M-Cubed: University of Michigan Multipurpose MiniSatellite with Optical Imager Payload

Kiril A. Dontchev[1], Kartik Ghorakavi[2], Cameron E. Haag[3], Thomas M. Liu.[4], Rafael Ramos[5]

Student Space Systems Fabrication Laboratory, University of Michigan, Ann Arbor, MI, 48105

Since the fall of 2007, over 20 aerospace, computer, electrical, mechanical, and space systems engineering students have been developing a pilot picosatellite program, M-Cubed (Michigan Multipurpose MiniSatellite), for the University of Michigan's Student Space Systems Fabrication Laboratory (S3FL). The objective of M-Cubed is to obtain better than 200 meters-per-pixel resolution color images of the Earth with at least 60% land mass and a maximum of 20% cloud coverage while providing student participants hands-on experience with an end-to-end space systems development cycle in a two-year, concept-to-launch timeline. The baseline system design is constrained to a 1-kg bus with dimensions of 10 x 10 x 10 cm. Solar arrays and batteries provide power generation and storage while a microcontroller processes image data and health status for the telemetry system, which relays the data through the amateur radio bands. A passive attitude determination and control system comprised of magnetic hysteresis rods is proposed to properly orient the spacecraft through the use of the Earth's magnetic field. Launch opportunities are expected through California Polytechnic State University's cubesat initiative. Dedicated subsystem teams of about five students each are present with upper-level undergraduates and graduate student leads. Upper-level undergraduates and a graduate student also form a systems engineering team taking on the roles of project manager and chief engineer. Through the successful completion of a first-generation bus, S3FL seeks to establish a multidisciplinary, design-build-test-fly space flight learning environment for training the future space systems workforce.

Nomenclature

S3FL	=	Student Space System Fabrication Laboratory
Cal Poly	=	California Polytechnic State University
DBTF	=	Design-Build-Test-Fly
CCD	=	Charge-Coupled Device
PDR	=	Preliminary Design Review
CDR	=	Critical Design Review
FU	=	Flight Unit
MRR	=	Mission Requirements Review
TRR	=	Test Readiness Review
FRR	=	Flight Readiness Review
ARC	=	Amateur Radio Club
C&DH	=	Command and Data Handling
I2C	=	Inter-Integrated Circuit
SPI	=	Serial Peripheral Interface
UART	=	Universal Asynchronous Receiver/Transmitter (UART)
P-POD	=	Poly Picosatellite Orbital Deployer
RBF	=	Remove Before Flight

[1] Program Manager, S3FL, kikod@umich.edu 1224 Space Research Bldg, Ann Arbor, MI 48109, Student Member

[2] Chief Engineer, S3FL, gvkarik@umich.edu, 1224 Space Research Bldg, Ann Arbor, MI 48109, Student Member

[3] Subsystem Lead, S3FL, cehagg@umich.edu 1224 Space Research Bldg, Ann Arbor, MI 48109, Student Member

[4] Graduate Advisor, S3FL, liutm@umich.edu, 1224 Space Research Bldg, Ann Arbor, MI 48109, Student Member

[5]Graduate Advisor, S3FL, arramos@umich.edu, 1224 Space Research Bldg, Ann Arbor, MI 48109, Student Member

I. Introduction

Inspired by the opportunity for a new major project in the University of Michigan's Student Space Systems Fabrication laboratory (S3FL), a small group of students took the initiative in the summer of 2007 to determine a new direction for the student lab. The result was the start of the M-Cubed program at the university. The project was made possible by S3FL and the cubesat initiative offered through the California Polytechnic State University (Cal Poly). Through this initiative, a launch opportunity is provided at the low cost of $40,000. The cubesat platform shall not exceed a mass of 1 kg and shall fit within the envelope of 10 x 10 x 10 cm to satisfy the design requirements imposed by Cal Poly.

The objectives of the project are both educational and functional. The primary educational objective is to provide students with a design-build-test-fly (DBTF) learning environment for training the future space systems workforce. Students will learn the engineering design process in a real-world setting and application. Furthermore, once the first iteration of the mission is completed, the project will be documented and refined as to facilitate future projects using the cubesat platform, such as curricular development of intermediate laboratory courses for undergraduates.

The functional objectives of the mission is to obtain the highest color image resolution to date (the current design of 1600 x 1200-pixel Charge-Coupled Device (CCD) camera can provide better than 200-m resolution) of Earth with at least 60% land mass and a maximum of 20% cloud coverage from a single cubesat platform. Along with this, S3FL is developing the M-Cubed bus with the intention of making it a heritage design, thus allowing for future missions to be flown on the developed bus.

II. Programmatics

M-Cubed employs a team structure consisting of a project manager, systems team, and subsystem teams each with a respective lead, as shown in Fig 1 below.

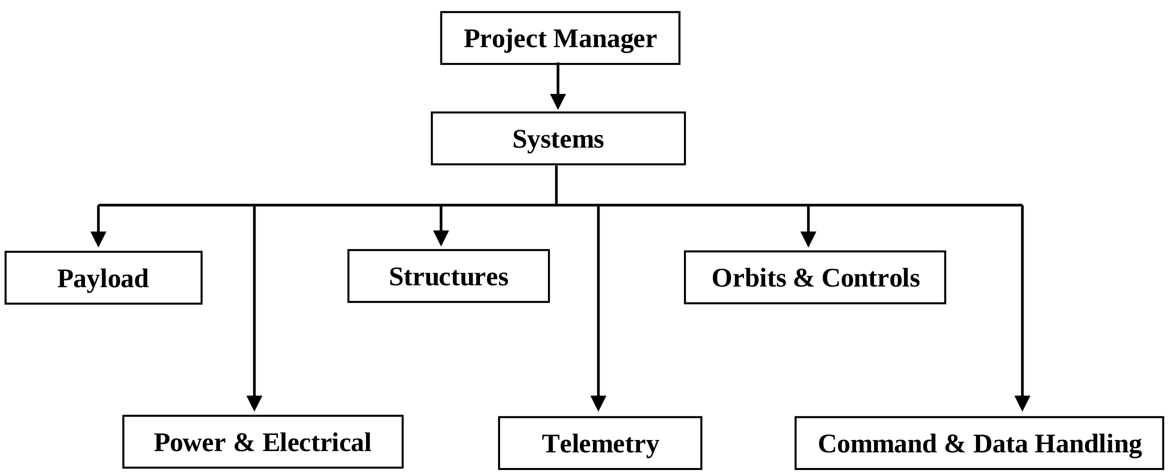

Figure 1. Organizational structure of M-Cubed

M-Cubed maintains a diverse age range to ensure the retention and transition of knowledge from graduate and upperclass undergraduate students to underclass undergraduate students, usually in the form of leads to team members. M-Cubed also relies on input from senior lab members (graduate and upperclassman undergraduate students) and affiliated faculty in both informal meetings and formal design reviews for project advising. The M-Cubed personnel organization is also the architecture for S3FL projects in general.

