small satellites power is a huge problem because of the limited amount of solar panel coverage possible. CACTUS – Hermes 3.0 ran into the issue where our input power was so low that our Raspberry Pi in sleep mode would drain more power then was generated by the solar panels. The greater power conversion efficiency the more power that can be extracted from the solar panel area. The solar panels used were TrisolX Solar Wings which are triple junction Gallium Arsenide solar cell with 28% efficiency, shown in Figure 9. 28% efficiency is quite high when talking about solar panels, and triple junction will typically be the typical panel used for any space application because of their much higher efficiency, however, they are fragile so handle with care.

However, packing efficiency is also a large concern, this is defined as the amount of wasted area (non-solar panel) on the solar panel board. Figure 9 shows the shape of the solar panels that were used on the CACTUS payload, and Figure 10 shows the design of the solar panel PCB. While these panel may be high efficiency, you can see their odd shape. This odd shape led to a lower packing efficiency then was possible with rectangular cells of the same efficiency. Space is needed between the panels for solderability and to prevent short circuiting of the panels, however, it is evident if the solar panels were rectangular, the packing efficiency could have been much higher, increasing the solar panel area on the board, and increasing the total power of the board, under the assumption that the rectangular solar panels were the same efficiency. Because of packing efficiency, it may be advantageous to select a lower efficiency panel if it increases the packing efficiency enough to offset the loss.

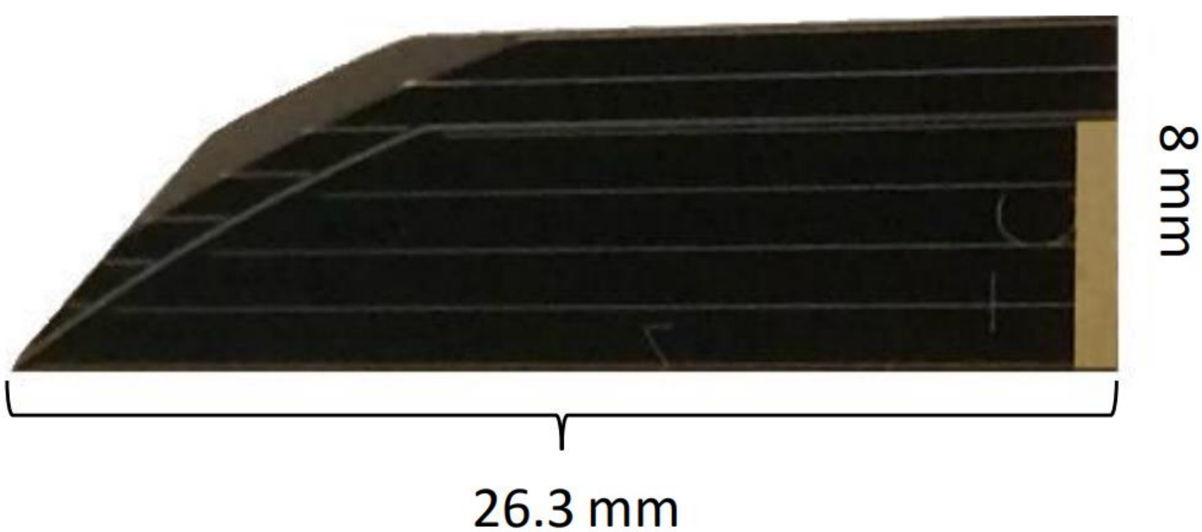

Figure 9 - TrisolX Solar Wing panel - TrisolX

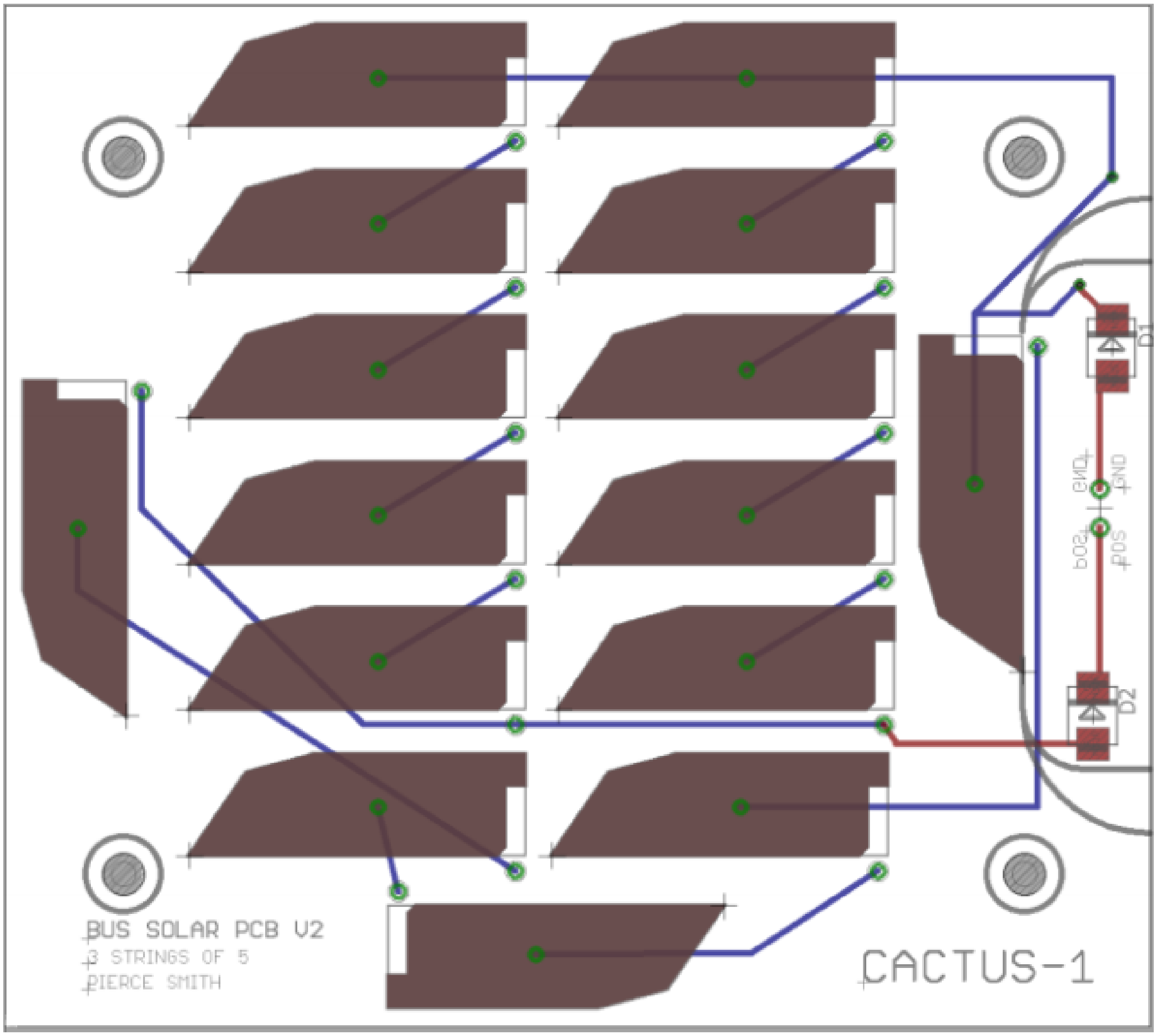

Figure 10 - CACTUS Solar Panel PCB Layout - Smith, R. P.

Solar Panel Selection: It is recommended that you select multiple different options for solar panels and create a PCB layout to determine the maximum packing efficiency possible. Remember some keep out space must be kept between the panels to allow them to be properly soldered in and to prevent electrical faults. From this design you can calculate the maximum power output of the board. From there you can select the board with the most power while also considering the total cost of the solar panels (Another reason the TrisolX panels were picked were their high efficiency and low cost). Always ensure the operating temperature is within limits.

There is some selection of solar panels on DigiKey, you can find them by searching Solar Cell and selecting Solar Cell then select the following filters:

- Part Status: Active
- Stock Status: In Stock
- From here you can browse the selection, paying attention to the size of the cell mainly (this can be restricted in the filters if desired) and the voltage the cell produces. I would recommend looking at the image/datasheet of the cell to determine whether the cell comes with wire leads or a solderable tab, while both can be used, the solderable tab will permit a higher packing efficiency.

This is not the only place to find panels however, many independent companies sell panels (such as TrisolX) and research must be done to find a panel which best suits your mission in terms of size, price, and efficiency.

Voltage: Just like batteries, solar cells can be connected in series to increase the voltage of the string, with the positive terminal of one cell connected to the negative of another cell and one overall negative and positive connection for the string, shown in Figure 11. Strings of the same voltage can then be connected in parallel with each other to increase current. A diode should always be connected on the overall positive of each string. This is because when a cell or string is not within sunlight, they can turn into current sinks, absorbing all or most of the current produced by the other cells.

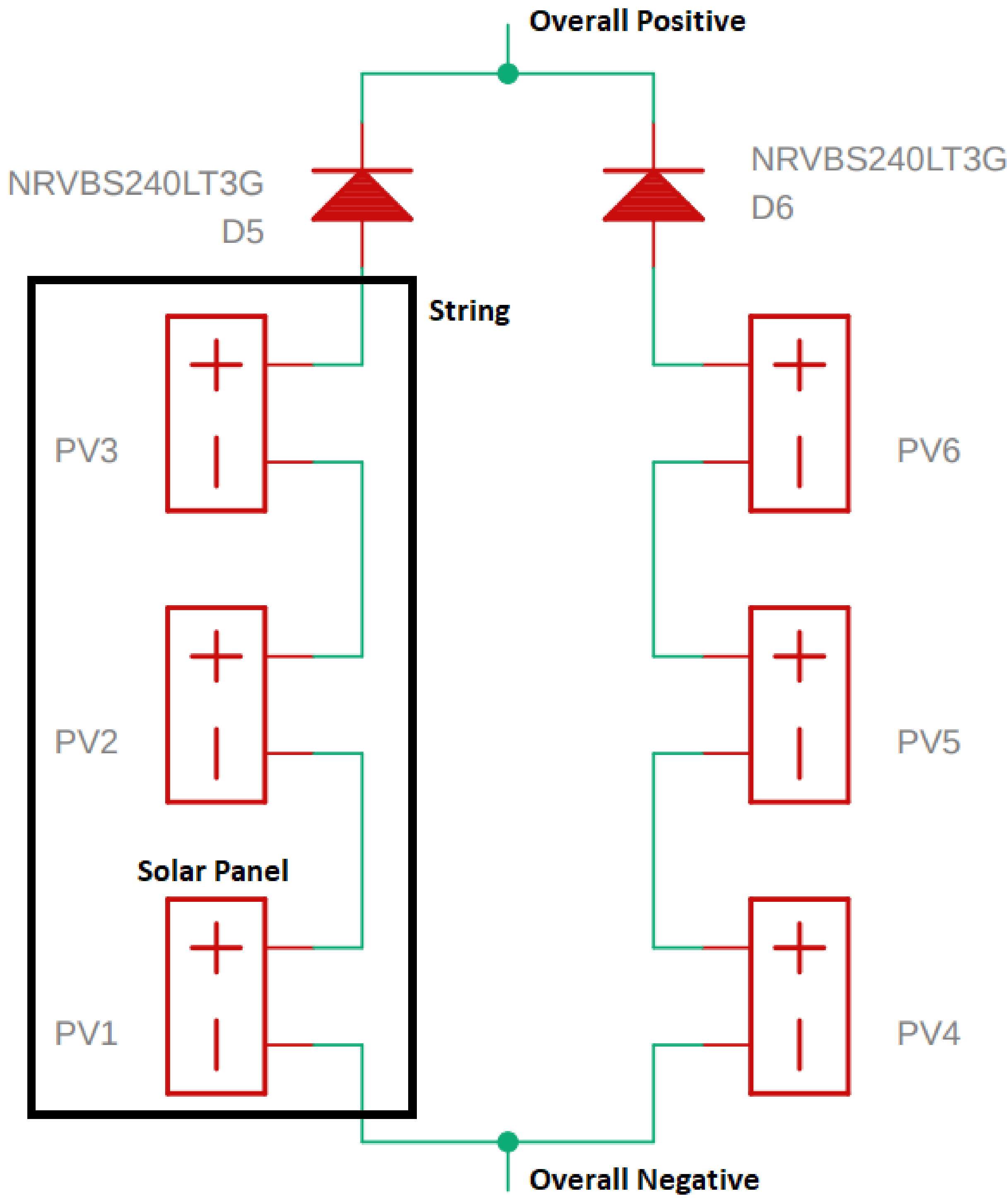

Figure 11 - Solar panel string configuration

Part Selection: This circuit provides electrical connections for power input into a system from any number of solar cell strings.

D5 & D6: These diodes protect from current sinks as described previously. These ideally should be low forward drop Schottky diodes to reduce losses. To find these search Diodes on DigiKey and select Diodes – Rectifiers – Single then select the following filters:

- Stock Status: In Stock
- Packaging: Cut Tape (CT)
- Part Status: Active
- Diode Type: Schottky
- Mounting Type: Surface Mount
- Supplier Device Package: Again, I would recommend an SMB or SMC for solderability, but this is not necessary
- Voltage – DC Reverse (Vr) (Max): This value must be equal to or greater than the total sum of the open circuit voltages of the solar panels in the string. If each cell has a 2.5 V open voltage in Figure 21, then this value must be equal to or greater than 7.5 V, headroom is encouraged (40 V for the example).
- Current - Average Rectified (Io): This value should be higher than the short circuit current of the panels in the string. Notice this is not the sum of all the panels, just the maximum of one panel because that also sets the maximum current of the string. If the short circuit current of the panels in Figure 11 is 20 mA, then the value must be equal to or greater than 20 mA
- At this point a selection can be made, I would recommend sorting by Voltage - Forward (Vf) (Max) @ If Ascending to select the lowest possible value in this column, keeping price in mind. Doing this will minimize efficiency losses for the strings.
    - Ensure the operating temperature is within limits.

Input Conditioning

At this point the voltage output of the solar panels needs some way of interfacing with the batteries, there are 3 ways to do this.

DC/DC Converter: This is the most efficient and recommended way to interface the solar panels with your energy storage. This will convert the voltage created by the solar panels into a voltage usable by the batteries with minimal waste. The downside of this circuit is that it is more complex and has more components then the other circuits. With this circuit the solar panel string should have a maximum open circuit voltage that is lower than battery voltage to ensure the converter is always operating in an efficient manner. Figure 12 shows the example circuit.

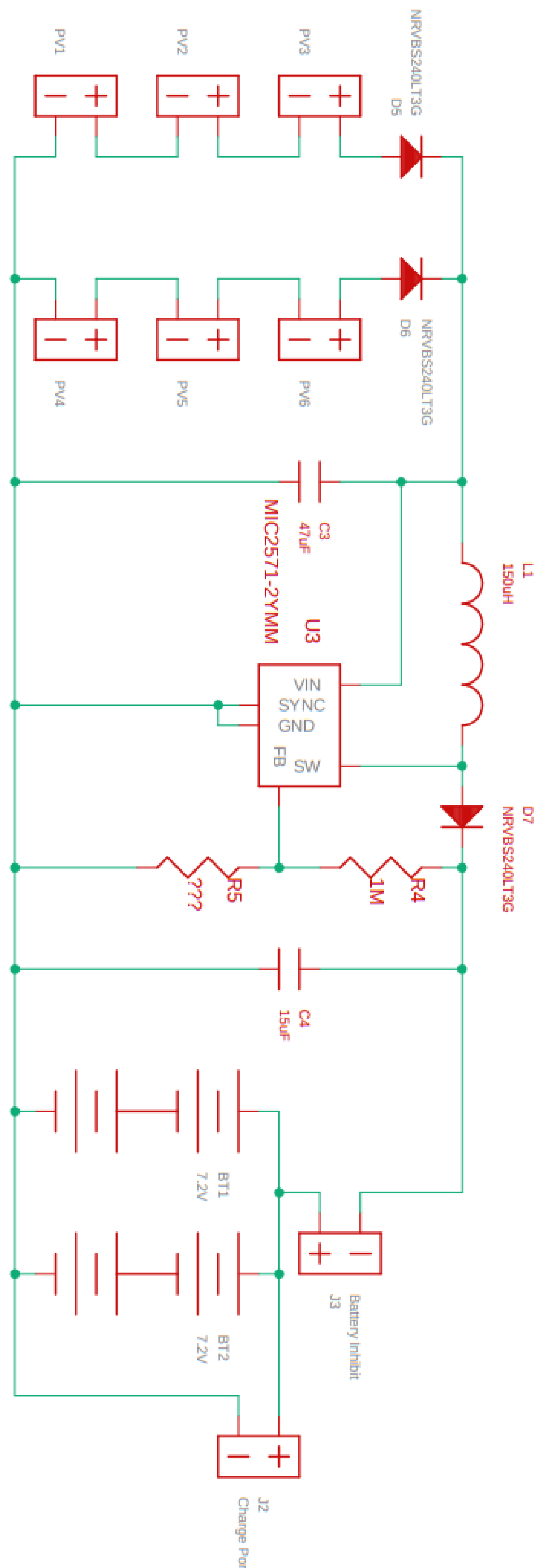

Figure 12 – DC/DC converter interface between a solar input and energy storage

Component Breakdown: This circuit takes the solar panel input voltage and converts it into a charge voltage for the batteries.

