Cube Quest

Design Package

SATELLITE DEVELOPMENT CLUB
AT WORCESTER POLYTECHNIC INSTITUTE
Rev 1.0

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Goddard Orbital and Atmospheric Testing Satellite (GOATS)

Satellite Development Club
Worcester Polytechnic Institute

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Revision 1.0

Contents

1 Introduction

The Satellite Development Club at Worcester Polytechnic Institute is excited to submit this Cube Quest Design Package for the NASA Cube Quest Centennial Challenge as the team Goddard Orbital and Atmospheric Testing Satellite (GOATS). We are an organization of students, professors, and sponsors inspired by the challenge of sending our own technology into space and driven by WPI's motto, "Theory and Practice."

We aspire to follow in the footsteps of the father of modern rocketry, Robert Goddard, as well as our university president Laurie Leshin for her work on the Curiosity Rover by launching our school's first CubeSat into deep space.

The following document describes our CubeSat design and plans for development.

1.1 Team Information

Team Name: Goddard Orbital and Atmospheric Testing Satellite (GOATS)

Sponsoring Organization: WPI

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1.2 Contact Information

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1.3 Revisions

Revision	Effective Date	Description
Revision 1.0	2/5/16	Document Baseline

2 System Design

2.1 Mission Objectives

Our team intends to compete in the Deep Space Derby, prioritizing the Best Burst Data Rate and Farthest Communication Distance prizes. Any subsequent prizes are considered secondary mission objectives.

As a secondary mission objective, the team strives to be among the first CubeSats to demonstrate in-space radio reconfiguration with flexible communication payload in deep space. This configuration is described in greater detail in the Mission Concept Registration Data Package. Although this is not listed as Deep Space Derby prize, doing so will allow us complete our chosen objectives while demonstrating the performance of such operations in deep space with a CubeSat's limited resources. We believe our team as well as NASA will gain valuable knowledge and experience with such demonstrations during the challenge.

Another secondary mission objective that coincides with Deep Space Derby prizes is the exceptional durability and survival capability of a connection between the CubeSat and ground station during events such as coronal mass ejections, electromagnetic storms, and solar flares. Such a robust connection will particularly aid in achieving the Farthest Communication Distance prize. The following Gantt chart depicts the mission timeline for these objectives.

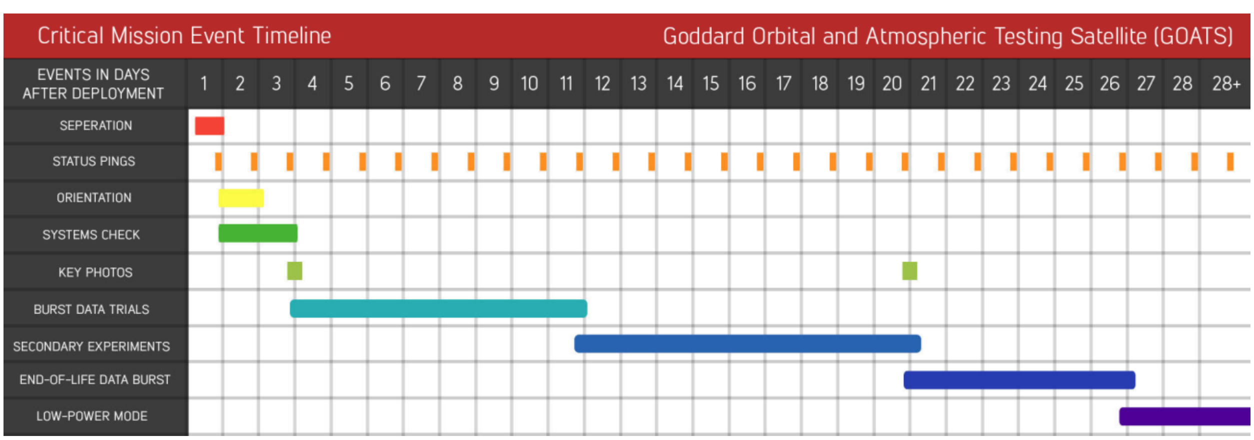


Figure 1: Critical Mission Event Timeline

2.2 System-Level Design

2.2.1 System Level Requirements

The primary mission of our CubeSat is to demonstrate the capabilities of CubeSat deep space communications, specifically, best burst data rates and farthest communication. In that pursuit of this mission our CubeSat will be capable of the following:

- Reliable communication with earth
- Responsive to ground station command
- Accelerated downlink communications for 30+ minutes
- System lifespan at minimum 28 days

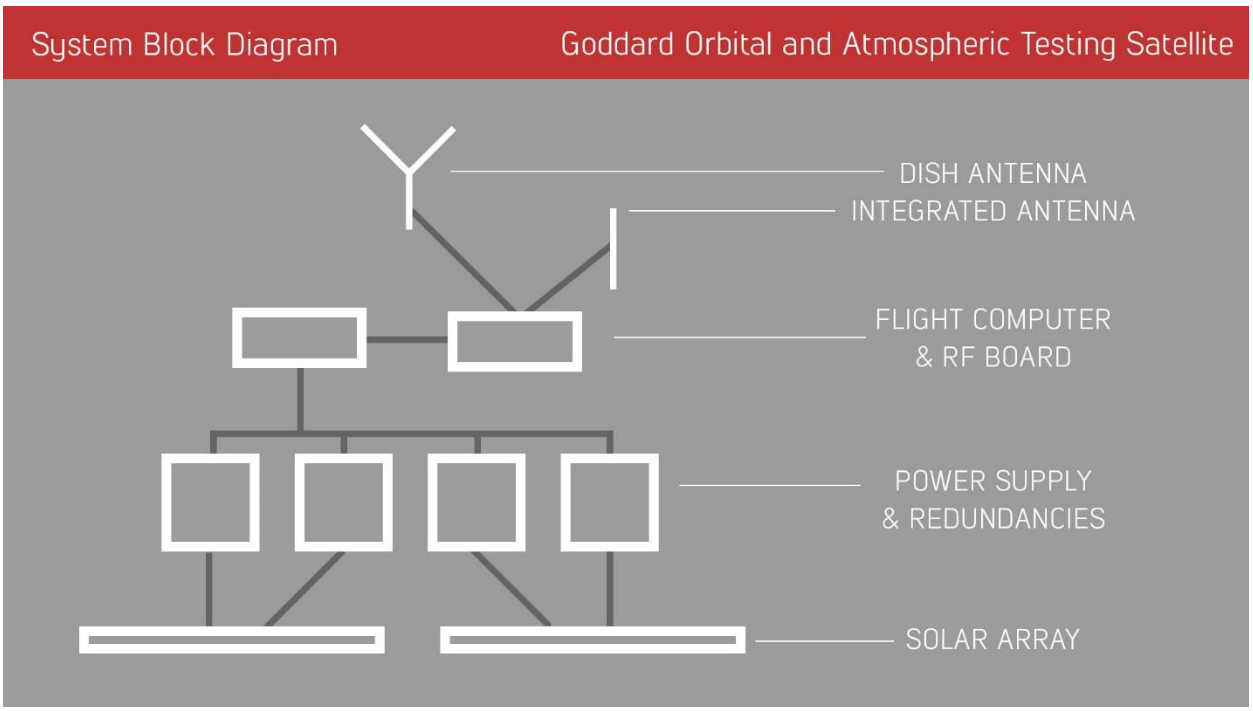


Figure 2: System Block Diagram

The focused purpose of our CubeSat mission allows us to focus subsystem design that maximizes our chance of success. Power will be generated by a body mounted solar array covering the external surface of the CubeSat. Generated power will be stored in redundant series of rechargeable power banks and resupplied to system electronics. The primary flight computer controls all satellite functions including attitude and thermal control with its primary function communication. The flight computer's primary interface is the RF board and deployable dish antenna. Highly detailed overviews of these systems can be found in the chapter on subsystem design.

The tables below contain a breakdown of the volume and mass budget awarded to each subsystem.

