THE DESIGN OF A POWER SYSTEM FOR THE PETSAT MODULAR SMALL SPACECRAFT BUS

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ABSTRACT

There is considerable interest in the benefits of having a modular spacecraft where it is possible to construct a satellite using a number of modules with identical mechanical and electrical interfaces, but with each performing a specific function to achieve the required platform specification. In recent years, steps have been made towards modular spacecraft becoming a reality and the concept is due to be demonstrated in-orbit later this year with the first flight of the PETSAT spacecraft concept on the mission, SOHLA-2.

This paper describes the approach to the design of the SOHLA-2 power system. The approach is significant; PETSAT is an excellent example of a modular approach to spacecraft design. The PETSAT concept consists of a number of ‘Panel Modules', roughly the same size as a pizza box. The panels stack together in stowed configuration for launch, and unfold once in orbit. Apart from being a very novel approach to spacecraft design and construction, this concept offers advantages in power generation as, once unfolded, there is significant surface area on which to mount solar cells for power generation.

The power system for PETSAT has been designed such that each Panel Module contains a power system that can either operate in isolation for the purpose of unit testing, or as part of a larger spacecraft power system once connected to other Panel Modules. When connected together, the power systems on each module share the energy from the solar arrays and the batteries. The approach to the design of the system has provided a simple solution to difficult problem.

1 INTRODUCTION

There is considerable interest in the benefits of having a modular spacecraft where it is possible to construct a satellite using a number of modules with identical mechanical and electrical interfaces, but with each performing a specific function to achieve the required platform specification. The concept is now due to be demonstrated in-orbit later this year with the first flight of the PETSAT spacecraft concept on the mission, SOHLA-2.

The task of developing modular spacecraft is being enabled further through the use of wireless technology on board spacecraft to communicate between subsystems and payloads; providing a step change in simplification of the integration process. However, the issue of power management and provision is still a significant challenge and is inherently not simple to solve.

Modules of differing functions require differing demand levels of power and may also be operated for only parts of the orbit. For small, modular spacecraft especially, it is not practical for each of the modules to generate and store their own power. Additionally, it is not practical to have a 'Power Module’ as this goes against the whole modular spacecraft philosophy as a power module would be mission specific. Therefore, this poses the issue of how to generate, store and make available power across the spacecraft

This paper describes the approach to the design of the SOHLA-2 power system. The PETSAT concept consists of a number of ‘Panel Modules', roughly the same size as a pizza box. The panels stack together in stowed configuration for launch, and unfold once in orbit.

The power system for PETSAT has been designed such that each Panel Module contains a power system that can either operate in isolation for the purpose of unit testing, or as part of a larger spacecraft power system once connected to other Panel Modules. The power system on each module provides several functions including solar array interfacing, battery charge management, lithium polymer battery, power distribution, regulated 5V and 12V buses, digital interface and an activation circuit. When connected together, the power systems on each module share the energy from the solar arrays and the batteries. The approach to the design of the system has provided a simple solution to difficult problem.

2 THE CONCEPT OF PETSAT

PETSAT is the first satellite concept of its kind. The design and construction of the spacecraft is highly novel. The innovation in this concept comes from its construction and the inherent modularity that the structure lends itself to. In an age where responsive and flexible spacecraft design is of great interest, the PETSAT concept is certainly a very appropriate solution to the need for modular spacecraft design.

PETSAT is constructed of several 'Functional Panels', each of which has a dedicated spacecraft 'subsystem' function or payload. Each Panel resembles a 'pizza-box' sized housing and is identical in size and shape to Panels irrespective of its function. The Panels are connected together using a reliable electrical and mechanical interface.