The Preliminary Design phase began in September 2007 and shall conclude in March 2008 with a Preliminary Design Review (PDR). The Detailed Design phase shall begin after the conclusion of the Preliminary Design phase in March 2008 and conclude in November 2008 with a Critical Design Review (CDR). The Flight Unit (FU) Production phase shall take place after the Detailed Design phase from November 2008 to February 2009, with a final Test Readiness Review (TRR) in April 2009. The FU Qualification phase shall commence after the FU Production phase in April 2009 and conclude in May 2009 with a Flight Readiness Review (FRR). The final Launch & Operations phase will begin after the FU Qualification phase and end with a prospective launch window in the fall of 2009. The schedule is shown below in Fig 2.

ID	Task Name	Start	Finish
1	**Cubesat Long-Term Plan**	**Wed 9/19/07**	**Tue 4/21/09**
2	System Definition	Wed 9/19/07	Fri 9/28/07
3	**System Requirements Review**	Fri 9/28/07	Fri 9/28/07
4	Preliminary Design	Mon 10/1/07	Wed 10/31/07
5	Prototype Readiness Review	Thu 11/1/07	Thu 11/1/07
6	**Preliminary Design Refinement**	**Thu 1/3/08**	**Mon 3/24/08**
66	**PDR**	Wed 3/26/08	Wed 3/26/08
67	Spring Break	Sun 2/24/08	Thu 2/28/08
68	**Engineering Design Unit**	**Tue 6/3/08**	**Thu 10/30/08**
72	Detailed Design Refinement	Thu 3/27/08	Wed 11/5/08
73	**CDR**	Thu 11/6/08	Thu 11/6/08
74	Design Revision (CDR Action Items)	Thu 11/6/08	Tue 12/16/08
75	**MRR**	Tue 12/16/08	Tue 12/16/08
76	Flight Unit Production	Wed 12/17/08	Tue 2/3/09
77	**TRR**	Tue 2/3/09	Tue 2/3/09
78	Flight Unit Internal Testing	Wed 2/4/09	Tue 3/3/09
79	Flight Unit Qualification Testing	Wed 3/4/09	Tue 4/21/09
80	**FRR**	Tue 4/21/09	Tue 4/21/09

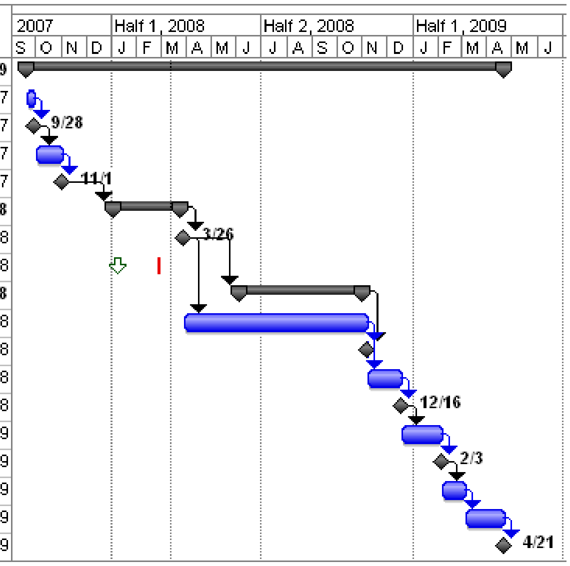

Figure 2. Gantt chart for M-Cubed schedule.

The total budget for M-Cubed is $100,000. The projected cost budget is provided below in Table 1.

Project Component	Cost ($)
Launch	40,000
Prototype/EDU/FU	30,000
Personnel	30,000
Total	**100,000**

Table 1. Project Cost Budget.

To improve the marketability of M-Cubed, a business team was created to maintain the project cost budget and marketing. The business team represents a concentrated effort to better integrate these aspects of the project.

In an effort to more fully integrate the University of Michigan into the existing cubesat community, M-Cubed plans on participating in two conferences, the CubeSat Developers Conference and the AIAA Region III Student Conference and Paper Competition.

III. Satellite Description

M-Cubed is flying a CCD camera in order to fulfill the objective of taking a better than 200 meter-per-pixel color picture, the highest resolution image taken on the cubesat platform. It will be powered by a battery that is charged by solar arrays on the outside of the structure. A microcontroller will process and send the image to the telemetry system for transmittal to ground, and the ground station will receive the picture over a period of time. The orbit of the satellite will be controlled by a passive attitude control system and will be oriented based on the Earth's magnetic field. The structure has specified requirements from Cal Poly for launch vehicle integration, but will be designed such that M-Cubed will meet its mission objective. An overall systems requirements matrix defined by Cal Poly can be found in Appendix A.

The following sections describe the satellite subsystems, providing an overview of the architecture of the satellite. Due to the preliminary nature of the design, not all design parameters have been considered, but a general description of each subsystem is provided.

A. Payload

A payload has been chosen such that it will fulfill the mission objective and provide color images of Earth in the visual spectrum with a size of at least one megapixel, at a ground resolution of better than 200 meters per pixel. To achieve this, the payload subsystem will consist of a CCD camera and a plano-convex lens, with focal length designed to provide the required resolution.

1. *Camera*

The chosen camera is a STC-C202USB Color CCD Camera. The progressive scan CCD has 4.4 micron square pixels in a 1628 by 1236 array, which allows for a two megapixel image at full resolution. The data format is 8 bits per pixel, making each image two megabytes. Using JPEG compression algorithms, this data will then be compressed on-board before transmission by a factor of around 10. This will minimize transmission time while preserving visual quality of the image.

2. *Optics*

The plano-convex lens will be rigidly mounted inside of the cubesat, as close to the wall as possible to allow for maximum focal length. The diameter will be 25.4 millimeters (mm), while other geometrical attributes will be designed to satisfy structural constraints and resolution requirements. With a worst case scenario maximum altitude of 800 kilometers (km), a focal length of at least 17.6 mm is necessary to achieve the desired ground resolution. The structure, however, may allow for a focal length approaching 60 mm, which allows for a ground resolution of better than 60 m per pixel, far exceeding the requirements.

