Power Subsystem Design for the Montana EaRth Orbiting Pico-Explorer (MEROPE) Cubesat-class Satellite [1][2]

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Abstract— Montana State University's Space Science and Engineering Laboratory (SSEL) under support from the Montana NASA Space Grant Consortium is engaged in an earth orbiting satellite student project that will carry a reproduction, using current-day technology, of the scientific payload flown on Explorer-1 in 1958 into a 650 km sun-synchronous polar orbit. The off-the-shelf emphasis of the MEROPE component selections has required the power system to adapt to widely different electrical needs across subsystems. The size limitations of the Cubesat-class specifications confine body-mounted solar arrays to approximately 64 cm^2 per side, restricting overall power production and necessitating the use of an extremely efficient power bus. MEROPE will employ dual-junction GaAs solar cells (19% efficiency) to produce the 5W necessary for satellite operation and battery maintenance. Included in the system will be two Li-ion battery cells chosen for their high energy density, rapid charge characteristics, low mass, and lack of memory effects. The power system is responsible for providing a highly regulated 5 V bus to the microcontroller subsystem and a 6 V bus to the communication subsystem. In addition, the Geiger tube scientific payload aboard MEROPE requires a stable 500 V high voltage power supply (HVPS) to operate the experiment. This will be accomplished using a prototype HVPS requiring +/- 5 V busses. This paper describes the challenges and solutions involved with powering a successful scientific mission within the boundaries of the CubeSat-class design specifications.

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1. INTRODUCTION

The CubeSat concept is a program conceived by Professor Robert Twiggs of Stanford University's Space Systems Development Laboratory to expose students to all aspects of satellite design, manufacture and operation [1]. Ideally intended for university master's degree programs, CubeSats are planned to go from design through construction and testing of a finished product within approximately a one-year timeline. The design constraints of the CubeSat concept limit the total satellite mass to 1 kg and the total volume to 1 liter within a 10 cm cube. One Stop Satellite Solutions of Ogden, Utah, has arranged a launch for 18 individual CubeSats as a secondary payload aboard a Russian Dnepr rocket (converted SS-18 Inter-Continental Ballistic Missile), with a launch window now slated to open in May, 2002.

The Montana EaRth-Orbiting Pico Explorer (MEROPE) is the Montana Space Grant Consortium's (MSGC) CubeSat program, being built by the Space Science and Engineering Laboratory (SSEL) at Montana State University in Bozeman. MEROPE is being constructed on a low-cost budget of less than $50,000, including launch, by using mostly off-the-shelf hardware. MEROPE's four-month mission will be to map the Van Allen radiation belts using a Geiger tube, repeating the 1958 experiment of Explorer-1. For a complete description of MEROPE's mission and subsystems, please see [2].

To accomplish this mission within the CubeSat design restraints, an innovative, simple, robust and reliable power system must be constructed. In the first section of this paper an overview of the power system is provided, with discussion of the major concerns and obstacles faced during design, construction and operation. Subsequent sections describe implementation of power generation, voltage conversion and regulation, and power storage, respectively. Finally, unresolved issues and future work yet to be completed will be reviewed.

[2] IEEEAC paper #197, Updated Dec 05, 2001

2. Power System Overview

Summary

While MEROPE will be in a 650 km sun-synchronous polar orbit, the exact orbital characteristics will not be known until well after construction is completed. Therefore, the power system design is incorporating both solar panels (see section 3) for power while MEROPE is in sunlight and batteries (see section 5) for storing and providing power when MEROPE may be in the Earth's shadow. Keeping the satellite powered in the dark adds considerable complexity to the design, since the power system must be responsible for determining the power level of the batteries and maintaining them at an adequately charged level.

In addition, the power system is required to provide several different voltage busses (see section 4) to different subsystems within MEROPE and to distribute power throughout these subsystems (see section 6). Regulated busses to the computer systems [4] and payload are essential for a successful science mission. Other duties assigned to the power subsystem are determining which solar panels are active at any given time (for attitude control analysis) and cycling of the communications subsystem on and off to conserve power.