- **U3**: This is the main converter chip which will produce the correct output voltage. The datasheet for this part will also have all the other parts needed for the circuit as well as equations to calculate their values. To find these parts search DCDC on DigiKey and select PMIC - Voltage Regulators - DC DC Switching Regulators. From there refine the search with the following filters:
    - Packaging: Cut Tape (CT), and Tube
    - Part Status: Active
    - Function: Step Up
    - Output Configuration: Positive
    - Topology: Any selection containing Boost (not slashed with another word, only ones separated by commas)
    - Output Type: Adjustable
    - Number of Outputs: 1
    - Mounting Type: Surface Mount
    - Stock Status: In Stock
    - From here you can sort by price ascending and begin searching, the following things must be kept in mind.
        - Voltage - Input (Min): This must be equal to or lower than the voltage the solar panels produce, headroom recommended. Ideally this should be as low as possible, allowing the converter to work when the solar panels are not producing much voltage.
        - Voltage - Input (Max): This must be equal to or higher than the maximum voltage the solar panel string can produce, headroom recommended.
        - Voltage - Output (Min/Fixed): This must be equal to or lower than the minimum battery voltage, headroom recommended.
        - Voltage - Output (Max): This must be equal to or higher than the maximum battery voltage, headroom recommended.
        - Current – Output: This must be equal to or higher than the maximum current that can be produced by any complete solar panel (the entire PCB on one side of the satellite), headroom recommended. If each panel can produce 20 mA max and the maximum number of strings on any one panel is 2 then this value is 40 mA.
        - Pay attention to the package design to make sure it can be soldered easy, SOT-23-5/6, 8-VSSop, and 8-SOIC or 8-SO are relatively easy to solder.
        - Check the operating temperature to ensure it is within limits.

- **C3 & C4**: These are input and output filtering capacitors, respectively, whose value can be found in the application circuits of the datasheet of U3. Follow the guide for C1 & C2 to find this part and select the needed capacitance.
    - Note: Adding more capacitors in parallel with C3 would not be a bad thing if there is room on the PCB, they will help stabilize the output from the solar panels to help the converter run more efficiently. 100 nF, 1, and 10 µF capacitors are always a good choice (100 nF is most important, then 1 µF, then 10 µF). You could add one of each or two of each room permitting.
- **L1**: This is the inductor that U3 uses to convert the input voltage to the output voltage. The value needed can be found in the application circuits of datasheet for U3. To find this part search Inductor on DigiKey and select Fixed Inductors. From there refine the search with the following filters:
    - Packaging: Cut Tape (CT)
    - Part Status: Active
    - Inductance: Select the required inductance found in the datasheet of U3.
    - Current Rating (Amps): This needs to be equal to or higher than the maximum output current of U3 (1 A for the example), headroom recommended. If U3 has a very high current rating, one that will never be achieved by the solar panels the maximum current that can be produced by any complete solar panel (the entire PCB on one side of the satellite) can be chosen.
    - Current – Saturation: This needs to be equal to or higher than the maximum output current of U3 or any complete solar panel (1 A for the example), headroom recommended.
    - Mounting Type: Surface Mount
    - From here you can sort by price ascending and select a part, pay attention to the package size and ensure it is not too large.
        - Attempt to find an inductor with the lowest resistance possible to maximize efficiency.
        - Ensure the operating temperature is within limits.
- **D7**: This diode will typically have a recommended part within the datasheet which can be used, however, you may be able to find a low forward drop Schottky diode which will increase the efficiency of the converter. One of these should be used for D5/D6 which should be able to be reused so long as the max current of the diode is equal to or higher than the maximum current that can be produced by any complete solar panel with headroom (the entire PCB on one side of the satellite). If each panel can produce 20 mA max and the maximum number of strings on any one panel is 2 then this value is 40 mA. The reverse voltage standoff must also be equal to or higher than the maximum voltage of the batteries with headroom.

- **R4 & R5**: These resistors adjust the output voltage of the converter. R4 will typically be given in the datasheet of U3 as well as an equation to calculate the value of R5 for a desired output voltage. The higher these values are the more efficient the converter will be due to less current loss through the resistors, however U3 will typically have a max value for them due to noise and instability of the converter. For the example U3, R4 was given as 1 MΩ and the equation for V_{out} was given as $V_{out} = 0.22\,V * (1 + \frac{R_4}{R_5})$, allowing you to calculate the needed value for R5. To find the needed resistors follow the same process as R1 and select the needed 1% resistance value. Table 3 gives the R5 values for different battery voltages for the example circuit. I would recommend buying a few resistor values around the theoretically needed value to tune the output voltage.

Table 3 – Resistance values for differing battery pack configurations for the example circuit.

Number of Cells	Resistance (kΩ)
1 Cell (4.2 V)	54.9
2 Cells (8.4 V)	26.7
3 Cells (12.6 V)	16.9
4 Cells (16.8 V)	11.8

- **J4**: This is an inhibit switch for the batteries, this will prevent them from accidental overcharge during storage which may lead to destruction of the cells, as well as ensure they do not activate until the inhibit is removed before launch. This should be a locking switch or jumper cable that is easily accessible on the outside of the payload.

This concludes the component breakdown for the DC/DC converter solar panel interface, if current from the solar panels stays within the limits of U3 all parts should be able to be recycled between payloads with different amounts of batteries in series by only changing R5, whose value for different batteries can be found in Table 3.

Linear Regulator: The next option for the interface between solar panels and energy storage is to use a linear regulator. This option is inefficient because a linear regulator wastes any voltage that is above its output voltage. However, it is simpler with fewer parts. To use this option the solar panels voltage must be higher than the battery voltage by typically at least 1.25 V, however the voltage should be higher, so the solar panels are still able to charge the batteries when they are not perpendicular to the light source which is when they produce their maximum voltage. Figure 13 shows the example circuit.

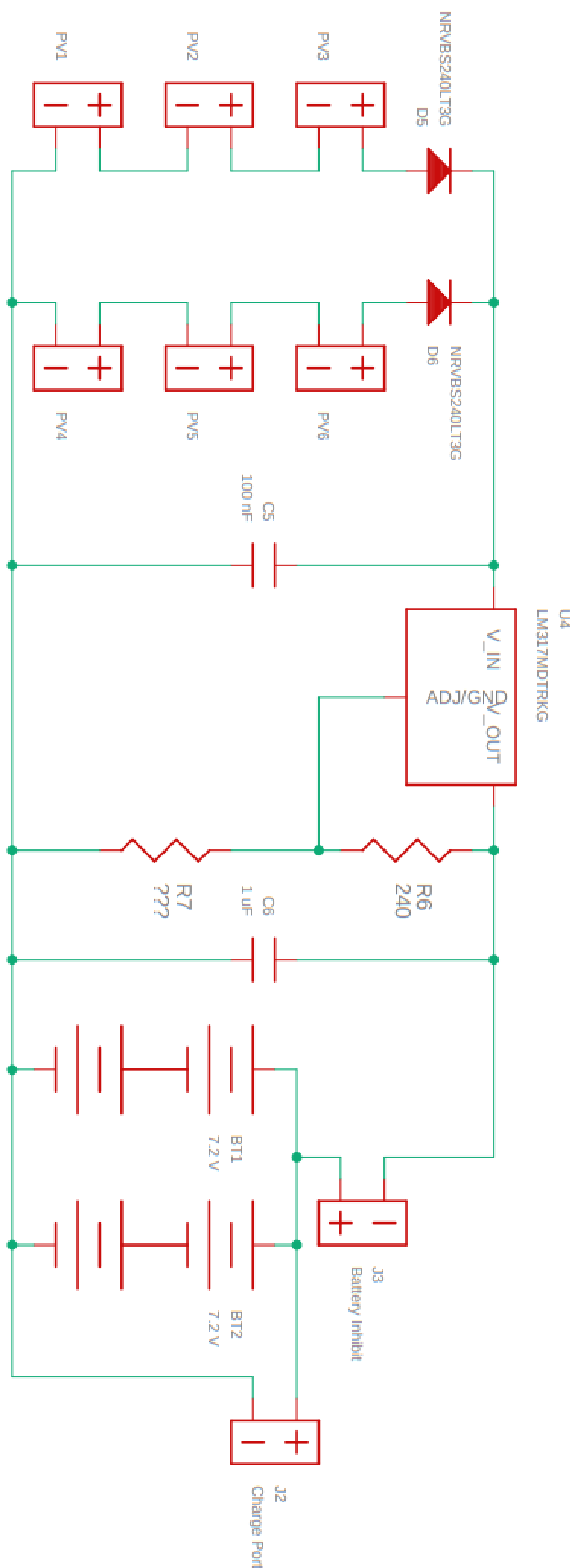

Figure 13 - Linear regulator interface between a solar input and energy storage

Component Breakdown: This circuit takes the voltage produced by the solar panels and outputs the maximum battery voltage to charge the batteries.

- **U4**: This part is the linear regulator which will produce the voltage needed to charge the battery. They have a dropout voltage (1.25 V in this example), which the input voltage needs to be higher than for it to produce the desired output voltage. To find these parts search Linear Regulator on DigiKey and select PMIC - Voltage Regulators – Linear, then use the following filters:
  - Packaging: Bulk, Cut Tape (CT), and Tube
  - Part Status: Active
  - Output Configuration: Positive
  - Output Type: Adjustable
  - Number of Regulators: 1
  - Mounting Type: Surface Mount
  - Stock Status: In Stock
  - Voltage – Input (Max): This value must be equal or higher than the maximum voltage of the solar panel string, headroom recommended.
  - Voltage – Output (Max): This value must be equal or higher than the battery voltage you need to charge to, headroom recommended.
  - Current – Output: This must be equal or higher than the maximum current that can be produced by any complete solar panel (the entire PCB on one side of the satellite), headroom recommended. If each panel can produce 20 mA max and the maximum number of strings on any one panel is 2 then this value is 40 mA.
  - From here you can sort by price ascending and select a part with these considerations:
    - The lower the dropout voltage, the more efficient the part will be
    - These parts produce a lot of waste heat, so power must be taken into consideration. Within the datasheet of the part there should be a Maximum Output Current within the Electrical Characteristics table. It may have a few values at different input minus output values, and then a current will be given. You can calculate your input – output value by subtracting the output voltage of the linear regulator from the maximum string voltage form the solar panels. Using this you can see if the Maximum output current the part is able to supply around that voltage difference is higher than the maximum current that can be produced by any complete solar panel. Larger parts will provide larger maximum current values. DPAK and D^2PAK are great packages for high power linear regulators.
    - Ensure operating temperature is within limits.

- **C5 & C6**: These are input and output filtering capacitors, respectively, whose value can be found in the application circuits of the datasheet of U4. Follow the guide for C1 & C2 to find this part and select the needed capacitance.
    - Note: Adding more capacitors in parallel with C5 would not be a bad thing if there is room on the PCB, they will help stabilize the output from the solar panels to help the converter run more efficiently. 100 nF, 1, and 10 µF capacitors are always a good choice (100 nF is most important, then 1 µF, then 10 µF). You could add one of each or two of each room permitting.
- **R6 & R7**: These resistors adjust the output voltage of the linear regulator. R6 will typically be given in the datasheet of U4 as well as an equation to calculate the R7 for a desired output voltage. The equation for U4 in the example is $V_{out} = 1.25\ V * (1 + \frac{R_6}{R_7})$, allowing you to calculate R7 for a known output voltage, this is also the typical equation for 1.25 V dropout linear regulators. Table 4 gives the values for R7 for different battery voltages. You can use the guide for R1 to find the 1% resistor needed. I would recommend buying a few resistor values around the theoretically needed value to tune the output voltage.

Table 4 - R7 values for different battery cell counts for the example circuit.

Number of Cells	R7 (Ω)
1 Cell (4.2 V)	100
2 Cells (8.4 V)	41.2
3 Cells (12.6 V)	26.1
4 Cells (16.8 V)	16.9

This concludes the component breakdown for the linear regulator interface between the solar panels and the energy storage. All parts should be able to be used for any payload, just ensure that the maximum current that is able to be supplied by any single side of the satellite in full sunlight is within the constraints of the linear regulator. To recap, for this to function the voltage the solar panels supply must be higher by at least 1.25 V then the output voltage which is the maximum battery voltage. However, the voltage should be higher than 1.25 V above the output to ensure the batteries will charge even when the solar panels are not perpendicular to the Sun.

Direct Linking: The last method for interface the solar panels with the batteries is by a direct linkage. This method may or may not be more efficient then a linear regulator, depending on some factors, but it is by far the simplest of the three. For this to work the open circuit voltage of a solar panel string must be the same or slightly higher than the battery voltage for the batteries to ever gain a full charge. This raises a safety issue, if the open circuit voltage is higher than the maximum battery voltage, the batteries run the risk of overcharging which will lead to a failure. To prevent this, the activation circuit, which will be outlined later, will passively activate to turn the payload on and drain the batteries. Figure 14 shows a direct linkage interface.

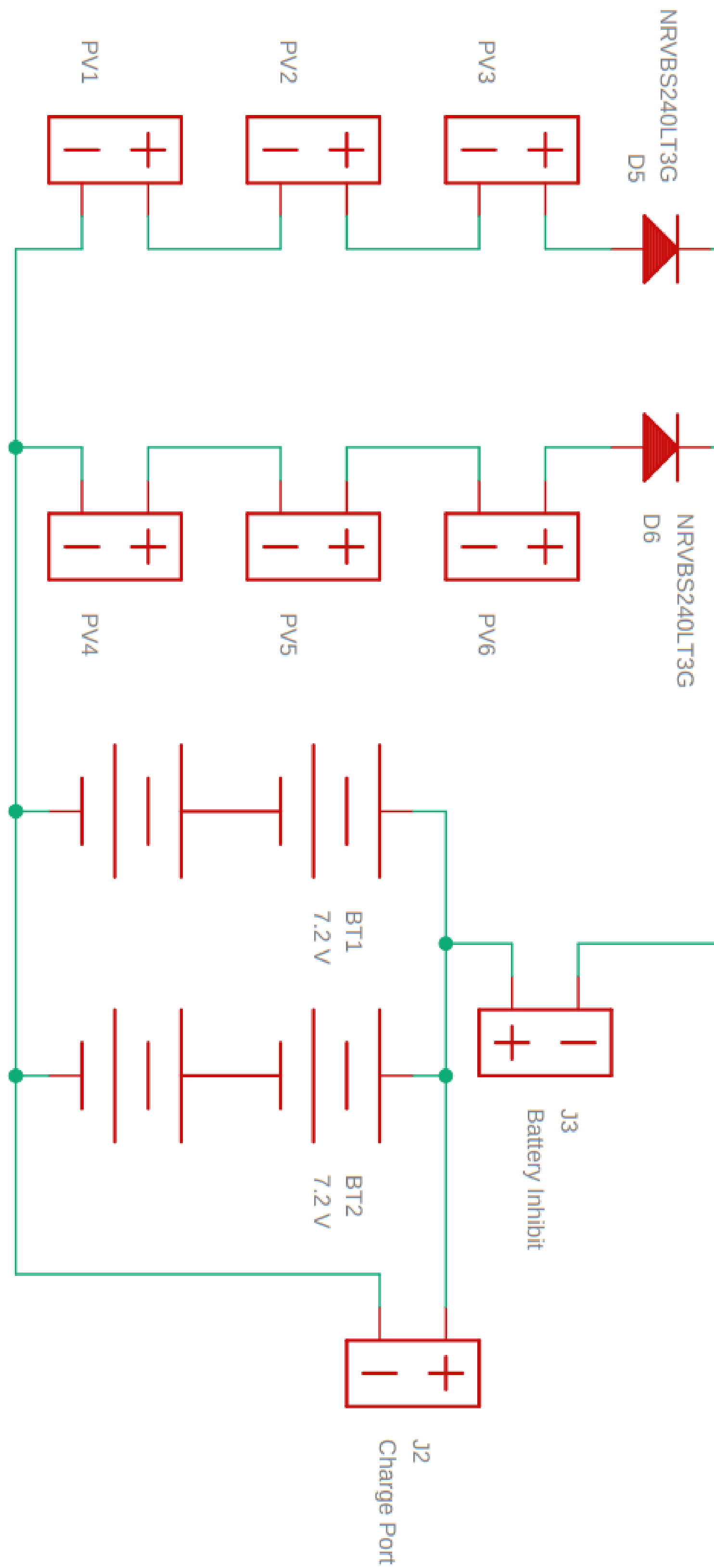

Figure 14 - Direct linkage interface between a solar input and energy storage

This interface can work because solar panels act like current sources. When the solar panel is illuminated the voltage of the panel string will increase until it is equal to the voltage of the batteries. Then it will begin behaving as a current source, sinking current into the batteries which charges them.