Subsystem	Mass (kg)	Parts Included
Structures	1.1	CubeSat chassis
Communications	2.1	Flight computer, radios, integrated antenna, dish antenna
Electrical	4	Solar panels, batteries, wiring
Thermal	1	Radiator, insulation, shielding
GNC	5	Sensors, reaction wheels
C&DH	0	none
Propulsion	0.8	Thruster and Propellant
TOTAL	14	

Table 1: Subsystem Mass Allocations

Subsystem	Volume (U)	Parts Included
Structures	0	CubeSat chassis
Communications	2	Flight computer, radios, integrated antenna, dish antenna
Electrical	2.75	Solar panels, batteries, wiring
Thermal	0.35	Radiator, insulation, shielding
GNC	0.5	Sensors, reaction wheels
C&DH	0	none
Propulsion	0.4	none
TOTAL	6	

Table 2: Subsystem Volume Allocations

**All values in the tables above are estimates and subject to change as refinements are made to subsystem designs.*

2.2.2 Transport, Storage, Launch & Operating Environments

Given our team is awarded a launch on EM-1 and construction of the CubeSat is complete (including P-POD interfaces), the team will transport the CubeSat to the NASA launch facility by vehicle. The CubeSat will be configured to comply with Cube Quest requirements for pre-flight storage. The system will be shut down aside from basic functions like battery maintenance and communication silence will be observed. In preparation for launch, the CubeSat and its associated P-POD having met all volume, sizing and mass requirements will be ready for payload storage. Support interfaces such as power to charge batteries will comply with EM-1 specification and the CubeSat will remain off for the duration of the Orion mission until the P-POD has been ejected. Upon ejection the CubeSat will wait to power on until it has cleared the Orion spacecraft. Upon boot communication with ground station will begin immediately and the mission will be underway. Sensitive components will be shielded from radiation and thermally insulated to handle the environment of outer space.

2.2.3 Key Mission Risks and Redundancies

The greatest risk to mission success is the environment of space causing critical hardware failure. Protection of sensitive components though careful design and in regards to radiation and thermal shielding will be afforded in every way, but protections from unidentified hazards can still have to potential of prematurely ending the mission. For a complete list of identified hazards, please see Appendix 3 in Section 6.3. of the submitted *Mission Concept Registration Data Package*. To avoid mission critical hardware failure, the team has incorporated redundancies and backups in the design of critical subsystems.

2.2.3.1 Power Storage/Supply

Given electrical power is the most precious resource onboard the CubeSat the electrical team has built in several redundancies to combat hardware failure. Power will be stored in two independent arrays of rechargeable battery banks. In the event an array exhibits signs of failure or begins underperforming for any reason onboard systems will automatically switch to the supply. The status of every cell will be closely monitored on the ground as part of the information relayed during scheduled system status pings. In addition to the redundancies above both arrays will be wired independently to avoid the chance of wiring/connection failure. In terms of power generation, solar arrays are traditionally considered reliable systems however, should the array fail to operate properly the onboard batteries will contain enough charge to perform basic communication functions and at least one data burst. For more detail see the section on electrical subsystems.

2.2.3.2 RF/Communications

The primary dish antenna will greatly accelerate downlink communication with earth however; deployment complications would incapacitate the CubeSat. An integrated antenna (requiring no deployment) capable of all necessary communication will also be included to combat this possibility. The integrated antenna will also be responsive to communications from earth from any orientation in the event that the satellite trajectory has become disrupted or GNC systems are incapable of adequately pointing the primary dish antenna. For more detail see the section on communication subsystem.

3 Implementation Plan

3.1 Development Schedule

Our team is committed to meeting all Cube Quest deadlines in a timely and professional manner. Given that many team members are students and subject to the requirements of their schoolwork, our development timeline may vary slightly. Reference the Gantt chart below for an overview of our hardware development timeline.