3. *Shutter System*

During the initial tumble, and potentially other periods during orbit, the aperture may be pointed directly into the sun. Prolonged exposure to the sun may damage the CCD and jeopardize the mission. Necessary precaution is being taken with the design of the optical system. If further analysis deems protection of the detector necessary, a small motorized shutter will be placed between the lens and the focal plane. The on-board controller will obtain sun vector data from solar panels, and determine when the shutter should be open or closed. This system will not be used as an operational shutter (used to limit exposure time), but rather used as an emergency protection device for the detector.

4. *Testing and Validation*

Various aspects of the payload configuration must be determined by in-lab testing. Image quality tests will be conducted by simulating Earth's luminosity at altitude in the lab, and taking pictures of a modulation transfer function test chart. The minimum necessary exposure time will also be determined in lab. Finding this time is critical to reducing any blurring that may occur due to the satellite's motion. Additionally, focal length tolerances will be analyzed to aid in the determination of the lens mounting system.

B. Orbits and Controls

The orbits and controls subsystem team has two key objectives: to characterize the implications of the expected orbital trajectory, and to provide the cubesat with the proper attitude to facilitate Earth imaging.

1. *Orbit*

Since each group of cubesats is typically launched as a secondary payload, its precise orbital trajectory is dictated by the requirements of the primary mission. However, basic historical trends can be observed between each significant cubesat launch, which can be used to establish an approximate "reference orbit" to aid in mission design.

Based on previous cubesat launch trends, a sun-synchronous reference orbit has been chosen with an inclination of 98 degrees and an altitude of 650 km. As shown in Fig B.1, a sun-synchronous orbit has a polar orbital plane that remains fixed with respect to the Sun. This reference orbit is a design guide constructed from historical averages, and additional worst-case figures must be considered whenever possible throughout the mission design process. For instance, the "local time" of previous sun-synchronous cubesat orbits, or the orientation of the orbit plane relative to the Sun (θ), has no apparent trend. As a result, the implications of every local time must be considered during the design process. Each of the four large cubesat groups has been launched into a sun-synchronous orbit of this type. The upcoming cubesat group launch in March of 2008 is also planning a sun-synchronous orbit. While a sun-synchronous orbit is very likely for our mission, it is only an educated assumption until our specific launch vehicle is confirmed.

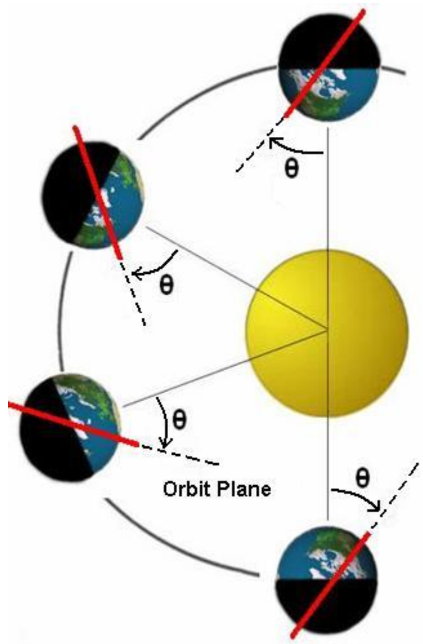

Figure B.1. Sun-synchronous orbit configuration.

2. Passive Attitude Control

M-Cubed utilizes a passive magnetic attitude control system to achieve a proper orientation for Earth-imaging. As shown in Fig B.2, the system consists of a single permanent magnet aligned on one cubesat body axis, along with additional magnetic hysteresis materials aligned on each additional perpendicular body axis. In this configuration, the permanent magnet aligns one body axis of the cubesat with the local Earth magnetic field direction. Since the magnet still permits cubesat rotation about this single axis, the hysteresis materials are added to dampen unwanted rotation. Chosen for their high magnetic permeability, the HuMy80 hysteresis materials create internal current as they are rotated through the local magnetic field. This dissipates rotational energy as heat, effectively damping the rotational motion of the cubesat. If each magnetic component of the passive attitude system is properly sized, a controlled spin rate can be achieved about the local magnetic field direction.

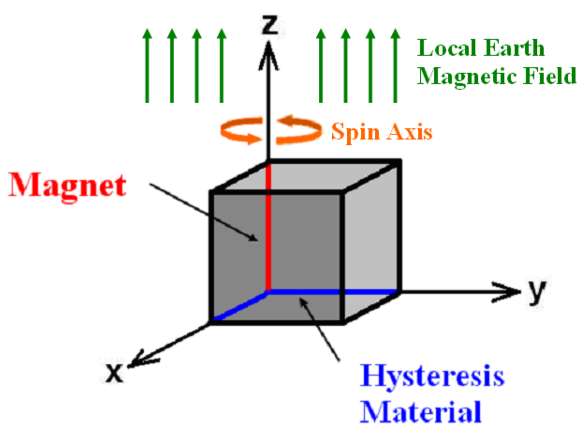

Figure B.2. Configuration of passive magnetic attitude control system.

In practice, this passive attitude control system will allow for Earth-imaging throughout only a designated portion of the M-Cubed orbit. Ideally, the camera will continuously point in the nadir direction or straight down towards Earth. Since the camera is aligned along the permanent magnet axis, however, its direction relative to nadir is dictated by the cubesat's orbital position. Figure B.3 illustrates the shape of the Earth magnetic field lines, as well as the camera orientation at each point in a typical polar orbit.

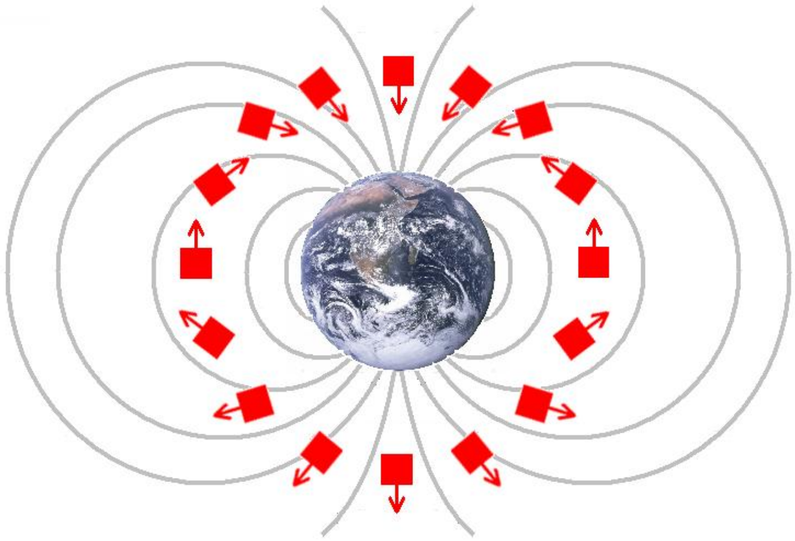

Figure B.3. Earth magnetic field lines and camera orientation throughout polar orbit.

