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Picosats as Payload Carriers

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Abstract. MEROPE, the Montana State University Earth orbiting student satellite is currently scheduled for a November 2002 launch. The notion of building a fully-functional, 1-kg, 1-liter satellite is a very challenging one. Since design and construction began in early 2001, the low mass and low volume constraints have driven the need for difficult tradeoff decisions. In the process, much has been learned about the power, telemetry, weight, and volume allocations that could realistically be provided to a third-party payload using the picosat as a complete, prefabricated system bus. This paper will address the lessons learned in the effort of creating a generic picosat that would provide a known amount of power, radio communication, and designated volume. Included with this baseline model would be the flexibility to tailor subsystems to meet the needs of a specific payload. In this way, inexpensive carriers would be made available to pico-sized experiments with a shortened lead-time to launch, with design, construction and much of the bus testing time eliminated.

Introduction

The Montana EaRth Orbiting Pico Explorer (MEROPE) is part of the international CubeSat concept first conceived by Professor Robert Twiggs of Stanford University.[1] It is being built by the Space Science and Engineering Laboratory (SSEL) at Montana State University in Bozeman under support from the Montana Space Grant Consortium (MSGC). It is scheduled to launch from Baikonur Cosmodrome aboard a Russian Dnepr rocket in November, 2002.[2]

Several goals are to be fulfilled by the MEROPE mission. MEROPE's scientific mission is to re-measure the Van Allen radiation belts, first discovered by Explorer 1 under the direction of Professor James Van Allen's group of the State University of Iowa (now The University of Iowa). A miniature Geiger tube and associated electronics will survey the flux of geomagnetically trapped electrons and protons in the Earth's radiation belts. MEROPE's engineering goals consist of space-rating hardware, especially a high-voltage power supply provided by Southwest Research Institute, and proving the concept of a passive magnetic attitude stabilization system in a satellite as tiny as a CubeSat.

As a Space Grant Consortium project, though, MEROPE's primary goals are educational. The opportunity to design and build actual satellite hardware has been an invaluable learning experience for the nearly 75 students who have been involved with the project. The difficulties encountered throughout design and construction present problems with solutions that are not taught in the classroom.

Throughout the year and six months of the MEROPE project, it has been realized that Cubesats are capable of performing a wide range of missions, from science experiments to hardware testing and space rating. Yet, designing an innovative, scientifically meaningful experiment within the CubeSat constraints of 0.001 m^3 of volume and mass of 1 kg in under a year as originally planned is difficult. The attempt by the MEROPE team to do so has led to numerous lessons learned and project subtleties that may help other student satellite projects be completed quicker. This paper details many of these observations, beginning with the structural and power constraints, and ending with how these constraints affect the design of other subsystems. Over the course of this endeavor, an appreciation has been gained for the capability of CubeSat-class as payload carriers.

Structural Constraints

The primary driver of the MEROPE design was the structural stipulations. CubeSat size and mass requirements have been established in the launch contract with One Stop Satellite Solutions (OSSS). All CubeSats on the current mission must fit into a 10 x 10 x 11.4 cm volume inside the Poly Picosatellite Orbital Deployer (P-POD), the deployment vehicle designed by a team at California Polytechnic State University (CalPoly). CubeSats must weigh no more than 1 kg and have a center of mass within 2 cm of their geometric center. There is a 0.65-cm allowance for clearance space on each side of a CubeSat. Lastly, each CubeSat must be equipped with a kill switch and remove-before-flight (RBF) pin. The kill switch ensures that power is off in the CubeSat while inside the P-POD. When inserted the RBF pin prevents power in the CubeSat. After these considerations were taken into account, other subsystems could begin to be designed to fit within the given structure.

The decisions of the MEROPE CubeSat structure itself were driven not only by the above structural and mechanical requirements, but also by a design philosophy which tried to balance the following three criteria: (1) the structural chassis should provide maximum inner volume and minimal weight without overly compromising strength, (2) the chassis-subsystems interface should remain as flexible as possible to allow for modifications in subsystem design, and (3) the chassis should accommodate commercial-off-the-shelf mechanical components (i.e., kill switch and RBF pin) to maximize reliability and minimize design time.