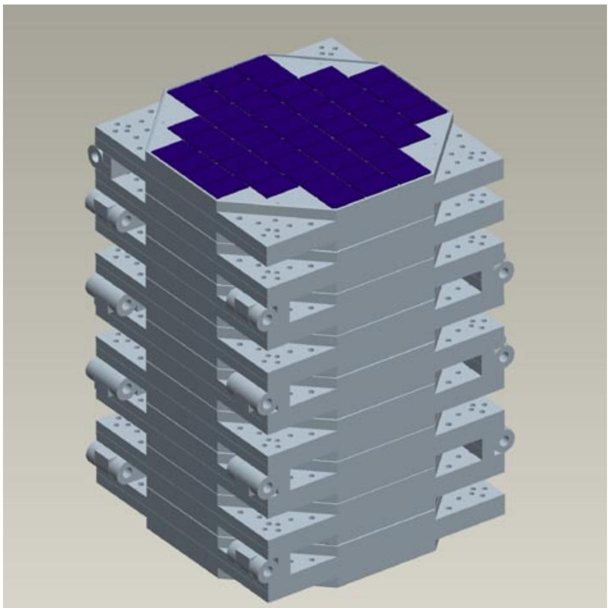

Figure 1 PETSAT in Stowed Configuration

The mechanical interface takes the form of a latching hinge that allows the spacecraft to be launched in a stack-like fashion (see *Figure 1*) and then deployed into its flight configuration once in orbit (*Figure 2*). The highly flexible nature of the spacecraft design means that this flight configuration can be a multitude of variations in order to either best serve the payload function, ensure maximum power delivery from the solar arrays, to provide gravity gradient stabilisation or to point different panel functions in different directions.

The PETSAT concept is intended to provide the opportunity to shorten the development cycle in the following way:

1) Each functional panel can be produced in mass quantity to reduce cost and improve reliability. The panels can then be held in stock ready for use when required.
2) When a mission is required, the spacecraft configuration required for the mission can be achieved by connecting the appropriate panels in the required quantity without much effort or test (given that the structure will have already been qualified).

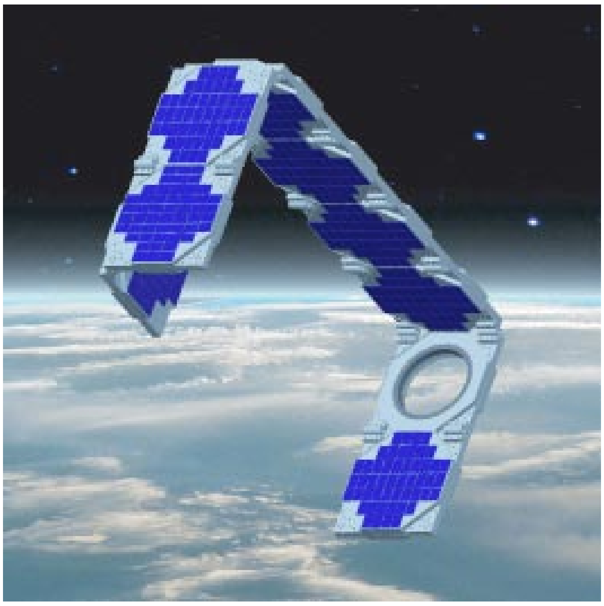

Figure 2 PETSAT in Deployed Configuration

The concept of PETSAT represents a highly capable spacecraft platform that has numerous applications. However, there are several challenges in the design of the spacecraft that must have appropriate solutions in order for the concept to work. These include effective and scalable communications between the Panels, distributed On-Board Data Handling and, importantly, a scalable approach to the power system design.

Astro-Technology SOHLA was responsible for the design and production of the first mission that would use the PETSAT concept. Clyde Space was tasked by Astro-Technology SOHLA with the design of power sub-system for SOHLA-2. This paper discusses the design and trade-offs of the power system that has been used on the SOHLA-2 mission.