Major Concerns

Design of the power system for the MEROPE CubeSat involves special considerations. This system requires the functionality of a complete, self-contained power cycle, on which larger satellites spend as much as 50 percent of their mass budget, in about 100 cm^3 volume and less than 300 grams total mass. The unique challenges presented by these constraints require innovations and use of materials that have yet to be tested aboard other satellites. The result is that MEROPE will test Lithium-Ion batteries with dual junction GaAs solar cells to power a series of switch mode DC-DC converters more commonly found in cell phones.

In designing the power system, the characteristic of greatest concern is the efficiency of each system. The efficiency dictates the volume and mass necessary for the power system and limits the operational capabilities of the satellite. The DC-DC converter and the battery charging circuit efficiencies cause the greatest concern. Efficiencies less than 70% cannot be tolerated and cause the power system to become unreliable. The conversion efficiency of the solar cells is also of great importance. The solar cells generate the power, and given the size of a CubeSat-class satellite, are the limiting factor in the power system design. Therefore, the highest available efficiency should be used. However, other concerns, such as cost, change this view and will be discussed later.

The ability of the components of the power system to withstand the environmental stresses they will encounter produces the next concern. The components must withstand temperatures as low as –40 °C and as high as 85 °C. They must withstand several times the force of gravity on launch (up to 16 g [3]) and operate in a high radiation vacuum environment for a minimum mission lifetime of four months. In addition to the environmental electromagnetic pollution, the noise generated by the power system, communications array, flight processor, and payload must not affect the operation of the power system. This can be accomplished by, and indeed necessitates the use of shielding, filtering and proper component selection.

Next, the actual physical characteristics of the power system components must be examined. This amounts to another type of efficiency, though of slightly lesser importance. Mass, volume, and printed circuit board (PCB) footprint are the characteristics of concern. The mass must be minimized to allow for the power system to be complete while allowing mass for the remaining systems and maximizing the quantity of mass available to the scientific payload. Alternatively, minimizing the mass of the system can result in a larger mass budget, which can then incorporate greater redundancy or shielding for the power system thereby improving the system. The volume of the power system must also be minimized. With less than a liter to work with inside the CubeSat, space becomes of great concern. Additionally, due to the batteries and multiple individual circuits plus connecting wires the power system occupies a great deal of the available space and wastes a fair amount by necessity. Finally, the power system must fit the majority of its circuitry on a single PCB shared with the passive magnetic attitude control stability system and the scientific payload of MEROPE. Thus, the PCB footprint, the area occupied on the PCB by the component and its connections, must be minimized. This has been one of the more difficult tasks of the project and has resulted in the need to spend a great deal of time working specifically on the arrangement of components on the power PCB and the satellite in general.

Another physical characteristic demanding consideration is the heat dissipative capacities of the components. Depending on how much heat each component generates and the ability of it to shed the heat or tolerate operations at an increased temperature, the location and spacing of the components are dictated. Additionally, the amount of heat generated and where it is located in the satellite can be used to help warm components that are sensitive to the extreme cold the satellite systems will encounter. Conversely, systems that are sensitive to high temperatures must be placed more distant to the high heat components.

Table 1. Total Power Draw per Component

Item	Voltage	Current	Conversions (70%)	Total Power Draw
TNC	8V	55 mA	1	630 mW
Receiver	6V	150 mA	1	1286 mW
CPU	5V	60 mA	1	429 mW
Pulse Shaper	5V	15 mA	1	108 mW
Payload HVPS	+/- 5V	67 mA (Total)	1	480 mW
Sub-Total				2933 mW
Transmitter (est.)	6V	350 mA	1	3000 mW
Monitoring/Line Losses(est.)				300 mW (~5%)
Worst Case Total (est.) Transmitting				**6230 mW**
Off Cycle Total (est.)				**1075 mW**

After considering the individual characteristics of the components, a general overview of the entire power system including the loads must be evaluated. For the MEROPE satellite, the power system cannot generate enough power to run all the systems all the time. The communications package (terminal node controller (TNC), transmitter, and receiver) draws nearly 65% of the power load when not transmitting and twice as much when transmitting (see table 1). To ensure that the satellite will have enough power to run in eclipse and to run the communications package, a cycling system has been devised (see section 6). Additionally, the charging circuit for the batteries functions as a "power sink." This will allow enough power to operate the satellite, charge the batteries and transmit data when queried.

