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Huge Power Demand...Itsy-Bitsy Satellite: Solving the CubeSat Power Paradox

Craig Clark
Clyde Space Ltd
West of Scotland Science Park, Glasgow G20 0SP; +44 141 946 4440
craig.clark@clyde-space.com

ABSTRACT

Payload developers are becoming increasingly aware of the benefits that very small spacecraft, such as CubeSats, can offer for fast turn-around, low-cost missions. This increased interest in CubeSats for commercial, military and scientific missions is resulting in some exciting and challenging applications for this miniature satellite platform. The challenges include the ability to realize fine attitude control, the need to overcome the physical challenge of payload accommodation, but most consistently, is the capacity to generate and store enough power on-board the spacecraft to fulfill the mission requirements. So how do we overcome the power problem on CubeSats?

Power provision on board any spacecraft is not simply about how large the solar arrays are - size helps, but it isn't everything - it is the configuration of the solar arrays, the efficiency and effectiveness of the power management system and the choice of battery technology that all combine to provide a power system that packs a punch on a tiny satellite. Through the use of a custom designed, CubeSat power analysis design tool, this paper evaluates some common and novel solar array configurations for typical CubeSat orbits. This included both body mounted and deployed solar panel approaches

Having been asked recently, ‘Can I fit my LiDAR on a CubeSat platform?’, it is clear that power provision on CubeSats will continue to be a bottle neck for new CubeSat applications. This paper shows that CubeSats can provide surprisingly respectable peak and orbit average power levels when configured appropriately.

INTRODUCTION

CubeSats are becoming more popular with the space community, with users from the commercial, military and scientific sectors looking to see if CubeSats can meet their growing needs for the use of space to gather data. CubeSats are ideal for fast turn-around, low-cost missions, but the increase in interest in the platform is also highlighting some of the limitations of this class of spacecraft. These limitations currently include attitude control, payload volume and mass restrictions and power generation and storage.

One of great things about CubeSats is that these challenges are being tackled by universities and organizations across the globe, so they will eventually be overcome. In the meantime, this paper will look at what is possible in terms of power generation on board a 3U CubeSat today. Having been in the business of designing and building power systems for small satellites for 16 years, the author thinks that prospective CubeSat users will be pleasantly surprised at the amount of orbit average power is possible from a CubeSat when using deployable solar panels in various configurations and using an appropriate power management system.

YOUR BASIC 1U CUBESAT POWER SYSTEM

Life is easy with a 1U CubeSat from a power perspective. No-one expects much power and, let’s face it you don’t get much power. Our 1U Electrical Power System (EPS) provides the interfaces and outputs necessary for a successful 1U CubeSat mission.

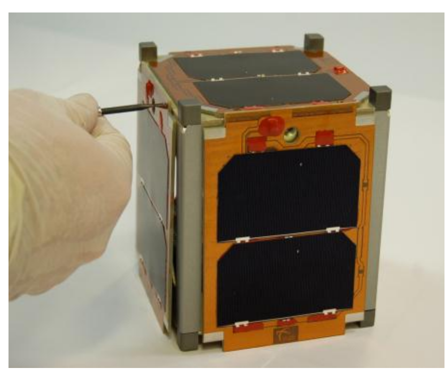


Figure 1 1U CubeSat

For instance, the typical Orbit Average Power (OAP) for a 1U CubeSat in a sun synchronous orbit with maximum eclipse should be no more than 1.9W (the panels are 100mm x 83mm, so even with high efficiency cells the maximum power per panel is about 2.1W). Assuming 10% albedo power is available, this figure would increase to 2.3W.

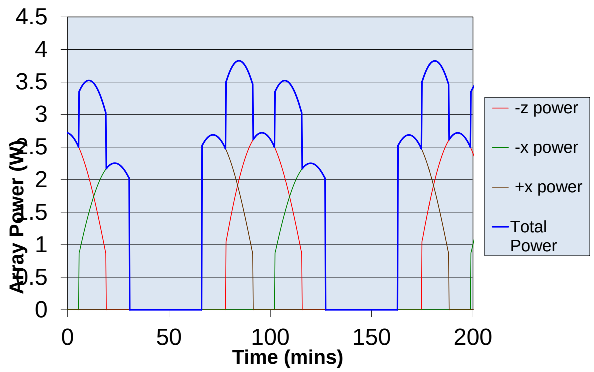


Figure 2 Typical Power Profile of a 1U CubeSat.