3 POWER SYSTEM CHALLENGES FOR PETSAT

Given the modular nature of the PETSAT concept, the design of the power system must also be equally modular. The end design must allow for a spacecraft design that increases in power generation and storage capacity with each Panel that is added to the platform. Also, the design must be such that the power generated and stored on each panel is readily available for all of the Panels in the platform. There is also the issue of having a simple method of holding the spacecraft OFF whilst on the launch vehicle, which is a standard requirement for small spacecraft as they are generally 'piggy-backed' onto the launch of a larger spacecraft (or several small spacecraft).

Before Clyde Space was involved in the design of the power system, there was already a power system concept designed to address these very issues. This concept involved complex connection of power between Panels, using switches and relays, in order to 'top-up' the capacity of batteries on adjacent panels.

Although there was good reasoning behind the original power system concept, it was overly complex. Something that you quickly learn as a power systems engineer is that complexity and power systems are best kept apart. This has been the approach to power systems design by the Clyde Space team for many years with excellent success with no power system failures on over 20 small satellite missions. Therefore, the first task in the power system design was to remove the complexity and arrive at a system design that was simple, efficient and effective.

3.1 Power System Architecture Trade-offs

When evaluating the most suitable power system architecture for a mission, especially in the case of small satellite design where the constraints are often the budget and schedule, as much as the technical requirements, it is always necessary to take into account the entire mission, its environment and operating conditions. In the case of the PETSAT concept, this becomes doubly challenging given that the spacecraft must be designed such that it can be configured in a multitude of ways.

For the start of the project it was easy to rule out several power system architectures due to their inflexibility for this application:

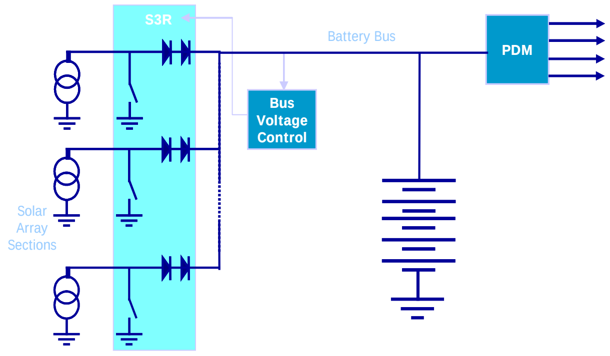

Figure 3 Direct Energy Transfer with Battery Bus

The **Battery Bus Direct Energy Transfer** system. This was ruled out for two main reasons;

1. It is highly probably that the Panels will incorporate solar arrays of differing characteristic, if not different technology. This would make it very difficult to match the solar arrays to the characteristic of the battery to ensure that as much energy is obtained from the panels as this topology will allow – it would also be highly likely that the solar arrays would be at different temperatures given the nature of the spacecraft design and illumination conditions in LEO, for instance.
2. There would be a need for a distributed analogue shunt of some sort to prevent the battery being over-charged – this was considered to be overly complex and would also cause thermal design issue in each panel.

Direct Energy Transfer Regulated Bus. This system is slightly more suitable to the spacecraft concept. This is because it is possible to have a battery charge and battery discharge regulator in each Panel, thus enabling each battery in each Panel to be independent in terms of state of charge and voltage to each other. However, there is still the problem with solar array temperature and compatibility with the regulated voltage, resulting in significant loss of potential energy from the solar arrays. There would also need to be some kind of shunt system in order to maintain the regulated bus voltage when the load on the bus is less than the available power from the solar arrays. In addition, the complexity in the control of the bus voltage across the panels, and the question of ease of scalability and modularity.

In fact, all power systems that require connection of the solar arrays onto a single bus on the spacecraft must be ruled out due to issues of complexity and flexibility.