There are no needed components for this circuit, making it the cheapest as well. J3 prevents an overcharge case during storage, and after launch the activation of the payload will constantly drain the batteries, not allowing an overcharge failure. The solar panels must have an open circuit voltage equal to or slightly above the maximum battery voltage to allow the batteries to get close to a full charge before payload activation, allowing for a longer payload on time.

Payload activation

This circuit is meant to supply power once the batteries reach a certain state of charge, and then allow the current to continue to flow until the batteries have depleted to a certain, safe voltage, where the payload will then switch off to allow the batteries to recharge from the solar panels until their next activation. Figure 15 shows the activation circuit. The components will be discussed following the figure.

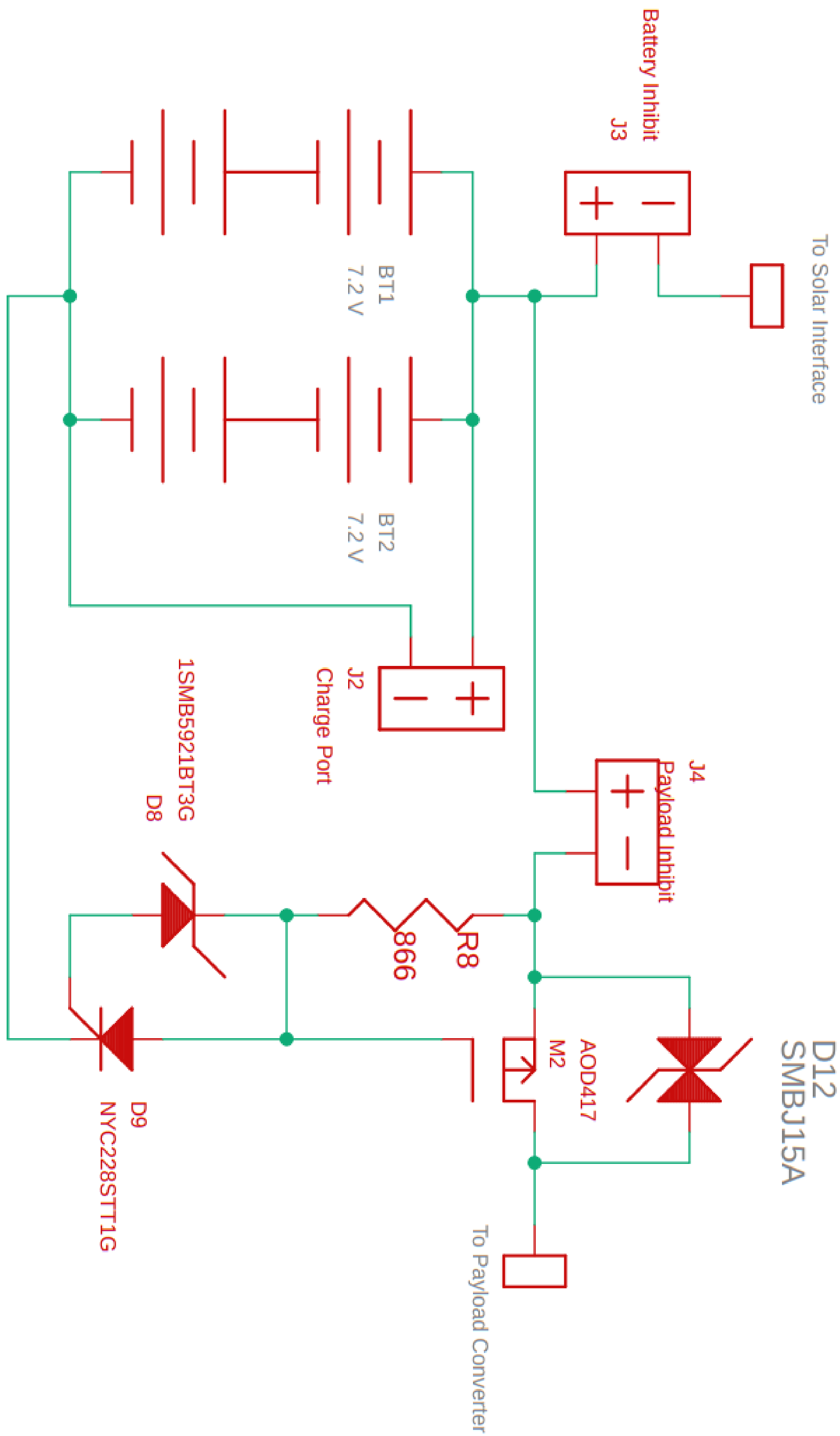

Figure 15 - Payload activation circuit

Component Breakdown: As an overview of the circuit, the MOSFET (M2) is normally off and will block current flow to the payload, keeping them off and allowing the batteries to charge from the solar panels. Once the batteries charge to a certain point, the Zener diode (D8) will break down and activate the SCR (D9). This will turn the MOSFET on and allow current flow to the payload, activating it. Resistor R8 establishes a holding current through D9, keeping it on until the batteries discharge to a certain point, where the holding current can no longer keep D9 on and D9 will close, closing the MOSFET.

- **M2**: This MOSFET must block the voltage of the fully charged battery voltage, as well as be in the on state with a logic level at its gate. This is the same part that is used for M1 in the RockSat section and is interchangeable between the two payload types. The guide for selecting a different MOSFET can be followed in the guide for M1.
- **D12**: This is a protection diode for the MOSFET, the same as D4 on the RockSat example circuit.
- **D9**: This is the SCR that will turn the MOSFET on and off. This is the same part as D3 in the RockSat section and is interchangeable between the two payload types. As a reminder, this SCR must block the voltage of the fully charged batteries in its off state. This part should have the lowest holding current possible to minimize energy losses in the payload. The guide for selecting a different SCR can be followed in the guide for D3.

- **D8**: This is the Zener diode that will activate the SCR. Zener diode will reverse conduct once a certain voltage threshold is reached, much like the TVS diode. To find the needed breakdown voltage value for this you need to select the voltage you wish to activate the payload at. This should be higher than the nominal voltage of the batteries (3.7 for each cell in series) but lower than the maximum charge voltage of the batteries (4.2 V for each cell in series). This is because over multiple cycles the batteries will not be able to charge to their maximum voltage as they slowly degrade, and if the Zener diode breaks down at that voltage it will never be able to reach its breakdown threshold. To find a Zener diode search Zener of DigiKey and select Diodes - Zener – Single then select the following filters:
  - Packaging: Cut Tape (CT)
  - Part Status: Active
  - Mounting Type: Surface Mount
  - Stock Status: In Stock
  - Supplier Device Package: I would recommend selecting SMB and SMC for solderability, however this may limit the breakdown voltages available to you, so if you do not find a voltage usable by you after you select this filter you could undo it and go with another package.
  - Voltage - Zener (Nom) (Vz): This is the voltage the Zener diode will break down at. You want this number plus the Voltage - Gate Trigger (Vgt) (Max) of the SCR you selected to be in between the nominal and maximum battery voltage. The SCR gate trigger voltage for the example is 0.8 V, and with a 6.8 V breakdown Zener this will give an activation voltage of 7.6 V, above the 7.2 V nominal voltage but below the 8.2 V maximum voltage.
  - Ensure the operating temperature is within limits.
- **R8**: This resistor establishes the holding current for the SCR and determines at what state of charge the SCR will turn off. The guide for R1 can be followed to select this 1% resistor. To determine the resistance value, you need to know the Voltage - On State (Vtm) (Max) and Current - Hold (Ih) (Max) of the SCR. The batteries should be turned off at or above 3 V for each cell to keep the batteries healthy, 3 V per cell was selected for the example. This gives a total voltage at turn off of 6 V. From the 6 V subtract the Voltage - On State (Vtm) (Max) which was 1.7 V, giving 4.3 V. At 4.3 V the current must be equal to the Current - Hold (Ih) (Max) to turn the SCR off, so $R = \frac{V}{I} = \frac{4.3\ V}{5\ mA} = 860\ \Omega$ (866 Ω was chosen as a standard 1% value which will turn the payload off just before 3 V which is preferred over slightly lower than 3 V). This needs to be prototyped and tested, I would highly recommend buying a few resistor values around this theoretical resistance (both higher and lower) in case of variances between the SCRs.

This concludes the component breakdown for the passive payload activation which will activate at a certain battery voltage threshold and then turn off before the state of charge of the batteries goes too low. Prototyping is important with this circuit as it may take a few resistor values to tune the turn off voltage of the batteries.

Payload Converter

The next section is the converter for the different payloads and subsystems on board the satellite. There are two ways to accomplish this. Multiple converters may be needed as different payloads may require different voltages. If two subsystems require the same voltage, they may be put onto the same converter rail to save PCB space if the converter is able to supply the current. If the payload can support a wide input range that is inclusive of the minimum and maximum voltages of the battery pack, such as the amplifiers and VIPE transformer on the Aether payload, then they may be directly connected to the payload activation circuit. If the payload has a range of accepted voltages but conversion is still needed, the center value is a good target to aim for.

DC/DC Converter

The most efficient method to the this is to use a DC/DC converter to convert the changing battery voltage into a constant output voltage that is usable by the subsystem. This is the same concept as the DC/DC converter interface between the solar panels and the batteries. Figure 16 shows an example circuit with recommended parts to build this DC/DC converter.

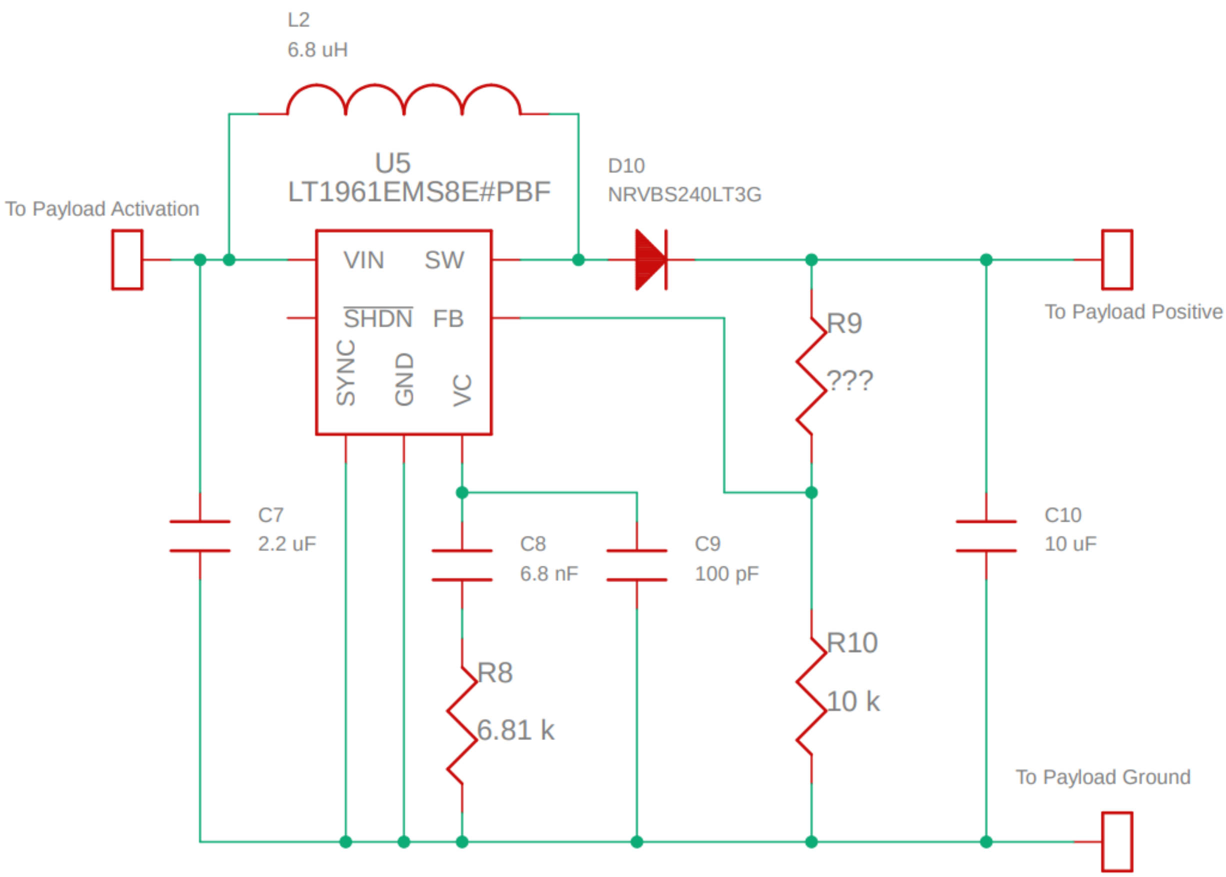

Figure 16 - DC/DC converter for battery voltage to stable payload voltage conversion

Component Breakdown: This circuit accepts the full voltage range of the batteries as shown in Table 5 (using 3 V as the minimum for each cell) and convert that changing voltage with battery state of charge into a stable output voltage that is usable by a payload or payloads. The selected part is a Step-Up/Step-Down converter with a wide input and output. It can accept 3 to 25 V input, greater than the entire range of all Minimum and Maximum Voltages for each battery pack. It can output 1.2 to 35 V at 1.5 A. This converter should be able to handle most applications needed by small satellites.

Table 5 - Minimum and maximum voltage for each battery cell count

Number of Cells	Minimum Voltage (V)	Maximum Voltage (V)
1 Cell	3	4.2
2 Cells	6	8.4
3 Cells	9	12.6
4 Cells	12	16.8

- **U5**: This is a step-up/step-down converter, meaning that it can accept a lower, higher, or equal input voltage then its set output voltage. This was chosen in case the voltage range of the battery cells started higher than the needed voltage then drops lower than the needed voltage as the battery discharges. This may be the case if 3.3 V (common for logic devices) is needed and one cell is being used, the voltage starts higher at 4.2 V but as the battery discharges it will eventually drop lower than the output. The $\overline{SHDN}$ is intentionally left disconnected as the datasheet says to leave the pin floating to turn the converter on. To find these parts search Converter on DigiKey and select PMIC - Voltage Regulators - DC DC Switching Regulators, then select the following filters:
    - Packaging: Bulk, Cut Tape (CT), and Tube
    - Part Status: Active
    - Function: Note, choose all the selections with Step-Up, Step-Down, or Step-Up/Step-Down if separated by a comma, there may be multiple (e.g. select Radiometric, Step-Up if Step-Up is needed).
        - If the Maximum Voltage of your chosen pack is below your needed output voltage: Step-Up
        - If the Minimum Voltage of your chosen pack is above your needed output voltage: Step-Down
        - If the voltage requirement is between the Minimum and Maximum Voltages of the chosen pack: Step-Up/Step-Down
    - Output Configuration: Positive
    - Output Type: Adjustable
    - Number of Outputs: 1
    - Voltage – Input (Min): Everything equal or lower than the Minimum Voltage of your chosen cell.
    - Voltage – Input (Max): Everything equal or higher than the Maximum Voltage of your chosen cell.
    - Voltage - Output (Min/Fixed): Everything equal or lower than the required output voltage.
    - Voltage – Output (Max): Everything equal or higher than the required output voltage.
    - Current – Output (Max): Everything equal or higher than the current requirement of the payload or payloads.
    - Mounting Type: Surface Mount
    - You can now sort by price ascending and select a part, pay attention to the package to ensure if can be soldered easily (such as 8-SO). The additional components needed will be in the typical application section along with formulas to calculate certain values. The circuit will most likely not look like the example if a new IC is chosen.