To make matters even more challenging, it isn't actually practical to just cover the spacecraft in as many solar cells as possible (a power guy's dream?), there are cut-outs, holes, antennas, etc. This all consumes precious solar cell area leaving many faces on a 1U CubeSat looking like those in the image below:

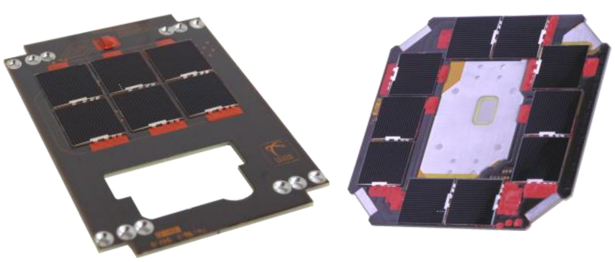


Figure 3 1U CubeSat Solar panels using 20mm x 20mm Spectrolab solar cells.

Even with deployable solar panels, there isn't much scope for generating sufficient power from a 1U CubeSat to do meaty operations or fly a payload that takes any kind of significant energy over a sustained period of time.

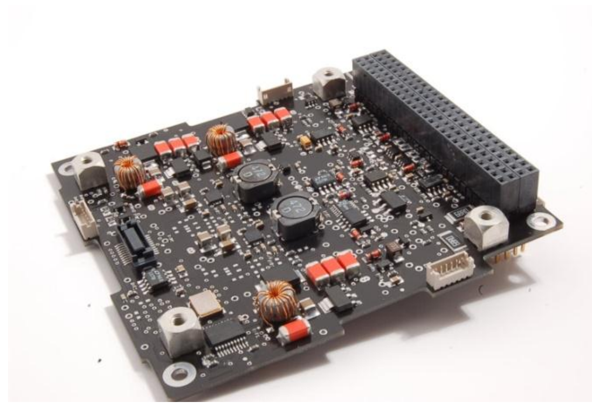
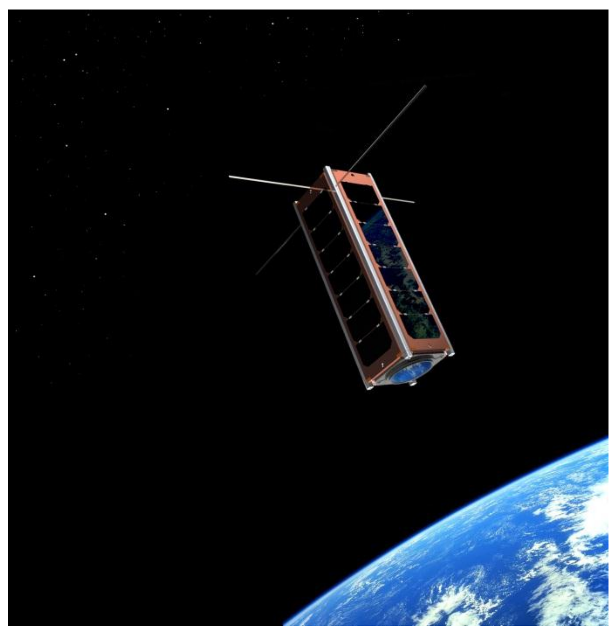


Figure 4 1U CubeSat EPS Does a good job, but is limited by the solar cell area of a 1U CubeSat.

This is one of the reasons that most missions flying challenging payloads opt for a 3U CubeSat bus. Due to its popularity, this paper is going to concentrate on having a look at configuring 3U CubeSats to get some impressive power figures using technologies available today.