Due to this Earth magnetic field configuration, the passive magnetic control system will allow for ground coverage over a significant portion of the Northern Hemisphere. As M-Cubed passes over the North Pole, the permanent magnet and camera will be aligned in the nadir direction, due to the vertical direction of the local Earth magnetic field. As the M-Cubed orbit continues toward the Southern Hemisphere, the camera-nadir angle will increase until the Earth leaves the camera field of view. The Earth will then reenter the camera field of view after M-Cubed crosses the equator into the Northern Hemisphere. On average, this control strategy will allow for approximately 15 picture opportunities of the Northern Hemisphere per day (once per each 90 minute orbit). Although the Northern Hemisphere will remain in the camera field of view for approximately 40 minutes during each overpass, the window of opportunity will vary depending on ground lighting conditions.

Although limited in performance, this type of passive control system was chosen for several reasons. When compared with active attitude control systems, such as magnetic torque coils, passive systems of this type require less mass and no power consumption. Furthermore, passive attitude systems offer a robust, simple control strategy that boasts extensive flight heritage in similar Earth-imaging cubesat missions.

3. Testing and Validation

Each individual component of a passive magnetic control system must be carefully sized in order to achieve proper cubesat attitude dynamics. Several software packages, such as CubeSim, have been developed within the cubesat community to simulate passive magnetic control systems in various orbital configurations. Although simulations offer a design starting point, the results must be validated through experimental testing.

One standard experimental setup used to validate such systems is a Helmholtz coil, shown below in Fig B.4. A Helmholtz coil consists of two magnetic coils aligned along a common axis. If each coil radius matches the distance of separation between the coils, a roughly uniform magnetic field can be produced within the test section by providing equal current through each coil. Magnet and hysteresis samples can then be hung within the test section and characterized by their resulting motion inside the uniform magnetic field. The illustrated Helmholtz coil, for instance, has a pair of 12 inch diameter coils, each composed of 170 wire loops. With an input current of 300 mA, the Helmholtz coil produces a roughly uniform axial magnetic field that is 3 times stronger that the local Earth field at ground level.

Figure B.4. Helmholtz coil.

C. Power and Electrical

The main purpose of the power and electrical subsystem is to distribute adequate power to all of the subsystems. To accomplish this, M-Cubed utilizes both a battery and solar arrays placed on every side of the cubesat. The power collected by the solar cells is sent through current and voltage sensors connected to the microcontroller and then through a 5 Volt (V) voltage converter, where is it dispersed between active buses controlled by switches (during Discharge Mode) or to the battery charger (during Charge Mode). When M-Cubed is in Discharge Mode, the solar cell power is supplemented by the battery power through either a 3.3 V or 12 V voltage converter to power other buses. In Charge Mode, the microcontroller opens all switches to remove power from all other subsystems and directs all solar power through the battery charger. A block diagram of the system is shown below in Fig C.1. The entire satellite is expected to require 1.2 Watts (W) of average power and 4.7 W of peak power.

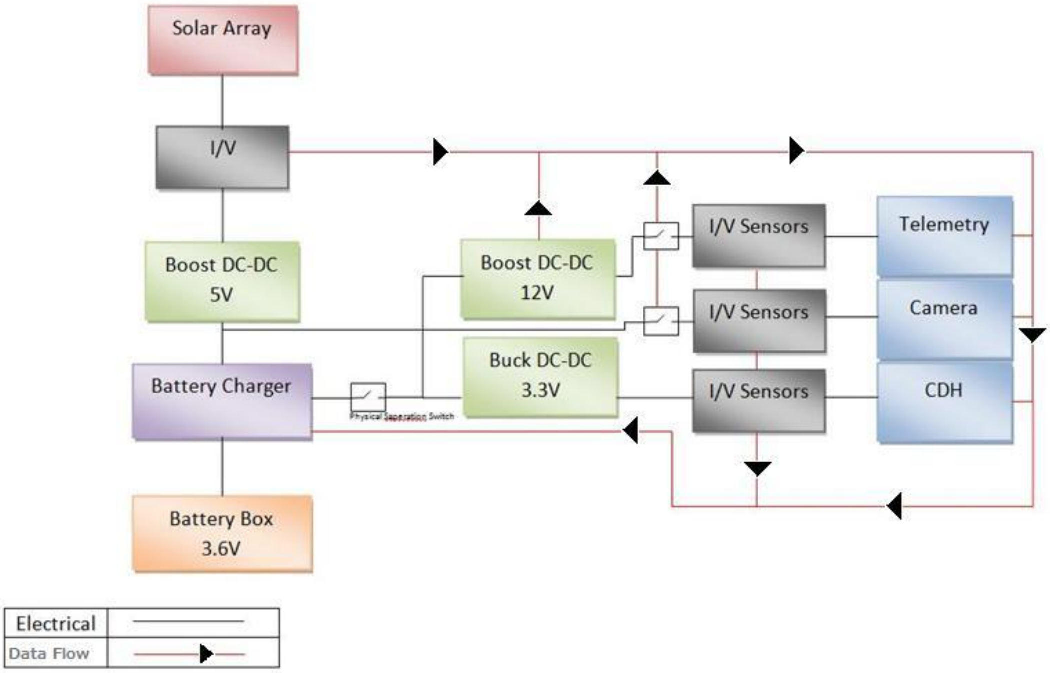

Figure C.1. Power system block diagram.

The power and electrical subsystem has to accommodate a variety of power needs. While M-Cubed is in eclipse, all components will be in low-power or standby mode. If the cubesat is in sunlight and takes a picture, the shutter, camera, and microcontroller will all need full power to operate. After a useable picture is taken, the cubesat will wait again in low-power mode until it enters the ground station coverage area at which point the transmitter will be switched to full power mode. A versatile power system requiring the use of a rechargeable battery system is necessary to accomplish these tasks.

1. Solar Arrays

Solar arrays cover each side of M-Cubed and send power through the main circuit board to be sent to various components on the satellite in 3.3 V, 5 V and 12 V power-buses. On the way to the main circuit board, the power is passed through a charging circuit, where the power is either stored in the battery during the charging phase or, if necessary, supplemented with power from the battery. These arrays are also used by the orbits and controls subsystem to create a sun direction vector used to calculate spacecraft orientation.