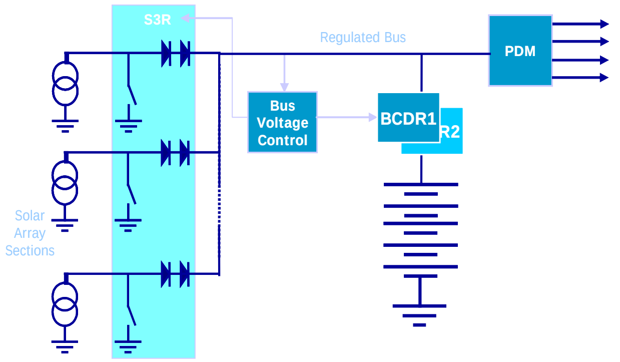

Figure 4 DET with Regulated Bus

It was quickly decided that the most appropriate system for the spacecraft was a **Maximum Power Point Tracker with a Battery Bus**. The reason why this system is ideal for PETSAT is because it is inherently modular, it offers significant flexibility in the type and characteristics of the solar arrays used on each panel, and it ensures that each solar array is operating at its optimum voltage in order to maximise power to the bus and take advantage of the large solar array area offered by the platform.

This power system architecture incorporates a Maximum Power Point Tracker (MPPT) between the solar arrays and the battery. As described by Alcindor [1] and Clark [2], this system works on the principle of charging the battery and supplying the bus during sunlight while setting the array voltage at the maximum power point.

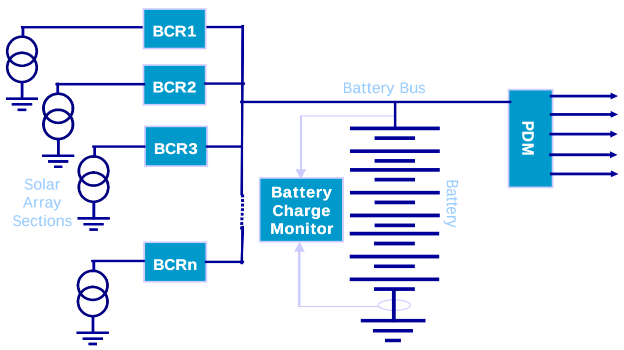

Figure 5 MPPT with Battery Bus

Once the battery has reached its end of charge state, the MPPT fixes the bus voltage at the end of charge voltage and allows the battery current to naturally taper off to a trickle charge level, at the same time backing off the power from the arrays. By backing off the arrays, there is no need for shunt regulators to dissipate unwanted solar array power. A block diagram of the topology is shown in *Figure 5*.

Although array power is maximised, there is an inefficiency associated in the MPPT system, and approximately 5-10% of the array power will be lost before it reaches the bus. This is because the MPPT system is a DC-DC converter, stepping down the array voltage to the bus voltage, and using a control loop to track the maximum power point. The efficiency of this converter is about 90-95%, and introduces the main inefficiency in the power system.

The benefits of this MPPT system are only realised in situations where the maximum power point (MPP) of the array is changing significantly whilst the spacecraft is in sunlight, and this is highly likely to be the case in many of the PETSAT configurations, especially for a mission to LEO.