YOUR BASIC 3U CUBESAT POWER SYSTEM



Similar to a 1U CubeSat, a basic 3U has six sides; however, four of the sides are 340mm tall instead of 110mm. This results in a typical power generation per panel of about 7.3W to 8.3W when using 7 series cells per panel. This means that we need to increase the power handling ability of the solar array interface. A basic 3U CubeSat EPS is configured as follows:

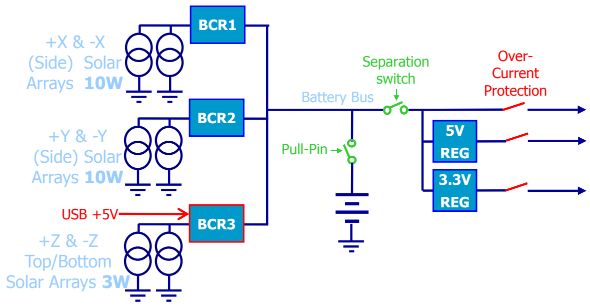


Figure 5 Block Diagram 3U CubeSat Power System

Solar Array Interface

With so little power available on a CubeSat, it is essential that the interface between the solar arrays and the rest of the spacecraft is optimized for both energy transfer efficiency and systems design. The BCR (BCR stands for Battery Charge Regulator) system ensures that the voltage of the array remains at its optimum value (Peak Power Point) when the power requirement is high, and leaves power in the solar panels when the power requirement is low (i.e. no longer tracks the peak power point.

Peak Power Tracking is implemented in hardware only, essentially by just two op-amps. By using such a low component count we are able to maintain high efficiency even at low power levels. It also means that the design is more reliable since there are fewer components that can fail. Furthermore, the power electronics of the BCR is designed such that the overall efficiency of the circuit is high at about 90%.

In order to make the maximum use of the system volume and mass, the BCR operates when connected to two solar panels, each on opposite sides of the spacecraft. This is possible because only one solar panel on the same axis can be in sunlight at any time. For a basic 3U CubeSat, this means that 3 BCRs interface to SIX solar arrays.

Power Conditioning Module

The Power Conditioning Module (PCM) consists of two dc-dc converters; one regulating its output to 5V and the other 3.3V. Each converter can provide up to 4.5A at an efficiency of 95-98%. Regulating and distributing numerous voltages to the rest of the spacecraft makes the CubeSat EPS a ‘Centralized’ power system; due to the small physical size of CubeSats, this is the most efficient method of supplying standard regulated voltages.

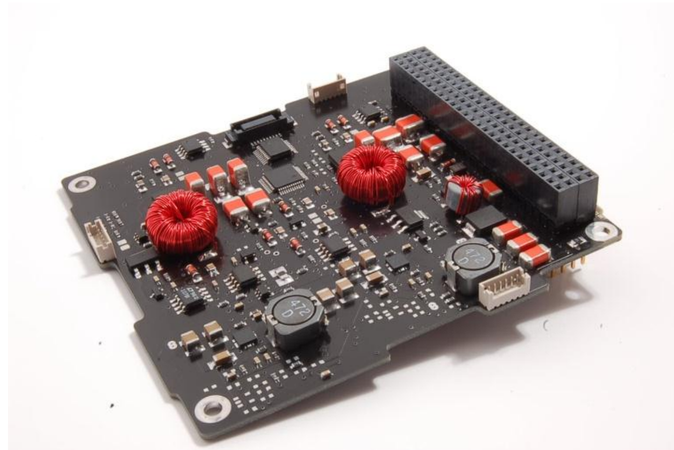


Figure 6 3U CubeSat EPS

The PCM provides additional protection features that are essential for protection of the spacecraft from anomalous operational modes. The PCM ‘unloading function’ disables the output of the 5V and 3.3V converters once the battery voltage reaches its minimum acceptable level (i.e. close to zero capacity).

Over Current Protection

As previously mentioned, three power buses are provided to the main CubeSat header. These buses are protected against over-current in order to ensure that the power system survives a short circuit event down-stream of the power system. The protection circuit continuously tries to remake the connection to the bus in the event of an over-current condition - Given that most CubeSats are single string with no redundancy; this was determined to be the best approach.