The final major concern in developing a power system for a CubeSat-class satellite is the robustness of the system. The power system must be able to recover from a shut down and eventually bring the satellite back to normal operations. If the mission fails due to a mechanical failure, the goal is to make sure that power is not the responsible subsystem. The difficulty of accomplishing this with the enormous power requirements is daunting. However, with a simple logic gate the power system becomes independent of the flight processor for determining whether to charge or run on batteries. The switches that are controlled by the logic gate open the batteries to the converters when there is a power failure. This allows the system to operate independent of CPU control and allows it to function as a self-contained unit. The other half of robustness, redundancy, cannot be utilized extensively in this satellite class. However, the most important chips on the power system, the DC-DC converters, have a little redundancy. A single chip on the 5V and 6V battery bus or 5V solar bus may fail and the system will still operate.

3. Power Generation

The MEROPE satellite generates power through the use of photovoltaic cells. Initial considerations focused mainly on finding the maximum efficiency available. Size, cost, and total coverage were looked at afterward. This constraint was mainly a result of the limited area available for non-deploying solar cells. Non-deploying solar arrays were selected for their simplicity and ruggedness. The satellite is only stabilized passively along two axis of motion, spinning about its third. This would make a deploying solar array that had to be aimed at the sun impractical and would have required redesign of the entire stability system. Finally, with the fixed solar arrays, overall mass of the system is kept to a minimum.

Therefore, the maximum per side available area was ~80 cm^2 with the intended shape a 20 mm X40 mm cell. Eight would be used on each side with four series groups of two in parallel. Actual use per side though is much lower considering some sides contain objects that would interfere with the maximum area, such as antenna deployers or the Geiger tube viewing window.

This led to the selection of triple junction GaAs solar cell technology. Next, suppliers were looked at and asked for prices for varying types of cells. The special-order cells required were prohibitively expensive to produce for the satellite. Some solar cells were found to have a shape (37mm X 76mm) difficult to integrate into our design. This would allow for only two cells per side. Additionally, the unavailability of cells manufactured with the backing and cover glass attached prior to purchase (CIC's) narrowed the search.

Finally, Spectrolab Dual Junction solar cells manufactured into CIC's were selected. These cells are ~19% efficient but with a size of 31.242mm X 69.088mm, three cells could be fitted on four sides while due to obstructions, the other two sides have two cells.

The total estimated power generated by the system, taking into account efficiencies, is listed in Table 2.

Table 2. Total Power Generation (Best Case)

# of Sides in Sun	Solar Power Generated (W)	Albedo Power Generated (W)
1	1.67	.450
2	2.36	.637
3	2.505	.676

Three solar cells will be in series generating a total of 6.12V per side at the above powers. With the Spectrolab dual junction cell CIC's, a diode to prevent inactive cells from becoming a power drain is integrated into the package. The two sides with two cells each will have the 4.08V generated stepped up to 6.12V by a MC34063 converter (see below).

4. Voltage Conversion and Regulation

DC-DC Converters

The MEROPE power system primarily consists of switch mode DC-DC converters. These have been through several system designs and after much work are now based around the On Semiconductor MC34063A-D multifunction DC-DC controller and the On Semiconductor CS8321 low dropout linear regulator. The converters will provide 5V, -5V, 6V, and 8V buses for the other flight systems. Each bus requires separate chips for the solar cells and the battery circuit. Additionally, some buses will require multiple chips to run the bus.

The primary difficulty results from finding DC-DC converters of a high enough efficiency to allow the satellite to operate with a minimum waste. Ten companies were reviewed. Unfortunately, we were unable to get the first choice chips to perform at their specified efficiencies and at the output currents they are rated to source. Extensive testing indicated that the chips were 40% efficient while running at the maximum current they could source, 50mA. This was in stark contrast to the design parameters. They should have been able to source up to 10A at 80% efficiency even with the voltages being used by the satellite.