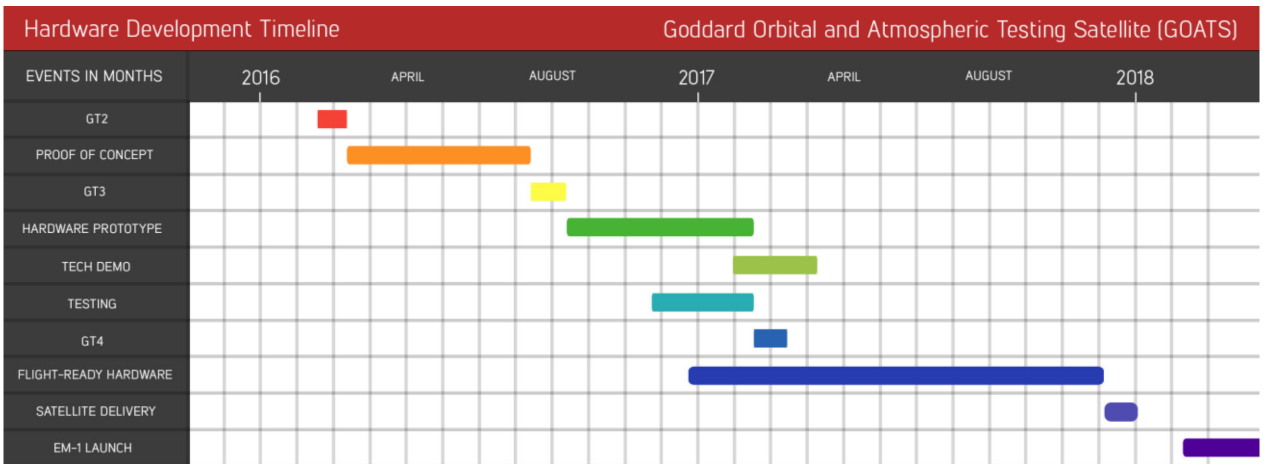


Figure 3: Hardware Development Timeline

By GT-3 the team will present a proof of concept with a compilation of hardware to demonstrate successful communication in a lab setting. Subsystems will still be early in the design phase but completed work will be presented here. Leading up to GT-4 subsystem design will mature and prototypes of flight-ready hardware will be complete. Communication testing and optimization will continue during this phase and great performance gains are expected. Design and fabrication will overlap as subsystems near completion and as more resources are made available. In preparation for GT-4 the team will prepare a technical demonstration of the CubeSat's abilities. This demonstration will touch upon the current progress of each subsystem allowing for GT judge feedback. The focus of the demonstration will be a benchmark of our communication system's ability to perform sustained burst data transfer. Following GT-4, the team will begin to construct a flight-ready CubeSat in preparation for EM-1 launch.

3.2 System Testing

Each subsystem will be tested independently as well as part of the larger system of the CubeSat. Functional tests will be performed in the laboratory environment on an as-needed basis to establish preliminary functionality of the system. Once each subsystem and the CubeSat as a whole are deemed fully functional in a laboratory environment, we will test the whole system in the following test environments:

- Thermal vacuum
- Shock and vibration
- EMI
    - For compliance with FCC radio frequency band, and to check the final irradiation pattern when antenna is connected to the CubeSat

These tests will likely take place at the Busek facility in Natick, Massachusetts with facility personnel as well as the club president and technical subsystem leads. This list of tests is subject to change due to budget and time constraints. Test profiles will be determined according to the standards in the Interface Definition and Requirements Document in order to achieve flight qualification. These tests will take place starting in December 2016 through GT-4.

Operational tests will be performed with DSN approximately three months prior to launch. More detailed test procedures will be developed as greater detail is established in the CubeSat design and as tests approach.

The dispenser will be verified that it conforms to the technical and safety requirements specified in SLS-SPIE-RQMT-018 IDRD Section 4.0.

Safety reviews will occur according to the SLS-PLAN-217 SLS Secondary Payload Safety Review Process, Section 4 on the following approximate dates:

- Phase I: April 2016
- Phase II: November 2016
- Phase III: January 2017

4 Ground Systems and Mission Operations Design

The club maintains lab space provided by WPI for the purpose of CubeSat design and construction. This has been our primary base of operations and will function as “mission control” while our mission is under progress. In addition to lab space the WPI equipment we’ll be using for communication includes an 18-foot tower with 2m and 70cm Yagi-Uda antennas and an IC-910H transceiver. While the mission is underway, the CubeSat will be contacted on a daily or otherwise regular basis in order to ensure nominal health and status, and make modifications to its operations as necessary. The communication equipment is currently operational and maintained by the WPI radio association, WPIWA. The equipment will be operated by team members in conjunction with WPIWA.

More research is being conducted into the possibility of instead using DSN for communication with the CubeSat given the limits to our existing hardware.

5 CubeSat Subsystem Design

5.1 Communications Subsystem

The communications subsystem is composed by three main devices: flight computer, RF board, and power amplifier. Since the antennas are external components they are covered in the Structures subsystems subsection. The communications subsystem is responsible for reception of commands and controls, and transmission of telemetry and data related to the main challenge.

The choice of hardware is driven by technical specifications as well as cost, size and weight. Because the radiation hardened requirement was removed from individual components to the entire CubeSat structure cover, internal on-board electronics components and devices are assumed to be protected. This choice greatly decreases the cost of the equipment used.