Another added feature of this system is that it is impossible to fully turn-off any of the power buses. However, there is a command line that will cycle the power buses; useful when a power reset is required for one of the on-board systems.

Digital Interface

The power system has a small microcontroller to provide a serial bus interface using the I2C standard through which system telemetry data can be monitored the power bus reset command can be sent.

Due to the high number of telemetry channels on the power system, there is a need to interface the signals to the microcontroller via a 32 channel analogue multiplexer.

Solar Panels for a 3U

We typically use the Spectrolab UTJ cells for our satellite solar panels, and we as much as possible for the large area cells as these are the most cost effective for the missions we supply to. The UTJ solar cells have dimensions of 39.70mm x 69.11mm. They are GaInP2/GaAs/Ge multi-junction cells, have an efficiency of about 29% and, equally as important for CubeSats have terminal voltage of over 2V (at least double that of other typical cell technologies).

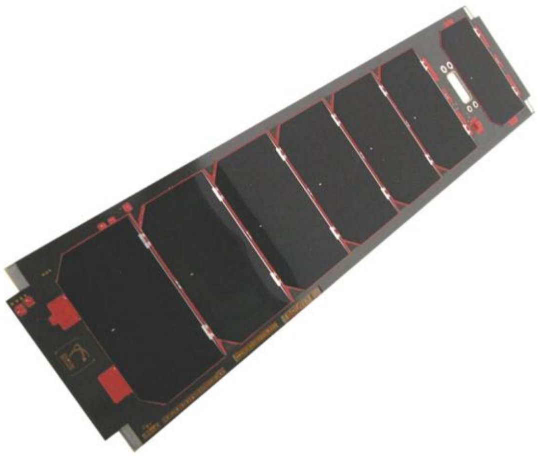


Figure 7 1U Clyde Space 3U CubeSat Solar Array

Batteries for a 3U

At Clyde Space we have in-house expertise in the use of commercial Lithium Polymer cells in space, and we have developed a screening program for the use of our cells on space missions. The cells that we use have dimensions of 59mm x 37mm x 5mm, and are the perfect size for a slim 2 cell CubeSat battery. Furthermore, 2 lithium ion cells in series provide an ideal voltage of 7V - 8.4V, making it simple to efficiently generate the 5V and 3.3V buses using step-down converters.

The battery is scalable; integrated two or four cell battery (2s1p or 2s2p) for 1U CubeSats and a separate scalable battery for up to 2s3p per battery unit. Each two cell lithium polymer battery string provides a nominal BOL capacity of 2 x 3.7V x 1.25Ah = 9.25Whrs. Being a Lithium ion based technology the battery also has an excellent return factor, with little energy being lost in the battery due to self-discharge and internal losses.

Figure 8 2s1p CubeSat remote battery board.

For a standard 3-axis controlled, nadir pointing, 3U CubeSat in a sun synchronous orbit, with an LTAN of 12am (essentially with worst case eclipse) and the use of a Clyde Space EPS, the orbit average power from the panels, taking losses and errors into account, is approximately 4.5W. The solar panel power profile for a typical orbit is shown below, clearly showing that the cold solar panel, illuminated just after leaving eclipse, provide the peak power from the solar panels of just above 9W. Assuming 10% albedo power is available, orbit average power would increase to 4.9W.

Typical Power Generation

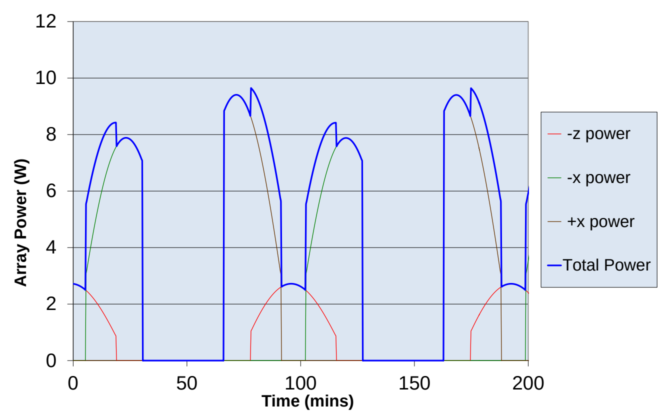


Figure 9 Power profile for standard 3U CubeSat.