- **C7 & C10**: These are the input and output filtering capacitors for the converter. Follow the guide for C1 & C2 and select the capacitance value listed in the typical application section of U5.
    - Note: Adding more capacitors in parallel with C7 would not be a bad thing if there is room on the PCB, they will help stabilize the input to the converter to help the converter run more efficiently. 100 nF, 1, and 10 µF capacitors are always a good choice (100 nF is most important, then 1 µF, then 10 µF). You could add one of each or two of each room permitting.
- **R8, C8, & C9**: These are passive components needed by U5 that were listed in the typical supplications section. Use the guide for R1 and C1 & C2 to select them and select the required capacitance. If a different U5 chip is chosen these may or may not be required, check the typical applications section.
- **L2**: This inductor is required by U5 to convert the voltage. Follow the guide for L1 to select this, ensure the maximum current and saturation current are higher than the Current – Output (Max) of U5 or the required current by the payload or payloads.
- **D10**: This diode is needed by U5 for operation. Follow the guide for D5 & D6 to select this diode, it should be a low drop Schottky to keep the efficiency of the converter as high as possible.
- **R9 & R10**: These are the feedback resistors needed by U5 to sense and adjust the output voltage as necessary. For the example part R10 was given. The needed output voltage is known from the part requirement so the formula for R9 is given as $R_9 = \frac{R_{10}(V_{out}-1.2)}{1.2-R_{10}(0.2\ \mu A)}$. Values of R9 for common voltage are listed in Table 6. Use the process to select R1 to select these resistors. I would recommend buying several parts around the theoretical R9 to tune the output voltage for the specific U5 chip (requires testing).

Table 6 - R9 values for common voltages for the U5 part of LT1961EMS8E#PBF

Output Voltage (V)	**R9 (kΩ)**
3.3	17.4
5	31.6
9	64.9
12	90.9
15	115
20	158
25	200
30	243
35	280

This concludes the component breakdown for a DC/DC Converter for a payload or payloads. The selected component for U5 is a wide input and wide output device which should be able to handle most needs in small satellites. Multiple converters may be required for multiple payloads with different voltage needs. If two payloads have the same voltage requirements it will save space and design work to have both payloads using one converter if the currents are within the limits of the converter.

If additional current is needed by the payload and another IC for U5 cannot be found with current capabilities high enough it is possible to place multiple converters in parallel. The issue with doing this is the converters will not all supply the exact same voltage, leading one converter to 'feed' current into the other converter or converters. To prevent this a protection diode should be placed after the output filtering capacitor (C10) which could be the same diode as D10 (it does not replace D10, two diodes are now needed). This will mean that the output voltage will need to be the required voltage plus the forward drop of the additional diode.

The other option to supply higher current or simplify the circuit is to find a prebuilt DC/DC converter. These will be more expensive than building a circuit such as Figure 16. To do this search DCDC on DigiKey and select DC DC Converter (there may be 2 options, select the one with a higher number of items), then select the following filters:

- Packaging: Box, Cut Tape (CT), & Tube
- Part Status: Active
- Number of Outputs: 1
    - If multiple voltages are needed you may be able to find a multioutput converter that meets your requirements, if so select more outputs to search
- Voltage – Input (Min): Everything equal or lower than the Minimum Voltage of your chosen cell.
- Voltage – Input (Max): Everything equal or higher than the Maximum Voltage of your chosen cell.
- Voltage – Output 1: Select the required output voltage for the payload.
- Current – Output (Max): Everything equal or higher than the current required by the payload or payloads.
- Mounting Type: Surface Mount & Through Hole
- Part Status: In Stock
- Sort by price ascending and find a part which will work for your payload, be mindful of the package design as some can be very difficult to solder.
    - Ensure the operating temperature is within limits.

Linear Regulator

Like the linear regulator linkage between the solar panels and batteries, a linear regulator can be used to regulate the battery voltage to a constant output voltage for a payload. This will be less efficient versus using a DC/DC converter, however the advantages of using this are more prevalent for payloads. DC/DC regulators can produce some noise in their output voltages since they are switching regulators. To dampen this noise filters can be added to the output in addition to the output capacitor, however often there is still some noticeable noise. For noise sensitive payloads, such as a communications circuit, the noise may be too high for optimal operation. Because of how they operate, linear regulators provide a smooth voltage rail which is typically very low noise. This can be very useful for noise sensitive payloads.

To use a linear regulator the minimum voltage of the chosen battery pack (given in Table 5) must be 1.25 V higher than the needed output voltage. Values lower than 1.25 V exist but will not be examined in the example circuit. A note will be made of how to search for low-drop linear regulators. If the battery voltage drops too low over the battery discharge cycle and a linear regulator is necessary a step-up converter will need to convert the battery voltage at least 1.25 V higher than the needed output voltage, then a linear regulator can regulate the output from the DC/DC converter to the voltage needed by the payload. Figure 17 shows an example payload converter using a linear regulator.

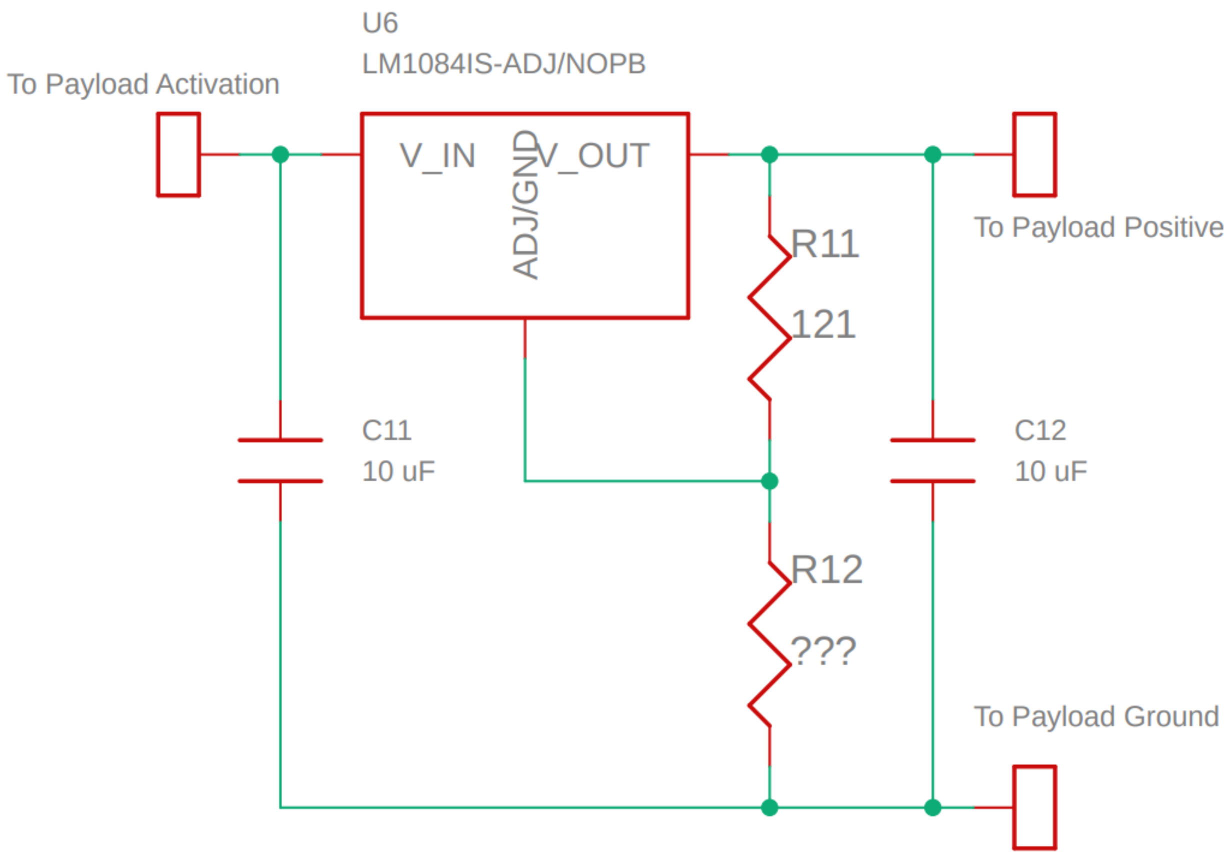

Figure 17 – Linear regulator for battery voltage to stable payload voltage conversion

Component Breakdown: The linear regulator (U6) selected is a very large package with a lot of power dissipation, meaning it can supply a lot of output current. This large of a package may not be needed if the payload does not require much power, in which case I would recommend selecting a lower power linear regulator since this is quite large and expensive. It can accept up to 29 V which is greater than the battery voltage maximum range and can output 1.25 – 27.5 V at 5 A (Note, this is if the difference between input and output voltage is only 1.25 V, the minimum difference possible). This will produce a clean, low noise output voltage.

- **U6**: This is the linear regulator which will convert the input voltage to the needed output voltage by turning the excess voltage into waste heat. This part may get warm or even hot during normal operation. Excessive waste power may overheat and possibly fail the device. The same process to select U4 may be taken to find these parts with the following amendments:
    - Voltage – Input (Max): This value must be equal or higher than the maximum voltage of the batteries (Table 4).
    - Voltage – Output (Max): This value must be equal or higher than the needed voltage for the payload.
    - Current – Output must be equal to or higher than the needed voltage by the payload, however, pay attention to the Maximum Output Current within the Electrical Characteristics table which shows different output voltages with different differences between input and output voltages, as noted in U4. Use the maximum battery voltage to find the maximum difference between the input and output voltages of the linear regulator.
- **C11 & C12**: These are the input and output capacitors to filter and stabilize the input and output of the linear regulator. These values may be different if a different U6 component is selected. The suggested values will be listed in the typical application section of the datasheet for U6. The process to select C1 & C2 can be followed to select these.
    - Note: Adding more capacitors in parallel with C11 would not be a bad thing if there is room on the PCB, they will help stabilize the input to the converter to help the converter run more efficiently. 100 nF, 1, and 10 µF capacitors are always a good choice (100 nF is most important, then 1 µF, then 10 µF). You could add one of each or two of each room permitting

- **R11 & R12**: These resistors set the output voltage of the linear regulator. The recommended value for one of these resistors will be given in the typical applications section of U6, as well as a formula to calculate the other resistor. R11 was given as 121 **Ω**. Typically for 1.25 V drop linear regulators (the example U6 included) the formula is $V_{out} = (1.25\ V) * (1 + \frac{R_{12}}{R_{11}})$. The process to choose these resistors can be followed from R1. Common values that may be needed for R11 are listed in Table 7. I would recommend buying several parts around the theoretical R11 to tune the output voltage for the specific U6 chip (requires testing).

Table 7 - R12 values for common voltages for the U6 part of LM1084IS-ADJ/NOPB (and typical 1.25 V dropout linear regulators)

Output Voltage (V)	**R12**
3.3	200 Ω
5	365 Ω
9	750 Ω
12	1.05 kΩ
15	1.33 kΩ
20	1.82 kΩ
25	2.32 kΩ
27.5	2.55 kΩ

This concludes the component breakdown for the linear regulator payload voltage converter. The selected linear regulator in the example should have enough power dissipation and voltage possibilities to meet the requirements of most payloads. If space is limited or not that much current is required I would recommend finding another part for this linear regulator, otherwise it is by far over-engineered.

The following 4 figures show complete configurations that are possible using this guide, all using 2 cells in series (1 – 4 is usable with all designs and components with some resistor values needing adjustments). Note the addition of J4 in the small satellite examples, this is another inhibit to add to the payload to ensure the payload or payloads are not activated by the solar panels before launch. All the boxed components are the only components that need to be changed depending on the battery pack voltage if all the other components are left the same and they also are within the current limits of the payload or payloads.

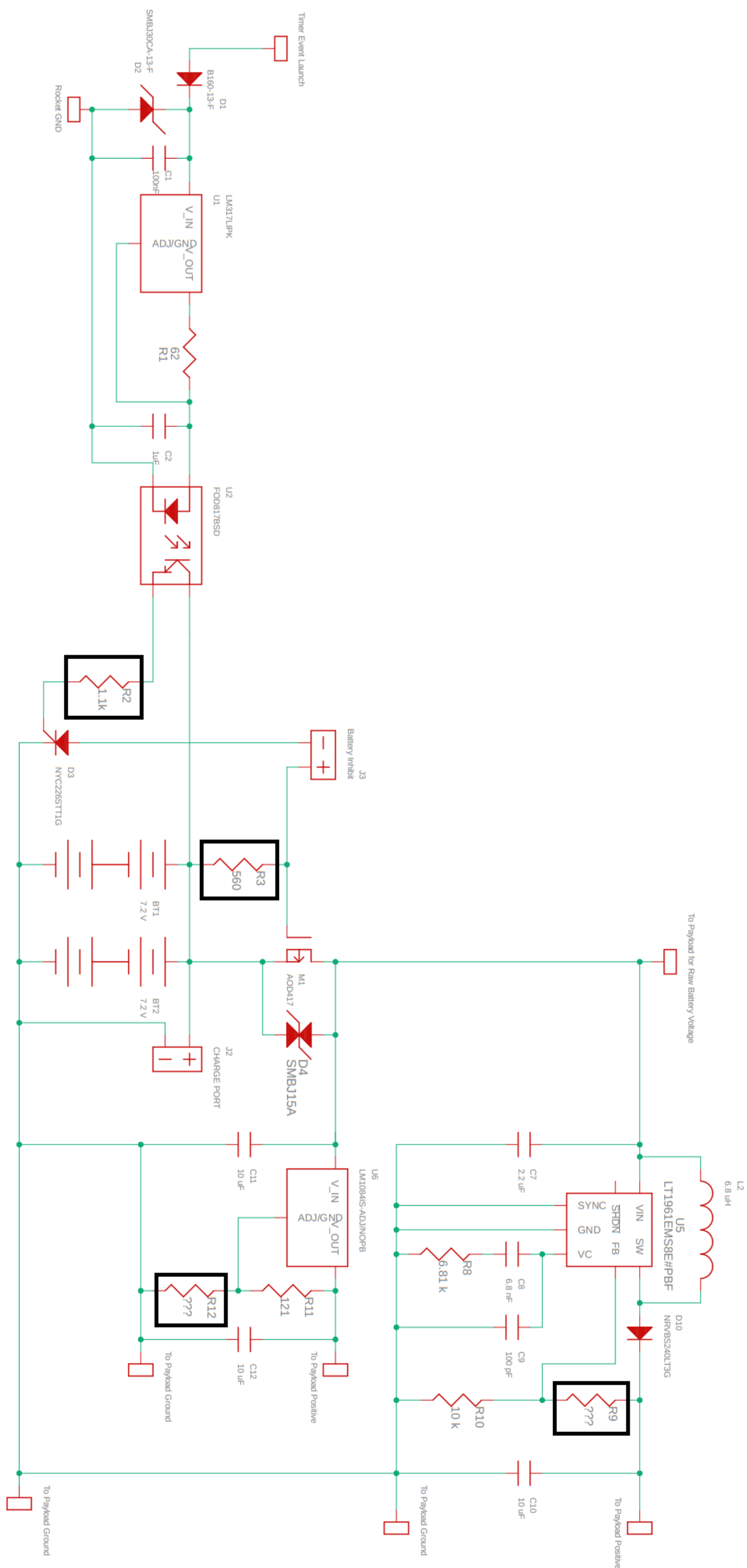

Figure 18 – Example RockSat or like-flight circuit designed from the information contained in this guide.