From strength considerations, we decided to use Aluminum 7075 for chassis material and all-metal micro-mini locknuts for chassis fasteners. In an effort to maximize modularity and flexibility in subsystem component placement, PC cards and card retainers were chosen to secure components to the MEROPE CubeSat chassis. PC cards and retainers make efficient use of limited space and are easy to move, thus are very flexible to changes in component placement.

The current MEROPE CubeSat chassis design consists of four identical side panels fastened together with screws and all-metal locknuts, and a top and bottom attached with screws. To maximize flexibility in the design, we chose to use a CNC mill for fabrication. The redundancy in side panel design and use of the CNC lessened development and fabrication time and increased the assembly's relative simplicity. The systematic fabrication procedures involved in our design allowed the production of multiple CubeSat chassis's for prototyping, flight, and a future mission. The side panels were milled in a vacuum chuck on the CNC from a 1.6 cm-thick aluminum plate. Material left on the panels during the milling process provides tabs (i.e., areas of thicker material) for fasteners. A before and after view of the panels during constructions is shown in Figure 1.

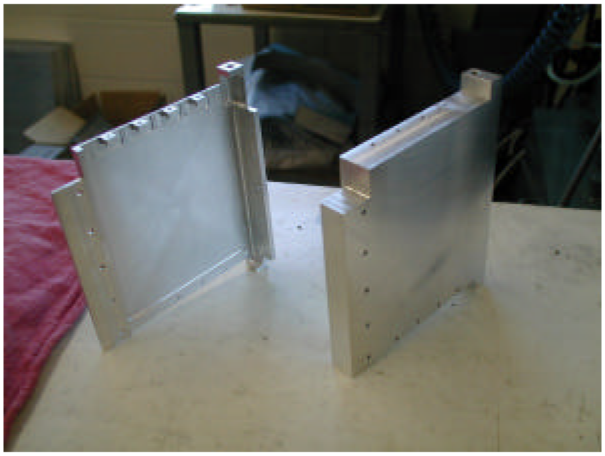

Figure 1. MEROPE side panel before and after CNC machining.

There are many advantages to the current CubeSat structural design. The current chassis design is simple (consisting of three *different* parts) and uses off-the-shelf mechanical components for the kill switch and RBF pin. This reduces the chance of mechanical failure. The structural design has thus far been very flexible and adaptable to changes in subsystem design. The current fabrication procedure using the CNC mill is much faster and easier than non-computerized fabrication methods. This coupled with the simplicity in design makes possible the production of multiple CubeSat chassis's. Without the need for final "dusting" on the mill, the accuracy of the final assembled CubeSats have been about one-half of the tolerance allowed in the CubeSat Design Specifications document from CalPoly and Stanford.

The current MEROPE CubeSat design also has its disadvantages. The current chassis design requires time on the CNC mill for fabrication, something that may or may not be available. Moreover, fabrication on a CNC mill may involve more cost for some CubeSat developers. A possible disadvantage of using PC cards with CubeSat dimensions is that, as indicated by shake table tests and finite element modeling, their lowest natural frequency *without mounted components* is around 200 Hz. This frequency is close to the peak spectral density of random vibrations expected during launch on a Dnepr rocker from Kazakhstan. Since changing the PC card size doesn't seem to be an option, there may be a need for structural supporting members between PC cards. Shake tests are currently underway on assembled PC cards to determine this.

An attitude control system also needed to be produced to allow the satellite communication and payload systems to function. The design philosophy for attitude control on the first generation SSEL CubeSat was to keep it as simple, low mass, and inexpensive as possible. This ruled out the possibility of an electromagnet torquing system or gyroscopes. For attitude control, we chose a two-axis passive stabilization system that uses magnets for torque about the Earth's magnetic field and hysteresis rods for libration damping. An eddy current system was also considered for damping, but lab tests indicated that hysteresis rods work just as well if not better. Solar cell feedback data in telemetry will be analyzed to determine the effectiveness of the current attitude control system.

An advantage of our current attitude control design is minimal cost and volume. Furthermore, the design does not require cutouts in the CubeSat sides, thus leaving more surface area for solar cells. The disadvantages of the current design is that it will at best control rotations along only two axes. The attitude system is a necessary requirement, though, and further constrains the available volume and mass for the other subystems.