POWER FROM DEPLOYED SOLAR PANEL CONFIGURATIONS

CubeSats are successful because they provide an agreed standard. However, the need for more power from a 3U platform is pushing the power system configuration towards a need for even more flexibility to configuration. For this reason Clyde Space developed our ‘FleXU EPS’. This EPS is modular, scalable and designed to cope with a number of solar panel configurations.

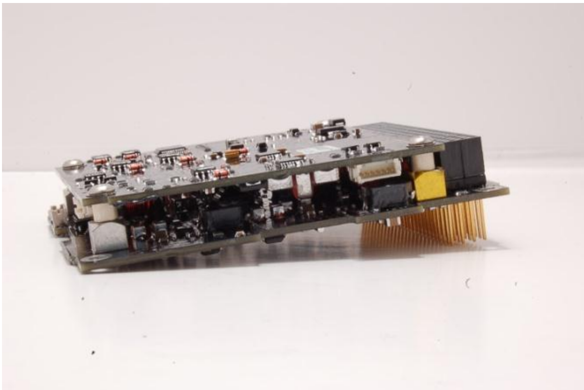


Figure 10 FleXU EPS for CubeSats with more solar panels

To test out this modularity, and also to demonstrate just how much orbit average power can be generated on a CubeSat, we have analyzed three different deployed solar panel configurations. The rest are detailed in the following sections:

Standard 12 Solar Panel Deployment

Figure 11 Standard 12 Solar Panel Deployment

This deployed solar panel configuration has four 3U body mounted solar panels, and four, double-sided, deployed solar panels at 135 degrees to the main spacecraft body. In this configuration, it is possible to achieve a relatively steady power delivery from the solar panels over an orbit. This solar panel configuration has been proposed for several missions, including the proposed developments for the National Reconnaissance Office (NRO). In this analysis, the velocity vector is through one of the large body mounted side panel.

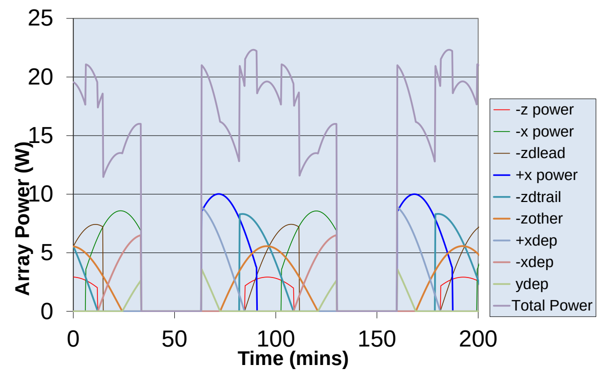


Figure 12 Power Analysis for Standard 12 Solar Panel Deployment

Taking the same constraints as for the standard 3U (3-axis controlled, nadir pointing, sun synchronous orbit, an LTAN of 12am and the use of a Clyde Space EPS), the orbit average power from the panels, taking losses and errors into account, is approximately 11.7W. Assuming 10% albedo power is available, orbit average power would increase to 12.9W. As can be seen from Figure 12, the total power profile is fairly constant, changing between 15W to about 22W peak. The simulation also accounts for the shadowing effects of the deployed panels on the other solar panels. Temperature effects on the solar cell are also accounted for.

This is a very useful power level for such a small spacecraft and is comparable with the orbit average power levels of 30-50kg microsatellites with body mounted solar panels.