5.1.1 Radio

The radio is one of the main components of the CubeSat design. Due to the recent advancements on integrated circuits and miniaturization of electronic components, it is possible to build a Field-Programmable Gate Array (FPGA) together with a complete RF front-end transmitter and receiver chains, completely controlled by software, in this case, the flight computer. The choice of the radio used in this project could not be made until September 2015. The board is the size of a credit card and completely reconfigurable via software through the usage of the FPGA. Although not planned to be used in the main mission, the same board also provides a wide operational frequency band. The entire transmitter and receiver chains are created and controlled via software through the flight computer. The software for both development and control of the radio functions is the open-source GNU Radio. Below are some technical specifications of the chosen radio board:

- Radio board model: USRP B200mini
- Frequency covered: 70 MHz - 6 GHz
- PC interface: 1 USB 3.0
- FPGA: Xilinx Spartan-6 XC6SLX75
- Open-source dev. Software: GNU Radio
- URL: http://www.ettus.com/product/details/USRP-B200mini

5.1.2 Planned RF frequency bands

The final decision on the RF carrier frequencies to be used during the mission will be made upon NASA's final response to our request on using DSN's ground stations. If the response is positive we might end up using one of DSN's and one of its possible three frequency bands: S-, X- or Ka-band. Since the ground station RF front-end might be provided by NASA, the signal to be transmitted and the received signal from our CubeSat might be in baseband or at S-band.

If NASA's response is negative, the RF frequency bands used during our mission might be at S-band (2-4 GHz) or C-band (4-6 GHz), since these are the amateur satellite frequency bands covered by the RF front-ends planned to be used in our CubeSat.

In any case after deciding upon the RF carrier frequencies the team will apply for its licensing with the Federal Communications Commission (FCC), International Amateur Radio Union (IARU), International Telecommunications Union (ITU), and/or National Telecommunications and Information Administration (NTIA) depending on each case.

5.1.3 Ground Station

Our team currently has two options for ground-station. The ideal one is to request access to use NASA's Deep Space Network (DSN). By the time of this document submission the team was finishing the planning and putting together all the information required to apply for it. The team foresees minimal impact while using DSN's ground station network infrastructure. It is expected that items such as antennas, high power amplifiers, directional antenna pointing systems and staff to operate these are provided by NASA as part of the access provided, in case of an eventual application approval. Since all the RF infrastructure is expected to be provided, only the software required to communicate with the CubeSat might be required for the purposes of exchanging messages for command, control, telemetry and data payload between the CubeSat and the ground station. This can be easily achieved since our communications design is software-defined and allows for flexibility to be achieved with ease. Also the radio on-board the CubeSat is also software-defined and can be reconfigured. Thus since our team is provided the transmitter and receiver chains in baseband, the mission can take place by controlling the CubeSat as well as demodulating the received signals using the software transmitters and receivers developed by our team.

The secondary option includes the amateur radio ground station located at WPI. Currently it is very limited in terms of infrastructure to achieve deep space communications with spacecraft. However, it remains as a valid option and in case the team decides to use it, additional evaluation in terms of antennas and amplifiers might be considered.

5.1.4 Transmitter Power Amplifier

Due to the limitations of power output from the radio transmitter on-board the spacecraft, it is foreseen the requirement for power amplification of the transmitted signal before it is fed into the transmitter antenna.

- Transistor/CI based
- Very simple design; inexpensive parts;
- Off-the-shelf: expensive (TWTA)
- Powered by dedicated battery
- Will require some testing and validation
- May have a direct impact on the total number of battery unit number, as well as operational up time.

5.1.5 Receiver Power Amplifier

Due to the limitations of power output from the radio transmitter at ground station amplification on-board might be required. Testing is still needed in order to determine if the amplification by the Rx chain on-board the radio hardware is sufficient or not. If not, an amplifier might be required to be designed and installed, with the electrical input voltage and current radio board constraints in mind.

5.1.6 Antenna

5.1.6.1 Integrated Antenna

The customized off-the-shelf deployable turnstile antenna is circularly polarized and consists of four monopole antennas combined in a phasing network in order to form a single circular polarized antenna. The antenna pattern is almost omnidirectional and there are no blind spots which can cause fading with tumbling satellites.