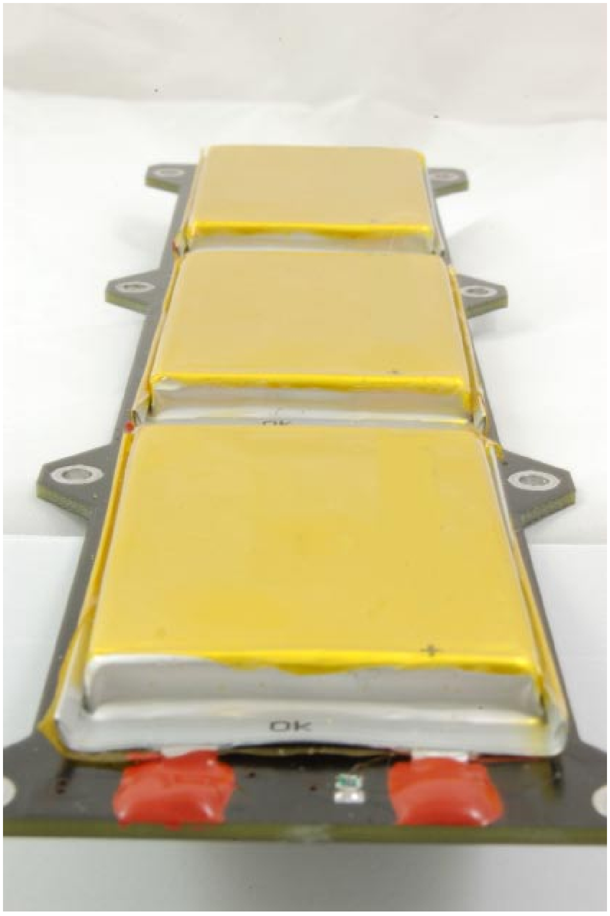

Figure 6 SOHLA-2 Lithium Polymer Battery String with built in cell balancing, over-current protection and thermostatically controlled heater.

During eclipse, energy is directly transferred from the battery to the bus. This is especially relevant for spacecraft in orbits that experience frequent or long duration eclipse, which is again a highly likely scenario for a PETSAT platform mission.

The relatively high efficiency of the solar array interface also means that the power system is still efficient if the spacecraft is launch into orbits where it would enjoy much longer periods of sunlight and or longer eclipse periods, this makes the MPPT system ideal for the PETSAT platform concept.

4 THE PETSAT POWER SYSTEM DESIGN

Figure 7 shows a block diagram of the PETSAT power system in its final configuration. As can be seen, there are TWO Battery Charge Regulators (BCRs) on each Panel. This is for the purpose of connecting the power system to solar arrays that are on opposite sides of the Panel Module (i.e. top and bottom of the module). In addition, each Panel Module houses a 15Whr, 12V lithium polymer battery, a voltage regulator that supplies +5V and +12V, and a number of commandable over-current protection switches in the Power Distribution Module (PDM). Each power system also has an I2C digital interface to provide telecommand and telemetry.

The spacecraft is held in an OFF state when on the launch vehicle by a relay that is connected in series with the power to the Voltage Regulator and the PDM. This relay is held in the OPEN state when a plunger switch on the launch interface of the spacecraft is depressed. Once deployed from the launch vehicle, the plunger switch closes and the relays on each of the Panel Modules are commanded to a CLOSED state. This function is performed completely in analogue electronics for simplicity.

