KYSAT-2 ELECTRICAL POWER SYSTEM DESIGN AND ANALYSIS

A Thesis

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In Partial Fulfillment

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Master of Science

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by

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Accepted by the faculty of the College of Science and Technology, Morehead State University, in partial fulfillment of the requirements for the Master of Science.

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Brandon Molton
Morehead State University, 2013

Director of Thesis: Dr. Benjamin K. Malphrus

In 2012, Kentucky Space, LLC was offered the opportunity to design KYSat-2, a CubeSat mission which utilizes an experimental stellar-tracking camera system to test its effectiveness of determining the spacecraft's attitude while on orbit. Kentucky Space contracted Morehead State University to design the electrical power system (EPS) which will handle all power generation and power management and distribution to each of the KYSat-2 subsystems, including the flight computer, communications systems, and the experimental payload itself. This decision came as a result of the success of Morehead State's previous CubeSat mission, CXBN, which utilized a custom built power system and successfully launched in 2011.

For the KYSat-2 EPS to be successful, it was important to design a system which was efficient enough to handle the power limitations of the space environment and robust enough to handle the challenges of powering a spacecraft on orbit. The system must be developed with a positive power budget, generating and storing more power than will be stored by KYSat-2 over mission lifetime. To accomplish this goal, the use of deployable solar panels has been utilized to double the usable surface area of the satellite for power generation, effectively doubling the usable power of the satellite system on orbit.

The KYSat-2 EPS includes of set of gold plated deployable solar panels utilizing solar cells with a 26% efficiency. Power generated by this system is fed into a shunt regulator circuit which regulates the voltage generated to be stored in a 3-cell series battery pack. Stored powered is maintained using a balancing circuit which increases the efficiency and lifetime of the cells on-orbit. Power distribution includes raw battery voltage, four high-power outputs (two 5V and two 3.3 V) and a low-noise, low power 3.3V output for use with noise sensitive devices, such as microcontrollers. The solar panel deployment system utilizes the nichrome wire which draws current directly from the battery pack which a solid state relay receives logic-high signal. This nichrome wire, while under current, cuts a nylon wire which holds the solar panels in a stowed state prior to deployment on orbit. All logic control, current/voltage measurement, and commanding/communications is handled through the use of a Texas Instruments MSP430 microcontroller over UART serial communications.

Results of the completed EPS demonstrated high-power output efficiencies approaching 90% under the highest anticipated loads while on orbit. They showed maximum noise levels of approximately +/- 41.30 mV at 83.10 MHz under maximum load. The low-noise 3.3V outputs displayed very little noise, however, this came at the cost of efficiency showing only 26% efficiency at the outputs when under maximum load. The EPS has been successfully integrated with other KYSat-2 subsystems including the spacecraft flight computer, in which the flight computer was able to communicate with the EPS and carry out its functions while functioning solely off the power distributed by the power system. Finally, testing on the solar panels show that a positive voltage margin was achieved when under light and the deployment system was able to cut the nylon wire completely under control by the EPS.

Accepted by:	Dr. Benjamin K. Malphrus, Chair
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CHAPTER I

INTRODUCTION

1.1 General Area of Concern

Within the last decade, the state of Kentucky has made a push for increasing its presence in the space industry through various initiatives across a range of local academic and business institutions. Kentucky Space, LLC has made large investments toward small satellite technologies which are researched, developed, and built and operated primarily by state universities in Kentucky, including many primary contributions by Morehead State University. Morehead State's contributions, ranging from independent full CubeSat missions and to partnerships with the University of Rome, Italy, the United States Department of Defense, and major aerospace companies have allowed Morehead State University's Space Science program to develop a firm foundation on which to build future space related endeavors.

One of the first major partnerships between Morehead State University and Kentucky Space began in 2006, when Morehead State was contracted to design the communication systems (both space-based and ground-based) for KYSat-1. This project involved the development of a series of monopole antennas for UHF, VHF, and S-band communications, spacecraft radios, and providing communications testing and ground station controlling of the satellite system using the Morehead State University UHF/VHF ground stations and the Morehead State University 21-Meter Space Tracking Antenna. Morehead State also provided critical input into the overall systems design of KYSat-1. After four years of development and several launch delays, KYSat-1 finally launched in Spring 2010, but was met with an issue on the launch vehicle when the fairing failed to separate. This led to the vehicle retaining too much mass to reach orbit, with estimations predicting the vehicle's payloads (including KYSat-1) impacting the Earth somewhere in the Pacific Ocean.

Although KYSat-1 can be classified as a mission failure, the failure stemmed from the launch vehicle, not from a failure on the part of the CubeSat architecture. Valuable insight was gained from the experience of working within the KYSat-1 program and the Morehead State University Space Science program continued to make large strides in the small satellite industry, taking increasingly larger roles in the development and production of satellite subsystems in partnerships with the University of Rome, Italy, and taking the leading role in constructing its own CubeSat system, the Cosmic X-Ray Background Nanosatellite (CXBN). CXBN's mission involved developing a total functional CubeSat 2-U system, complete with satellite frame, flight computing, power management and distribution, RF antenna design and communications, and ground station management (all of which was designed and fabricated completely by the Morehead State Space Science program). The system housed a payload designed by astrophysicist Garrett Jernigan to study the background X-ray emissions which can be observed in the intergalactic medium. New proprietary systems were engineered by Morehead State University Space Science students to create a highly capable, fully functional satellite bus. Of significance to the research and engineering in this report, is the development of an in-house power management and distribution system and a new solar panel design technique, which worked effectively and gained flight heritage when CXBN launched in October 2012, providing valuable feed back into the efficiency of the system design (Drebs, 2013).

In 2012, Kentucky Space was offered the opportunity to design a follow-up to the KYSat-1 mission through the NASA ELaNa program, KYSat-2. This mission required a robust, efficient power management and distribution system coupled with an effective power generation technique in order to ensure that each subsystem and the primary payload would receive enough power to complete the project's mission throughout the estimated timeline of approximately one year. Based on the success of the power systems incorporated on the CXBN mission, Kentucky Space contracted Morehead State University to construct the entire power system and communications system for KYSat-2.

CubeSats are 10cm X 10cm X 10cm cubic satellite systems which are small enough to be developed affordably on a university level. The standard was conceived and developed by Robert Twiggs, a well-known satellite figure within the small satellite community, and now faculty member at Morehead State University (Twiggs, Robert J., 2013). CubeSats follow a set of standards which is constantly updated and enforced by California Polytechnic University, who works with NASA and other launch providers to ensure that each CubeSat conforms to the procedures required for all potential satellite payloads (Munakata, 2009).

1.2 Objectives

1. Design the hardware for a complete power management and distribution (PMD) system capable of maintaining and supplying power to each component of the KYSat-2 subsystems (Reference Table 1.1 for power requirements).
2. Design a power generation system which will lead directly into the power management and distribution system.
3. Develop the power system to generate an overall positive power budget, generating and storing more power than will be used by the KYSat-2 system over the mission's lifetime.

4. Design a deployment system which will be powered by the power management and distribution system and will activate the deployment of the solar panel and antenna system designed for KYSat-2.
5. Fabricate, verify, test, and produce the power management and distribution system, power generation system, and deployment system for KYSat-2 in time delivery deadlines for flight onboard NASA's ELaNa program.
6. Develop related documentation including schematic designs, performance specifications and testing reports.
7. Meet the power requirements specified by Table A.2 (Appendix).

1.3 Significance of the Study

One of the most critical single points of failure for any CubeSat mission is the electrical power system. Typically the electrical power system is solely in charge of providing power to each of the other critical subsystems, including flight computing, communications systems, and payload operation and maintenance. It is of great importance, for any CubeSat developer, to obtain or develop as efficient and robust a power system as possible in order to enhance the projected lifetime and probability for success on a CubeSat mission. CubeSats could potentially run the cost range of $100,000 to several tens of millions to develop, making mission failure a catastrophic consequence of system malfunction. This leads credence to having a solid foundation to your system bus, starting at the power system, in order to allow for the remaining subsystems to produce mission data which could be recovered, preventing the total cost of the mission from being completely lost. Without a reliable source of power for each CubeSat subsystem, it is not possible for any mission data to be retrieved from the satellite once it has achieved orbit.

KYSat-1 suffered in its developed from its reliance on a commercially available power management and distribution system developed by Clyde Space. By relying on a proprietary closed system, there was no opportunity to optimize and improve the power system to ensure complete functionality within the mission. This led to many compromises to the system design due to being unable to improve the power system, including having to develop workarounds to power usage do to being incapable of meeting the require power budget for the mission goals.

Completing this project will allow for the Morehead State University Space Science Program to further the currently existing technologies the program has in developing power systems for nanosatellite missions. This mission will allow us to take advantage of the lessons learned from Morehead State's previous CXBN mission, which was the first internal satellite to utilize its own proprietary power system, and develop an improved variation which can be utilized by not just KYSat-2, but is scalable for future 1-U, 2-U, and 3-U CubeSat missions taken up by the Morehead State University Space Science Center.

1.4 Definition of Terms

- *Electrical Power System (EPS)* – Term used to identify, collectively, all of the components of the power system described in this report. This includes power generation, storage, management and distribution. This also includes any form of solar panel deployment system.
- *KYSat-2* – Mission conducted by Kentucky Space as a follow up to KYSat-1. Primary mission is to test an experimental, photographic-based attitude determination and control system using onboard processing. Power system for this mission was contracted to the Morehead State University Space Science Center.

- *Power Management and Distribution (PMD)* – Refers to components of the EPS which specifically manage the power received by any power generation devices on the EPS, as well as, components which use logic to manage the distribution of power across the outputs of the EPS.

1.5 Summary

Chapter I provided an introduction into this thesis project by describing the general area of concern for development of the electrical power system on KYSat-2, the objectives/goals of the project, and the significance of the study being performed. Also provided by Chapter I was a definition of terms section, which outlines key terms which the reader will encounter throughout this thesis report, which can be referenced as needed.

CHAPTER II

REVIEW OF LITERATURE

2.1 Historical Background

CubeSats are miniature sized satellites, used in space research, which typically only have a volume of exactly one liter and have a mass of no more than 1.33kg (Edmonds, 2013). They are designed in discrete 100 X 100 X 100 mm cubic units, the most fundamental of which is a 1-U CubeSat. CubeSats are also capable of being scaled up to 3-U systems and 6-U systems have previously been proposed ("Some useful information", 2013). They were developed with the idea of providing an inexpensive experimental platform to launch due to their small size and mass. Various fields of science were being limited from being unable to conduct research in the space environment due to the high cost of launching experimental payloads. Fields such as space weather research understanding satellite-based tracking systems have greatly benefitted from the recent boom of the CubeSat industry which occurred over the last decade (Edwards, 2013).

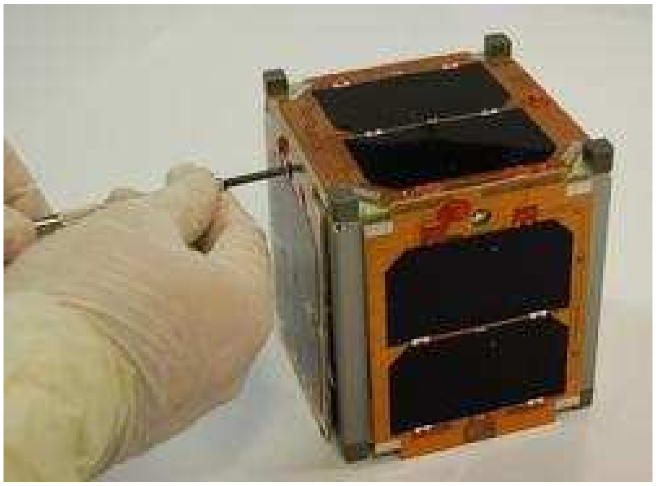


Figure 2.1: A Clyde Space 1-U CubeSat. This helps to demonstrate the scale of the size of the satellites developed within the CubeSat industry ("Some useful information", 2013).

CubeSats were developed in the late 1990s by a group of scientists who set out to find a method to get devices into the space environment without the need of diverting all department funds into one launch. It was during this period that satellite innovator, Robert Twiggs, worked with his colleagues at his institution, Stanford University, and Jordi Puig-Suari at California Polytechnic State University to develop the concept of the CubeSat (Edwards, 2013). Robert Twiggs is now currently employed by Morehead State University assisting with the CubeSat program implemented by the Morehead State University Space Science Center.

Robert Twiggs proposed acquiring cheaper launches by building CubeSats in order to be granted rides onboard launch vehicles as secondary payloads to larger more expensive primary satellite programs. This led to professionals in the satellite industry becoming concerned that a device so small would increase a chance of the components from the secondary payloads getting damaged and inadvertently damaging primary payloads before achieving orbit. This led to the decision for the team at Cal Poly to develop the Poly-PicoSatellite Orbital Deployer (P-POD) which completely encapsulates the CubeSat systems prior integration into the launch vehicle and deploys the CubeSats only after the vehicle achieves orbit (Edwards et al., 2013).

The development of the CubeSat has led to CubeSat developers advocating numerous cost-saving measures, including (Some useful information, 2013):

- Fewer necessary management roles.
- University implemented student labor incorporating expert oversight.
- Reliance on Commercial-Off-The-Shelf (COTS) components.
- Use of amateur communication frequency bands and support from amateur ground stations.

- Simple design and architecture.
- Limited built-in redundancy.

The Morehead State University Space Science Center has embraced the development of CubeSat through its numerous missions which it has either cooperated or led. Morehead State University worked with other organizations, including Kentucky Space, LLC and the University of Kentucky, beginning in 2006, on the development of KYSat-1. One of the primary challenges which developers faced was how to design the power system. Power generation consisted of solar panels using smaller sized solar cells as opposed to the typically larger cells used on many CubeSats. This means that instead of having only one to two cells per face of the CubeSat, that 8 to 16 cells could be used on each face. Although this lead to a smaller packing factor on the cells due to the increased circuitry, the cost of the solar panels were effectively lowered due to the nature of the production of the smaller cells. This led to an average power of 0.25 W being generated on the satellite, which was only sufficient so long as the radio duty cycle remained low (Chandler et al, 2006).

The power management and distribution system used onboard KYSat-1 was a Clyde Space power system. This system included an interface for developed solar arrays, high power 3.3 V, 5 V, and raw battery buses at 12 V and 2.5 V, included compatibility with lithium ion and lithium polymer batteries. It also incorporated bus over-current and battery under voltage protection and the capability to start a satellite from a truly dead start (meaning that the satellite could boot after receiving charge on orbit with drained cells) ("CubeSat Power", 2012). The decision was made to use this power system due, in part, to the inexperience on the KYSat-1 team with working with CubeSat architecture and, in part, due to the availability and cost-effectiveness of the Clyde Space System. Figure 2.2, below shows a picture provided by Clyde Space of their 1-U CubeSat EPS.