This led to some redesign and On Semiconductor MC34063A-D converter chips were selected. These chips must be individually designed for the input and the output voltages. Additionally, they must be designed to account for step up, step down, step up/down, or voltage inverting operations. The increased design work and specificity of the individual design reduces the modularity of the entire power system. Originally, the system was to be a basic off the shelf power system for future CubeSats from Montana State University (see section 7). This goal is still very elusive from the view of taking a power system off a shelf and placing into the satellite to fly immediately. The other chips would have brought this goal closer since they functioned as a step up/down without any extra design.

The On Semiconductor chips however have several significant advantages over the other chips. First, they have an integrated transistor switch built in the chip. This is more reliable than using the external transistor. Primarily, preliminary tests show the internal transistor works better in the environment in which we intend to operate the system. Second, the On Semiconductor chips have fewer external components and occupy a smaller total footprint per chip. This allows multiple chips to be used for each bus, which provides a limited redundancy to a system in which zero redundancy is the norm. Third, due to the very nature of the increase in design work, only one chip model (note: not chip family) is used for all voltage step up functions. This greatly simplifies the design work and actually accomplishes more of the "off-the-shelf" goals. For the 5V bus, a fully self-contained low dropout linear regulator chip (CS8321) has been selected to step down the 6.1V solar cell bus. These chips operate with a minimum dropout of only 300mV making them relatively efficient for MEROPE's operations.

In general, the inductor selection for the converters has been the absolute most critical step in design of the DC-DC converters. Initial testing with RF choke type inductors showed varying results. In the Maxim chips, the regulation voltage was never reached. However, it regulated the voltage well at around 2.5V. The On Semiconductor chips recorded an opposite result. They reached the design regulation voltage but could not maintain the voltage under any load. This was corrected by using low ESR shielded power inductors from Central Technologies. The CTCDRH74 Series in the 5% (J) tolerance were selected to operate the MEROPE power systems.

To operate the buses with these chips requires multiple chips for each bus. The chips have tested capable of sourcing up to 400 mA from the solar cell voltage and 350 mA from the battery voltage. Additionally, the solar cell and battery based converters must be separate to prevent waste and generation of excess heat if both the batteries and solar cells are to be able to run at the same time. Thus to provide the various bus voltages, two CS8321 LDO regulators will provide the 5V bus while operating on the solar arrays and two MC34063 will provide power to the bus while operating on batteries. The 6V bus will be unregulated on the solar array bus. This can be done for two main reasons. One, solar cells produce a relatively stable output voltage and two, the systems using the 6V bus all have built-in regulators so regulating this bus would be inefficient. While operating on the batteries, two MC34063 converters will provide power. The 8V bus will be generated by one MC34063 on the solar array bus and one MC34063 on the battery bus. Finally, the –5V bus will be generated using a MC34063 in its inverting configuration. Since the power for this regulator is drawn from the 5V bus, a single converter will be used for both daylight and eclipse operation. This power plan provides good redundancy in the voltage conversion circuit. Although they would be hard taxed and prone to a sooner failure, the 5V solar array bus, 5V and 6V battery bus converters can suffer a single chip failure and still allow the mission to continue.

Filtering

Although the On-Semiconductor chips are relatively noise free for our design, filtering has been considered to assist in stabilizing the system. Currently, only simple capacitive filters are being used on the input and output connections of the converter chips. We believe this is sufficient for our system. However, a fourth order filter package for the flight processor has been designed. This design would require little modification to adapt to using as a bus filter, after all the converter outputs have linked back together. Tests of the system while operating the load in a thermal vacuum chamber will indicate if this is necessary. Additionally, the effects of radiation on noise generation are being studied. Budget allowing, a full-scale power system will be subjected to radiation exposure over time and be periodically tested for function.

The power system generates noise in the RF range. The inductors in the converter design produce this "switching" noise. To reduce the noise pollution within the satellite, shielded inductors are being used. This also prevents the communications package from causing upsets in the power system by interfering with normal operation of the inductors during transmission.