Power Constraints

Other than the constraints in volume and mass, power is the de facto limiter. With the advent of new technologies, many different experiments can be fit into a CubeSat structure. However, the technology to produce large amounts of power in a small space has not kept pace with the ability to miniaturize components. This necessitates very careful design and part selection to provide enough power to all satellite subystems and a payload.

The MEROPE CubeSat requires a massive amount of power to be generated for its size.[3] The satellite uses this power to run all of its systems and charge the batteries. Since the satellite is launching with dead batteries, all power required by the systems must be generated on orbit. The total amount of power required by each system is summarized in Table 1. The required power also must be generated, converted, and stored by a system that has only half of a single printed circuit board available area and about 250 g total available mass.

The design philosophy of the satellite power system centered around three basic

Table 1. Total Power Draw per Component

Item	Voltage	Current	Conversions (75%)	Total Power Draw
Modem	5V	25 mA	1	170 mW
Receiver	5V	150 mA	1	1000 mW
CPU	5V	60 mA	1	400 mW
Pulse Shaper	5V	15 mA	1	100 mW
Payload HVPS	+/- 5V	67 mA (Total)	1	560 mW
Transmitter	5V	350 mA	1	2350 mW
Monitoring/Line Losses(est.)	5% of total maximum power draw			229 mW
Total Transmitting (est.)				**4809 mW**

concepts. First, use as many off-the-shelf components as possible. The cellular phone industry, which has extensive experience in developing high efficiency power solutions, has already designed components that can be easily used in a satellite, rather than trying to produce parts in house. Second, keep the system as simple as possible. This allows higher efficiencies and also improves the robustness by allowing some redundancy in the power system. Third, generate as much power and keep the efficiency as high as possible, but in the end realize that the other systems must adapt to the available power.

The most powerful solar cells available today are extremely expensive and only capable of 27% conversion efficiency at maximum.[4] Additionally, with the size and mass restrictions of a CubeSat, the satellite cannot carry batteries large enough for a significantly long mission. Cubesats also cannot carry radioisotope-based power systems, again due to restrictions mentioned above. This means the best available solar cells must be used.

Even with using the most powerful solar cells available, the imposed limitations of the MEROPE mission require the use of body-mounted solar cells. Deployable solar cells are feasible but were avoided on MEROPE for simplicity and the desire to avoid, whenever possible, components that could end the mission after a failure. This presents significant difficulty in many respects. The solar cells must fit around everything else and will run hotter than a solar wing. The solar cells also will on average operate only about 50% of the time in daylight since the satellite will also be rotating. This leads to the satellite generating less power than is needed by the other systems.

To solve this problem, several techniques have been employed. First, to improve efficiency the batteries do not use a charging circuit. They are placed in parallel to the load and provide a constant power to the converters. Second, the most powerful solar cells available are being used. Additionally, to fit a maximum number of cells to the satellite, extensions on two sides into the top and bottom areas will allow two extra solar cells. Third, the communications system is the largest draw on the power supply. Therefore, the receiver will be cycled on and off to reduce the power consumption of the satellite. These measures bring the power requirements to a manageable level.

Size constraints allow the use of two cells on four sides and three cells on two sides. Given this configuration, the estimated electrical energy generated will be ~174 W*minutes. Using a 10%

receiver cycle and transmitting for 10 minutes per day, the satellite requires ~163 W*minutes.

Next the power must be regulated and converted to usable voltages. The solar cells generate anywhere from 3.4 V to nearly 9V during any given orbit. This is a result of both the differing number of cells per side and the thermal characteristics of the cells. To regulate this voltage so the converters can work more efficiently, the batteries have been placed in parallel to the load. This results in quicker battery degradation but should still allow up to a year before the batteries see significant loss of capacity.

The batteries chosen were originally Lithium Ion batteries similar to those found in cell phones. However, since the cell structure generally limits the voltages of the cells to multiples of 3.6 V or 3.7 V, these cells can only be used on one solar cells bus. The other solar cell bus uses a NiMH battery operating at 4.8 V. These two buses (3.7 V and 4.8 V) then are fed into a set of Boost DC-DC/Low Dropout Regulator converters. The chips selected are a fully integrated circuit containing both functions. This allows efficiencies in the converters to approach 85% when operating at the voltages the batteries will allow.