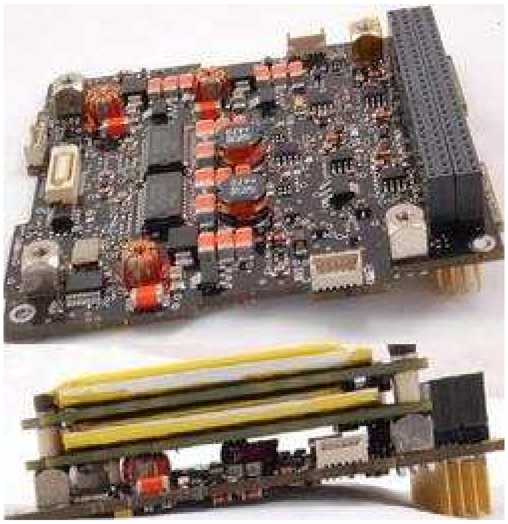


Figure 2.2: Clyde Space 1-U CubeSat EPS board (CS-1UEPS2-NB). This revision was similar to the EPS flown on KYSat-1. The board on the bottom demonstrates the EPS integrated with lithium-polymer battery cells.

Morehead State University later took the lead in 2-U CubeSat mission called the Cosmic X-ray Background Nanosatellite (CXBN). The mission team consisted of Morehead State University, the University of California at Berkeley, Noqsi Aerospace, Ltd., Lawrence Livermore National Laboratories, and Sonoma State University. The primary mission objective of CXBN was to measure X-ray radiation in the background space environment. To do so required an innovative, robust power system, which was developed by the design team at the Morehead State University Space Science Center. The power system consisted of four deployable solar panels for power generation, 4 lithium ion batteries for energy storage, and a power management system. The solar panels used triple-junction, 26% efficient solar cells, covered by a protective coating of polyimide. The power management board employed shunt regulation for charging and battery protection circuitry. It also employed a dedicated MSP430 processor which controlled the power system and gave the system the ability to be re-programmed after achieving orbit through ground station commanding (Brown et al, 2011).

Because the electrical power system was designed in-house and not purchased commercially, the Morehead State University team was able to completely accommodate the mission profile and meet the power requirements of the mission, a feat which may not have been possible under a closed system architecture. The team was able to focus on ensuring that the sytem could accommodate the primary science payload, as well as, radio communication and system computing. The success the program had with designing an in-house EPS on CXBN and the previous experience on KYSat-1, helped lead to a decision of the KYSat-2 mission team to contract Morehead State University to design the electrical power system onboard KYSat-2.

2.2 Power Management Literature Review

The function of an electrical power system in a satellite is to provide, store, distribute, and control electrical power throughout the entire spacecraft (McDermott, p. 407, 2008). In a typical breakdown of power system functionality, these important functions are typically broken down into subfunctions which must be considered when designing your electrical power system around mission requirements. These include, from McDermott, 2008:

- Supplying a continuous source of electrical power to sustain spacecraft loads through mission lifetime.
- Controlling an distributing electrical power to the spacecraft.
- Supporting power requirements for average and peak electrical load.

- Providing necessary regulation for AC and DC power buses, if needed.
- Providing command and telemetry capabilities for the EPS health and status.
- Protect spacecraft payloads against failures (McDermott, p. 407, 2008).

When designing the power system for any spacecraft, it is important to identify the mission requirements. For example, determining the average/peak electrical power requirements can help to size the power-generation system (such as determining the efficiency and total number of solar cells and primary energy storage system). Determining the estimated mission lifetime can help to determine requirements for solar arrays, batteries, battery charging, and redundancy designs. Defining the orbital parameters based on data provided by the launch provider is essential for defining incident solar energy, radiation environments, and eclipse/Sun periods. Finally, the spacecraft configuration (such as 3-axis stabilization) typically determines characteristics such as whether your power system utilizes fixed-body and deployable solar panels (McDermott, p. 408, 2008).

One of the most commonly utilized power sources for spacecraft are photovoltaic solar cells, which are typically utilized for Earth-orbiting space craft. These cells convert solar radiation incident to their surface directly into electrical energy, which can be used/stored by the spacecraft's EPS. When sizing a photovoltaic system, design your power requirements based on the end of the mission life, as opposed to the beginning of mission life. This is due to the natural degradation of the efficiency in photovoltaic cells over time. Missions lasting 10 or more years are typically considered poor candidates for photovoltaic based power generation systems.

Two aspects of the use of photovoltaics to be considered in power system design are the incidence angle, and temperature. Incidence angle is defined as the angle between a light source and the normal of a solar cell. The total irradiance projected on a solar cell is equivalent to the solar constant (the power density produced by the sun once it reaches Earth varying between 1331 to 1423 W/m^2) multiplied by the cosine of the incident angle (Erb, p.10, 2011). This cosine value can be translated into a ratio of the number of "suns" being illuminated on a photovoltaic cell. Figure 2.3 displays an I-V curve for the behavior of a solar cell under various illuminations.

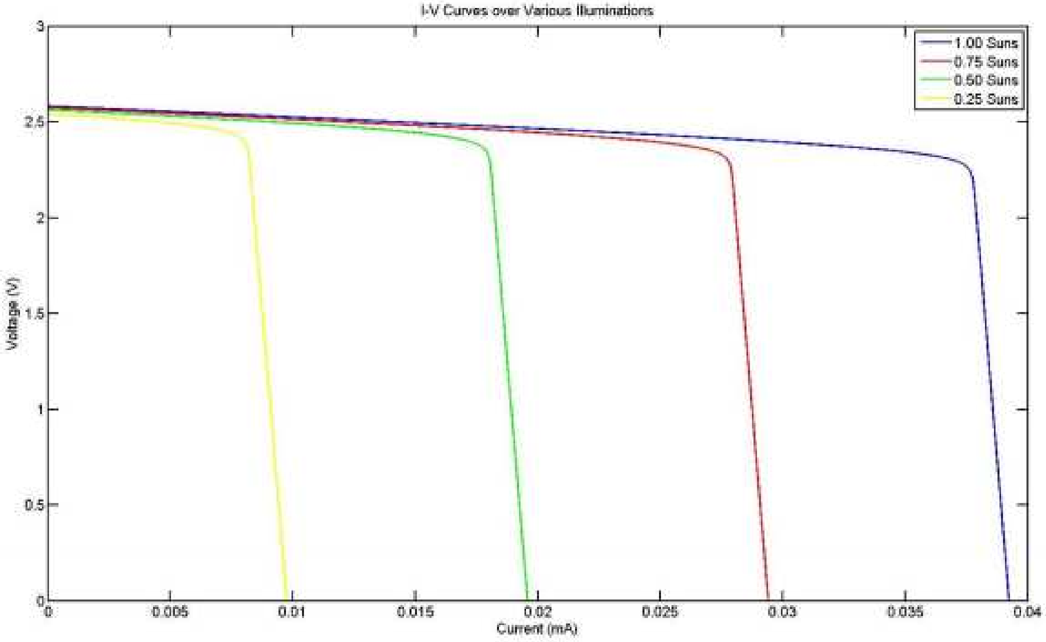


Figure 2.3: I-V curve of an ideal photovoltaic cell over various illuminations (Erb, p. 11, 2011)

In an orbital environment there are large temperature swings over relatively short periods of time. These fluxuations in a lower orbit can range from -30 to 50 C over the course of one complete orbit. The effect on the I-V curve of a typical solar cell is demonstrated in Figure 2.4.

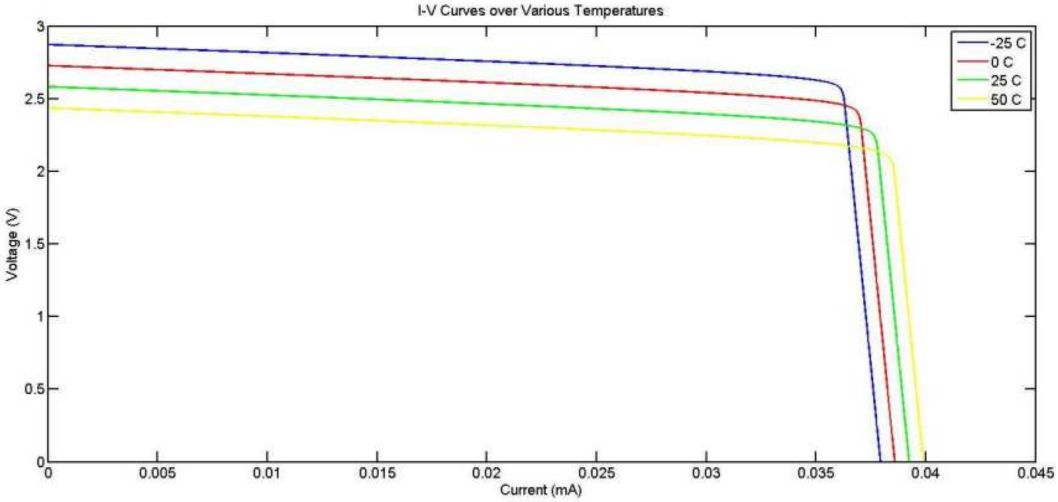


Figure 2.4: I-V curve over different temperatures (Erb, p.13, 2011)

Power systems which utilize photovoltaics must utilize a system to store energy during periods of peak power usage and eclipse period. This often requires utilization of a battery system. In designing the battery system for a mission, a designer should consider the number of battery cells required which is determined by the required bus-voltages and capacity of the individual battery cells. Battery cells can also be arranged in series (to increase voltage) or in parallel (to increase the current capabilities) (McDermott, p. 418, 2008).

Two types of batteries include primary batteries and secondary batteries. Primary batteries generate energy by converting chemical energy into electrical energy. This allows for higher energy densities, however, this conversion of energy is a one way process, meaning they cannot be recharged. Secondary batteries allow for recharging by allowing for the conversion of electrical energy back into chemical energy, however, this comes at a cost to energy density. One of the most commonly utilized types of secondary batteries is lithium-ion, which typically have a specific energy density between 70 – 110 W hr/kg. They also have the advantage of having a wider operating temperature range over other battery types, as well as, having lower mass and volume requirements due to the higher energy density. (McDermott, p. 419-421, 2008).

A spacecraft's power distribution includes cabling, fault protection, and the ability to turn power on and off to spacecraft loads. Often, power switches are mechanical relays due to their high reliability. Solid-state relays which make use of field-effect transistors to act as the switch in a power distribution circuit may also be used. It is important to either be able to turn on-off spacecraft loads or vary the total power consumption. Power distribution systems must also be able to manage transient noise which may be produced by a load from affecting other systems within the spacecraft. The use of direct current power of alternating current power is preferred for space applications in the nanosatellite level due to the low amount of electronics required to produce DC circuits as opposed to AC. If distributing current through cabling, the mass of the cables must be adequate for the amount of current being distributed to and from the EPS, however, this is more of a concern on larger spacecraft mission which higher power requirements than on small nanosatellite missions (McDermott, p. 423-424, 2008).

Electrical power generated at the array must be controlled in order to prevent battery over-charging. One primary power control technique is the utilization of a shunt regulator which operates in parallel to the power generation system and shunts current away when spacecraft loads or batteries do not need power. On small nanosatellite systems, it is often important to fully regulate power, not just on the charging circuits, but also on the discharge circuits on system buses. This ensures the correct voltage and power levels will be supplied to each subsystem of the spacecraft (McDermott, p.425-427, 2008).

2.3 Summary

This chapter provided a historical background for CubeSats and the importance of past experiences that Morehead State University has had with power system designs in applications on CubeSat architectures. Chapter II also reviewed the research conducted behind the hardware which was under consideration for the development of the KYSat-2 EPS.

CHAPTER III

METHODOLOGY

3.1 Mission Overview

KYSat-2 was designed with the primary payload to be a stellar imaging system. This imaging system takes successive images of background stars and completes onboard processing to determine the overall motion of the satellite as it orbits the Earth. This includes relative attitude and roll rate. The imager is also capable of taking full color earth images and relaying them to Earth ground stations located at Morehead State University and the University of Kentucky. These images will be implemented as part of an educational outreach program conducted by Kentucky Space and its partner institutions to educate pre-college students and amateur radio enthusiasts about space systems engineering.

The mission includes five primary individual subsystems including the electrical power system, the flight computer developed by the University of Kentucky, a gyroscope system, the communications system developed by AstroDev to communicate with mission ground stations at UHF, and the camera board developed by the University of Kentucky. The most demanding system to supply power to throughout the KYSat-2 mission is the communications system, which requires an estimated 475 mW of power in order to fulfill its mission requirements. This is approximately 43% of the total power required for all KYSat-2 systems. This is followed by the gyroscope which requires 302.5 mW of power accounting for nearly 28% of the total power consumption on KYSat-2. The complete details for the power budget of KYSat-2 are listed in the Appendix section of this report in Table A.2.

The power system must also effectively generate enough power to maintain a positive power budget and store extra power so that the satellite will have access to enough power to conduct normal operations when in eclipse while in orbit. The power system must also provide a method to shunt away excess power to improve the effectiveness of the power storage system and effectively manage and distribute the required power requirements to each subsystem on KYSat-2. This section of the report will detail the design decisions and techniques implemented in the design of the KYSat-2 EPS.

3.2 System Design

This section of the Chapter III will present the system design methodology used in the development of the KYSat-2 EPS.

3.2.1 Block Diagram

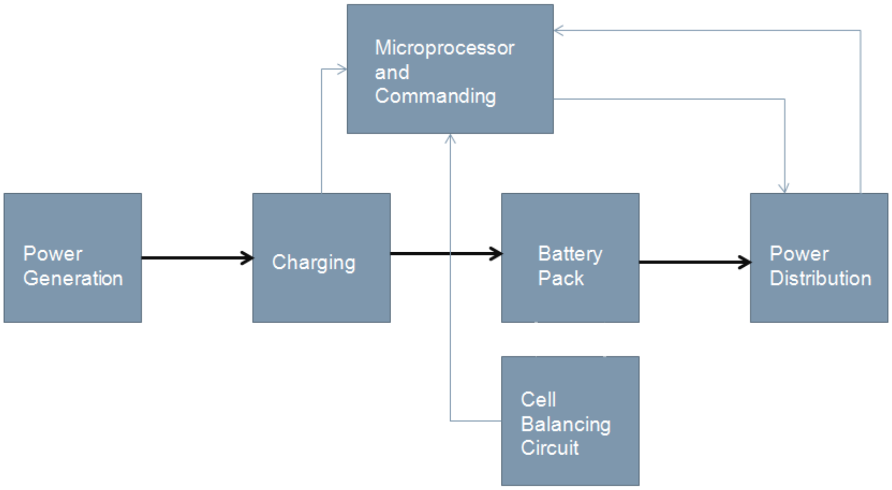


Figure 3.1: Basic block diagram of the functionality of the KYSat-2 electrical power system. The bold black lines represent the flow of power throughout the EPS, while the thin gray lines demonstrate communications with the microprocessor onboard the EPS.