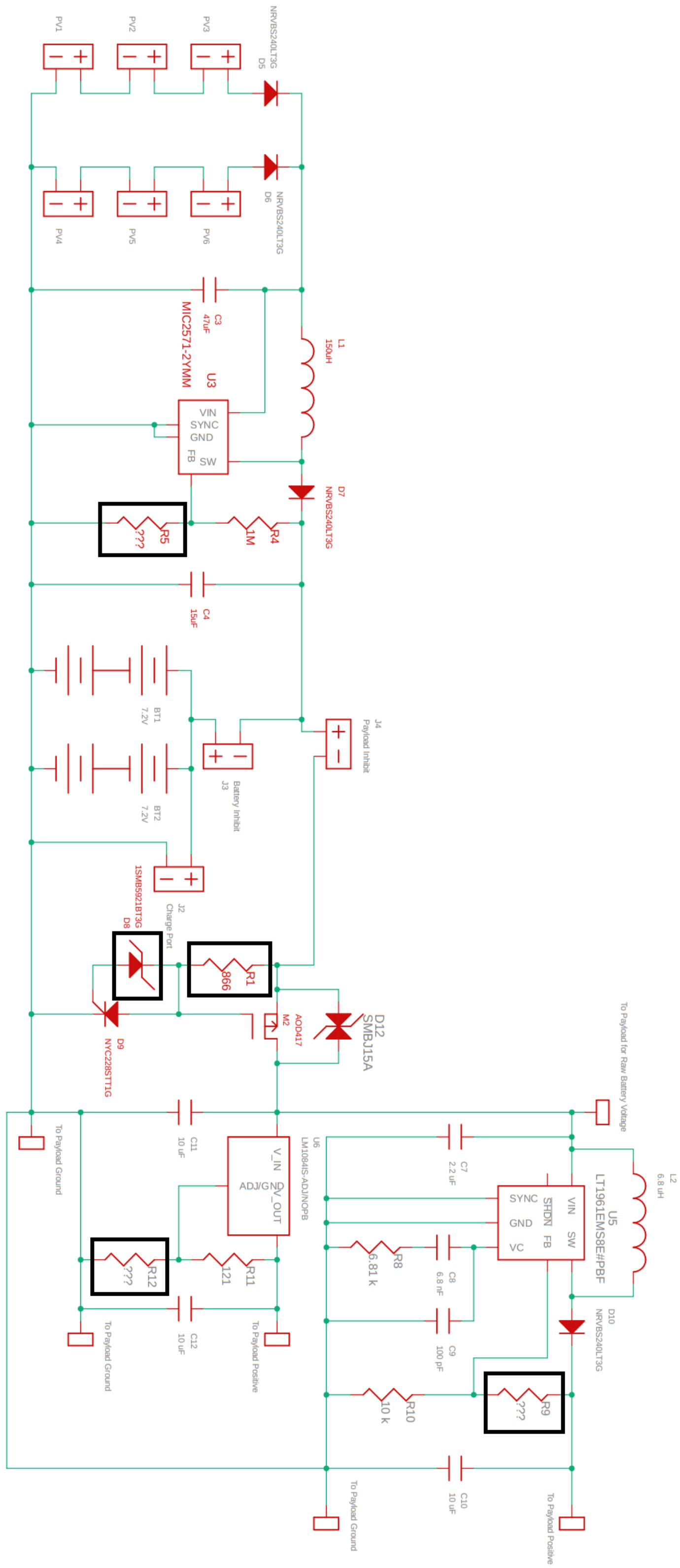

Figure 19 - Small satellite example circuit designed from this guide using a DC/DC converter interface between the solar panels and batteries.

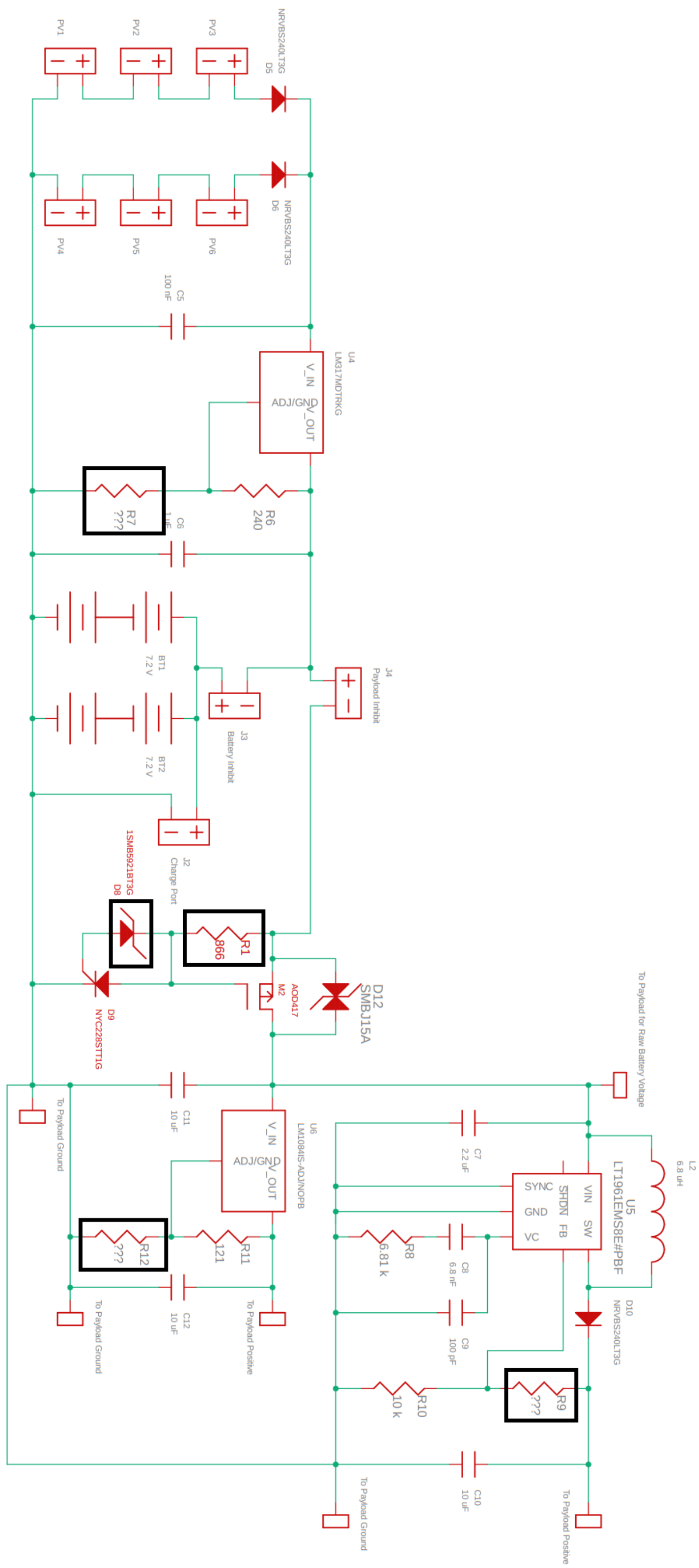

Figure 20 - Small satellite example circuit designed from this guide using a linear regulator interface between the solar panels and batteries.

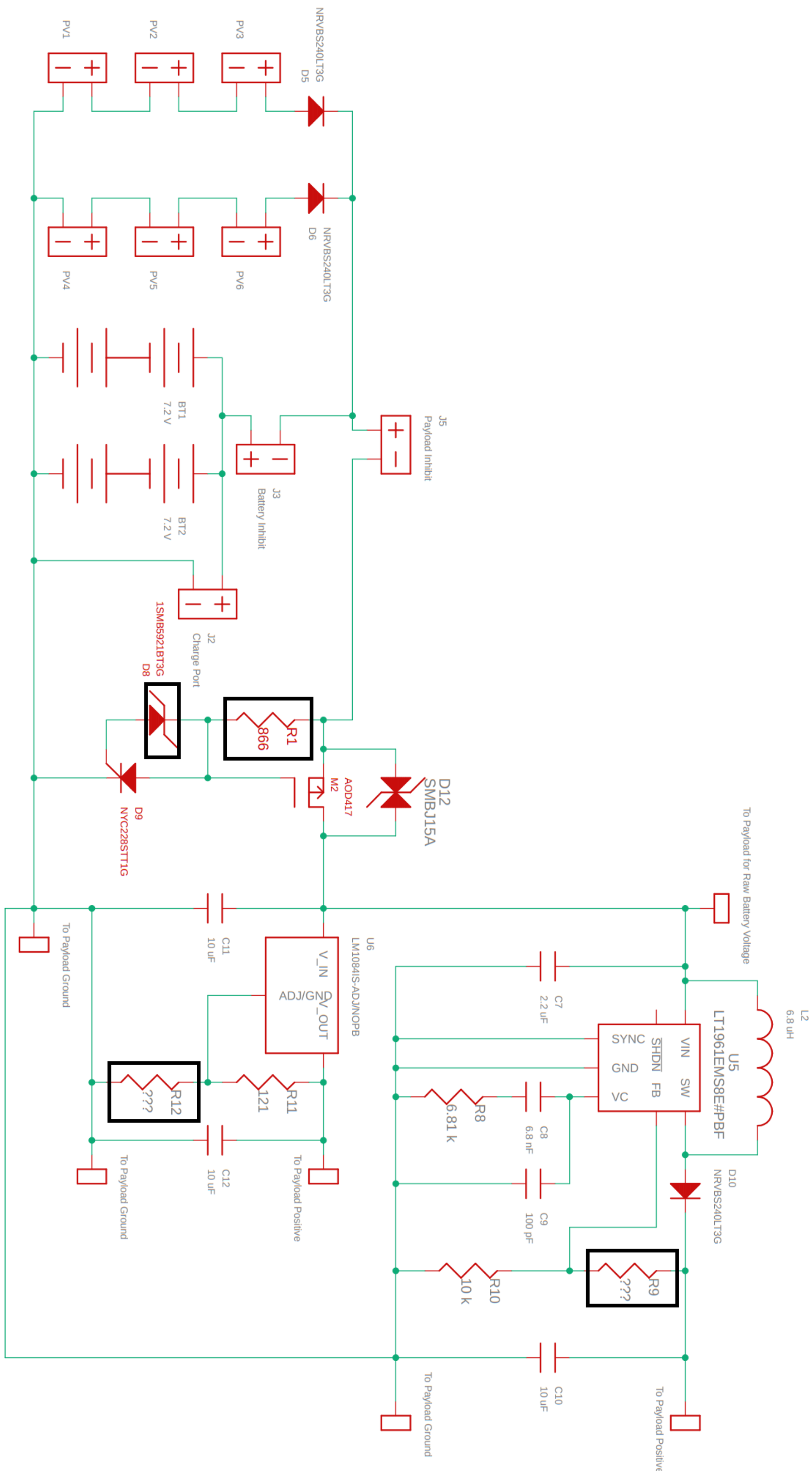

Figure 21 - Small satellite example circuit designed from this guide using a direct interface between the solar panels and batteries.

PCB and Other Considerations

This is a brief section about designing a PCB where I will highlight a few points. I would recommend using Advanced Circuits (www.4pcb.com) for ordering PCB, you can easily export Autodesk Eagle (which I would also recommend using to design the circuit and PCB, free from Autodesk with a student license) designs by going to File > Generate CAM Data. These files can then simply be zipped together and given to Advanced Circuits to run their Free DFM checker to ensure there are no electrical or manufacturing issues with the board. After the results are received from that, if nothing needs to be changed, you can give them the board number and they will manufacture the board.

- Before designing the PCB and especially before ordering it I would highly recommend ordering all the parts required to make the board and prototype and test the design on vector board. This is to ensure any issues are worked out before ordering the board which could prove costly if a revision is needed.
- For the RockSat example, all the inhibits should be locking switches or add-before-flight jumpers. For the small satellite examples all the inhibits should be locking switches or add-before-flight jumpers in series with the contact switches that close when the payload is deployed.
- These PCB should be designed as 2 layers, the traces are not too complicated as there is not too much logic needed, this will also reduce the price of manufacturing the PCB by a considerable amount.
- Keep solderability in mind, space the parts out enough to where you will easily be able to maneuver a soldering iron and achieve a good solder joint.
    - Think about other parts around as well, you may be able to easily solder in a resistor if you do it before you solder an IC, but if you need to change the resistor after testing it may be difficult.
- For best operation **filtering capacitors should be located as close as possible to the IC** that requires them.
- For rails (nets in the schematic that have a lot of connections, such as raw battery voltage and ground) make a plane on the top and bottom of the board for better performance.
    - Ensure there are no floating islands in the plane and the isolation for the planes are large enough (~20 mils).
- Traces should not be larger than the smallest solder pad on either end of the connection. ~20 mils is a good starting point for trace width.
    - Excessively large traces can cause troubles when soldering, but they need to be large enough to able to handle the current that will flow through them.
- Datasheets should contain recommended soldering pad layouts (if not you can find another part with the same package from a different manufacturing which may contain the recommended layout).

    - Often there are multiple layouts for different soldering methods (reflow, wave, etc.) if there is no specific hand soldering layout choose the layout with the largest pads or oversize the pads if you believe they are still too small to hand solder.
- **Silkscreen is free**, make sure it is large enough to read and label everything on the board that you think you will need, add test points if you think you may need to test certain areas or function of the board.
    - Test points can just be single pads which a lead can be soldered onto or probed by a multimeter.
- **Use lead solder**, lead free solder can whisker and cause short circuits in space applications.
    - Use plenty of flux when soldering, just ensure you give the board a thorough cleaning with isopropyl alcohol afterwards, there should be no flux residue (orange color) left. Use an acid brush to wipe the alcohol on the board, paying special attention to solder joints and underneath ICs.
    - A good solder joint resembles a smooth filet of solder from the top of the component to the far side of the solder pad, as shown in Figure 32. There is too much solder if the joint starts looking spherical, use a solder wick to remove the solder and resolder the joint.

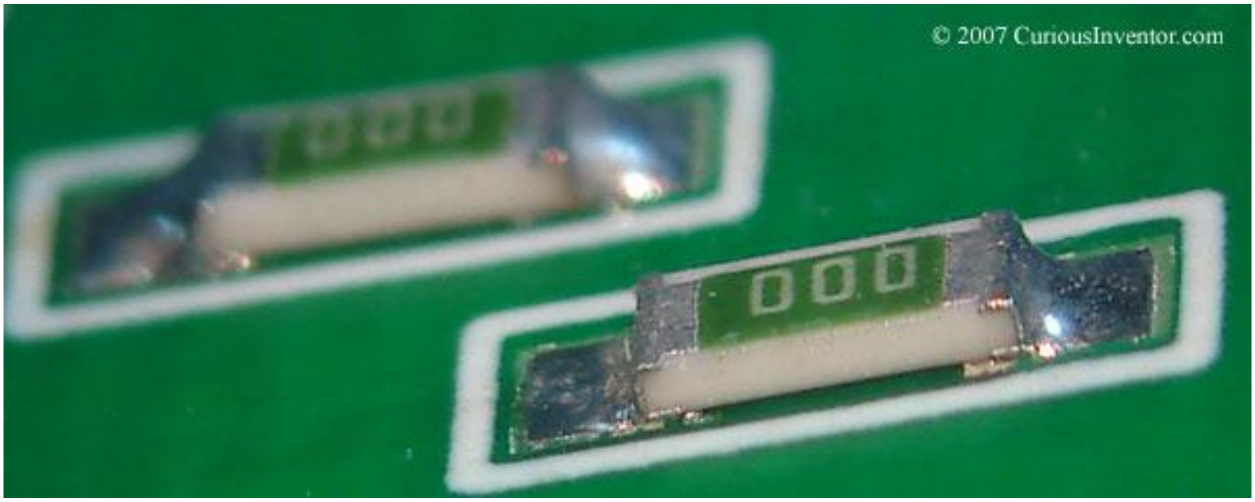

Figure 22 - Example of a good solder joint for an 0805 resistor – Curious Inventor

- **Do not use electrolytic capacitors for space application**. Look like a can, in Figure 33

Figure 23 - Electrolytic capacitor – DigiKey

- For electronic components DigiKey and Mouser are the two big companies, you can compare parts and prices from both if you desire.
    - For electronic parts a commonly use parts from:
        - Analog Devices
        - AVX Corporation
        - Bourns Inc.
        - CUI Inc.
        - Diodes Incorporated
        - Infineon Technologies
        - KEMET
        - Keystone Electronics
        - Linear Technology
        - Littlefuse Inc.
        - Maxim Integrated
        - Microchip Technology
        - Monolithic Power Systems Inc.
        - Murata
        - Nexperia
        - Ohmite
        - ON Semiconductor
        - Panasonic
        - Recom Power
        - Rohm Semiconductor
        - Samsung
        - Stackpole Electronics Inc
        - Taiyo Yuden
        - TDK Corporation
        - TE Connectivity
        - Texas Instruments
        - Toshiba
        - United Chemi-Con
        - Vishay
        - XP Power
        - Yageo

- When ordering parts always order more then you need for the circuit.
  - For small passive components (resistor, capacitor, and inductor) I will typically order at the next price break, usually at 10 components, though if the part is very cheap I often order 100 components as well.
  - For larger and more expensive ICs I typically buy 1-3 extra depending on the price.
- Use Silicone RTV to strain relief the connection between wires and the board after final integration. This will help absorb vibrations during launch.