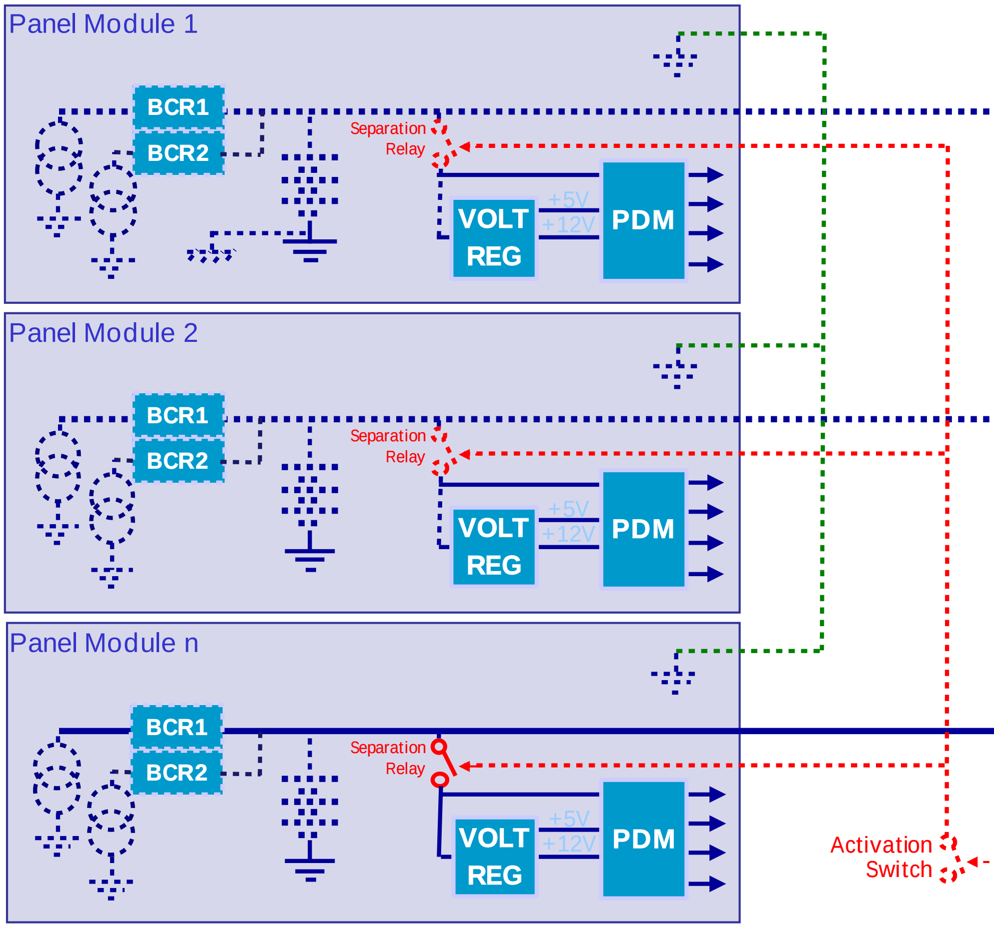

Figure 7 PETSAT/SOHLA-2 Power System Simple Block Diagram

As can be seen in the block diagram, the Battery strings in each of the Panel Modules are direct connected together. By doing this, we treat the battery on the spacecraft a single battery pack; again for simplicity and ease of power sharing between Panel Modules. The only potential draw back with doing this was that it may be possible that the spacecraft could experience a significant thermal gradient from one end of the spacecraft to the other once deployed. Generally, batteries do not like to have large thermal gradients across them as this may result in capacity imbalance.

In the case of SOHLA-2, we wanted to use the Clyde Space Lithium Polymer battery. From tests, it was known that the battery could handle a thermal gradient of 15°C or less without significantly impacting the life or performance of the battery. Therefore, it was then necessary to perform a thermal analysis of the spacecraft to determine whether it was likely that the spacecraft would see such gradients. Given the nature of the spacecraft design, this was not a simple task, however, it was determined that it was unlikely that the difference in temperature between the farthest Panels in the platform would exceed 15°C.

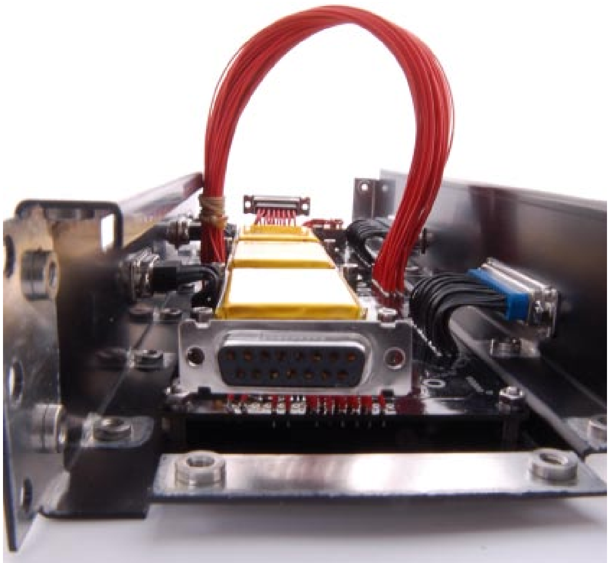

Figure 8 A Panel Module Power system and integrated battery

As an extra precaution, each battery in each Panel Module was designed with a built in, thermostatically controlled heater that would maintain a battery temperature of greater than 0°C. An image of the PETSAT battery is shown in *Figure 6*.