Figure 3.1 provides a general overview of the overall functionality of the electrical power system. The power generation system represents the solar panels which act as the main source of energy for the entire CubeSat. Current that is generated by the photovoltaic cells on the solar panels will be stored into a battery pack only after passing through a charging circuit which includes a shunt regulator to regulate the voltage running into the battery pack. Running in parallel with the battery pack is a cell balancing circuit, whose function will be to help balance the stored voltage across each of the batteries within the pack, improving the overall effectiveness within the system. Finally, a power distribution system will regulate the output power to 3.3 and 5 V outputs in order to power the various components within KYSat-2. The microprocessor onboard allows for communicating current and voltage values throughout the system, satellite power-on protocols, and communications between systems onboard the EPS and other KYSat-2 subsystems.

3.2.2 Power Generation

Power generation onboard KYSat-2 is handled through a series of mounted and deployable solar panels. Due to the limited surface area available on a 1-U CubeSat like KYSat-2, the deployable solar panels will be required in order tod achieve positive voltage margin compared to the voltage capable of being stored by the battery pack. The battery pack is currently tested to store 12 V, therefore, in order to optimize charging, it is best to generate more than 12 V on the system.

The solar cells purchased and tested for the KYSat-2 EPS are rated at approximately 2.4 – 2.7 V each, therefore, it is safe to assume that 5 cells would be enough to generate this required voltage. However, an engineering practice common among space systems is to implement a factor of safety in case some of the cells fail to generate the required voltage (it is impossible to make corrections to a system once it has achieved orbit). The decided factor of safety for this EPS design, when it comes to power generation, is 25 to 30%. This corresponds to the use of 7 cells (in series) in order to generate at a minimum 16.8 V which can be regulated appropriately to be stored into the battery pack.

The mounted and deployable solar panels will be attached to four sides of the CubeSat along the X and Y axes. Each set of solar panels consists of a deployable panel consisting of four cells at approximately 26% efficiency and a mounted panel containing three cells. These panels are connected to each other via JST brand connectors which allow for the cells to function in series. The deployable and mounted panels makeup one complete panel set with one set on each axis for a total four sets. The sets run in parallel to each other in order to improve current generation and to add redundancy to the system in case one set of panels should fail.

3.2.3 Power Storage and Cell Balancing

Power onboard the KYSat-2 EPS is stored in a 3-series lithium-ion 18650 cell system running in parallel with a custom cell balancing circuit powered by the BQ76925 chip. In order to create room onboard the relatively low volume accessible in the small 1-U CubeSat system, the battery pack must be integrated with the daughter board with the communications systems of KYSat-2. This not only alleviates the need to take up more volume on the spacecraft with a separate battery board, but it also allows the radio itself to serve the purpose of heating the battery pack in order to improve battery efficiency and lifetime. The battery pack is held together using 3D-printed clamps using a space rated carbon-based plastic material. Figure 3.2, below, demonstrates the overall design of this battery pack interface with the radio daughter board.

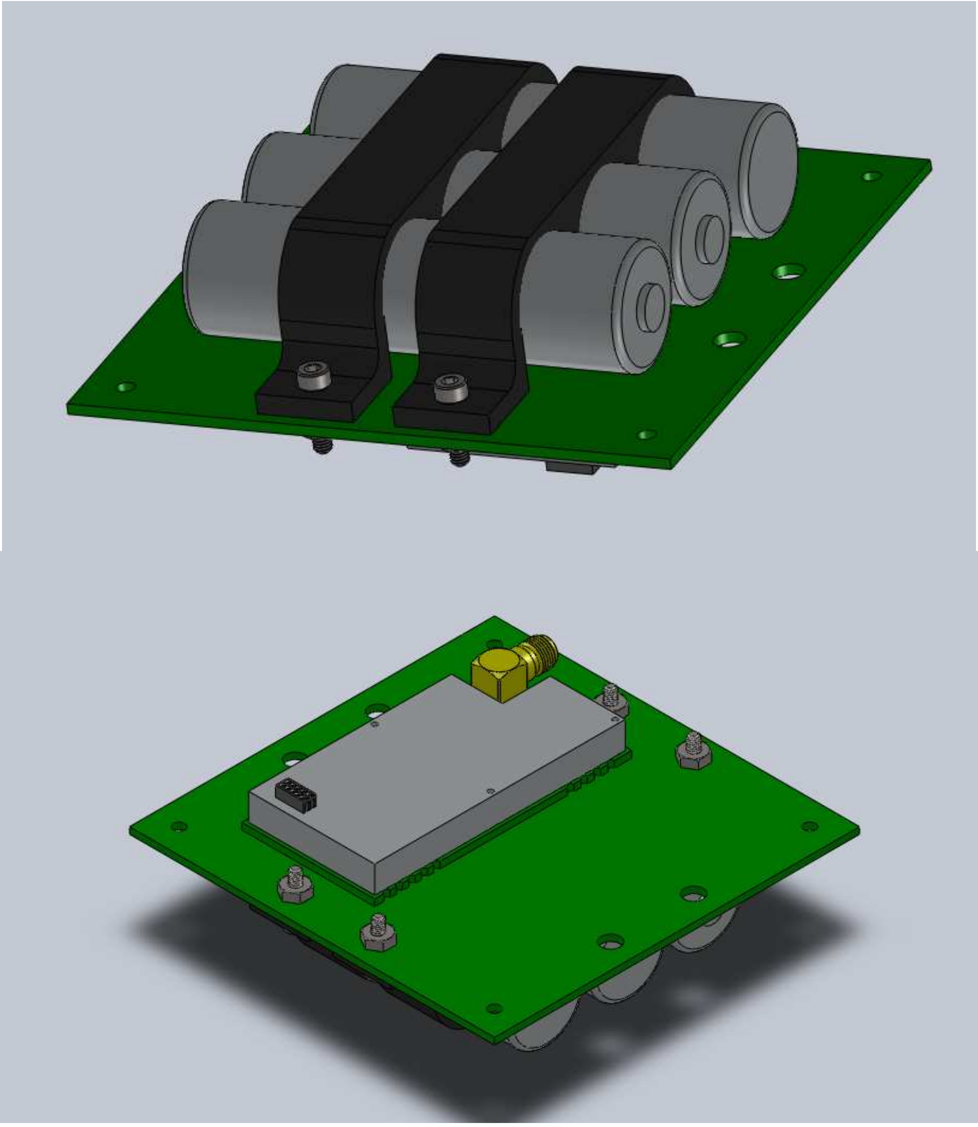


Figure 3.2: Top and bottom view of the battery pack interface with the radio daughter board for KYSat-2.

The battery pack is connected to the primary EPS module via JST connectors for charging, power distribution, and cell balancing. It will be in parallel to a cell balancing circuit featuring integrated cell balancing FETs, open wire detection, and low power consumption. Cell balancing improves the efficiency and lifetime of a series cell battery circuit by evenly distributing the charge among the individual cells and providing information to the microprocessor to help determine key functionality. Below in Figure 3.3 is an basic schematic created in Altium of the schematic layout of the cell balancing circuit in the EPS.

3.2.4 Power Distribution

Power distribution to each of the KYSat-2 subsystems is handled through two different methods, a low-power, low-noise method and a higher power method. The lower power method is designed to eliminate the noise which is typically produced by switching regulators by relying, instead, on the TPS70933. The consequence of relying on an LDO, however, is that the power output is considerably lower, meaning that this method of power distribution will only be effective on loads which use little power. Since the majority of the logic circuitry onboard KYSat-2 is based on TI's MSP430 architecture, which is typically more than capable of running below 100 mA at 3.3 V, this makes it the most effective method of powering the logic circuitry. This also eliminates possible issues with noise leaking into the logic system and corrupting data. There are three low power outputs installed on the EPS including one which directly powers the microprocessor controlling the EPS itself, one which powers the microprocessor onboard the KYSat-2 transceiver, and one which is set aside for the command and data handling system for KYSat-2 being developed by the University of Kentucky. Below in Figure 3.4 is the basic schematic for the LDO. The high power functionality of the power distribution system on the EPS is based on a higher efficiency switching regulator based on the TPS62133 switching regulator which can step down the approximate 12 V from the battery pack from an adjustable range of 0.9 to 17 V up to 3 A. Each subsystem of KYSat-2 is based on either 3.3 or 5 V design

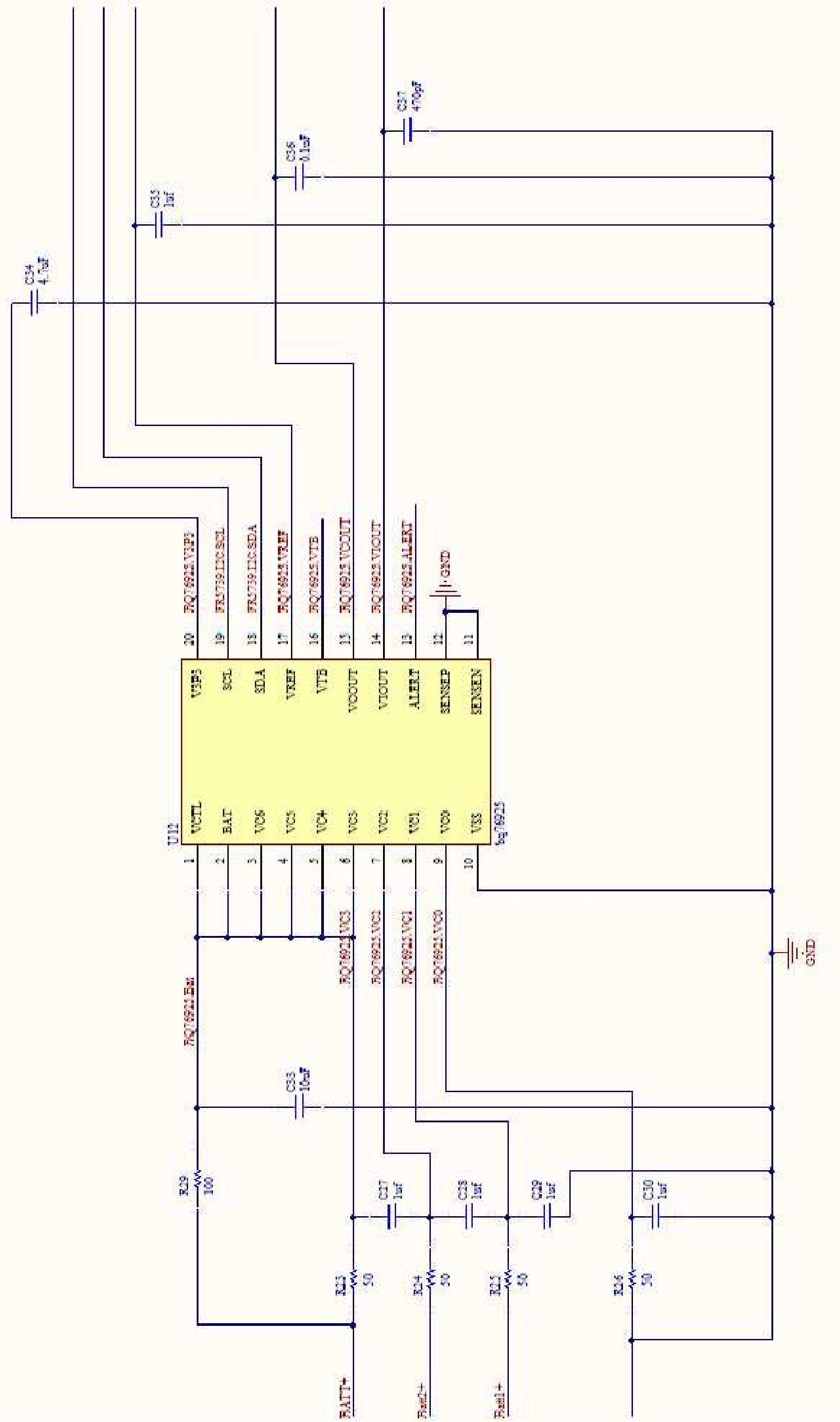


Figure 3.3: Abridged schematic of the cell balancing circuit.

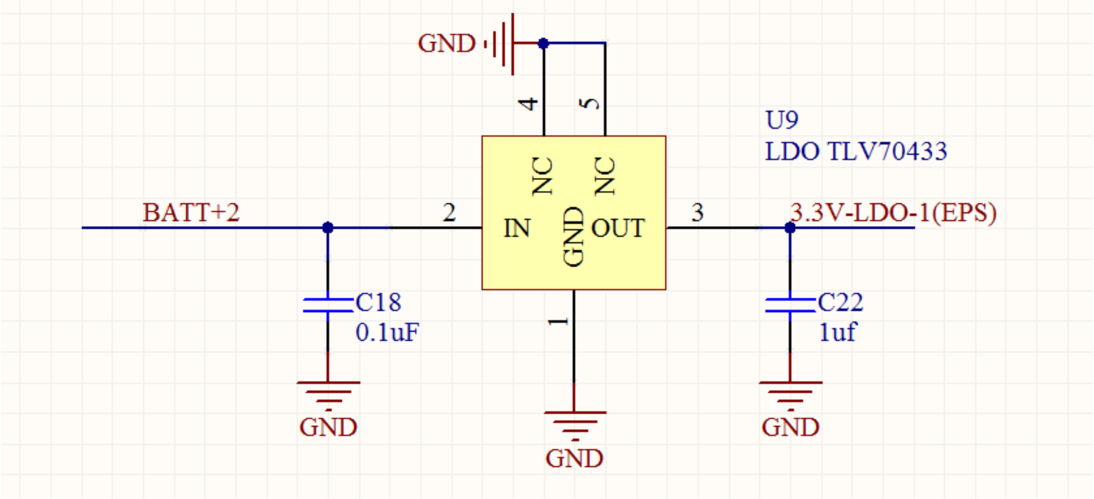


Figure 3.4: Abridged schematic of the LDO circuit.

and the combined current draw of each subsystem never reaches the threshold of 2 A, making these regulators a viable choice for power distribution. There are two of these regulators onboard the EPS with two power outputs per regulator for a total of four outputs. The 3.3V outputs are dedicated to the command and data handling system designed by the University of Kentucky and the transceiver system. The 5 V outputs are dedicated to KYSat-2's primary payload and to an onboard gyro which will determine overall motion of the spacecraft once it has achieved orbit. Figure 3.5 below shows the schematic for this switching regulator design.

Accompanying the high power regulators is shutdown commanding based on the TPS2590 which will allow the EPS to turn off power to any device if there is a fault in the KYSat-2 system, such as the need to reset a subsystem, which may be caught in a programming loop or current overdraw which can potentially put the EPS and the rest of the satellite mission at risk. These shutdown features are applied to the individual outputs, as opposed to the regulators, which prevents other subsystems from seeing effects from reset functionality. These functions can be switched on/off automatically due to programming within the system's logic, or by commanding from a viable satellite ground station.