Some difficulties encountered during the design could have been avoided with a little more careful planning. The structure and power system need to be the first two systems developed and need extremely good communication. Using body-mounted solar cells requires that all the other systems either plan around the solar cell configuration or use much less power. Additionally, the simplification of the voltages required by the systems results in higher efficiencies. When the project began, the systems required over seven different voltages. After months of study and redesign, this has been reduced to three and the efficiencies are much higher as a result. This also improves the reliability and robustness of the system.

Additionally, some errors in the initial calculation of the available power led to confusion within the satellite team. The power system requires near perfect calculations and design to achieve the mission, therefore engineers not associated with the power system (or simply another part of the power system) must be used to check the work. A great deal of time and effort would be saved if errors were found earlier.

Systems Engineering

The onboard computer subsystem is charged with the tasks of data collection, data handling, and satellite system control.[5] The hardware chosen for this subsystem includes a Motorola MC68HC812A4 (HC12) microcontroller, an Integrated Device Technology CMOS Supersync FIFO IDT72291 at 125Kbytes. The HC12, produced by Kevin Ross of the Seattle Robotics Club, is mounted on a board with all its supporting circuitry. This smaller board is then "piggy-backed" onto a board that fits the CubeSat footprint. This main board contains the IDT FIFO chip and other supporting circuitry and mounts into the card retainers built into the satellite.

The computer systems are impacted by the CubeSat limits in allowable volume and mass, but fortunately computer hardware has benefited from decades of miniaturization and optimization. Therefore, the parts decisions are the major obstacle involved in the formulation of the subsystem, since once the choice is made the development timeframe does not allow for major changes. The HC12 was chosen for its on-chip features, relative ease of programming and use, and mainly since it is the microcontroller used in the Montana State University computer engineering courses. The importance of this last point cannot be understated. MEROPE, as a student project, naturally uses students to do the development and work on the subsystem. The choice of the same microcontroller used in coursework offers a well-trained and capable student workforce. The IDT FIFO was chosen for ease of use and availability. The amount of memory fit with our downlink capability and made the choice easy.

The main lesson learned here is that this system takes a lot longer than it first appears as the several thousand lines of code take time to write, test, and understand. Future missions will be able to use this code with very few modifications to the existing code and hardware. Only new code routines need to be added for future missions. A project with a one-year lifetime has as many turns and twists as a larger project and that the computer subsystem (and all others) must also be able to bend and twist to meet the requirements of the other subsystems.

The MEROPE CubeSat Communications (Comm) Subsystem was heavily influenced by size and power limitations. Communication equipment needed to be located to fit within the CubeSat, or the equivalent hardware had to be built. Adding to the difficulty is the fact that Comm requires more power than any other subsystem, and therefore had to work within the power scheme.

The Comm engineering process was strongly influenced by three factors: (1) the initial MEROPE mission timeline of one year from project conception to delivery and launch, (2) available bandwidth allocations, and (3) the general lack of experience of the MEROPE Communications team. Given the short development timeline and the several universities and organizations that contracted with OSSS to share the same launch vehicle, Prof. Bob Twiggs of Stanford University proposed a band-sharing scheme—in the 2m and 70cm Ham radio bands—for the CubeSat developers to use, if desired. The MEROPE Comm development team determined that all mission data and telemetry transmission needs could be served by the allocated bandwidth. (Uplink is at a frequency of 145.835 MHz with 20 kHz of available bandwidth. Downlink is at 437.445 MHz with a 30 kHz bandwidth.) These link bandwidths and frequencies simplified the link design and hardware development processes considerably, as they enabled the MEROPE Comm team to utilize the great resources and expertise available through the Ham radio community. Furthermore, the general lack of "hands-on" telecommunications experience of the MEROPE Comm team meant that developing custom communications hardware would take too long. As a result, the design philosophy has been to use as much commercially available off-the-shelf (COTS) hardware as possible.