2. Battery

In addition to solar arrays, M-Cubed receives power from four small Polymer Li-ION batteries onboard. These batteries each have a capacity of 3.89 Watt-hours (W-h) and were chosen over a larger battery due to their higher discharge rate and energy density. The cubesat requires a battery for the mission because the solar cells alone cannot produce enough power when peak power is needed. The battery also provides power to subsystems that cannot be turned off while M-Cubed is in eclipse. Although we anticipate M-Cubed to have a sun-synchronous orbit, there is a chance that M-Cubed is launched into an orbit with an eclipse period. The battery has been the primary driver of the thermal subsystem due to the small range of temperatures in which the battery can operate.

3. Testing and Validation

To determine a close approximation of the power and electrical duty cycle, the solar cell efficiencies must be determined. To accomplish this, a full-spectrum lamp will be placed 1.5 inches from an individual solar cell monitored by a multimeter. The luminosity of the lamp will be determined by a luxmeter, and the percentage of energy converted by the solar cell will ascertain the efficiency. Another necessary validation involves the space-qualification of the battery. Because the manufacturer does not know how the battery will operate in space, vibration and vacuum tests will be conducted to ensure that the battery can withstand the launch and the space environment.

D. Telemetry

The telemetry subsystem's main objective is to transmit the data from onboard M-Cubed to the ground station. Using a 144 MHz uplink and a 437 MHz downlink, amateur radio bands will be used to control and receive data from the satellite. A basic beacon signal containing satellite health data will be transmitted intermittently throughout operations. Data and commands will be transmitted using the AX.25 protocol [1], a standard in amateur radio data transmission. This protocol is often a failure point for other picosatellites, therefore the system will utilize an existing software implementation for reliability. Figure E.1in Section E details the interaction between the telemetry and command and data handling (C&DH) subsystems.

1. Onboard Communications

A dedicated receiver will operate at all times, while the dedicated transmitter will be operated only to send a beacon signal or transmit picture data. Both receiver and transmitter are the same component, Analog Devices ADF7020-1 [7], hardwired to their independent tasks to save development time and costs. From the transmitter, the signal will be amplified to 1 W, the calculated necessary transmit power. A 0.33-m dipole and a 0.5-m monopole are the respective antennas for uplink and downlink. Significantly more analysis and design will be dedicated to this part of the subsystem.

2. Ground Station

The ground station will be able to autonomously receive data from M-Cubed throughout the day, reducing the human oversight required. S3FL is working closely with the University of Michigan Amateur Radio Club (ARC) on this task. The ARC has expressed great interest in sharing resources with other student groups such as S3FL and has a declaration of intent to expand its space communication capabilities. The ARC's facilities will be utilized for the duration of the mission and include a dedicated ground computer, IC-910H transmitter, a tracking 13.1 dBi circularly polarized Yagi antenna, preamps, and supporting cabling. This equipment will be adequate for M-Cubed's purposes and prevent further expenses.

3. Testing and Validation

Testing and validation will be established in four stages. First, all communication protocols will be implemented in a software simulation. Second, the ground station will automatically downlink data from existing amateur satellites. Third, the ground station will interact with a handheld radio hooked to another computer simulating M-Cubed. Fourth, the ground station will fully interact with M-Cubed as if it had already been launched.

E. Command and Data Handling

The command and data handling subsystem's main objectives are directly related to operation of the camera. The C&DH subsystem is required to control the camera, and to sample pictures to reject images of space, clouds, or open ocean. Once an acceptable picture is selected, the C&DH subsystem will compress the image for transmission. Additionally, the C&DH subsystem needs to collect system voltage and current health status to transmit to ground and will implement the AX.25 protocol. A block diagram of the C&DH and telemetry subsystem is shown below in Fig E.1.

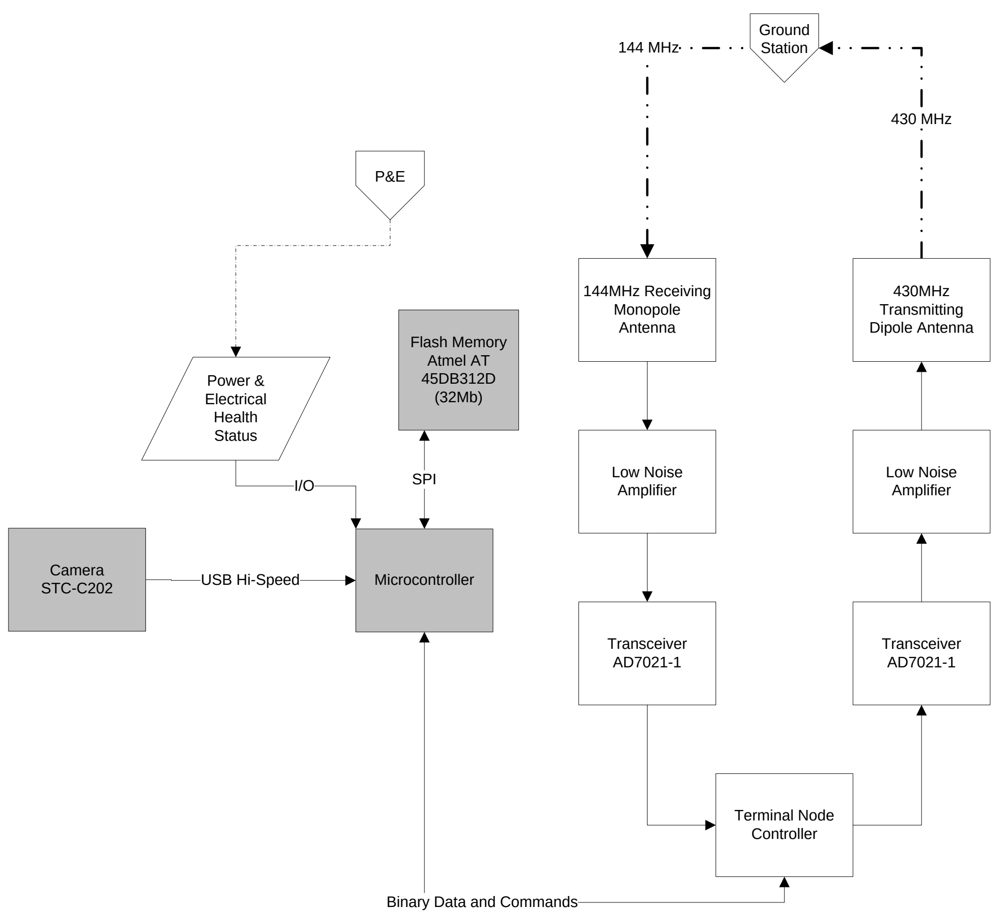

Figure E.1. Command and data handling block diagram.