The following figures are the electrical designs from the Aether and CACTUS – Hermes 3.0 missions to use as examples:

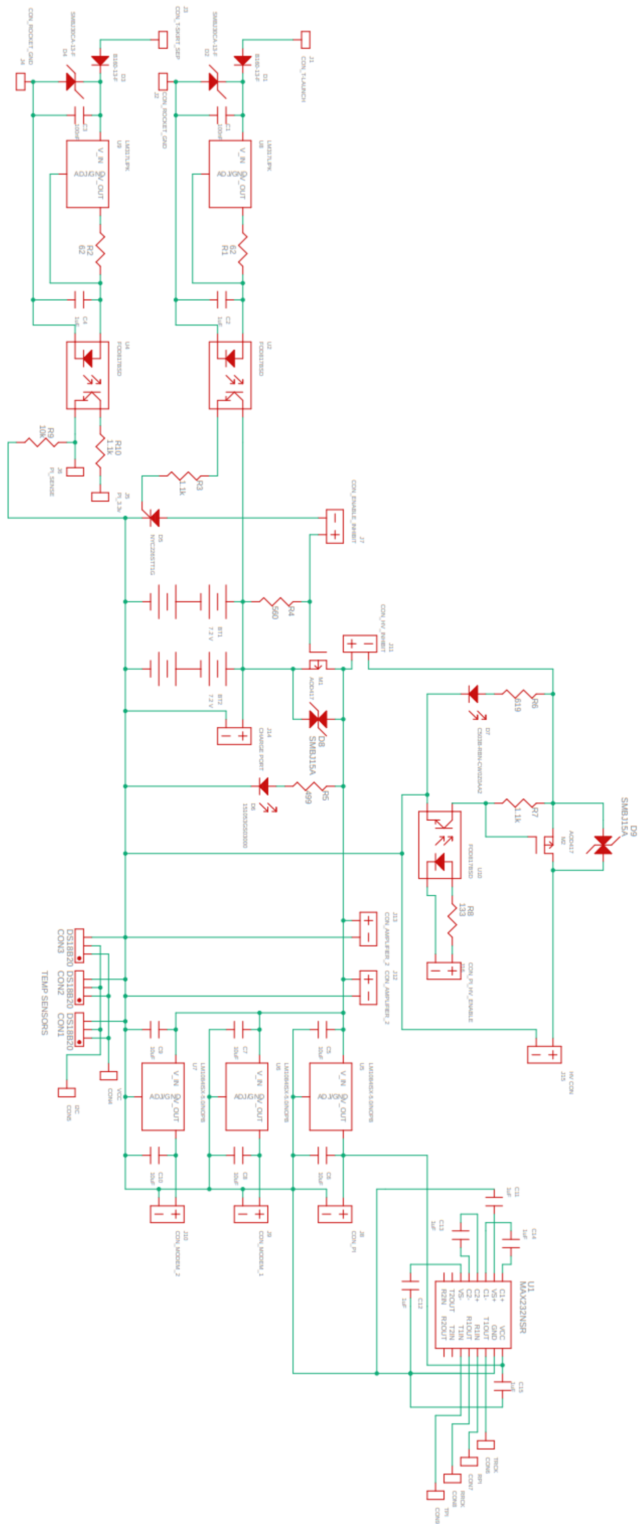

Figure 24 - Aether power board schematic. Only linear regulators and raw battery voltage were used for the payloads. Note D6 and D7 are status LEDs to give us a visual indication that power is flowing through the system and the high voltage inhibit is take out, respectively. Note, the U10 system allows the Pi to enable the high voltage payload (Appendix).

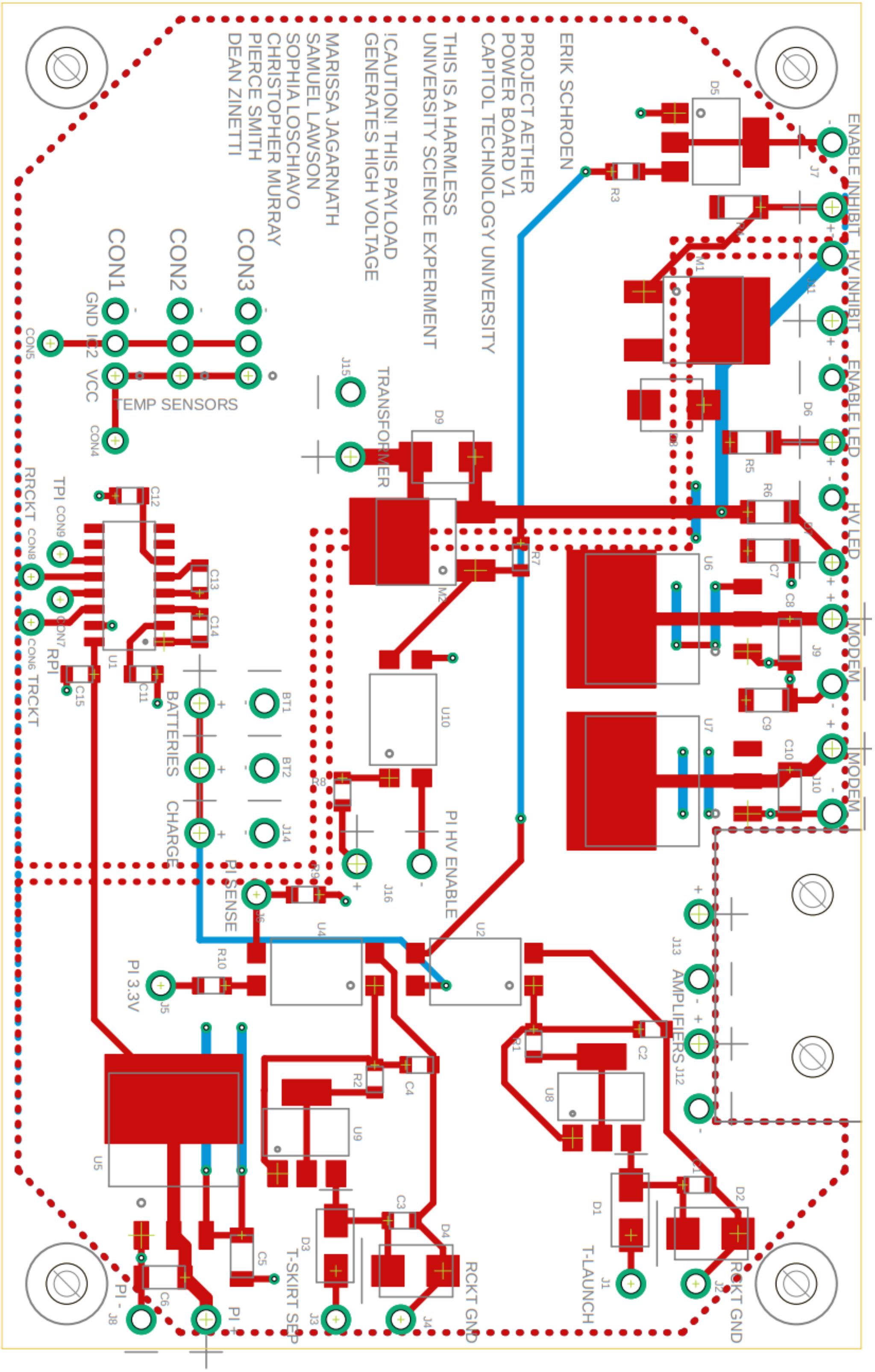

Figure 25 - Aether power board PCB design, the red and blue dotted line are the boundary of the battery voltage/5V rail and ground plane respectively.