5. Power Storage

Battery Choice

The batteries for MEROPE store the power generated during the day to allow the satellite to operate during eclipse. Therefore the batteries are of major concern during design. Three types of rechargeable battery are predominant today, NiCd, NiMH, and Li Ion. Although NiCd has generally been used for space applications due to good robustness and high cycle life, it has a low energy density. The batteries are much too heavy and large for use in a CubeSat-class satellite. NiMH batteries are beginning to see more space applications. These batteries have improved energy density and specific energy although they are still relatively heavy for a CubeSat. Though not generally tested, Li Ion batteries provide the best qualities for this mission.

Li Ion batteries have high energy densities and high specific energies. They are relatively easy to produce in prismatic rather than cylindrical packs and also have a higher per cell voltage than NiMH and NiCd. This makes them ideal for a CubeSat. The detriments to these batteries are that they are more expensive, harder to find, require specialized charging circuitry, and have a slightly reduced cycle life. For a CubeSat, the reduced cycle life is acceptable considering the initially shorter mission life and the specialized charging circuit improves charging efficiency and is therefore worth the additional mass.

MEROPE will use two Polystor prismatic Li Ion batteries. These cells are ~42 g, produce 3.7 V nominal, and have a capacity of 1350 mAh. By being two separate cells in parallel, the volume allocated can be taken from various parts of the satellite, helping with overall placement issues. The final placement of the batteries is shown in Figures 1 and 2.

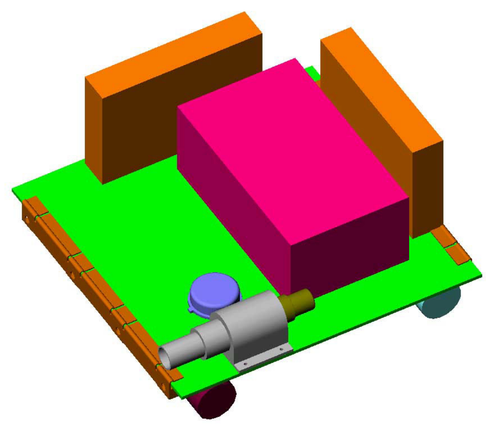

Figure 1 - MEROPE power PCB component layout. The two Li Ion batteries can be seen along the top two sides. The Geiger tube is located in the bottom corner, with the pulse-shaping chip next to it and the HVPS between the batteries.

Battery Charging

The battery charger circuit is designed to allow the Polystor Li Ion batteries to be fully charged and maximize their lifetime. The battery charger is centered on a Maxim IC MAX1757 switch mode variable charger chip. All functions necessary to charge the batteries are contained within the chip. The chip additionally monitors the power draw from the load and allows the batteries to be charged with the difference between load draw and a preset maximum. With the actual generation of power differing from moment to moment, a MAX4372 current sense chip will be used to monitor the power generation by the solar cells. Since the maximum total power draw allowed is based on a voltage that is set on the MAX1757, the MAX4372 will vary the voltage to produce a varying maximum. This allows the CubeSat to sink all excess power into the batteries whereas other configurations would waste power.

The maximum power the chip can send to the batteries is 1.5 A, 4.2 V in the configuration used for MEROPE. This charger will run at ~70 % efficiency. It will require a minimum 6 V input and use the same shielded inductors as the DC-DC converters. This system cannot talk to the CPU but runs independently of the other systems. Since the solar bus operates at 6.1V, no voltage converters will be necessary to operate the battery charger.

The batteries will not be charged at the same time as they are providing power to the system load. This allows the batteries a longer life and ensures the batteries will charge only when enough power is generated by the solar cells. To prevent the need for CPU control, the operation of separating the batteries from the system will be handled by a logic gate array controlling a pair of solid state switches. The logic gate array will consist of a three input AND and a logic inverter. A sensor will relay a binary input if there is enough power, if the radio is active (from CPU) and if the antennas are being deployed (from CPU). The sensor will be built from a MAX4372 that feeds into a MAX6064 Precision Voltage reference to generate the binary output. The switches will work in opposite, if one is active the other is inactive. This will be accomplished using Texas Instruments, TPS2085 (active HI) and TPS2087 (active LO) solid state power switches.