The MEROPE Comm subsystem consists primarily of four functional blocks: (1) an audio-frequency shift keying (AFSK) 1200 bps modem built around an MxCom MX614 modem; (2) a Yaesu VX-1R dual-band transceiver; (3) a custom-built antenna assembly; and (4) TTL-level data, power, and internal interfaces. The entire subsystem is mounted on uncoated FR-4 printed circuit board (PCB), and subsystem assembly and placement within the satellite structure were modeled and optimized by Steven Jepsen (Structures & Mechanical Systems team lead) using a CAD design suite. The entire subsystem weighs less than 115 grams and occupies a total volume (including antennas and interconnects) of 180cm3—less than 1/5 of the total spacecraft weight and volume budgets—with a hardware cost of less than $225.

The major subsystem components are almost entirely COTS equipment.[6] Relatively simple and robust, the heart of the subsystem is the MX614 modem, which packetizes and transmits all data from the processor through a Yaesu VX-1R dual-band radio using the Bell 202 format AFSK packet protocol at 1200 bps. Communications flow is controlled by the Motorola HC12 processor, which is linked through a 1200 baud TTL-level connection to the modem. The entire communications loop (ground-MEROPE-ground) is seamless, initialized by a single encrypted uplink command. Upon contact with MEROPE, the ground station instructs the processor to dump the contents of its memory to the modem, which packetizes the binary data and keys the transmitter.

The selection of the MX614 modem and Yaesu VX-1R transceiver were arrived upon after an extensive survey of COTS hardware that consisted of engineering discussions with manufacturers, technical representatives, and Ham radio users. Promising hardware candidates were then purchased and tested for functional and ease of integration.

After the primary subsystems of the satellite, which allow it to function, are designed, the remaining volume and mass may be utilized for a payload. Careful thought must be put into what type of payload to launch, since this unused volume and mass will likely be very small.

The MEROPE payload benefited from being simple. There are definite advantages to attempting a well-understood, previously performed experiment on a first attempt of a student satellite. The hardware choices were completed very early in satellite design process. Geiger tubes themselves are very simple, and therefore cheap and easy to find. The high voltage power supply was provided as a complete component by Southwest Research Institute, which saved time and effort in designing and preparing such a complicated device. The AmpTek 101 pulse shaping chip was the only other element needed to complete an actual science experiment. Integration with the satellite microcontroller, which will be storing the data, has been smooth due to the lack of complicating factors.

MEROPE's scientific experiment fit well into the overall satellite design due to its naturally small size and relatively low power requirements. Original scientific experiments can certainly be performed in future CubeSat missions, provided they are small and require little power as well. Many CubeSat designs now exist which may allow a substantial portion of the satellite to be used for the payload, and these designs will only improve, as technology becomes smaller and more efficient. The CubeSat is also very useful as a hardware tester. New types of miniature hardware can be integrated into a CubeSat for space rating. With the price of a CubeSat being far below that of a conventional satellite, this may well be one of the best and easiest uses for a CubeSat. Of course, innovation and imagination will continue to place more and more interesting payloads into CubeSats.

Conclusions

The Montana Earth Orbiting Pico Explorer will launch from Kazakhstan in November of 2002 carrying into orbit a student designed and built payload for measuring the lower Van Allen radiation belt. The design constraints of 1-kg total mass and 1 liter total volume lead to an ambitious and challenging project ideal for training students in the rigors of aerospace engineering.

The lessons learned by the MEROPE team during its 1.5 year lifetime include contributing thorough thought to the design while keeping each subsystem flexible for adapting to inevitable changes, keeping subsystems as simple as possible, and being realistic at the beginning of the project about the capabilities of the satellite. Over the course of the project, the design has benefited from the ability to utilize advice from experts outside of the project, insuring that calculations are accurate and reasonable. Avoiding design mistakes early will save large amounts of time later in the project. Trying to achieve the simplest design for each subsystem is perhaps the most important rule to follow on a student satellite. This will lead to less time spent on devising components from scratch and also will help in the testing and debugging efforts near the end of construction. Finally, the mass and volume constraints of a CubeSat are very restricting, and require much innovation to achieve for all but the simplest satellites. A realistic approach to what can and cannot be done within these restraints will avoid major delays or termination completely of a worthwhile educational project.

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