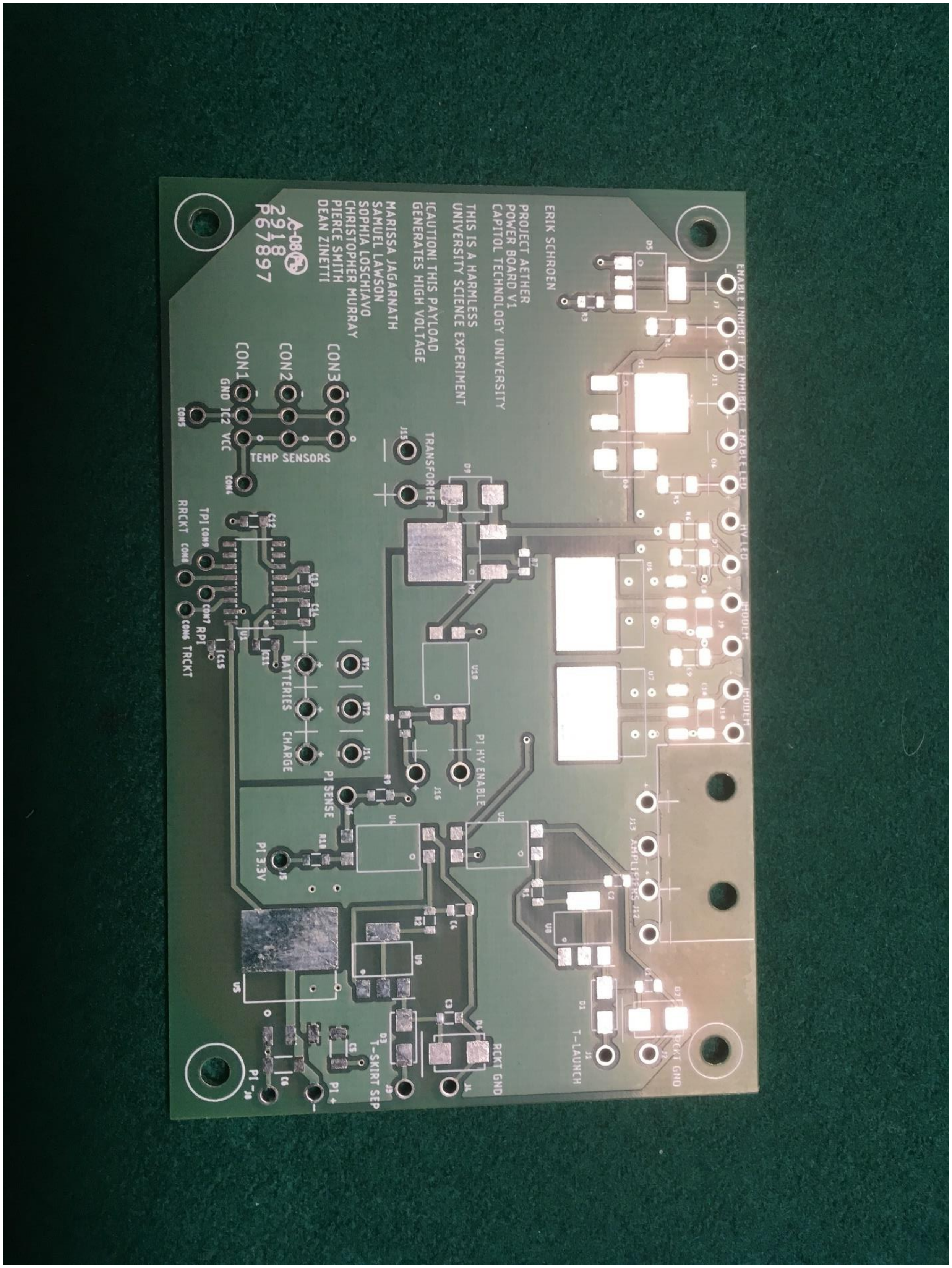

Figure 26 - Aether power board unpopulated PCB

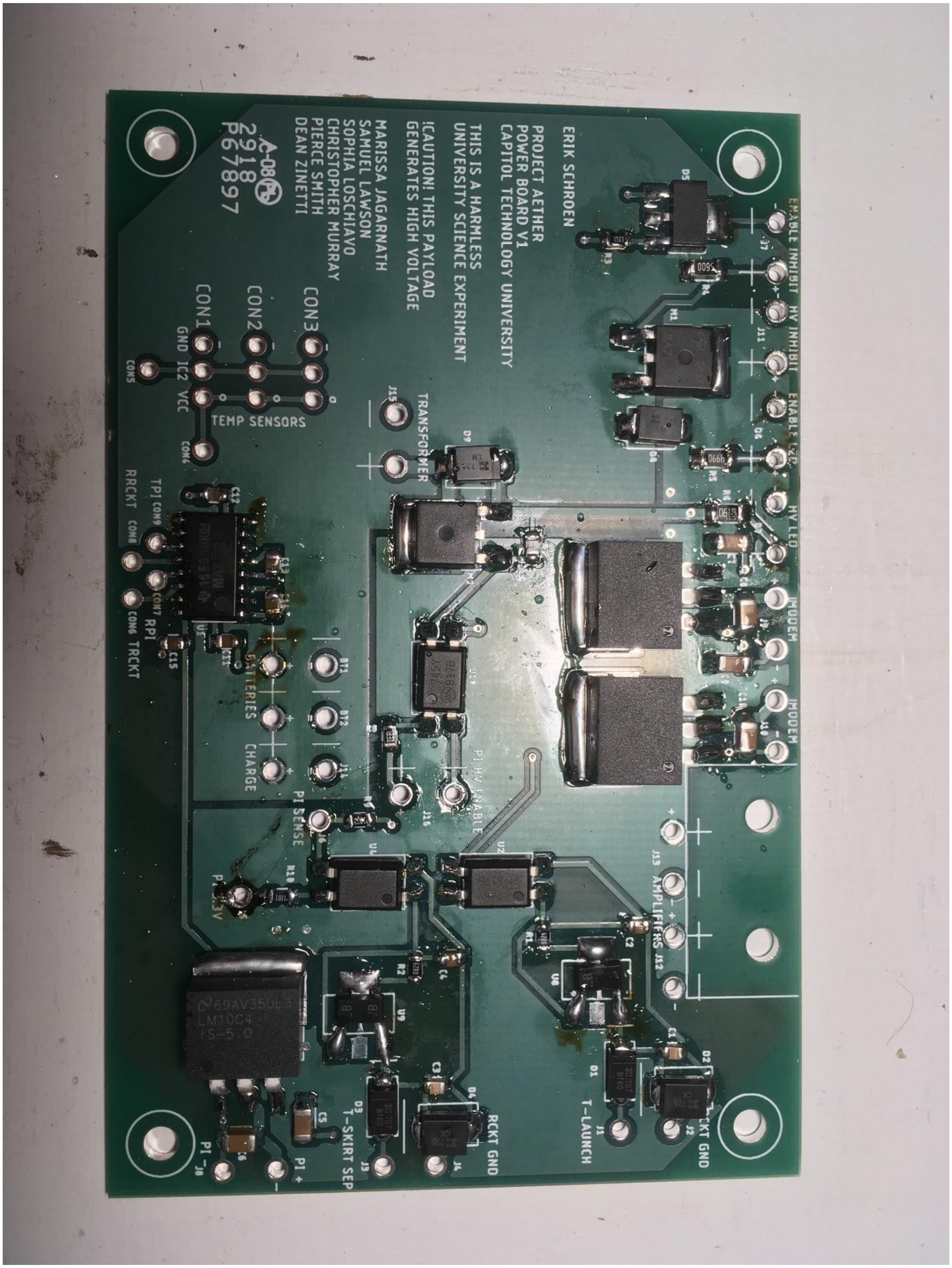

Figure 27 - Aether power board populated

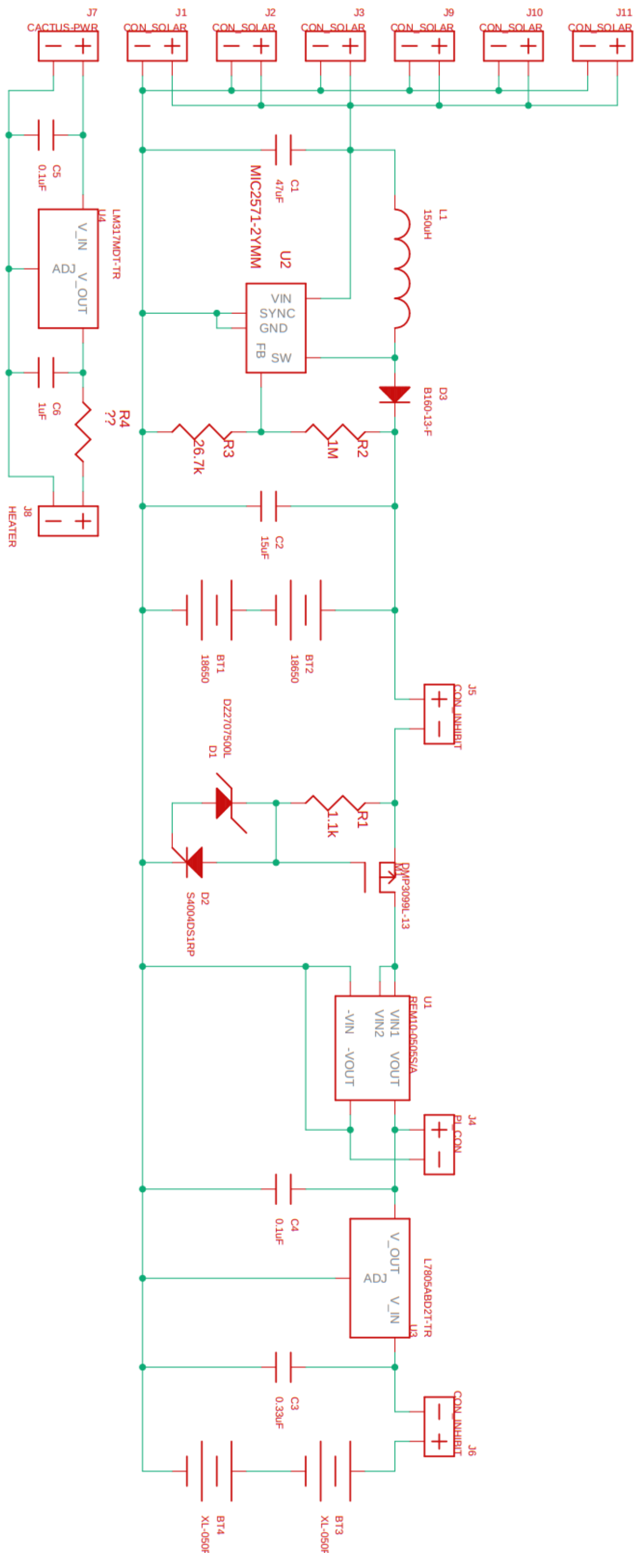

Figure 28 - CACTUS - Hermes 3.0 power board schematic. Only linear regulators and raw battery voltage were used for the payloads. A custom and prebuild DC/DC converter as well as a 5 V linear regulator were all used.

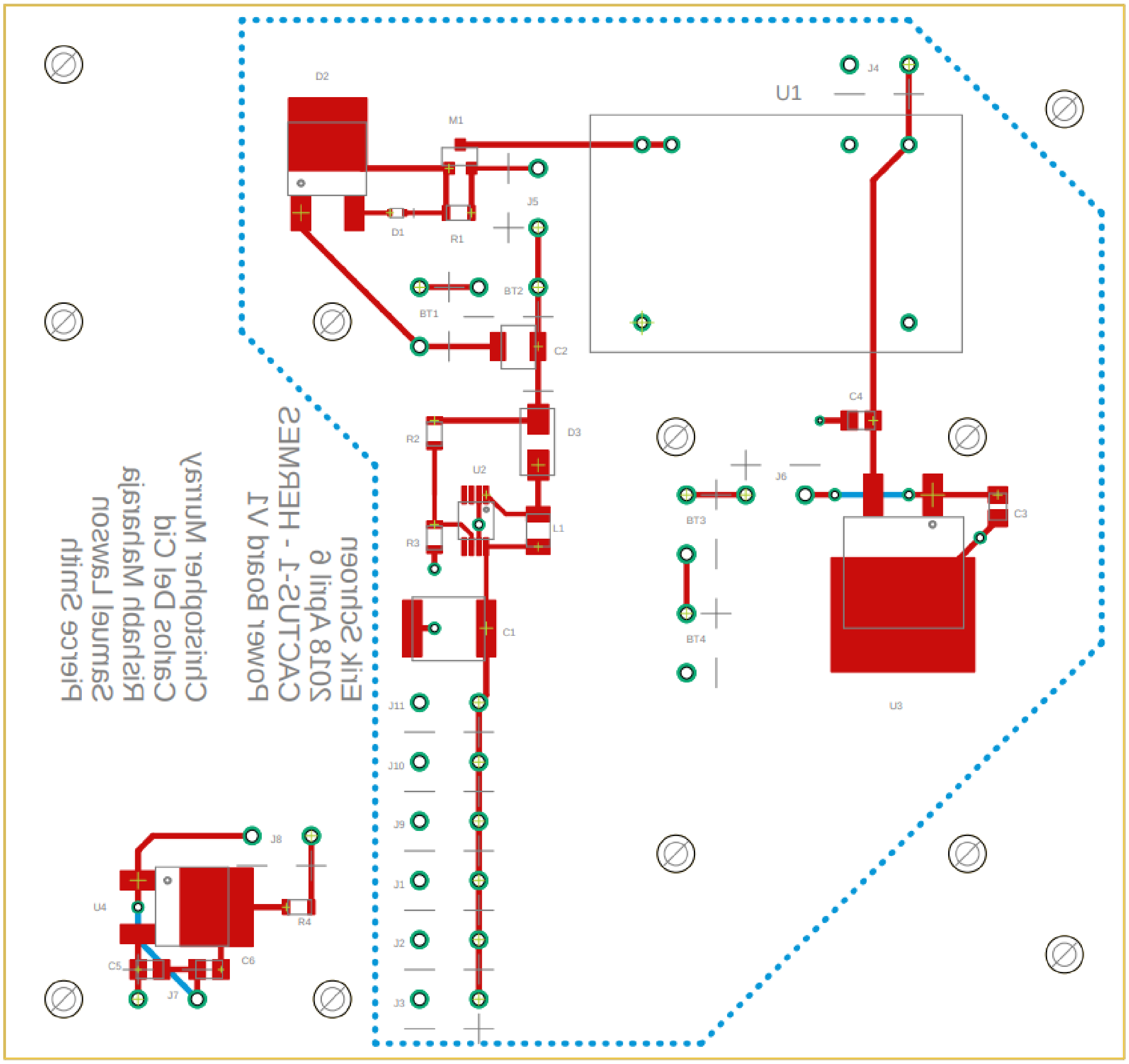

Figure 29 – CACTUS – Hermes 3.0 power board PCB design, the blue dotted line is the ground plane. This design used PC 104 standard.

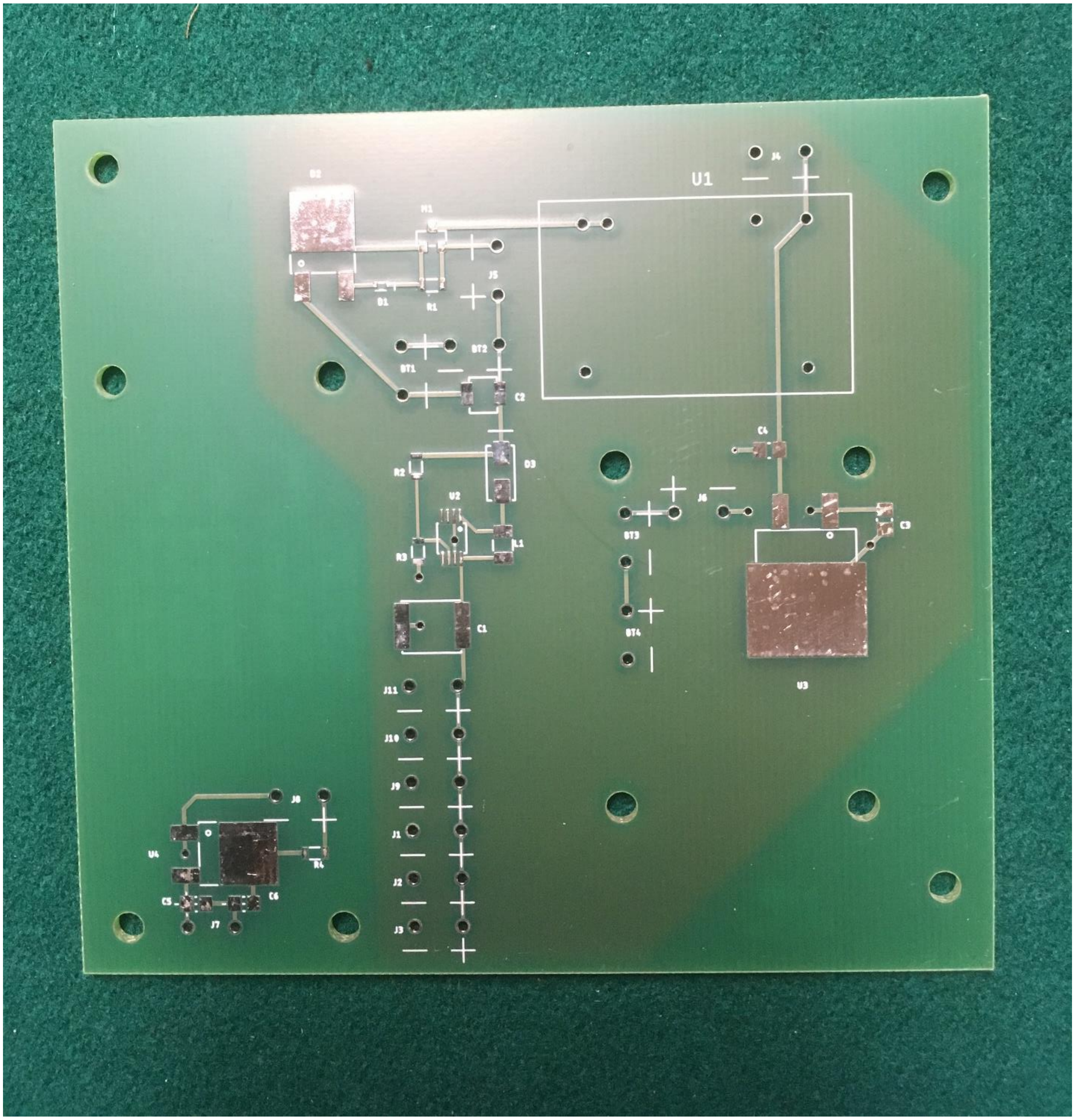

Figure 30 – CACTUS – Hermes 3.0 power board unpopulated PCB

References/Additional Reading

Bouwmeester, J. Gill, E. Langer, M. (2016). Survey on the Implementation and Reliability of CubeSat Electrical Bus Interfaces. Springer.

Burt. R. (2011). Distributed Electrical Power System in CubeSat Applications. Utah State University.

Clark, C. (n.d.). Huge Power Demand…Itsy-Bitsy Satellite: Solving the CubeSat Power Paradox. 24th Annual AIAA/USU Conference on Small Satellites.

Doering, T. J. (2009). Development of a Reusable CubeSat Satellite Bus Architecture for the Kysat-1 Spacecraft. University of Kentucky.

Erb, D. M. (2011). Evaluating the Effectiveness of Peak Power Tracking Technologies for Solar Arrays on Small Spacecraft. University of Kentucky.

Lim, T. M. (2016). A Modular Electrical Power System Architecture for Small Spacecraft. University of Kentucky.

Notani, S. A. (2011). Development of Distributed, Scalable and a Flexible Electrical Power System Module for CubeSat and Small Satellites. North Carolina State University.

Smith, R. P. (2018). CACTUS-I Design Documentation and Future Guidance. Capitol Technology University.

Appendix

Custom Battery Charger

If you are going to use this charging circuit, the battery should **constantly be monitored and disconnected immediately upon reaching the maximum voltage for the pack and current approaches zero**. These are all through hole components, so this can be built on vector board for ease of population. Note the part number is given for R1, this is because this needs to be a high-power resistor. This charger will charge the batteries at 500 mA, R1 can be adjusted for a slower charging rate and may allow a standard through hole resistor to be used, I would not recommend going any higher ($I = \frac{1.25\ V}{R_1}$, ensure you calculate the power and check the resistor used is rated at a high enough power). The values for R3 for the different battery packs is given in Table 8 ($V = 1.25\ V * (1 + \frac{R_3}{R_2})$). A potentiometer could also be used in place of R3 to allow any output voltage to be set, with no battery attached to the output use a voltmeter to read the output voltage and adjust the potentiometer until the desired voltage is reached (5 k**Ω** pot is a common value and will allow you to charge at greater voltages than 4 cells, the higher the turn count the greater the accuracy, I would use something like PV36W502C01B00). Ensure that during charging the potentiometer is not changed. Before connecting the charger to the battery pack always connect the power supply and ensure the output voltage is close to the maximum voltage of the battery pack (slightly lower is better than higher). Take caution when using this circuitry. Ensure at the end of the charge the current into the battery begins to drop off as the voltage approaches the setpoint value.

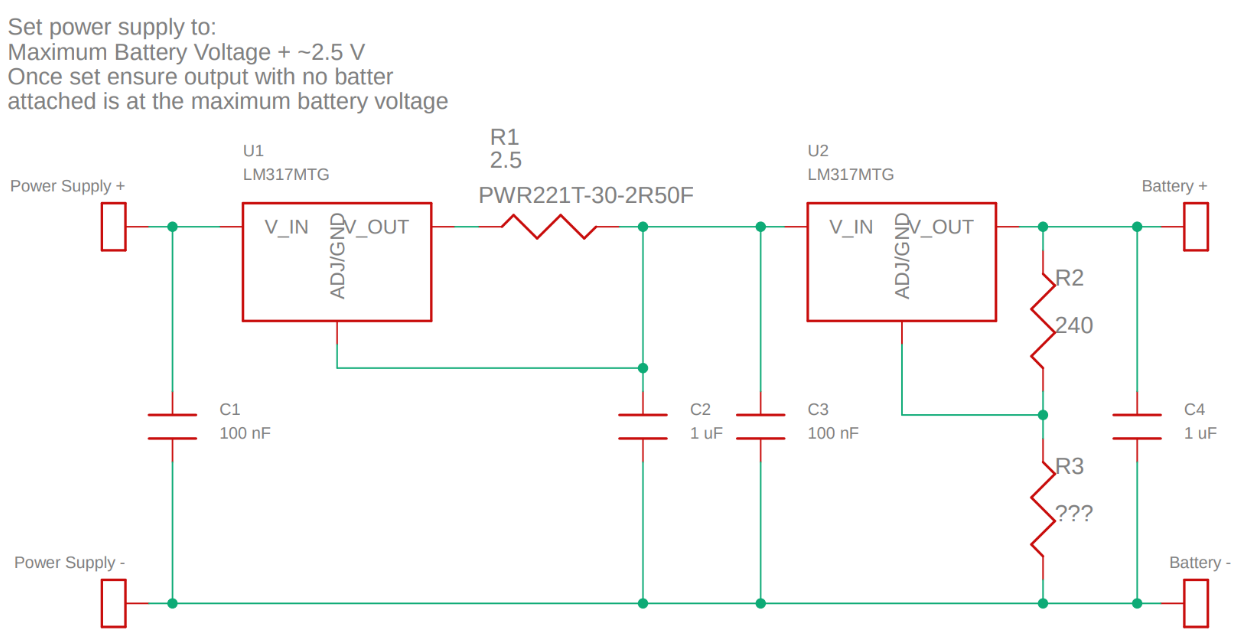

Figure 31 - Custom battery charger using 2 linear regulators, one in constant voltage and the other in constant current configurations.