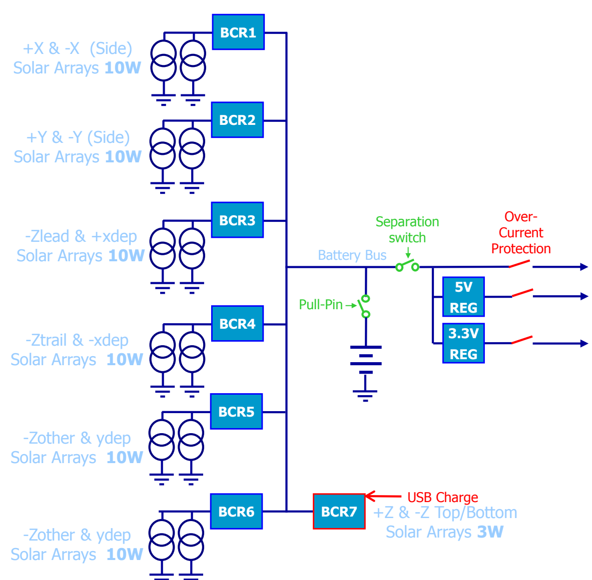


Figure 13 FleXU EPS Configuration 2

The FleXU EPS currently has two variants, one can interface to SIX 10W solar panel pairs and a 3W solar panel pair and the other can interface to FOUR 10W solar panel pairs and TWO 3W solar panel pairs. For this deployed solar panel configuration, the FleXU EPS with SIX 10W BCRs is required. Figure 13 demonstrates how each of the solar panels connect to the power system and then supply this power to the spacecraft bus. This system can easily manage the 20W+ instantaneous power from the solar panels, as it is still only one third of the maximum 63W de-rated, power handling capability.

Dart Configuration with Skirt Solar Panel Deployment

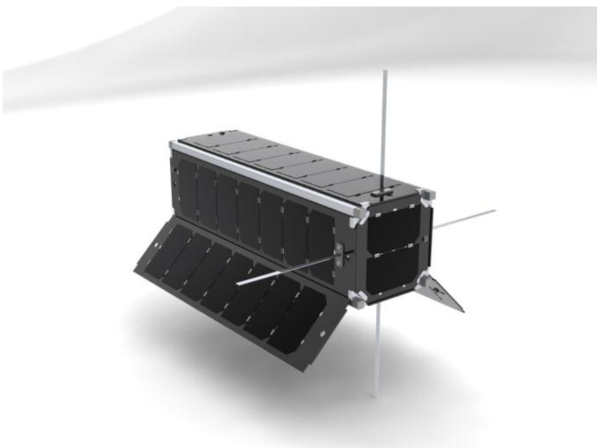


Figure 14 Dart Configuration with Skirt Solar Panel Deployment

This configuration is probably better suited to a non-sun-synchronous orbit, where the solar illumination angle is not fixed and a consistent power profile can still be achieved. It is still useful to see how the configuration performs within the constraints of this worst case power analysis. In this configuration, the spacecraft velocity vector is through the small panel (still defined as the x-axis in the graph).

Again, with the same orbit and attitude constraints, the orbit average power from the panels, taking losses and errors into account, is approximately 6.6W (7.3W assuming 10% albedo power). The solar panel power profile for a typical orbit is shown below, clearly showing that the cold solar panel, illuminated just after leaving eclipse, provide the peak power from the solar panels is close to 20W.

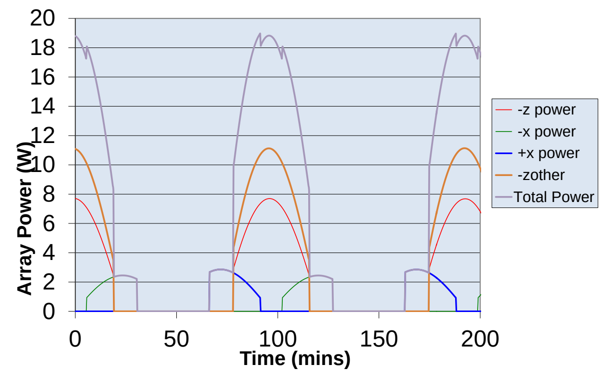


Figure 15 Power Profile for Dart Configuration with Skirt Solar Panel Deployment

This still represents a significant improvement on the standard body-mounted 3U configuration, and could be useful for missions using the 'long' side of the 3U platform for Earth facing payloads. It may also be possible to deploy two panels into a wing to increase the power further.