The power distribution system is also designed around a point-to-point wiring system, which means that the other developers on the KYSat-2 mission do not have to be overly concerned with mechanical layout in with respect to the EPS. Cabling will be JST standard cabling rated at currents which can run well above 2 A.

3.2.5 Logic

All logic on the KYSat-2 EPS is handled through a TI MSP430 microprocessor. This processor is programmed to have a series of commands which can be called on by other subsystems in order to control EPS functionality and communications. The command list is provided to the remainder of the KYSat-2 team prior to system integration in order to save extra time to complete integration of the KYSat-2 system. The MSP430 also monitors voltage and current from each component of the EPS and makes decisions on system functionality based on the data it receives.

All communication to and from the EPS is handled through standard UART systems. This decision was made to avoid I2C protocols which can potentially face issues on maintaining the ACK bit in the critical space environment where software communications are the only method of maintaining proper functionality.

3.2.6 Other Functionality

Other functionality is incorporated into the EPS which will allow for it to comply with CubeSat requirements for power system behavior. A hard-switch was installed in the system

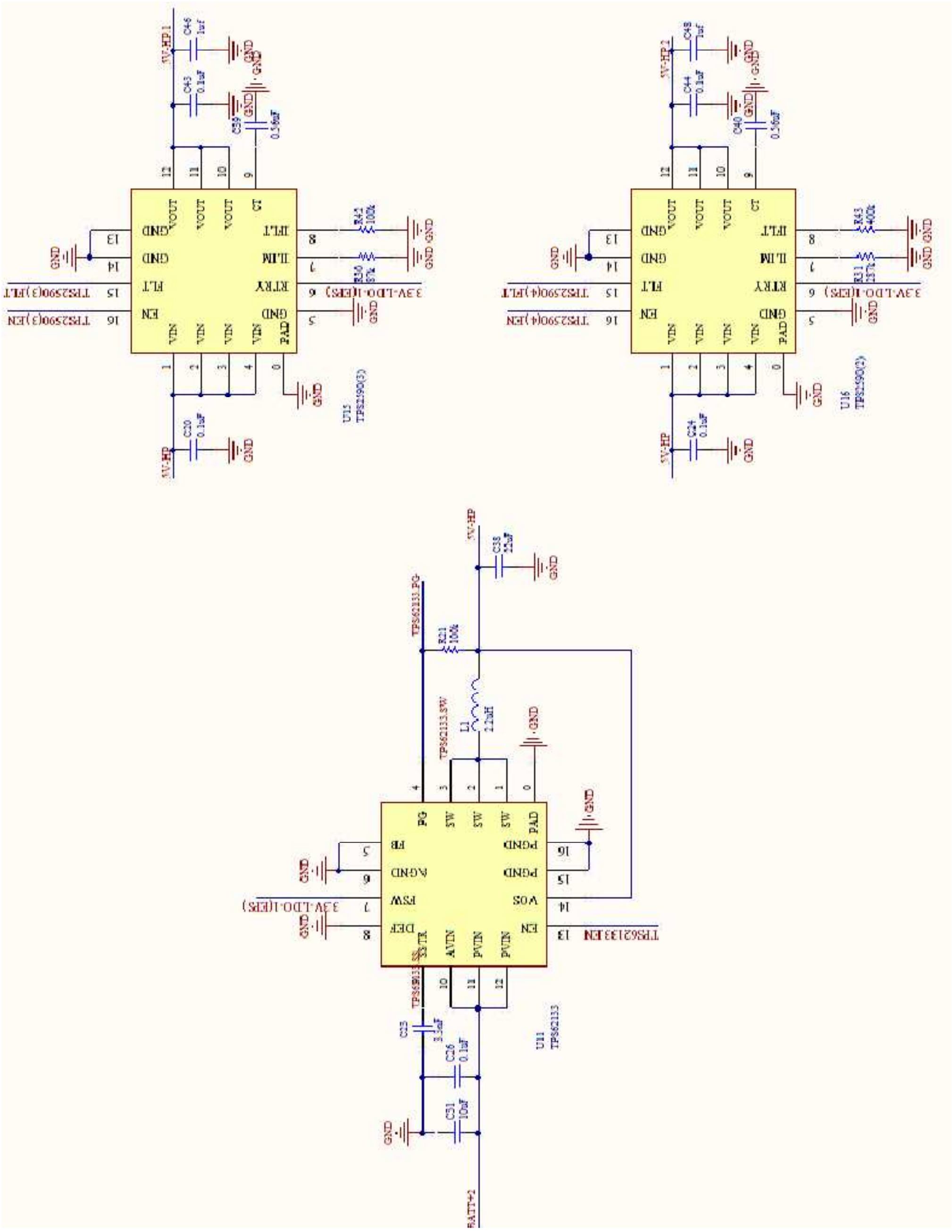


Figure 3.5: Abridged schematic of the switching regulator circuit.

which will prevent a satellite system start without removal of a “Remove Before Flight” pin prior to satellite integration with the launch vehicle. A footswitch is also incorporated into the system which prevents a power-on state in the CubeSat prior to satellite deployment from the launch vehicle after reaching orbit.

Also, the launch vehicle integration procedures for KYSat-2 require that minimal leakage current be present in the system while waiting for launch. To accommodate this requirement, another series of switches are integrated into the KYSat-2 EPS so that no power is running through the system while the system rests in its deployer while awaiting launch. These switches are designed so that they are open when the CubeSat is resting in the deployment system and closed once ejected, allowing current into the system so that it may power on.

Solar panel deployment methods are handled through the use of a nylon cutting circuit board which will rest on the positive Z-axis of the satellite. The function of this board will be to draw current directly from the battery pack in the EPS after start-up when KYSat-2 deploys from the launch vehicle. The cutting device is a short piece of nichrome wire in conjunction with a power relay. When the relay receives a 3.3 V signal form the microprocessor of the EPS, the relay is turned on and current from the battery pack runs through the nichrome wire. This current will heat the wire, cutting a nylon string which holds the solar panels in its stowed position. After cutting, torsion springs along each of the deployable panels will allow them to open to an approximate 170 degree position with respect to the mounted solar panels. This method of solar panel deployment has been previously tested and verified on three previous missions Morehead State University has been involved with, including CXBN, KYSat-1, and Frontier-1.

3.3 Component Selection

The following sections detail the component selection for the KYSat-2 EPS. Each individual section will describe the selected the component and the benefits/reasoning for selecting these components to maintain the power system for the KYSat-2 mission.

3.3.1 BQ76925

The BQ76925 is an analog front end which offers protection to 3-series to 6-series cell systems. It provides a variable gain current sense amplifier, a switchable thermistor bias out for temperature measurements, overcurrent protection, cell balancing FET's, open-wire detection, and an integrated 3.3 V regulator ("bq76925"). This IC is developed for those seeking a low-power cell management device (40 uA in normal operating mode), which is critical for space purposes due to the value of energy efficiency in an environment where it is difficult to come by. The device can be controlled through an external processor over an I2C protocol with multi-channel analog-to-digital capabilities. It is capable for cell systems ranging from 4.2 to 26.4 V ("Host controlled analog", 2011).

This component was selected for use on the EPS due to its effectiveness in testing with balancing 3-series cell battery systems. The component demonstrated robust capabilities under a variety of stress situations. The scalability of the component to accommodate more battery cells in series also made it a viable option when designing the EPS to be scalable for 2-U and 3-U power systems. Finally, the component demonstrated low values for quiescent current draw when the utilized for low-power standby situations.

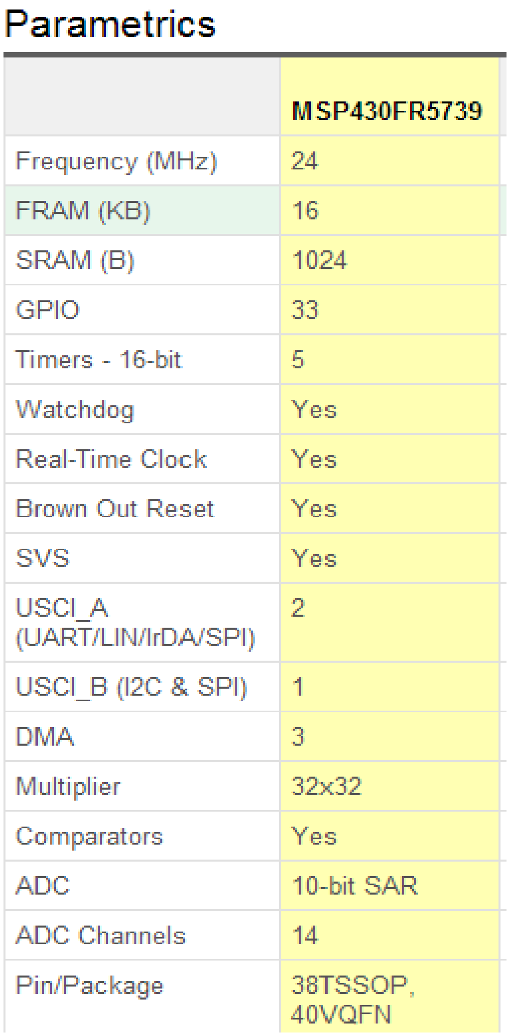
3.3.2 INA230

The INA230 is a high-side or low-side bidirectional current monitor which communicated with a microprocessor over an I2C interface. It offers the ability to measure current, as well as, voltage and power. It can measure current values and provide averaged values, depending on the preference of the programmer. It also provides an alert when values reach minimum or maximum thresholds. These typically operate on a 2.7 to 5.5 V supply ("High- or low-side", 2012).

This device was selected because its utilization eliminated the necessity to use analog to digital converters in order to take accurate readings of voltage, current, and power in devices across each major circuit in the EPS. Data is transmitted across sdata communications in an I2C protocol with the microprocessor with individual addresses for each INA230 utilized in the EPS set through hardware.

3.3.3 MSP430FR5739

The MSP430FR5739 is an embedded microcontroller running on a 16-bit RISC architecture up to 24-MHz. It has a wide operational voltage range of 2 to 3.6 V and is capable of operating at temperatures and radiation levels encountered in the space environment. While active, the device has a current consumption of 81.4 uA/MHz, or approximately 2 mA under optimal conditions. Some of the most important features of this microcontroller are its real-time clock with calendar and alarm functionality, a 16-channel analog comparator with voltage reference, a 14-channel 10-bit analog-to-digital converter, serial communications of UART, SPI, and I2C, and fully integrated LDO power management system, and an internal clock *("MSP430FR5739", 2012)*. Table 2.1 outlines the parametrics of the device.



Parametrics

	MSP430FR5739
Frequency (MHz)	24
FRAM (KB)	16
SRAM (B)	1024
GPIO	33
Timers - 16-bit	5
Watchdog	Yes
Real-Time Clock	Yes
Brown Out Reset	Yes
SVS	Yes
USCI_A (UART/LIN/IrDA/SPI)	2
USCI_B (I2C & SPI)	1
DMA	3
Multiplier	32x32
Comparators	Yes
ADC	10-bit SAR
ADC Channels	14
Pin/Package	38TSSOP, 40VQFN

Table 3.1: A table published by Texas Instruments which details the specifications of the MSP430 microprocessor used onboard the Morehead State University EPS ("MSP430FR5739", 2012).

3.3.4 TL1431

The TL1431 is a precision programmable reference with thermal stability capable of withstanding the environment of space. The output voltage of the device can be set between approximately 2.5 V and 26 V through the use of two external resistors. This feature makes it a good option for use on power regulation. Its behavior is similar to that of Zener diode, and is often used as a replacement if voltage regulation is required in the applied circuit (“TL1431”, 2013). The output voltage is determined through the reference voltage and can be achieved through something as simple as a voltage divider.

This device was selected primarily due to its robustness during testing and its flight heritage due to having flown on other small satellite missions, such as CXBN. The specifications of the device ran within bounds of the expected values on power generation. Also, the ability to set the output voltage through hardware was a preference to software defined voltage output to prevent software bugs from damaging the circuit.

3.3.5 TPS2590

The TPS2590 is a high-current load switch which is functional at currents up to 5.5 A at a voltage range between 3 to 20 V. This switch has a programmable fault timer and fault current function and can be set to have a hard current limit. The device is extremely useful when a voltage bus must be protected so that shorts do not damage other components drawing power from the bus (“3-V to 20-V high-current”, 2013).

This switch was selected due to its ability to quickly switch through a command sent using I2C protocol from the MSP430 microcontroller. The device also has low quiescent draw when not active preventing unnecessary lost power when waiting for commands from the EPS microcontroller. The switch was also preferred due to the ability to control each device independently of one another without affect other EPS buses. Also, the programmable shutdown function of the device ensures stability within the EPS system by preventing unnecessary lost power when overdraw is detected on their respective voltage bus.

3.3.6 TPS3838K33

The TPS3838 supervisory circuit simply provides circuit initialization and timing supervision for processor-based. The supply current is typically 220 nA with a supply voltage range of 3.3 V. The delay is selectable as well at 10 ms or 200 ms ("Nanopower supervisory circuits", 2010). This is a standard supervisory circuit for MSP430 applications and is considered to be rated for the space environment.

3.3.7 TPS62133

The TPS62133 is synchronous step down (buck) DC-DC converter for applications with high power use. It is capable of regulating voltages upwards of 17 V down to an adjustable output between 3 and 5 V. It also has a low quiescent current of approximately 17 uA when set to a power save mode. When powered on, the system can have a maximum output currently of up to 3 A ("TPS62133", 2013). They are rated to be functional in a space environment.

This device was selected for KYSat-2 based on its tested performance for applications requiring more than 250 mA of current on 3.3 V outputs and 200 mA on 5 V outputs. The efficiencies, when tested independently, ranged between 85 – 90 % when applied to higher power applications. This meets the expected power requirements of high power subsystems on KYSat-2.

3.3.8 TPS70933

The TPS70933 is a linear regulator with extremely low quiescent current for applications which are sensitive to the type of power it receives. They support a peak power output of approximately 200 mA, although it is typically ran only up to 150 mA. They regulate an input voltage between 2.7 to 30 V down to3.3V ("TPS70933", 2013). Although the current output is low, and efficiencies are lower than higher efficiency switching regulators, the lower noise output on these linear regulators make them more suitable for powering logic circuits not requiring more than 150 mA.