Table 8 - R2 values for differing 18650 series cell counts.

Cells in Pack	Power Supply Voltage Minimum (V)	R2
1 Cell (4.2 V)	6.7	562 Ω
2 Cells (8.4 V)	10.9	1.37 kΩ
3 Cells (12.6 V)	15.1	2.15 kΩ
4 Cells (16.8 V)	19.3	2.98 kΩ

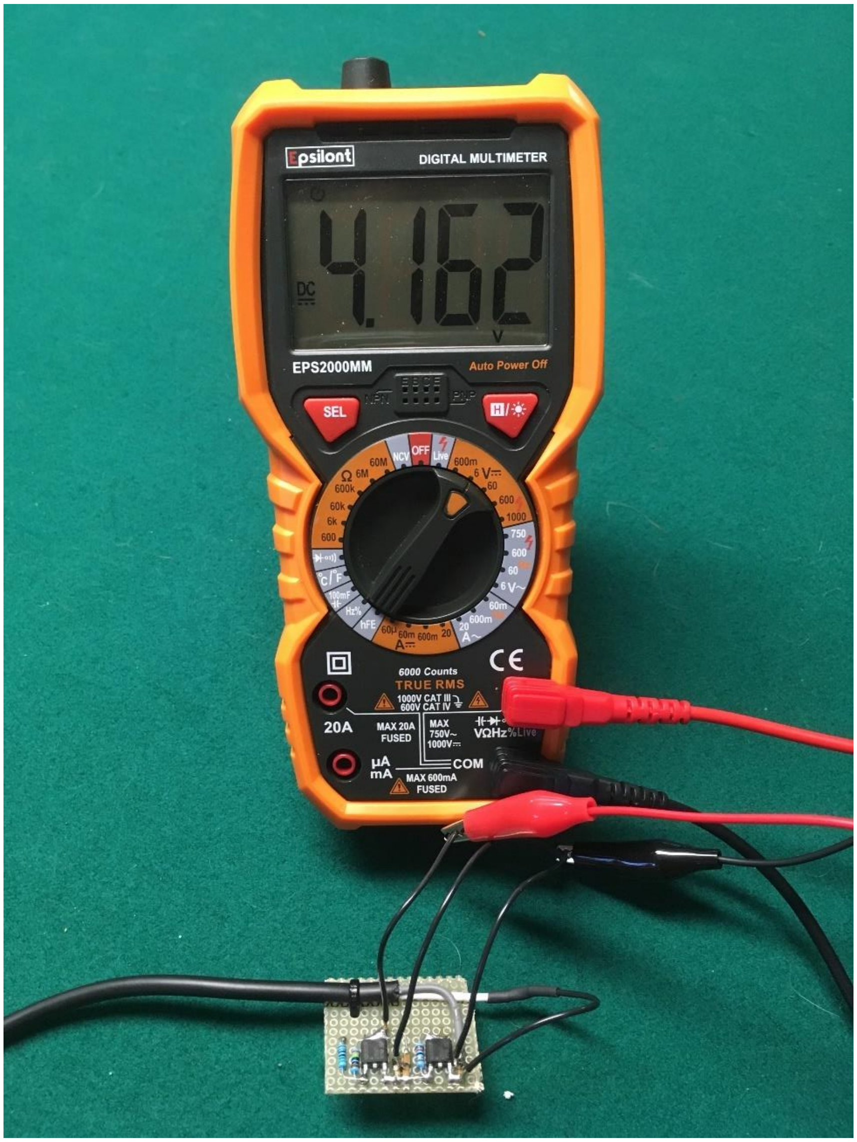

Figure 32 - Prototype board (not using listed part numbers but same functional parts) set up in a 1 cell configuration showing output voltage. A 19.5 V DC wall outlet converter is wired in from the left to provide power, allowing the board to be reconfigured to up to 4 cell charging (possible due to power because current was lowered to 100 mA). Total build time was around 1 hour.

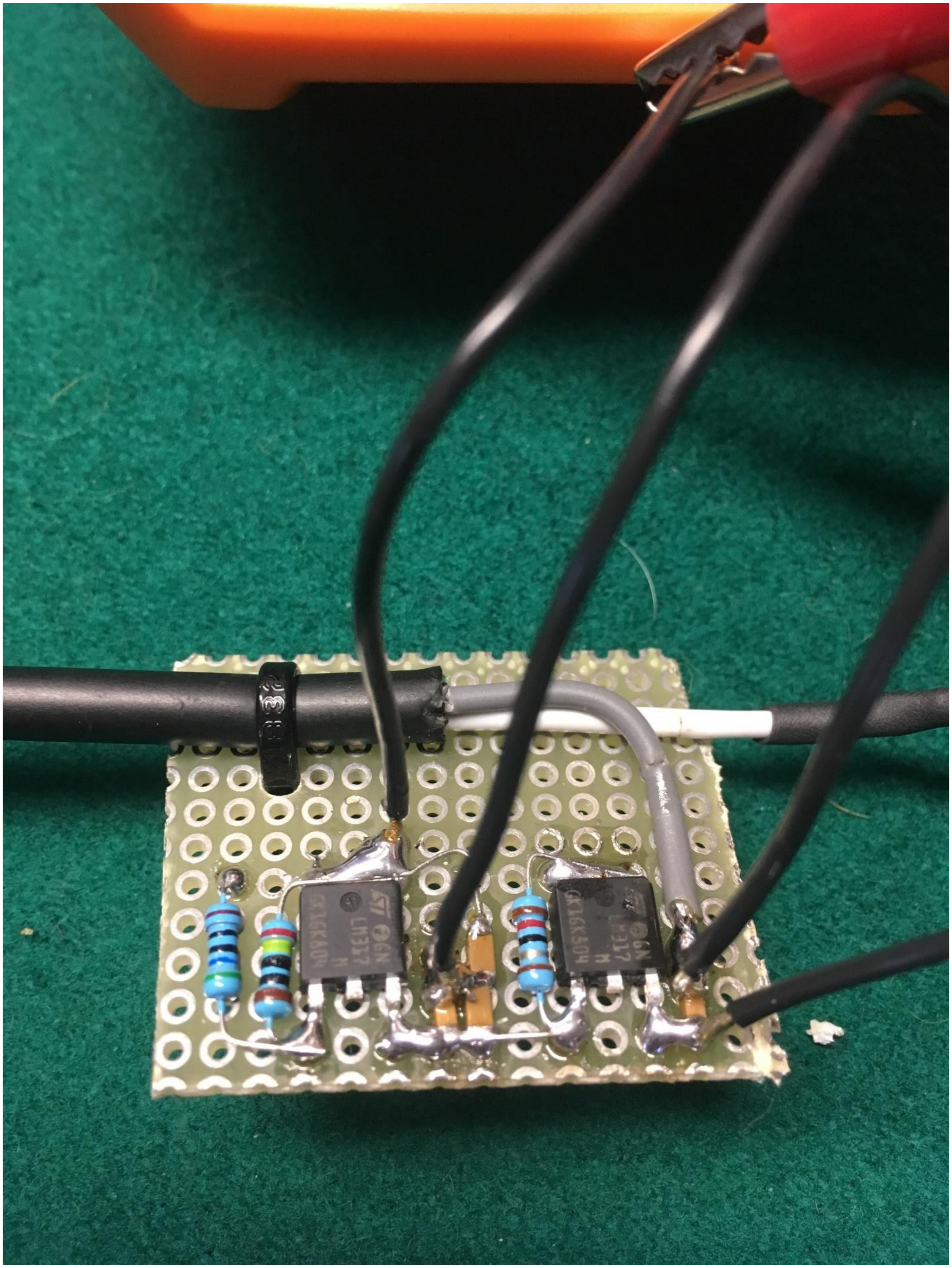

Figure 33 - Closeup of prototype board.

Payload Activation from Pi

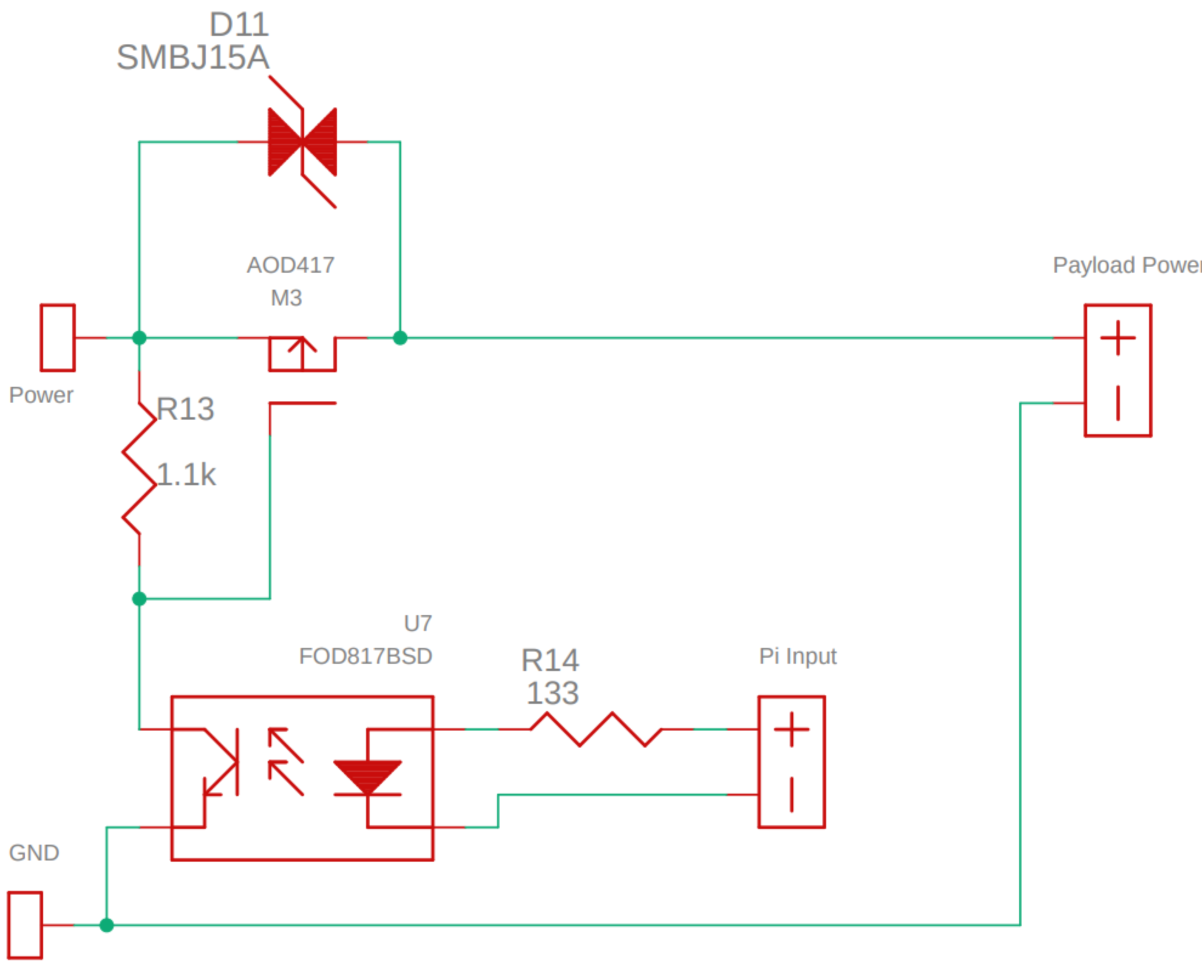

Figure 34 - Method for activating a payload from the control of a Pi (or Arduino etc.)

The circuit shown in Figure 34 will allow a processor to control when power flows to a payload. The circuit functions in the same way the as the power activation circuit for small satellites as previously described, but instead of being triggered by voltage it is turned on by a logic input from a processor. For this example, the Pi input was 3.3 V, so R14 was chosen as 133 to limit the input current to the forward current into the optocoupler to ~20 mA (To find this take the input voltage and subtract the forward LED drop found in the optocoupler datasheet then divide by the desired current to find the resistors, for a 5 V logic input a 191 Ω resistor should be used). R13 should limit the current through the BJT of the optocoupler to safe currents. D11 is a protection diode like D4.

Payload Converter Filters

If the output of the payload converters is too noisy for the system and using a converter to boost the voltage higher, then using a linear regulator to reach the desired output voltage, as discussed previously, is undesirable, then filters will need to be used. Capacitors are the most basic filters, sometimes adding capacitance to the output of the converter can greatly help with noise. If a 1 µF capacitor is used on the output I would recommend adding a 10 µF in parallel for example and observing the noise or doubling up on 1 µF capacitors in parallel. The most common filter for power supply noise reduction is the Pi Filter. To test the effectiveness of this filter, observe the voltage before filtering on an oscilloscope, then add the filter and re-observe. If the noise is still too high it is possible to cascade Pi filters, however their effectiveness will begin to decrease. Figure 35 shows a Pi Filter. Determining the values to this filter can be tricky but 10 - 100 µH and 1 – 10 µF is a good starting point (order a couple values to test).

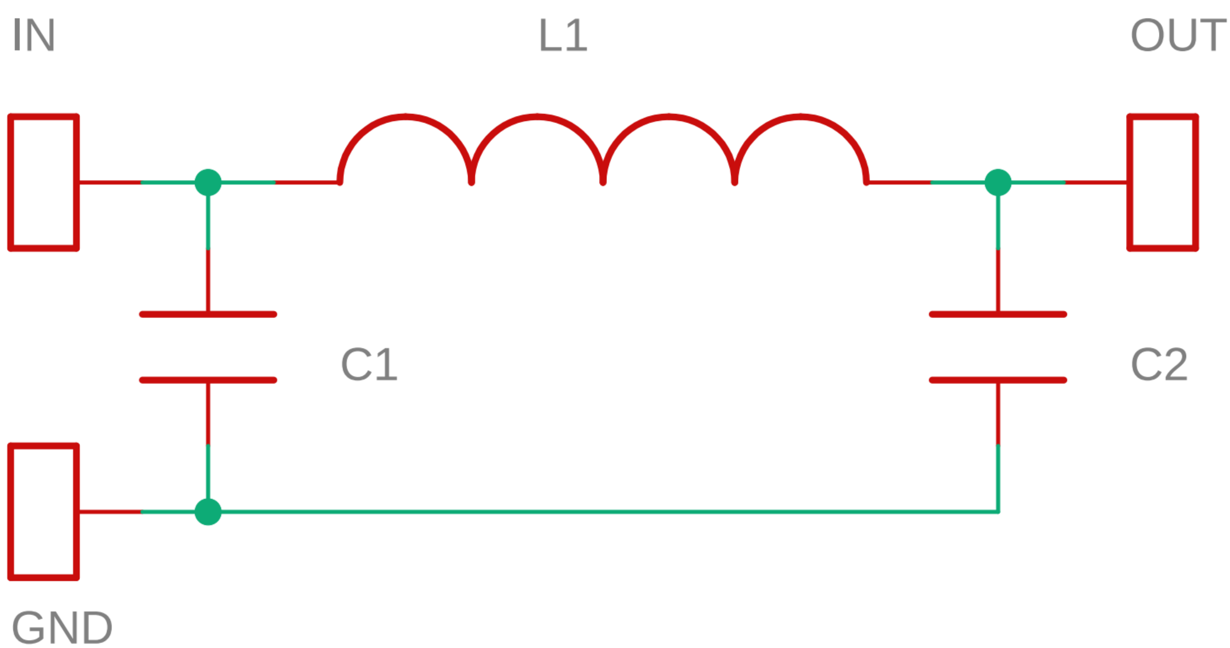

Figure 35 - Pi Filter