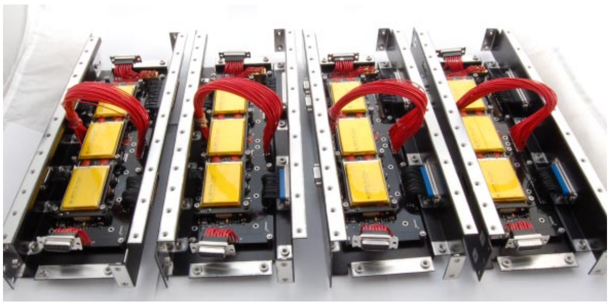

Figure 9 FOUR Identical SOHLA-2 Power Systems with Integrated battery

The ability to connect the batteries directly together on each Panel Module was critical to the success of this power system architecture. As a result of being able to do this, the power system becomes highly modular. A number of Panel Modules can be connected together and, as a result, the power generation and storage capacity of the spacecraft grows. The power system within each Panel Module was sized such that the increments by which the solar array area and battery increase the overall spacecraft capability was slightly more than the power required by a typically Panel. In addition, the Power system was designed such that it could operate when connected to *n* Panel Modules, or in isolation with no additional operational constraints or requirements.

Figure 8 and *Figure 9* show the Power System and battery in flight configuration. The housing shown in the image is integrated into the panel Module and provides mechanical stiffness, thermal stabilisation, radiation shielding and EMC screening from the rest of the Panel Module. All of the power system electronics are located on the PCB underneath the lithium polymer battery board. The lithium polymer battery is designed as a daughter board to the power system electronics and connects directly onto the power system electronics PCB; Battery telemetry is also routed through the power system I2C node.

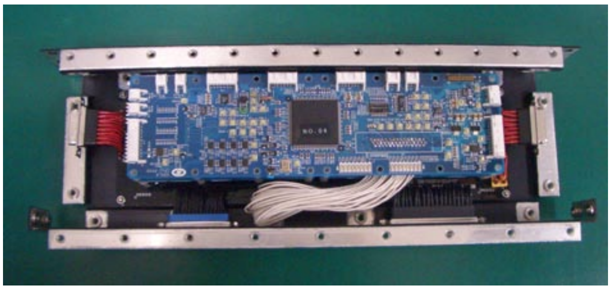

Figure 10 Power System integrated with the Panel Control Module Electronics

Figure 10 shows the power system electronics and battery integrated with the rest of the common electronics that is found in each Panel Module.

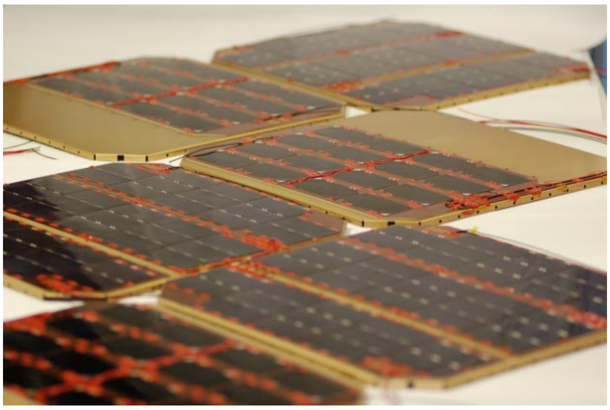

Figure 11 Silicon and High Efficiency GaAs solar arrays for SOHLA-2 from Clyde Space.

The image above is of the solar panels that were designed and built by Clyde Space for the SOHLA-2 project. For budget and schedule reasons, the solar arrays consist of both Triple junction GaAs solar cells and also space grade Silicon solar cells. Each of the solar arrays provides 16W of power when fully illuminated.

The nature of the power system electronics design means that it is possible to have solar panels with different characteristics connecting onto the same bus, because each solar panel is regulated independently.