3.4 Solar Panel Hardware

Following in the footsteps of the CXBN mission, KYSat-2 will utilize solar panel printed circuit boards designed by Morehead State University and produced by Advanced Circuits, using the organization's gold plate finish option. The electroless nickel immersion gold (ENIG) finish, expectedly, has a higher fabrication cost compared to standard PCBs, however the gold plating improves thermal characteristics in an orbital environment. The gold plating typically has a shelf-life of one year in an earth environment, but still retains limited rework capacity if deemed necessary ("PCB Plating Finishes", 2013). Solar cells mounted on the panels are triple-junction solar cells with a 26% efficiency. The cells are coated in a protective polyimide coating using a proprietary process developed by the Morehead State University Space Science Center team (Brown et al, 2011).

3.5 EPS Design Procedure

The KYSat-2 EPS has undergone several mechanical and electrical iterations to improve the quality of the system and to achieve the efficiency and robustness required for any flight capable CubeSat EPS system.

3.5.1 Mechanical Layout

System design utilized the CAE program SolidWorks. The shape and outline of each board and component of the EPS system was formed and fit checked (theoretically) with the CAD models provided by other KYSat-2 engineers to ensure that the mechanical fit of the proposed components would fit within the limitations of the 1-U CubeSat volume. Figure 3.6 (below) demonstrates using SolidWorks to mechanically fit-check system integration. Production of any printed circuit boards were also based on the components designed through SolidWorks, as the functionality of the program allowed for any mechanical models to be exported into other engineering programs to continue the design phase.

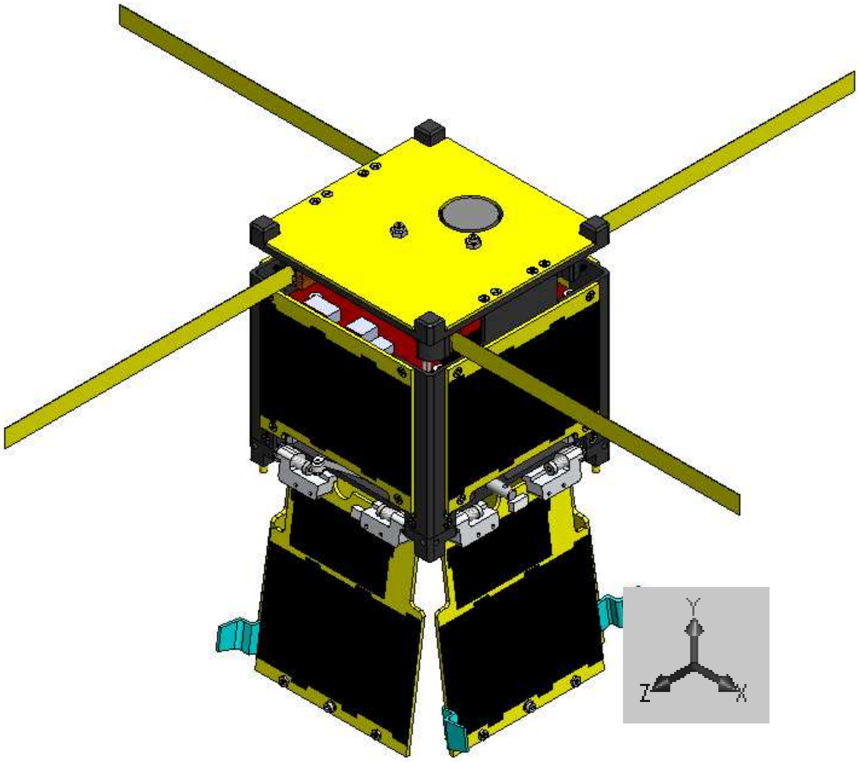
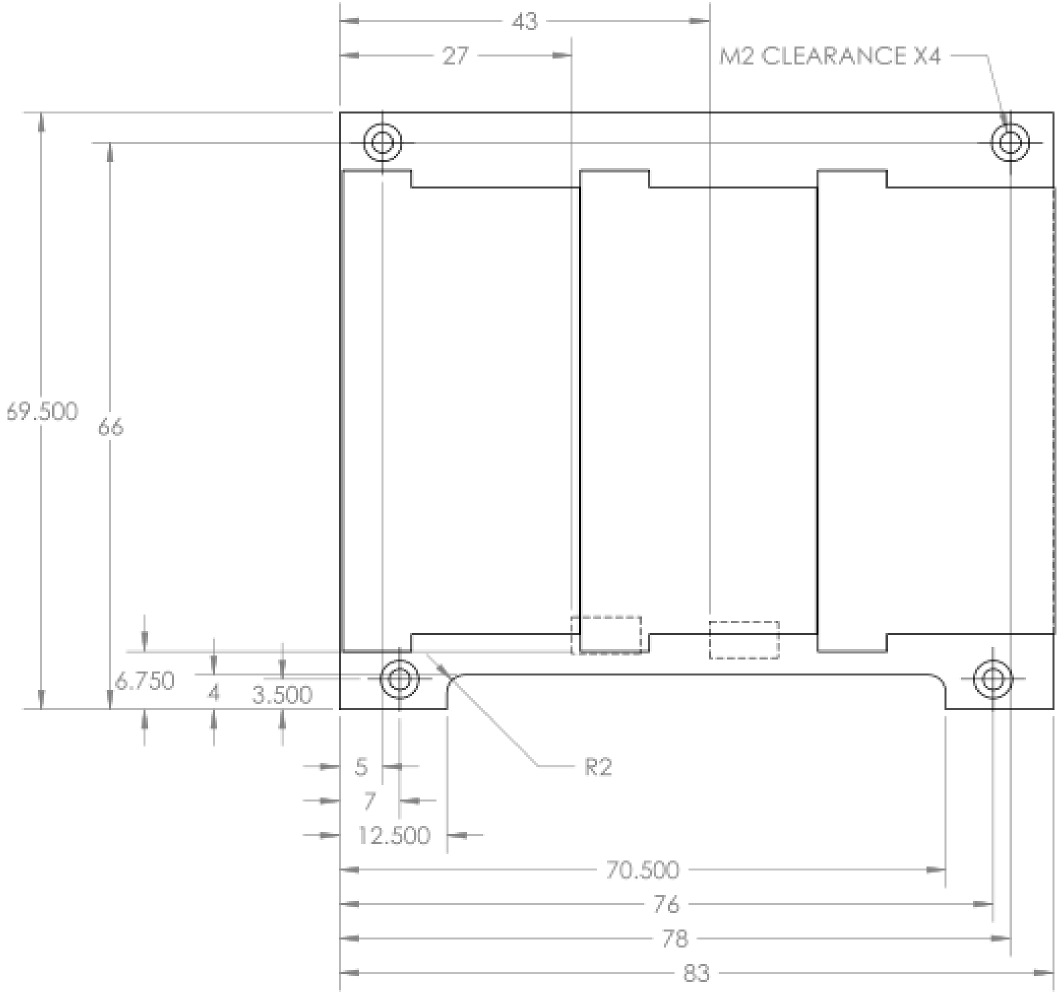


Figure 3.6: CAD model for KYSat-2 demonstrating how use of SolidWorks software assisted in the mechanical design for the spacecraft.

The solar panels onboard KYSat-2, implement a deployable solar panel design. This effectively doubles the available surface area allowed for solar power generation, however, the limitations of the CubeSat standard prohibit any components of the CubeSat from extending 6.5 mm beyond the surface of the 10 x 10 cm frame. This allowed the KYSat-2 mechanical design team to determine a suitable deployment method, which allowed for them to return to the EPS design team a required thickness for the solar panel boards. This thickness became approximately 2.5 mm. Another limitation of the CubeSat design is that the width of objects above the 10 X 10 cm frame cannot be wider than approximately 83 mm due to clearance requirements in the CubeSat deployment system. This forced the width of the solar panels to be 83 mm. Figure 3.7, below, shows a CAD drawing of the solar panel design.



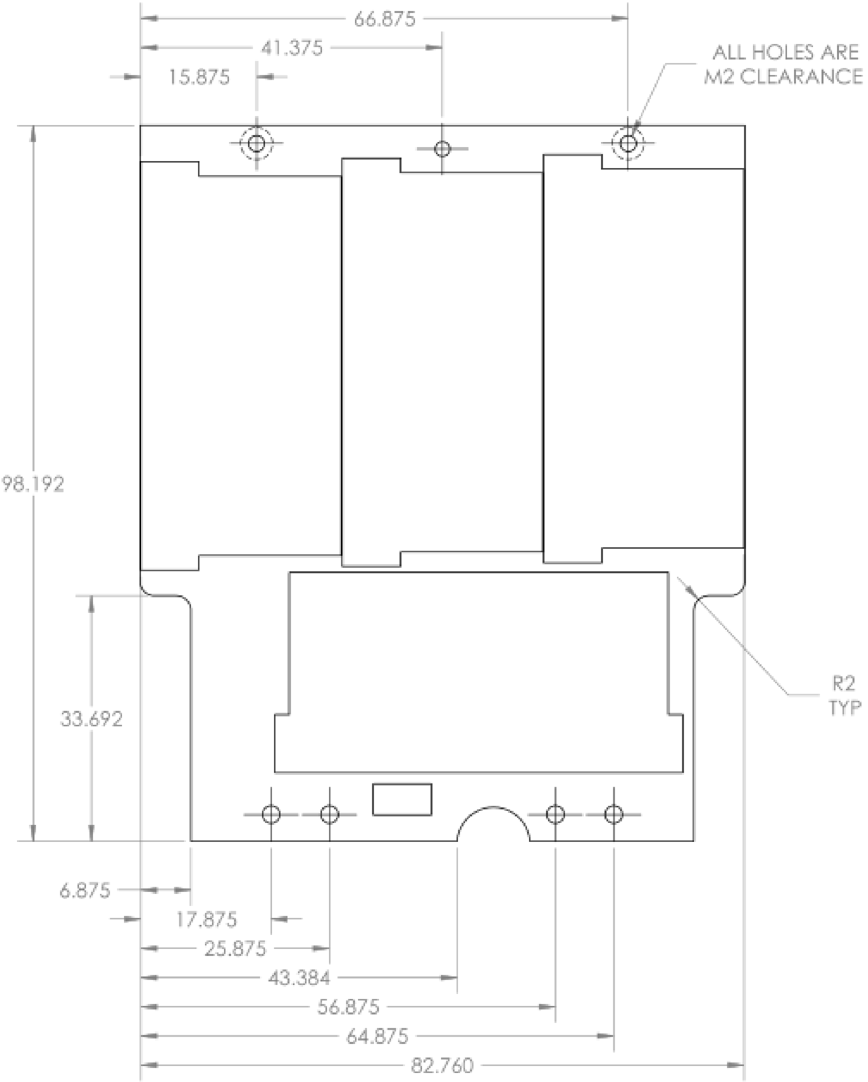


Figure 3.7: (Top) The solar panels mounted to directly the X-Y axes of the KYSat-2 frame which houses three solar cells. (Bottom) The deployable panels mounted below the mounted panels which house four solar cells. The solar cells measure at 50 X 25 mm.

Based on feedback from other KYSat-2 design team members, we were provided a maximum board size for producing the battery board, the primary EPS board, and the solar panel deployment board. Figures 3.8 through 3.10 provide the dimensions of these boards.

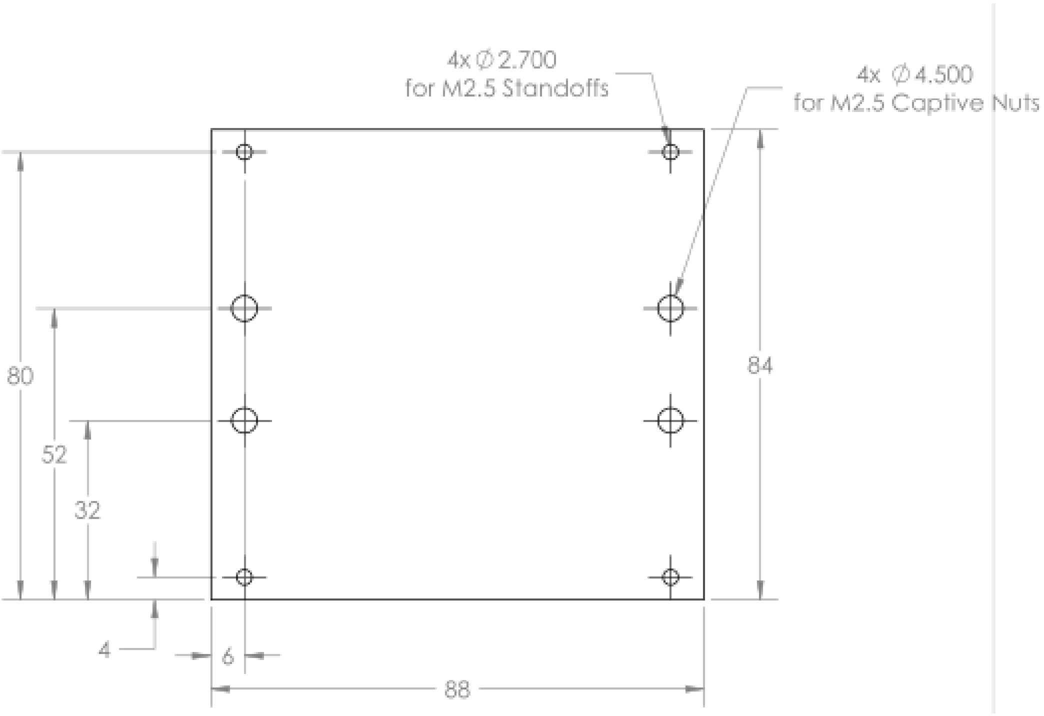


Figure 3.8: The radio/battery board for KYSat-2. The four 4.5 mm holes acts as the mounting holes for the printed battery clips, while the 2.7 mm holes act as the mounting holes to the satellite frame. The radio is soldered to one end of the board, while the batteries are mounted on the opposite side.