1. Computer

All satellite actions are initiated and monitored from the onboard Atmel AVR32 7002 microcontroller, shown below in Fig E.2. This model was selected for its integrated USB High Speed port, which is necessary for the selected payload. The microcontroller also supports serial protocols such as Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI), and Universal Asynchronous Receiver/Transmitter (UART).

The I2C interface will connect to an EEPROM containing program memory while SPI will connect to a flash device storing data memory, and the UART interfaces will connect to the telemetry system.

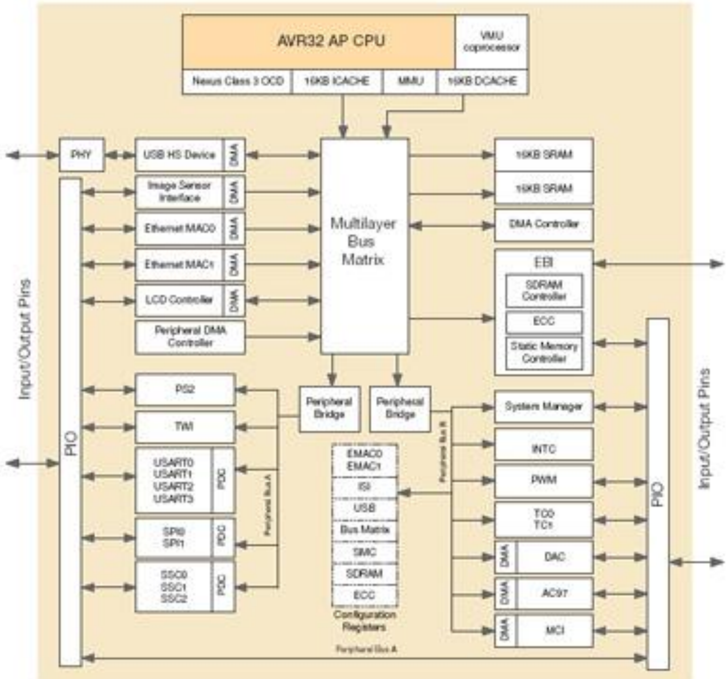

Figure E.2. AVR32 7002 block diagram [6].

2. Software

Another driving factor in the selection of a microcontroller was ease of programming and scalability. The Atmel AVR32 7002 microcontroller is capable of running a Linux operating system. To control the camera and compress the images along with the implementation of the AX.25 protocol, the software will use open source code which has already been thoroughly tested, decreasing development time and increasing reliability. An additional benefit is the scalability of the microcontroller processing, thus providing a flexible platform for future cubesats.

3. Testing and Validation

Debugging the C&DH subsystem will first be done on an evaluation board. Next, integration with other subsystems and a full operational test will be conducted to evaluate performance. Features will be added in stages, with components such as telemetry and camera control first. Other features such as picture compression and picture sampling will follow.

F. Structure

To design the structure, several criteria were set. First, the structure must comply with all requirements, shown in Appendix B, set by Cal Poly. Secondly, the structure needs to provide a proper vessel for the primary payload, the camera, to operate unobstructed. The structure was designed to minimize mass while maintaining structural strength capable of withstanding the greatest possible launch loads, which is currently the DNEPR vessel [4] with loads up to 10 G's. Finally, a structure was designed that can be accessed with ease by the different subsystems. This would provide a platform that would facilitate testing and if needed, changes to the components. Figure F.1 provides drawings of the preliminary structure and packaging schemes.

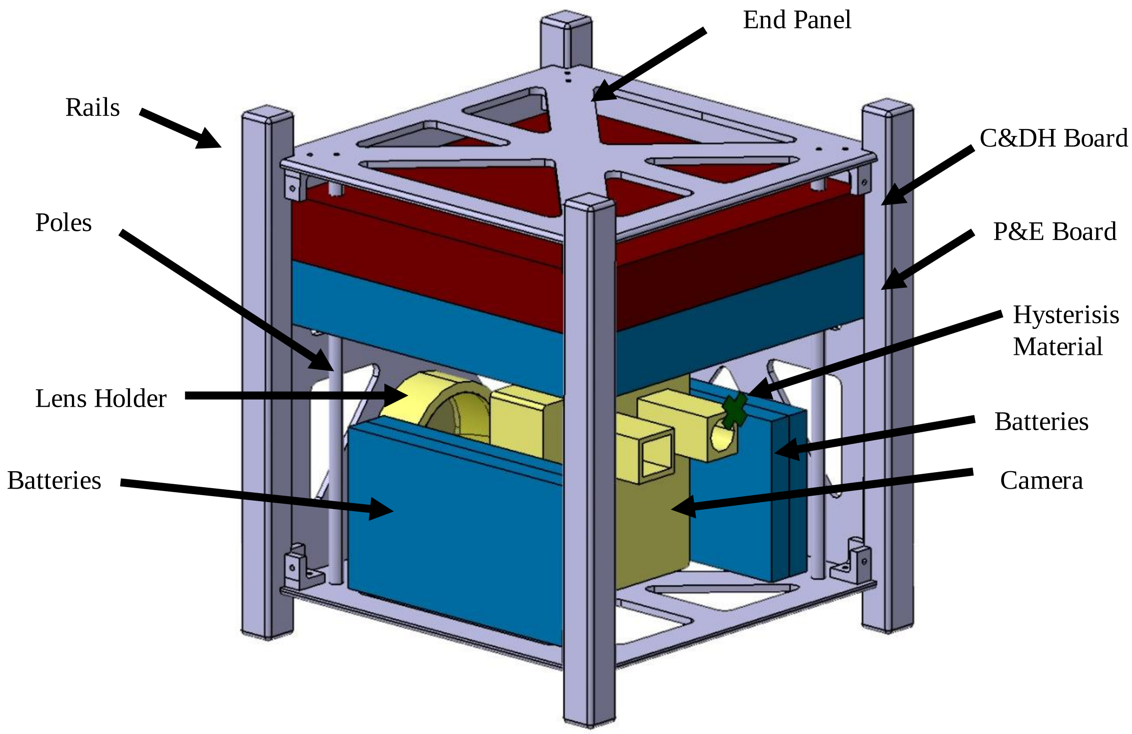

Figure F.1. M-Cubed assembly.