6. Power Distribution

Source Selection and Power Monitoring

Proper distribution of power is key to the success of the MEROPE mission. The power system is literally tasked beyond what it is capable of generating when all systems are in operation. Therefore several key procedures were implemented to allow the power system to function and the mission to succeed.

First, the power generated by the solar cells must be monitored to keep from crashing the system by asking too much of it. The power generation is monitored at each side and at the "power trunk" where all the lines from the sides are brought together. In the first case, the output signal is binary. This method allows the stability of the satellite to be monitored when the solar cell is active by attaching a current limiting resistor behind the 3rd solar cell and feeding this voltage into a CPU pin. Although this method saves power waste, it cannot distinguish between activation by sunlight or albedo.

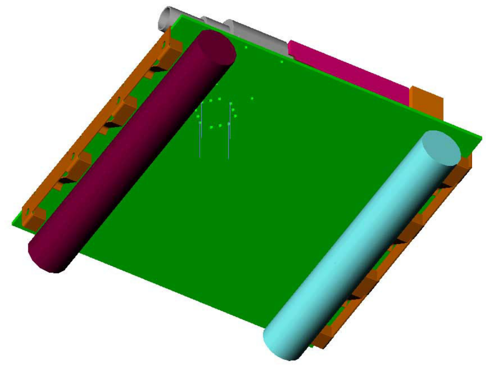

Figure 2 - Bottom side of the power PCB. The attitude control magnets and damping rod occupy opposite sides.

Next, the power trunk is monitored through an analog system. Once again a MAX4372 is used with a series resistor on the trunk. This however is sent to the CPU as an analog signal, which enters one of the A/D converters. Given the greater robustness of the CPU A/D, a 0 V reading will represent no power generation while a 5 V will represent full maximum expected power generation (~3.2W).

At this time, no power monitoring of the batteries is planned. By the mission design, we will know if the batteries do not work and also in-flight modifications cannot be performed if a problem occurs.

Power Saving Method

To save power, the MEROPE will cycle its receiver, transmitter, and terminal node controller on and off. The cycle is expected to be one minute on and six – seven minutes off. This allows enough power to charge the batteries while still allowing the satellite to be contacted by the ground station. If the ground station contacts the satellite, it will keep the communications package on until it finishes its downlink of data [5]. It will then resume the cycling. Given that communications is about 65% of the power budget, this produces significant savings.

7. Unresolved Issues and Future Work

Testing

With construction nearly completed on MEROPE, the testing phase has already begun. Before the late Spring 2002 delivery date to One Stop Satellite Solutions numerous systems tests will be performed on the flight model. Included in these will be bench tests where each system prototype is connected to the power system to test compatibility and successful operation. Next will be to combine all subsystems into the final flight model and continue compatibility testing through various environmental and mechanical stresses. Thermal and vacuum tests will be conducted on the flight model as well.

Modularity

After testing is complete and MEROPE is delivered for launch, a review of the current power system design will be conducted to determine which areas can be reduced in mass, volume, or power consumption and where improvements in efficiency can be made. Another goal of the power system review is to attempt to design a new system allowing for nearly total modularity for future missions. An "off-the-shelf" power system, which is adaptable to different choices of payloads and other subsystem components, would save time and money lost in redesigning each satellite for every mission. Designing a newer version of MEROPE's power system that could be simply modified to handle any mission would greatly enhance the usefulness, development time, and viability of a CubeSat-class satellite for space missions, making it a worthwhile goal for the future.

8. CONCLUSION

The Montana EaRth Orbiting Pico-Explorer is utilizing an innovative, robust power system which will allow the other subsystems and payload to operate at optimal levels. Included in the system are solar cells, Lithium-Ion batteries, and various regulation and distribution components individually chosen for their reliability and ability to fit within the constraints imposed by the mission itself and the CubeSat-class limitations of 1 kg total mass in 1 L total volume. Future improvements should only make this system sturdier, more powerful, and more modular to accommodate upcoming missions.

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