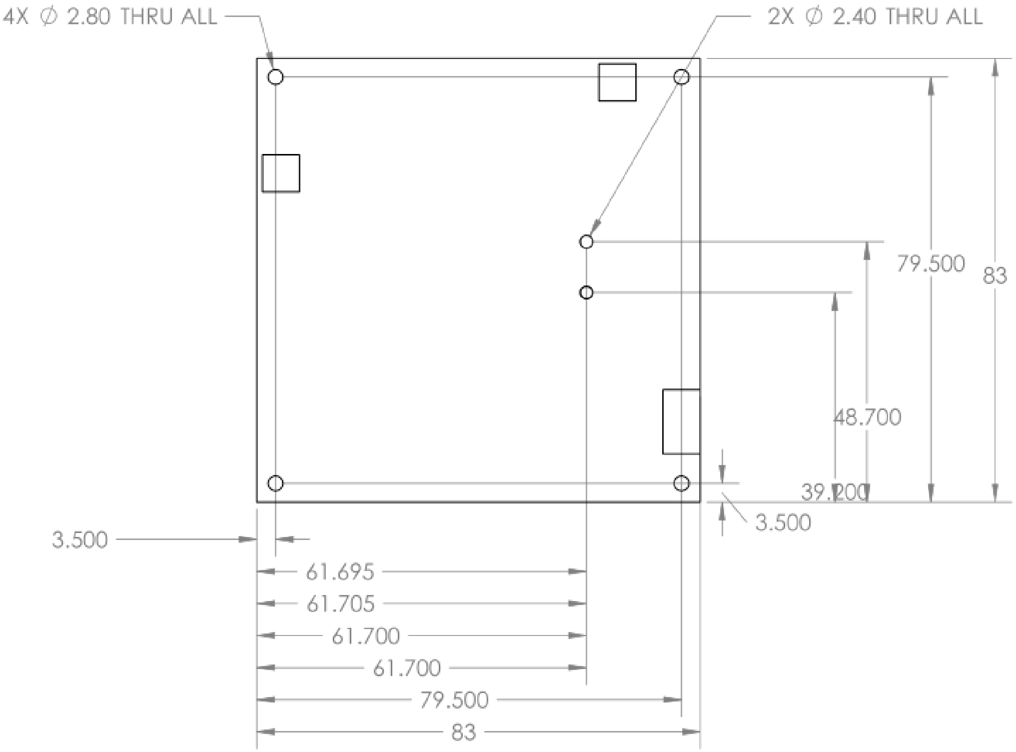


Figure 3.9: CAD drawing of the power management board for KYSat-2.

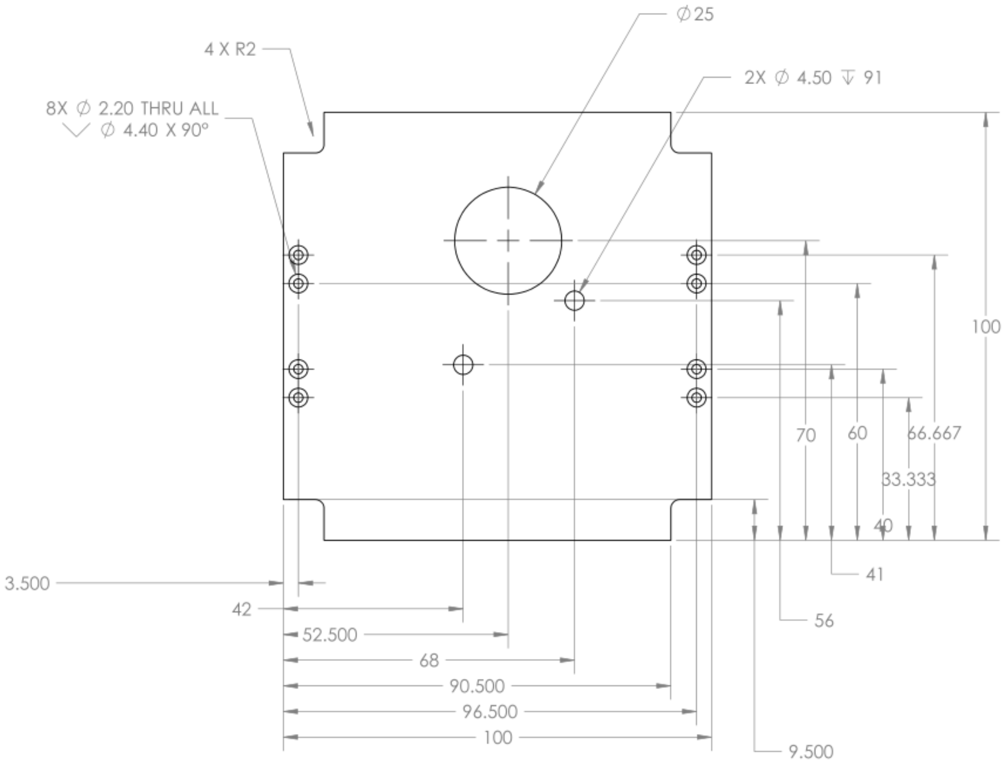


Figure 3.10: Deployment board on KYSat-2. The topmost portion of the deployment board carries a solid state relay on the underside of the board which will activate the cutting circuit. Nichrome wire is mounted to the two 4.5 mm holes. The eight 2.2 mm holes served as mounted to the –Z axis of the KYSat-2 satellite frame. The 25 mm circular cut-out is intended to make room for the KYSat-2 payload.

3.5.2 PCB Layout

All printed circuit board layout was performed using the Altium Summer 09 software package. Board size was predetermined through SolidWorks and verification that PCB layout matched circuit design was also handled through Altium. Verification that the boards met production requirements was handled through Altium’s built in design rule functionality and through the Advanced Circuits Gerber file check system. All PCB production was handled through Advanced Circuits. Figures 3.11 through 3.14 show the PCB design through Altium of the boards manufactured through Advanced Circuits.

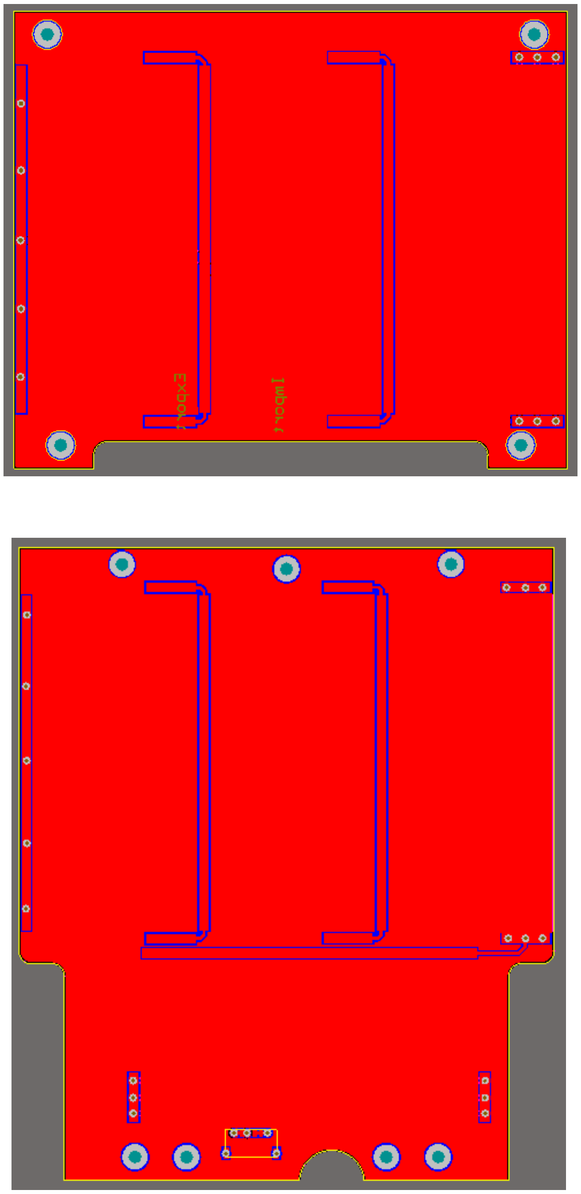


Figure 3.11: (Top) PCB layout completed in Altium for the mounted solar panels. (Bottom) PCB layout for the deployable solar panels.

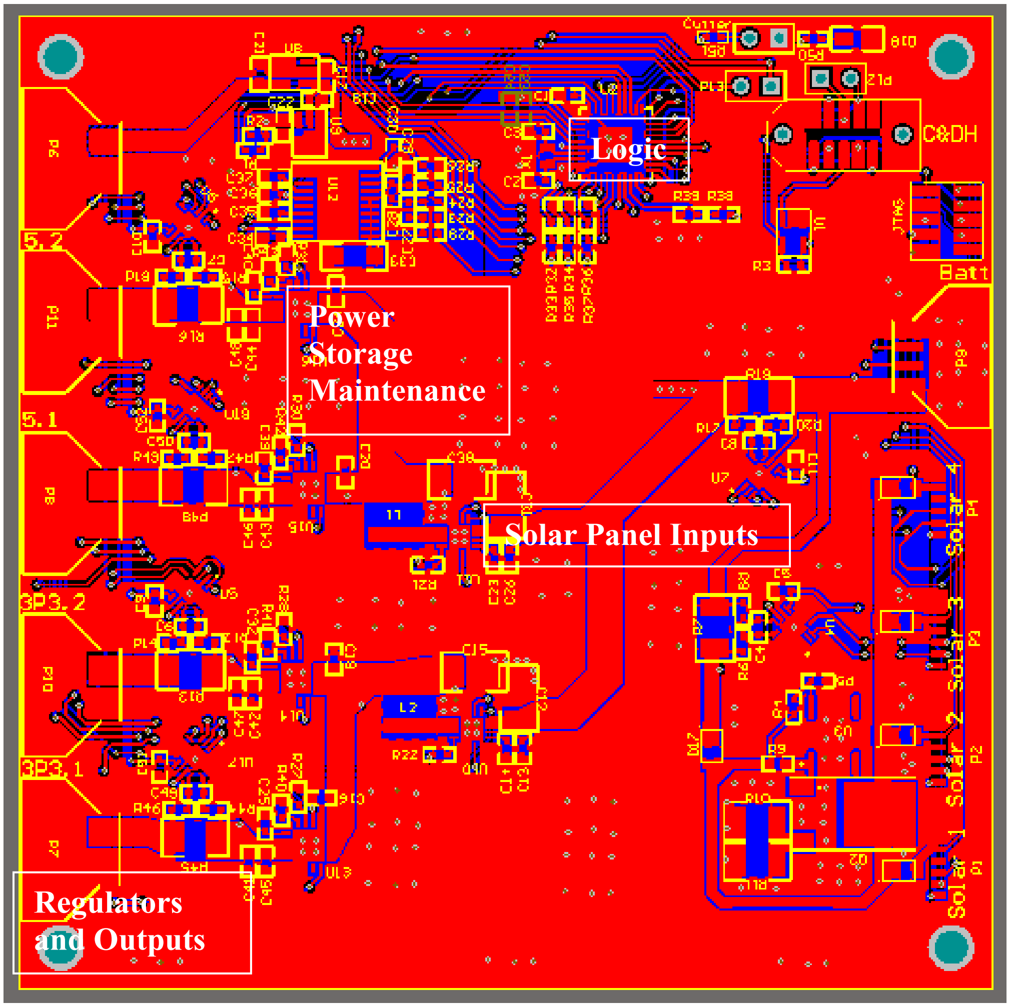


Figure 3.13: Most recent revision of the PCB layout for the power management board.

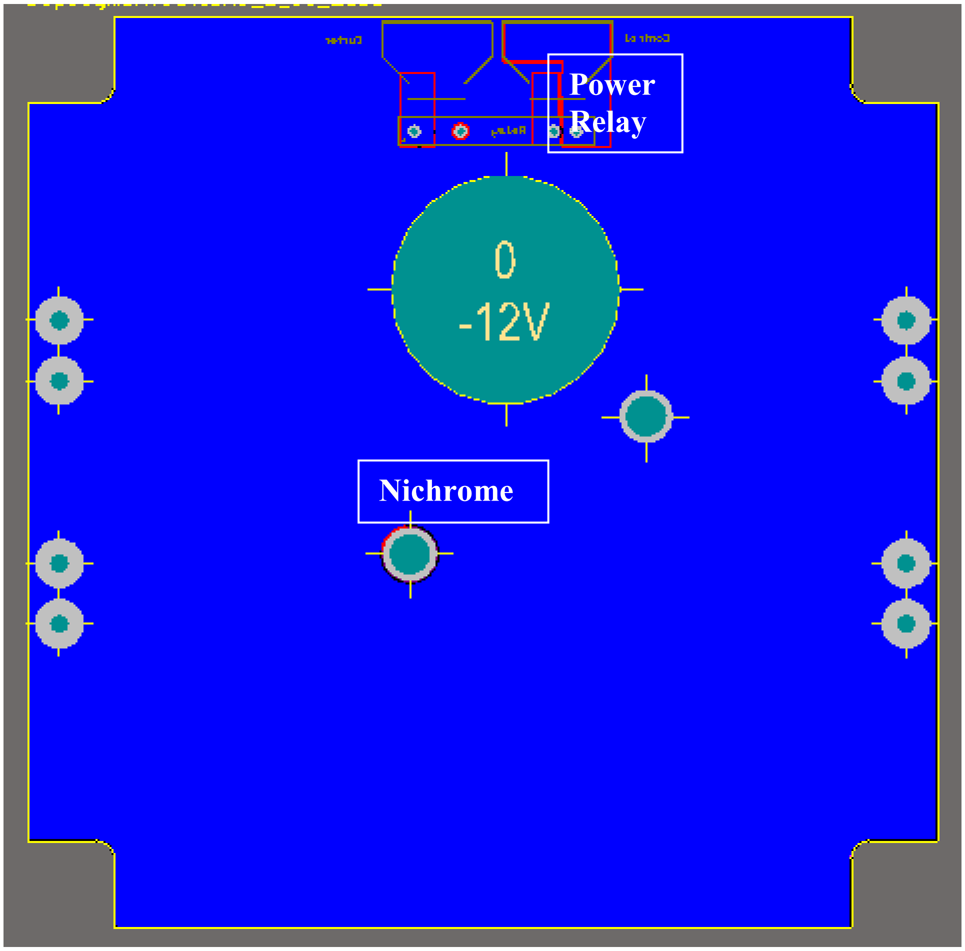


Figure 3.14: PCB layout for the deployment board.

3.5.3 Fabrication and Testing

Printed circuit board produced is all outsourced through Advanced Circuits. Once the printed circuit boards are acquired, however, the assembly of the different components of the KYSat-2 EPS occurs in-house. Testing and verification is handled in stages, starting with insolated testing to ensure that the performance of the EPS is reliable and meets the mission requirements. Once confirmed, the EPS is integrated with other KYSat-2 systems to ensure that the EPS is still meets mission requirements.

For the findings section of this thesis report, three key functions are measured and verified. First, the four high power outputs and the two low power outputs will have their characteristics measured and monitored to check the performance characteristics while under load. Second, the system must show charging capabilities and successfully charge the 3-cell battery pack and show effective cell balancing during charging. Finally, the deployment system must show that it was able to cut properly under power from the power management system.

3.6 Summary

This chapter presented the methodology behind the development of the KYSat-2 EPS. First, Chapter III outlined the overall design choices made for the key components of the KYSat-2 EPS. Second, methods and procedures for designing and producing the EPS were outlined. Finally, methodology behind testing and verification were discussed and will be further evaluated in Chapter IV.

CHAPTER IV

FINDINGS AND ANALYSIS

4.2 Output Characteristics

This section of Chapter IV details the finding concerning the ability of the KYSat-2 EPS to power other subsystems through its high power and low power outputs.

4.2.1 Output Efficiency

On the 3.3 V high power outputs, a series of 16 measurements were taken while the EPS operated while under a load. In each measurement the current draw from the load was increased and the output current and voltage was measured with respect to the source voltage and current used to power the EPS. Table 4.1, below, shows the data recorded.