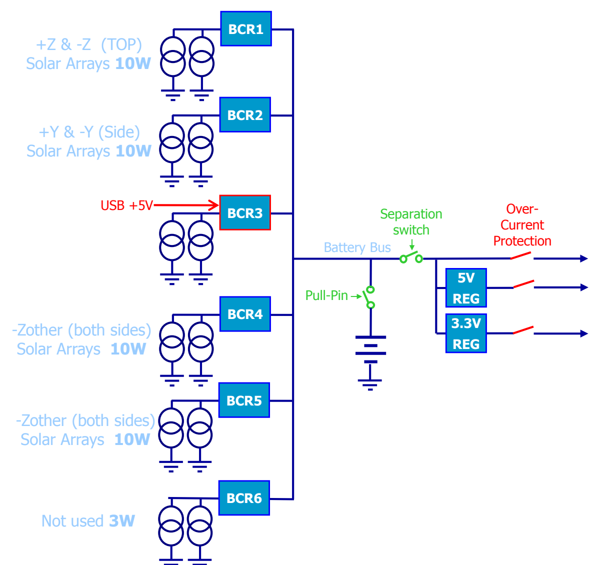


Figure 16 FleXU EPS Configuration 1

For this solar panel configuration, it is possible to use configuration 1 of the FleXU EPS. The solar panels are connected to the EPS as shown in Figure 16. The BCRs are rated to ensure that they can also handle any albedo power in addition to power as a result of direct solar illumination. This is particularly relevant for this solar panel configuration.

Side and Top Deployed Solar Panel Configuration

Figure 17 Side and Top Deployed Solar Panel Configuration

Aiming to make the most of both solar illumination over the poles and over the equator, this configuration deploys solar panels along the length of the 3U structure to face in the direction of the velocity vector; as will all the deployed solar panels in this paper, they are double sided, this is to catch illumination over both poles. The top-deployed solar panels are again at 135˚ to the spacecraft body, and these act to capture illumination as the spacecraft comes out of eclipse and also over the equator. The spacecraft velocity vector is through the corner (runner) of the structure (the front facing runner in Figure 17.

Again, with the same orbit and attitude constraints, the orbit average power from the panels, taking losses and errors into account, is approximately 18.9W. The solar panel power profile for a typical orbit is shown below, clearly showing that the cold solar panel, illuminated just after leaving eclipse, provide the peak power from the solar panels of just above 9W. Assuming 10% albedo power is available, orbit average power would increase to 20.8W.

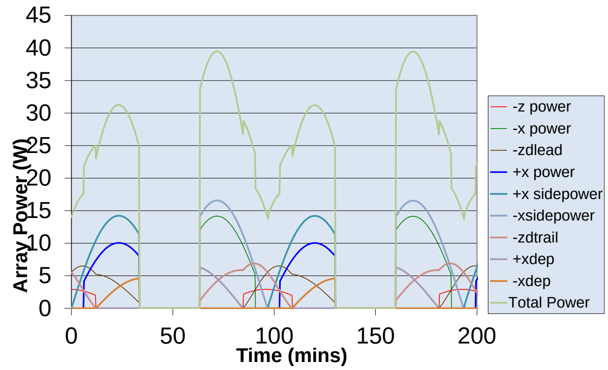


Figure 18 Power Profile for Side and Top Deployed Solar Panel Configuration

This power generation ability is significant for a <5kg spacecraft and starts to enable the accommodation of payloads that require that bit extra power in order to maximize the payload return. This would also enable high power downlinks, better link budgets and more power computing to be performed on the CubeSat. There is also scope to increase the power generation over the equator by deploying two further top-deployed panels and/or adjusting the angle of deployment from 135˚ to an angle closer to 90˚ (i.e. orthogonal to the Sun when over the equator).