5 CONCLUSIONS

The PETSAT spacecraft concept presents a highly innovative and practical design approach to providing a low-cost, modular and responsive spacecraft bus for many types of mission scenario. Clyde Space was delighted to be part of the PETSAT design team and to provide a highly modular and highly efficient power system that can both operate independently of other Panel Modules or when connected to an unlimited number of Panel Modules.

The highly modular nature of the PETSAT spacecraft bus called for the power system to reflect this requirement entirely. Clyde Space have design and produced the Power System Electronics, Battery and Solar Arrays in line with this design requirement and have also proven that it is possible to meet this requirement and still maintain a simple power system architecture, which is essential to reduce the risk of power system failure.

The launch of the SOHLA-2 spacecraft is hugely anticipated as it will herald what we expect will be the first of many spacecraft of this kind.

6 ACKNOWLEDGEMENTS

The Author would like to thank everyone involved on the SOHLA-2 mission design team, including all the staff and students from Astro-technology SOHLA and the University of Tokyo, and all of the design and assembly team for the power system at Clyde Space.

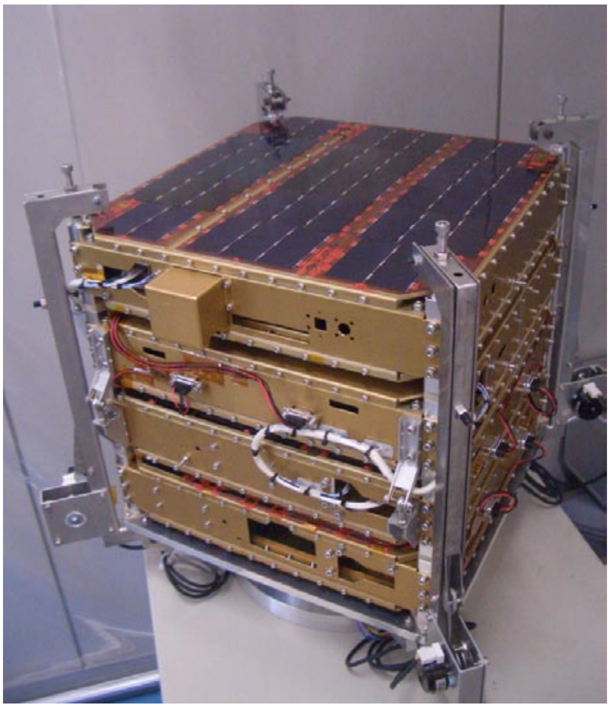

Figure 12 SOHLA-2 Spacecraft in Flight Configuration with FOUR Panel Modules

7 REFERENCES

[1] *'Non-Sequential Power Bus for LEO Applications'*, Peter Alcindor and Craig S. Clark, 7th European Space Power Conference, 9- 13 May 2005, Italy.

[2] *Commercial Nickel Cadmium Batteries for Space Use: A Proven Alternative for LEO Satellite Power Storage*, Craig S. Clark, Alan D. Hill and Martin Day, Surrey Satellite Technology Ltd., European Space Power Conference, Tarragona, Spain 21-25 August 1998.

[3] *'Power System Challenges for Small Satellite Missions'*, Craig S. Clark, 4S Symposium, Chia Laguna, Sardinia, 25 - 29 September 2006.

[4] *A Power System Design for a Microsatellite*, Dan Olsson, ESA/ESTeC, European Space Power Conference, Graz, Austria 23-27 August 1993.

[5] *'Evaluation of Lithium Polymer Technology for Small Satellite Applications'*, Craig Clark and Evelyne Simon, 21st Annual AIAA/USU Conference on Small Satellites, 13- 16 August 2007 Logan, UT

[6] *'A Novel Satellite Concept "Panel Extension Satellite (PETSAT)" Consisting of Plug-in, Modular, Functional Panels'*, Shinichi Nakasuka et al, 21st Annual AIAA/USU Conference on Small Satellites, 13-16 August 2007 Logan, UT