For these results, the current draw on the 3.3 V high power output was stepped through 1.5 A, the pre-programmed current limit applied to the switch installed on the out. At low current modes, the output efficiency performed poorly, only achieving 25% efficiency. However, at 100 mA, the efficiency improved to nearly 70% and achieves a maximum efficiency of approximately 86% around 1.1 A. Figure 4.1, below, displays a graphical representation of the efficiency behavior.

High Power 3.3 V Efficiency						
Current (A)	Voltage (V)	Power (W)	Source Current (A)	Source Voltage (V)	Source Power (W)	Output Efficiency (%)
0.010	3.30	0.03	0.011	12.00	0.13	25.00%
0.099	3.27	0.32	0.039	12.00	0.47	69.17%
0.198	3.26	0.65	0.070	12.00	0.84	76.84%
0.298	3.25	0.97	0.101	12.00	1.21	79.91%
0.399	3.25	1.30	0.132	12.00	1.58	81.87%
0.498	3.24	1.61	0.162	12.00	1.94	83.00%
0.598	3.23	1.93	0.190	12.00	2.28	84.72%
0.698	3.22	2.25	0.220	12.00	2.64	85.13%
0.798	3.21	2.56	0.249	12.00	2.99	85.73%
0.898	3.20	2.87	0.279	12.00	3.35	85.83%
0.998	3.19	3.18	0.309	12.00	3.71	85.86%
1.097	3.19	3.50	0.339	12.00	4.07	86.02%
1.198	3.18	3.81	0.369	12.00	4.43	86.04%
1.297	3.17	4.11	0.400	12.00	4.80	85.66%
1.398	3.16	4.42	0.430	12.00	5.16	85.61%
1.498	3.15	4.72	0.461	12.00	5.53	85.30%

Table 4.1: High Power 3.3 V Efficiency

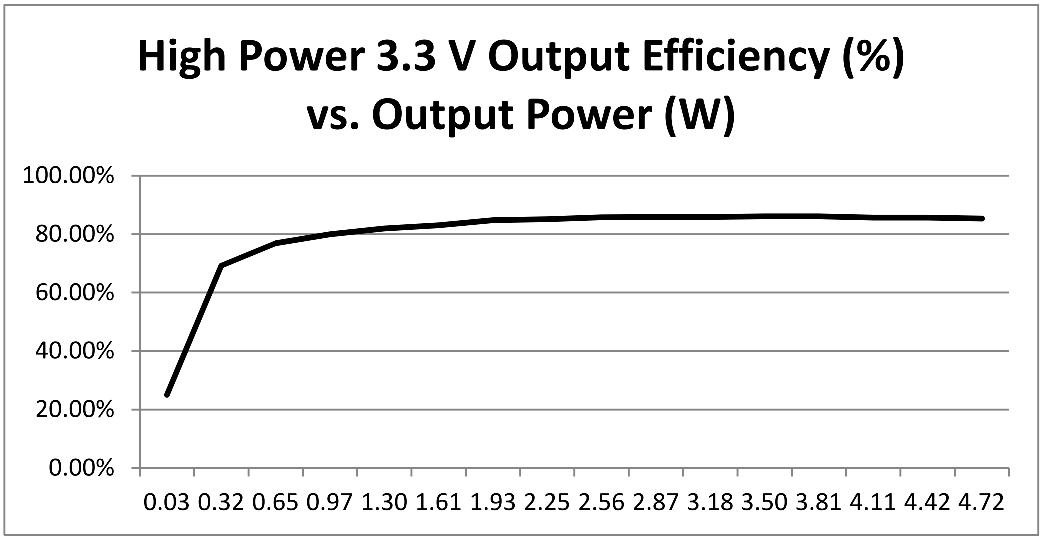


Figure 4.1: This graph displays the efficiency behavior of the 3.3 V high power output. The X-axis displays current in Amperes and the Y-axis displays the percent ratio of output power to source power.

Similar data was recorded for the high power 5 V output, except the current stepped through 1 A, which is the pre-programmed current limit for 5 V power outputs. Table 4.2 below displays the data.

High Power 5 V Efficiency						
Current (A)	Voltage (V)	Power (W)	Source Current (A)	Source Voltage (V)	Source Power (W)	Output Efficiency (%)
0.009	5.00	0.05	0.013	12.00	0.16	28.85%
0.099	4.97	0.49	0.054	12.00	0.65	75.93%
0.198	4.96	0.98	0.100	12.00	1.20	81.84%
0.298	4.95	1.48	0.145	12.00	1.74	84.78%
0.399	4.95	1.98	0.191	12.00	2.29	86.17%
0.498	4.94	2.46	0.236	12.00	2.83	86.87%
0.598	4.93	2.95	0.280	12.00	3.36	87.74%
0.698	4.92	3.43	0.323	12.00	3.88	88.60%
0.798	4.91	3.92	0.367	12.00	4.40	88.97%
0.898	4.90	4.40	0.412	12.00	4.94	89.00%
0.998	4.89	4.88	0.456	12.00	5.47	89.19%

Table 4.2: High Power 5 V Efficiency

The 5 V power output performed more efficiently overall, but still demonstrated efficiency issues at lower current levels. At 100 mA, the efficiency made a drastic jump to approximately 76%. This continued to improve, but began to plateau at approximately 1 A, where it nearly achieves a 90% efficiency. Figure 4.2, below, graphically displays the efficiency performance of the 5 V high power output.

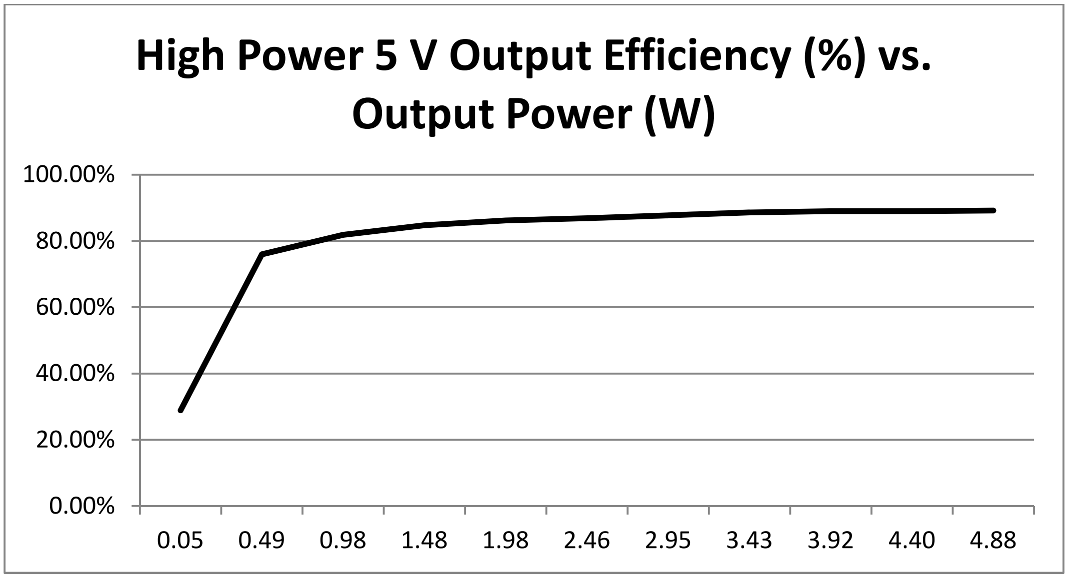


Figure 4.2: This graph displays the efficiency behavior of the 5 V high power output. The X-axis displays current in Amperes and the Y-axis displays the percent ratio of output power to source power.

The 3.3 V low noise, low power output has a much lower maximum power output and efficiency. Table 4.3, below, displays the data taken from this output.

Low Power 3.3 V Efficiency						
Current (A)	Voltage (V)	Power (W)	Source Current (A)	Source Voltage (V)	Source Power (W)	Output Efficiency (%)
0.009	3.29	0.03	0.018	12.00	0.22	13.71%
0.100	3.27	0.33	0.108	12.00	1.30	25.23%
0.128	3.41	0.44	0.139	12.00	1.67	26.17%

Table 4.3: Low Power 3.3 V Efficiency

The low noise output becomes unstable and unusable after the load current increase beyond 130 mA. Like the high power outputs, the regulator powering this out has worse efficiencies at lower current values and improves as it reaches its current limit. However, unlike the high power outputs, the max efficiency never improves beyond approximately 26%.

4.2.2 Output Noise

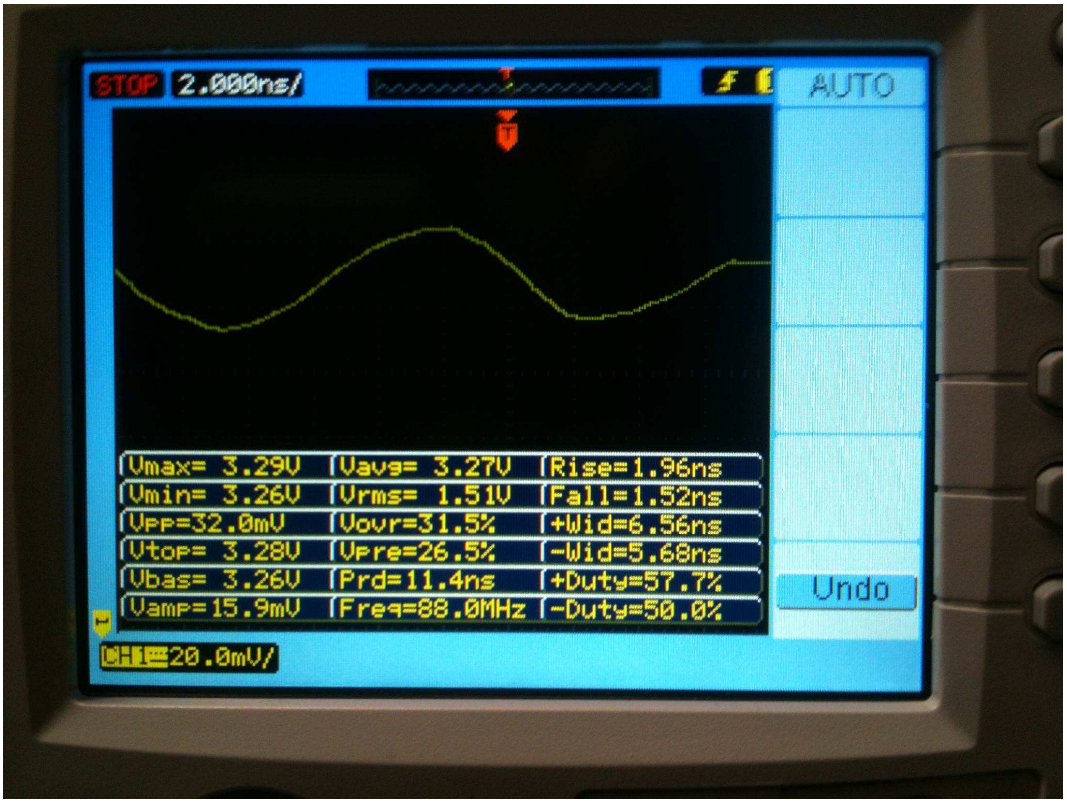
Table 4.4 displays the noise characteristics for each of the outputs on the KYSat-2 EPS.

EPS Noise Characteristics				
Vavg (V)	Current (A)	Power (W)	Vamp (mV)	Frequency (MHz)
3.3 V High Power				
3.27	0.10	0.33	15.90	88.00
3.25	0.50	1.63	18.10	61.90
3.22	1.00	3.21	33.30	85.30
3.16	1.50	4.73	41.30	83.10
5 V High Power				
4.97	0.10	0.49	24.10	N/A
4.96	0.50	2.47	22.60	84.70
4.91	1.00	4.90	32.60	75.30

Table 4.4: EPS Noise Characteristics

The important values to note in these results are the Power, Vamp, and Frequency values. In the 3.3 V output, the Vamp value increased as total power output increased. This Vamp value indicates the deviation in the average voltage value being seen at the output. The greater this value, the stronger the noise being generated. There was not as much deviation in the noise on the 5V output, however, the EPS is not currently designed to output more than 1 A at 5 V, therefore it became more difficult to determine a relationship. It did increase at substantially near the 1 A threshold, however, indicating this may be the case.

It is also important to note the frequency of the noise generated did not appear to show any relationship to the value of the power. Typically showing values around 80 MHz. Figure 4.4, below, demonstrates an example of the noise expected at the 3.3 V output at 0.1 A. Data is displayed on the bottom half of the oscilloscope screen showing characteristics of the waveform at the output when the system is under load.



```
Vmax= 3.29V   Vavg= 3.27V    Rise=1.96ns
Vmin= 3.26V   Vrms= 1.51V    Fall=1.52ns
Vpp=32.0mV    Vovr=31.5%     +Wid=6.56ns
Vtop= 3.28V   Vpre=26.5%     -Wid=5.68ns
Vbas= 3.26V   Prd=11.4ns     +Duty=57.7%
Vamp=15.9mV   Freq=88.0MHz   -Duty=50.0%
```

Figure 4.4: Oscilloscope display demonstrating the noise found at the output of the 3.3 V high power line. This particular measurement was done at approximately 1 A.

4.2.3 Integration to KYSat-2 System

Integration with the KYSat-2 flight computing system was successful, as the system was able to power the microprocessor system using both the low power and high power 3.3 V outputs. The flight computer was successfully powered with power being drawn purely from an engineering model battery pack. Data packets were acquired and transmitted from and to the flight computer indicating that noise was not a factor from the high power rails. Figures 4.5 displays the set up used for integration testing.

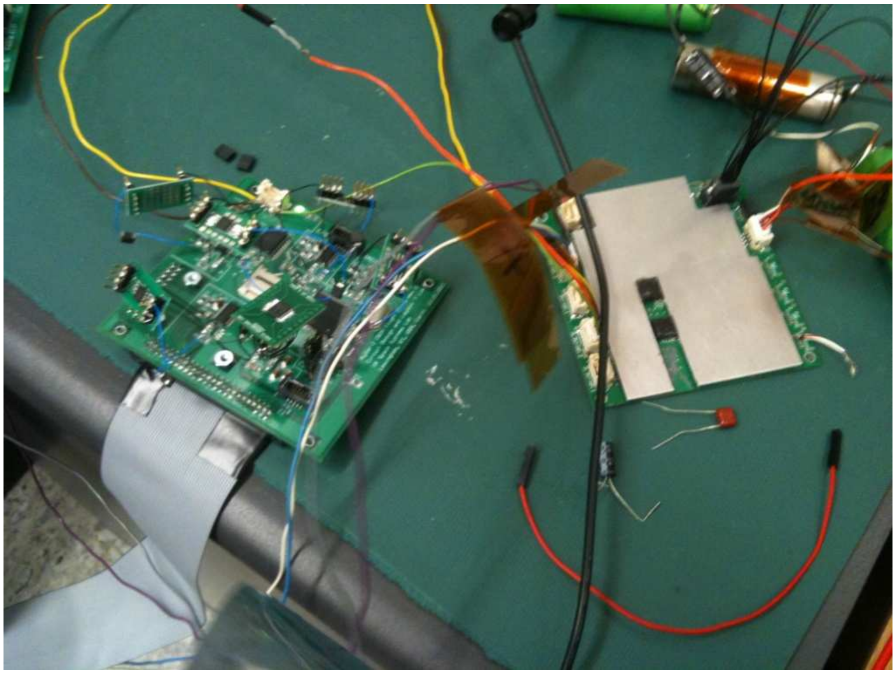


Figure 4.5: The power management board and engineering battery cells (on right) integrated with the KYSat-2 flight computer engineering model (on left). The EPS was able to successfully power on and communicate with the flight computer. The EPS was running solely on an engineering model battery pack.