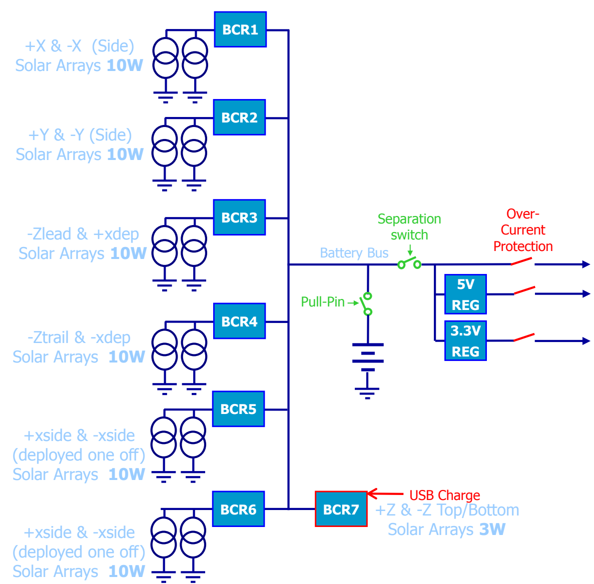


Figure 19 FleXU EPS configuration 2 for side and top deployed panels.

Again, the FleXU EPS is able to interface to all of the solar panels without exceeding the power ratings of the BCRs. At some points in the orbit, the peak power from the solar panels reaches 40W, but the EPS is also well within its power handling capability. Modifications would have to be made to the FleXU EPS if additional deployable panels were added, but because of the modularity of the system, this wouldn't be difficult to achieve.

PEAK POWER SUPPLY FROM THE POWER BUS

Now that all of this power has been used to charge the battery on the spacecraft, how much instantaneous power can be supplied to the rest of the spacecraft? The answer is that this relies on a number of other factors.

For instance, the capacity of the battery (if using lithium ion) limits the maximum safe discharge current to a peak of 2C (the average discharge and charge currents should be no more than C/2). If a 30Whr battery is on the spacecraft, then 60W can be supplied. If more power is required, then a bigger battery must be flown.

Another main limitation is the connections from the power system to the rest of the spacecraft. Most connectors that are used on CubeSats just cannot handle much current; 2-3A is typical of the maximum permissible current through connector pins. Through the use of more appropriate connectors, the 5V and 3.3V circuits can supply up to 4.5A at over 95% efficiency without any circuit modifications.

In short, peak power and current can be as much as you need, but it is still necessary to treat high current requirements individually to ensure that the overall system is capable of handling the currents safely and reliably.

CONCLUSION

The power generation capability on the most popular CubeSat platform size, the 3U, can be significantly improved through the use of deployed solar panels. What's more, the components and power management systems that are required to enable these configurations are already available today.

The use of this technology on a 3U platform provides the ability to achieve orbit average power levels that have been more akin with much larger small satellite platforms. These power levels have the potential to enable advances in CubeSat performance including higher downlink speeds, better attitude control, higher power computing and more ambitious payload types.

The examples described in this paper are based on a nadir pointing, 3-axis stabilized 3U CubeSat in a sun-synchronous orbit with an LTAN of 12 noon. It is noted that, to achieve similar or better orbit average power levels in different orbits, the solar panel deployment configuration may need to be altered, but the simulations do prove that it is certainly possible to overcome on-board power provision for more demanding payloads through careful consideration of how the solar panels are configured.

The paper also demonstrated the importance of using the correct electrical power system configuration. The FlexU EPS is only able to maximize the power from the panels due to having a dedicated BCR per solar panel opposite pair. This means that the BCR can track the specific solar panel characteristic that it is connected to. The characteristic of a solar panel changes considerably with temperature over an orbit, and without this configuration significantly less power would be generated by the solar panels.

Finally, for peak power delivery, it is noted that the ability to supply large currents is available. It is, however, still necessary to treat specific high current needs on an individual basis due to systems considerations relating to the internal interconnectivity of the spacecraft and the sizing of the on-board battery.

In conclusion, power on-board a CubeSat seems to be one of the areas that is less of a challenge than one might think. Now, hands up who wants to solve the attitude control challenge….

ACKNOWLEDGEMENTS

The author thanks the team at Clyde Space, in particular Dominic Reilly for the excellent 3D models of the CubeSat solar panel configurations – they look so real!

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