1. Assembly

The main structure is composed of six rectangular isogrid panels attached to four rails at each corner. The isogrid panels provide rigidity while being lower in mass than a solid panel. This reduction in mass allows for thicker panels that become a better medium through which necessary holes can be drilled. All panels, minus the bottom, contain similar patters as seen in Fig F.1. The bottom panel is modified to provide a circular opening for the camera lens as seen in Fig F.2. The rails to which these panels are attached will be hollowed out from the bottom face to reduce mass as well as providing a channel through which the power and electrical subsystem can access the spring-loaded plunger necessary to indicate M-Cubed's release from the P-POD (Poly Picosatellite Orbital Deployer).

To be compatible with the P-POD, M-Cubed must be hard anodized and have a height of 113.5 mm to allow distance between different cubesats. Another feature that was incorporated was the placement of the RBF (Remove Before Flight) pin. This pin must face the access panels on the side of the P-POD.

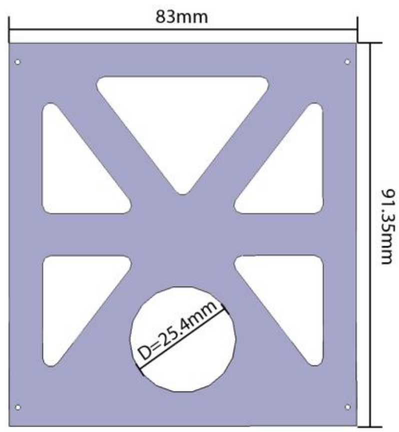

Figure F.2. Side panel with opening necessary for camera lens.

2. Payload Support System

The payload support system, shown in Fig F.3, consists of 4 cylindrical poles screwed into both end panels. These poles will be used to slide both C&DH and power and electrical boards into the structure and will be secured using stoppers. The battery will also be attached to the poles by a compatible casing developed by the structures subsystem. This support system can then be accessed by unscrewing the poles from one panel and detaching the opposite end panel, bringing with it the poles and all the components secured to it.

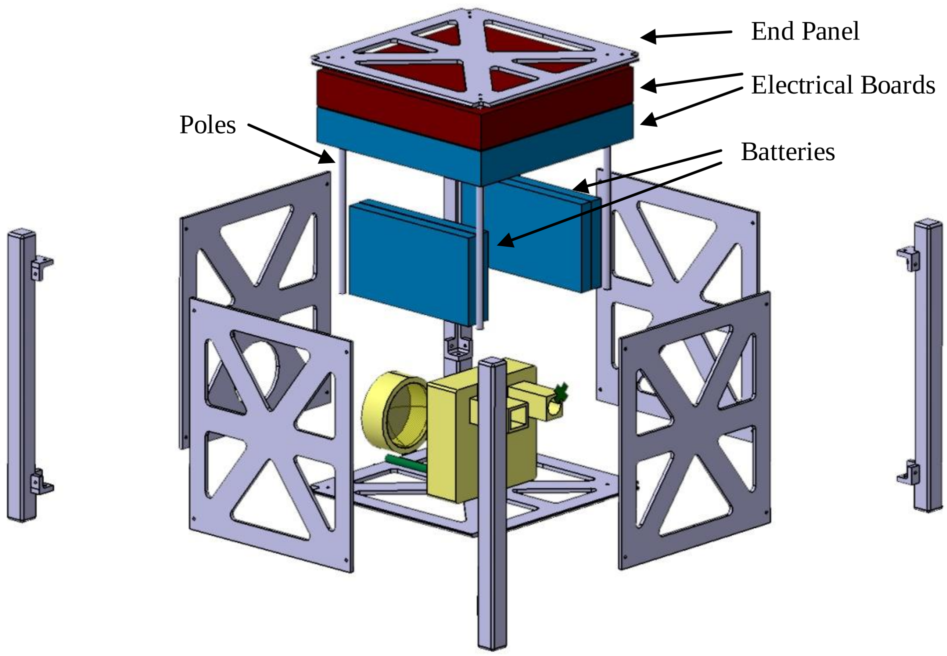

Figure F.3. Expanded view of payload support system with two removable electrical boards and batteries.

3. Antenna Deployment

M-Cubed requires a deployment mechanism for both antennas needed for communication with the ground station. The 130 MHz receiving antenna is a 0.33-m long dipole while the 435 MHz transmitting antenna is a 0.5-m long monopole. Both antennas are made of copper tape shaped to maintain a straight profile. The monopole antenna is fastened at one end while the dipole is fastened at its midpoint. Both antennas will be wrapped around the structure perpendicular to each other. The remaining ends are then tied down to the inside of the structure using nylon string with nichrome wire wrapped around it. When the antennas need to be deployed, a current will run through the nichrome wire, melting the nylon string and allowing for the antennas to release to their straight unfurled position. A schematic of the antenna release system is shown in Fig F.5.

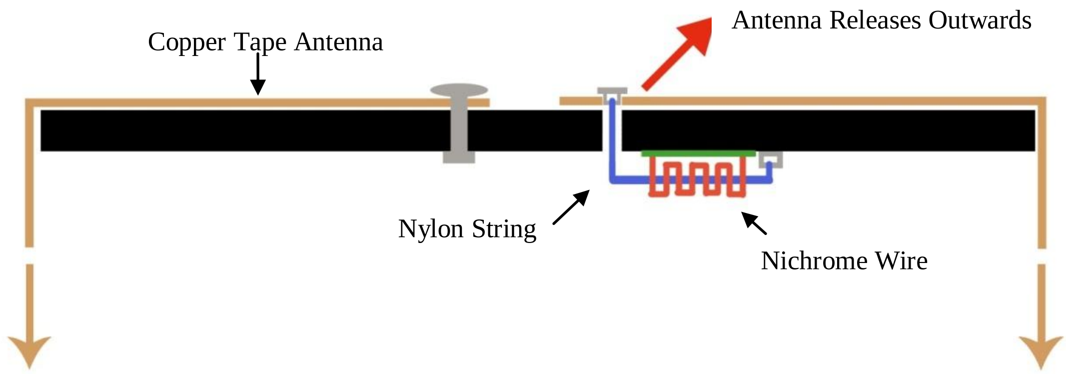

Figure F.5. Cubesat side view drawing of monopole antenna release system.

G. Thermal

To provide proper protection from radiation and heat fluxes, a passive thermal protection system consisting of proper insulation has been proposed. This insulation will consist of a layer of Kapton outside the panels, which will also act as an adhesive for the solar panels, and MLI inside the structure. Since solar panels will be covering most of the panels, the layer will be acting as additional insulation. Additional thermal covering will be used around the batteries, which are the most thermally sensitive components. A rendering of the insulation is shown below in Fig G.1.