4.3 Charging System Findings

In testing, it was found conclusive that the charging circuit was functional. The shunt which regulated the charge clamped the voltage ensuring that the battery pack received approximately 12 V to fully charge the battery pack. Also, the current monitoring circuits utilizing the INA230 devices correctly alarmed to the onboard MSP430 that current was being drawn when a voltage was applied to the solar power inputs on the power management board.

The balancing circuit was tested and demonstrated the ability to evenly distribute and correct charge when one of the cells on the battery pack was unevenly discharged and used in operation with the power management board. To simulate the effects of the EPS acting in an orbital environment, charging was allowed for a period of 60 minutes followed by a 30 minute period of no charging. This more accurately simulates the behavior of the EPS on orbit, where average orbits for low earth orbiting satellites tend to last 90 minutes with 60 minutes of each orbit receiving sunlight.

Another important finding was that the solar panels were effective at generating power. Due to the high cost of producing high efficiency solar panels, a test set was developed which utilized only one solar cell in conjunction with a series of jumped wires imitating a cell which completed a circuit but generated no current. When placed under a high wattage light source, the cell generated approximately 2.4 V, which if it were assumed equal voltage among 7 cells, would approximately equal 16.8 V, which has a very high voltage margin of nearly 30%, meeting the requirements of the solar panel design. Figure 4.7, below, displays this test set of solar panels.

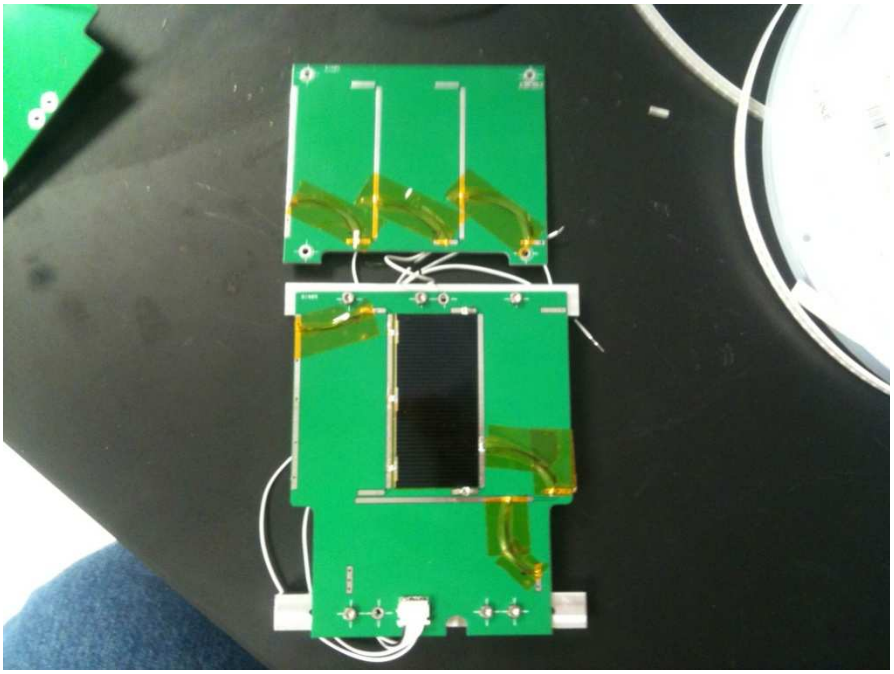


Figure 4.7: The test solar panel set used to simulate a fully populated solar panel set due to the high cost of production.

The layout of the solar panels allows for the satellite to generate 2-W continuous power per orbit. Comparing this to the minimum power requirements of all KYSat-2 subsystems per orbit demonstrates a power margin greater than 1-W. This means that the KYSat-2 EPS will meet the power requirements to conduct mission operation while on orbit.

Finally, the deployment board was fully tested using a 3-D printed model produced by Kentucky Space of the KYSat-2 system. The deployment board was successfully powered by the raw battery voltage supplied by the power management board and delivered enough current to the nichrome wire to cut the nylon line holding the solar panels closed. The solid state relay remained normally open until a 3.3 V signal was delivered at approximately 6 mA by the MSP430 microcontroller onboard the power management board. When the signal was received, the relay closed allowing current to the nichrome wire. This enabled the solar panels to be deployed. Figure 4.8, below, displays the completed deployment board.

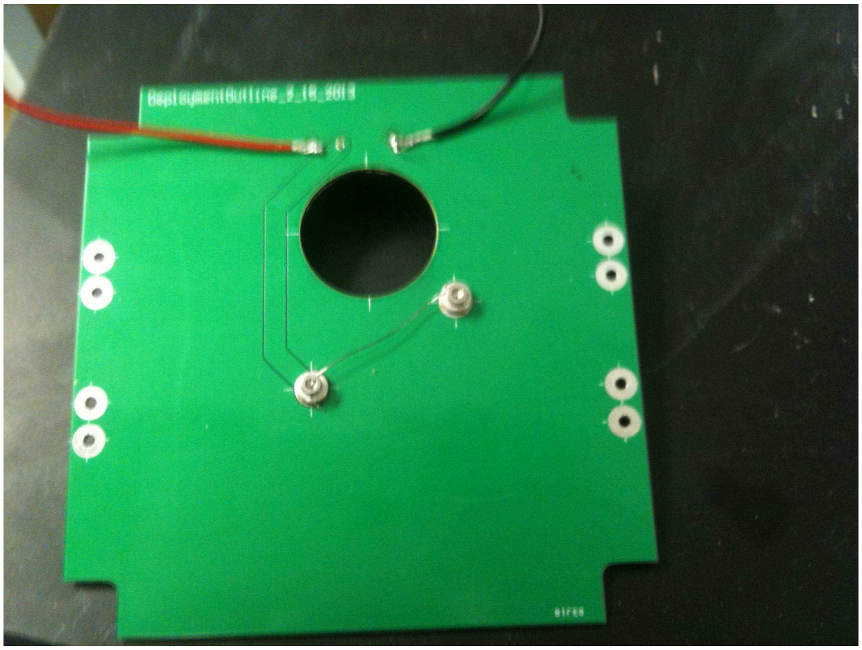


Figure 4.8: The completed deployment board for KYSat-2. The wires exist only for engineering purposes and are removed before launch. The solid state relay is unseen on the bottom side of the printed circuit board. The center of the board demonstrates the nichrome wire.

4.4 Summary

In this chapter, I presented the findings to the KYSat-2 EPS project where it currently stands. The findings showed that the outputs of the power system were able to effectively power other KYSat-2 subsystems designed by other KYSat-2 team members, that the charging circuit effectively charged the battery pack, that the solar panels were capable of producing adequate charge for the battery pack, and that the deployment circuit effectively deployed the solar panel system.

CHAPTER V

CONCLUSION

5.1 Discussion of Results

Currently, the electrical power system designed for KYSat-2 is showing positive results throughout testing. Data collected shows that the EPS complies with four fundamental facets of reliable EPS design. The EPS outputs high power and low power 3.3 V voltage and high power 5 V voltage. The high power regulation tended to show relatively low noise throughout its preprogrammed voltage range, however, if lower noise is required for any satellite subsystems, the low power regulator is a viable option, and is especially effective for logic applications, such as, powering microcontrollers.

The outputs tended to show high levels of efficiency with power received by the power management board from the high power outputs of the system, so long as approximately 0.5 W was being drawn by the load on the output. Below, the outputs demonstrated a drop on efficiency, which shows that these outputs may not be as effective in power management for low power needs.

Although it was not possible to populate and test a full set of solar panels due to the extreme cost of production at the time of this report, the simulated solar panel boards demonstrated positive results, demonstrating the solar cell installed generated a positive voltage margin relative to the number of cells installed. This indicates that the solar panel design should be able to adequate generate the positive voltage margin that was required for the battery pack determined at the beginning of the design phase for the EPS. The battery cells and charging circuit also showed positive results, demonstrating the EPS's ability to receive and store charge, and the power management board’s ability to balance the charge among the three series cells in the battery pack.

Finally, the functional test for the cutting circuit onboard the EPS confirmed that the nichrome wire received adequate current in the EPS system and effectively cut nylon wire allowed the solar panels to deploy.

5.2 Future Work

Relatively positive results were achieved during functional testing of the KYSat-2 EPS. Room for improve is still possible, however, should future revisions of the EPS system be desired prior for the launch of the KYSat-2 spacecraft. Investigation into the reasons for the low efficiency states of the high power outputs could prove to be beneficial into improving the system’s design. It is probable that the design of the regulators chosen for the output does not allow for higher efficiency at lower currents; however investigation into different regulators may yield more positive results across all power ranges. It may also be possible that the systems implemented around the regulator, such as the INA230 current monitoring devices and the programmable switch to activate the outputs may draw leakage current which affects overall efficiency at lower power levels. Research into these devices may also return more effective results for future iterations of Morehead State University CubeSat power systems.

Although most of the boards for the complete EPS system are completely tested and fabricated, the solar panels still require work to complete fabrication. The simulated panels yield positive results and are theorized to prove accurate, however more testing with completed panels should be required to confirm an adequate voltage margin will be achieved to charge the battery pack.

Finally, even though the EPS has been integrated with other KYSat-2 systems such as the onboard flight computer, a complete build of an engineering model of KYSat-2 has not been completed as of the time of writing of this report. This is essential to ensure compatibility both electrically and mechanically across the entire KYSat-2 system bus. This will occur over Summer 2013 in time for an estimated launch period of October 2013 for KYSat-2.

5.3 Summary

Design and analysis of the KYSat-2 EPS has shown great successes while still showing areas for potential improvement should research and design continue for potential future iterations. This design compliments past efforts of the Morehead State University Space Science Center in CubeSat system design and provides a method of power management, generation, and distribution for the challenge of low volume 1-U CubeSat design. By presenting the methodology of the design alongside with collected data and analysis, this report is able to demonstrate why the system is effective for the KYSat-2 mission. The objectives outlined in the first chapter of this report were achieved.

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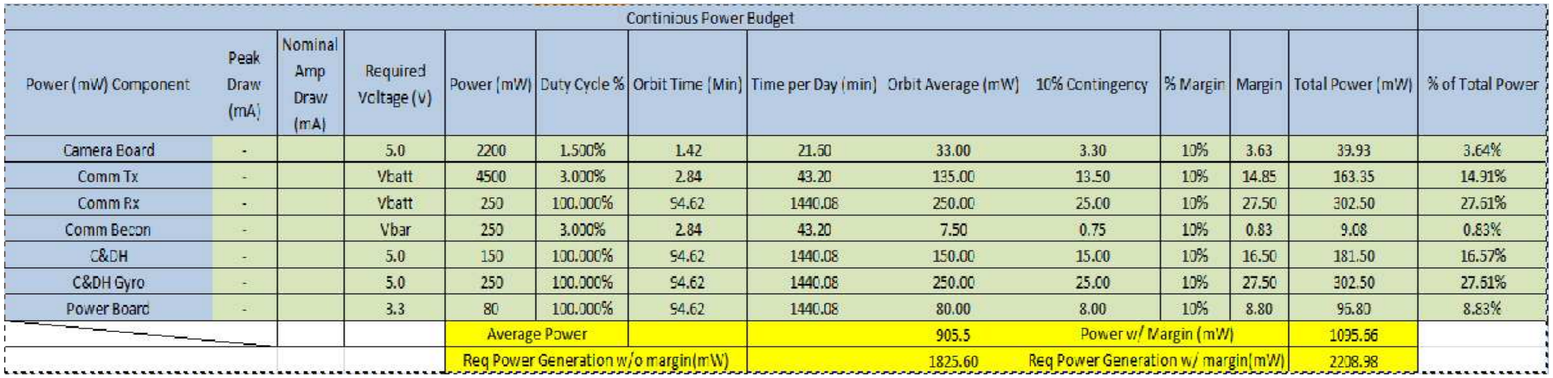
Appendix

Orbital and Period Parameters	
Orbital Altitude (Km)	500
Orbital Inclination	40.6
Orbital Period (min)	94.62
Total Orbital Period (sec)	5677.30
Eclipse Time (min)	35.96
Eclipse Time (sec)	3519.93
Eclipse Percentage	38.00%
Orbits per Day	15.22
Conversion Efficency (Sun)	0.8
Conversion Efficency (Eclipse)	0.8

Table A.1: Orbital and Period Parameters used in power budget calculations on KYSat-2.



Continious Power Budget														
Power (mW) Component	Peak Draw (mA)	Nominal Amp Draw (mA)	Required Voltage (v)	Power (mW)	Duty Cycle %	Orbit Time (Min)	Time per Day (min)	Orbit Average (mW)	10% Contingency	% Margin	Margin	Total Power (mW)	% of Total Power
Camera Board	-		5.0	2200	1.500%	1.42	21.60	33.00	3.30	10%	3.63	39.93	3.64%
Comm Tx	-		Vbatt	4500	3.000%	2.84	43.20	135.00	13.50	10%	14.85	163.35	14.91%
Comm Rx	-		Vbatt	250	100.000%	94.62	1440.08	250.00	25.00	10%	27.50	302.50	27.61%
Comm Becon	-		Vbar	250	3.000%	2.84	43.20	7.50	0.75	10%	0.83	9.08	0.83%
C&DH	-		5.0	150	100.000%	94.62	1440.08	150.00	15.00	10%	16.50	181.50	16.57%
C&DH Gyro	-		5.0	250	100.000%	94.62	1440.08	250.00	25.00	10%	27.50	302.50	27.61%
Power Board	-		3.3	80	100.000%	94.62	1440.08	80.00	8.00	10%	8.80	95.80	8.83%
				Average Power				905.5	Power w/ Margin (mW)			1095.56	
				Req Power Generation w/o margin(mW)				1825.60	Req Power Generation w/ margin(mW)			2208.38	

Table A.2: Required continuous power budget for KYSat-2 during mission lifetime.