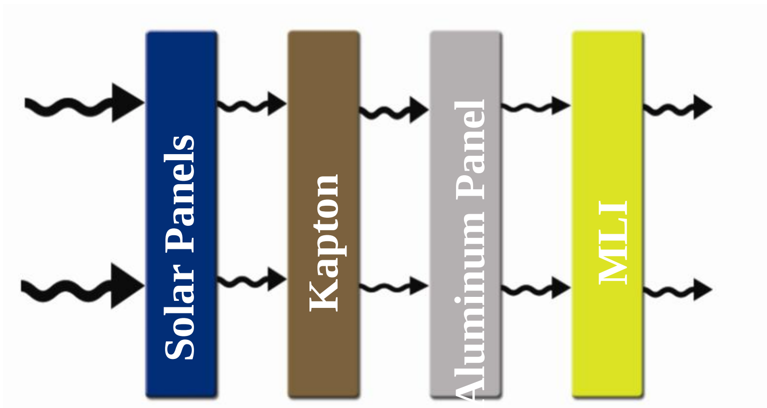

Figure G.1. Diagram of insulation layers.

IV. Future Work

As M-Cubed approaches the ¾ mark of the first year of development in the two year design timeline, the subsystems have begun component testing. The team is currently working toward PDR at the end of March, with each subsystem working on specified design and testing goals for PDR. A few students will be lost to graduation in April, but most of the current staff will be retained in the following academic year. Meanwhile, the summer will provide an opportunity for select students to work on specific component and system testing and analysis. This will provide the necessary steps to completing a CDR at the end of 2008 and launching into orbit by the end of 2009.

Acknowledgments

The authors thank S3FL, our supporting faculty in Prof. Peter Washabaugh, Prof. Brian Gilchrist, Prof. Nilton Renno, and Prof. Alec Gallimore, and the University of Michigan College of Engineering for their support technically and logistically. We'd also like to thank Yang Li, Selina Pan, Bradley Freyberg, Adam Avery, Fernando Saca, and Mike Lindsay for their support in putting this paper together. Finally, we would like to thank the Jet Propulsion Laboratory and Lockheed Martin for their funding and participation in this effort.

References

[1] Beech, W, and Nielsen, D., *AX.25 Link Access Protocol for Amateur Packet Radio* 4th ed., Tucson Amateur Packet Radio Corporation, 1997.

[2]Lee, S., "CubeSat Design Specification" *The CubeSat Program* [online design specifications], URL: http://cubesat.atl.calpoly.edu/media/CDS_rev10.pdf [cited 10 February 2007].

[3]Lee, S., "Poly Picosatellite Orbital Deployer Mk III ICD" *The CubeSat Program* [online design specifications], URL: http://cubesat.atl.calpoly.edu/media/P-POD%20Mk%20III%20ICD.pdf [cited 10 February 2007].

[4]Torian, A., "DNEPR Safety Compliance Requirements" *The CubeSat Program* [online design specifications], URL: http://cubesat.atl.calpoly.edu/media/Documents/Developers/compliance_dnepr_lv.pdf [cited 10 February 2007].

[5]Wertz, J.R., and Larson, W. J., *Space Mission Analysis and Design* 3nd ed., Microcosm Press and Springer, New York, 1999.

[6] "Atmel AV3232-bit MCU" *Atmel* [Online Design Specification], URL: http://www.atmel.com/dyn/products/product_card.asp?part_id=4085

[7] "Analog Devices ADF7020-1 FSK/ASK Transceiver IC" *Analog Devices* [Online Design Specification], URL: http://www.analog.com/en/prod/0,,ADF7020-1,00.html

Appendix A

The following table details the requirements specified by Cal Poly for the cubesat platform [2]

ID	Requirement	Source
SYS-001	The cubesat total mass shall not exceed 1 kg	Cal Poly Requirement
SYS-002	The cubesat shall have a remove before flight (RBF) pin to deactivate before integration with P-POD	Cal Poly Requirement
SYS-003	The cubesat shall not employ pyrotechnics	Cal Poly Requirement
SYS-004	The cubesat shall be fully deactivated in launch phase	Cal Poly Requirement
SYS-005	The cubesat shall withstand launch loading of TBD Hz	Cal Poly Requirement
SYS-006	The cubesat shall not present any danger to neighboring cubesats in the P-POD, the LV, or primary payloads	Cal Poly Requirement
SYS-007	The cubesat shall fit within a square volume with sides measuring 100 mm	Cal Poly Requirement
SYS-008	The cubesat shall keep all parts attached during launch, ejection, and operation.	Cal Poly Requirement
SYS-009	The cubesat structure must be compatible with the P-POD.	Cal Poly Requirement
SYS-010	The cubesat shall provide one deployment switch is required at a designated point per cubesat.	Cal Poly Requirement
SYS-011	The cubesat developers shall provide documentation of approval of an orbital debris mitigation plan obtained from the FCC.	Cal Poly Requirement
SYS-012	The cubesat shall undergo thermal vacuum bakeout testing according to the MTP.	Cal Poly Requirement
SYS-013	The cubesat shall not be disassembled or modified after qualification testing.	Cal Poly Requirement

Appendix B

The following table details the structural requirements specified by Cal Poly for the cubesat platform [2, 3]

ID	Requirement	Source
STR-001	Structural material(s) shall have a CTE within 22.5 to 24.5 µm/m-°C	Cal Poly Requirement
STR-002	The center of mass shall be within 20 mm of the geometric center of the cubesat	Cal Poly Requirement
STR-003	The structure shall meet random vibration test requirements as defined by MTP (TBD)	Cal Poly Requirement
STR-004	The structure shall meet thermal bakeout requirements as defined by MTP (TBD)	Cal Poly Requirement
STR-005	The rails of the cubesat must be smooth.	Cal Poly Requirement
STR-006	The edges of the cubesat must be rounded to a minimum radius of 1 mm	Cal Poly Requirement
STR-007	At least 75% of the rail must be in contact with the P-POD rails with no part of the rails exceeding the specification.	Cal Poly Requirement
STR-008	All rails of the cubesat shall be hard anodized.	Cal Poly Requirement
STR-009	Separation springs or a Cal Poly-approved custom separation system must be included at designated contact points.	Cal Poly Requirement
STR-010	The main structure material shall be Aluminum 7075 or 6061-T6 or otherwise approved by Cal Poly launch personnel.	Cal Poly Requirement
STR-011	The structure shall constrain any deployables	Cal Poly Requirement
STR-012	The antenna shall be deployed at a minimum of 15 minutes after ejection from the P-POD.	Cal Poly Requirement