5.1.6.2 Deployable Dish Antenna

The deployable dish antenna will be used to increase our capability of communicating with the ground station since it is capable of directing the signal power to Earth for transmissions as well as concentrating the received power for reception. If communication through this deployable antenna is achieved, it will be amongst one of the first usages of a low-cost deployable antenna in a 6U CubeSat in deep space.

5.1.6.3 Backup Dipole Antenna: Metallic Tape

A backup antenna is expected to be mounted in the corners of the CubeSat structure using metallic tapes. They might be used as a last resource.

5.1.7 Planned Transmission Powers, Modulation Methods, and Coding Approaches

The expected maximum transmission power from the CubeSat will be between 1 and 2 W amplified by on-board amplifiers, since the maximum power output by the USRP

B200mini is adjustable between 20 and 50 mW. For the receiver chain, even though there is an analog gain of almost 73 dB, due to the distances involved, the received signal will definitely need power amplification from on-board power amplifiers driven by power supplied by the power banks.

For robustness against the CubeSat tumbling it is desired to use a modulation scheme immune to phase shifting, same justification for the choice of a circular polarized antenna. Thus, the choice of Differential Binary Phase Shift Keying (DBPSK), Quadrature Phase Shift Keying (QPSK), 8-PSK and 16-PSK might be available during the mission. Convolutional encoding using Hamming encoding of rates 4/7 and 11/15 will also be available during the mission. In order to assess the reception error performance forward error correction (FEC) will be used through the Cyclic Redundancy Code (CRC) implementation.

5.1.8 Cables

Each set of primary or backup devices might require its own independent cable kits. These cables are standard cables to make the connections between the communication devices, for data and power transmission, depending on the devices being connected.

- USB to “standard” 5V4A DC PC power input
- USB 3.0 cables
- Battery to PC
- Battery to radio
- PC to radio
- SMA cable
- Radio to power amplifier 2x
- Power Amplifier to dipole antenna
- Power Amplifier to dish antenna
- Solar panel interface/connector to USB (power bank)

5.1.9 Analysis

Based on the usage of an SDR technology to implement the radios on-board the CubeSat, adaptation of modulation and coding (ACM) might be implemented during the different mission phases, such as when the CubeSat will closer to the Earth right after deployment from the P-POD and when it reaches its longest distance far from the Earth. Also, in case of any system anomaly more robust modulation and encoding schemes might be used.

5.1.10 DSN Timeline

The following figure describes the timeline for DSN scheduling and preparation. The numbers on the y-axis correspond to the following events:

1) Application for DSN

2) Set up source code and radio on base band to IF
3) Test and validate system off-air
4) Launch and standby
5) Best Burst Data Rate attempts
6) Longevity attempt
7) Hand off to DSN personnel
8) DSN returns radio

Figure 4: DSN Event Timeline

5.1.11 Data Architecture Approach

The data payload will follow the Recommendations for Space Data System Standards by the Consultative Committee for Space Data Systems (CCSDS) Blue Book Radio Frequency and Modulation Systems (CCSDS 401.0-B), CCSDS Bundle Protocol Specification (CCSDS 734.2-B-1). The implementation might follow what is currently implemented by the Interplanetary Overlay Network (ION) of Delay Tolerant Network (DTN).

5.2 Electrical Power Subsystem

5.2.1 Generation

The CubeSat will generate power using an array of solar panels. The solar array will be comprised of a "patchwork" of solar cells covering the satellites outer surface.

The array will produce enough power to operate and sustain the CubeSat for the duration of the mission. The array will be custom designed for this application. The array will be made from several modified 22W High Efficiency Solar Chargers from VINSIC. This solution provides the greatest amount of performance at our price point. If testing shows the array is not capable of delivering the required amount of power, the chassis will be fitted with two (or more) deployable articulating solar panels to increase the number of sun-facing cells. In addition to power supply, the contribution of each panel will be monitored for purposes navigation, and orientation. This data will be part of the information relayed in scheduled system status pings.

5.2.2 Storage

Power will be stored in an array of rechargeable power banks. The power banks are arranged in pairs that will switch states between recharge and supply. Each power bank pair will have a redundant “back-up” pair that can be switched to in case of supply failure. The supply will be comprised of eight 26800mAh cells from RAVPower. The total power available capacity split between primary and backup power banks will be approximately 214,400mAh. All power banks will launch fully charged and their capacities will be monitored by the flight computer. The status of every cell will be part of the information relayed during system status pings.

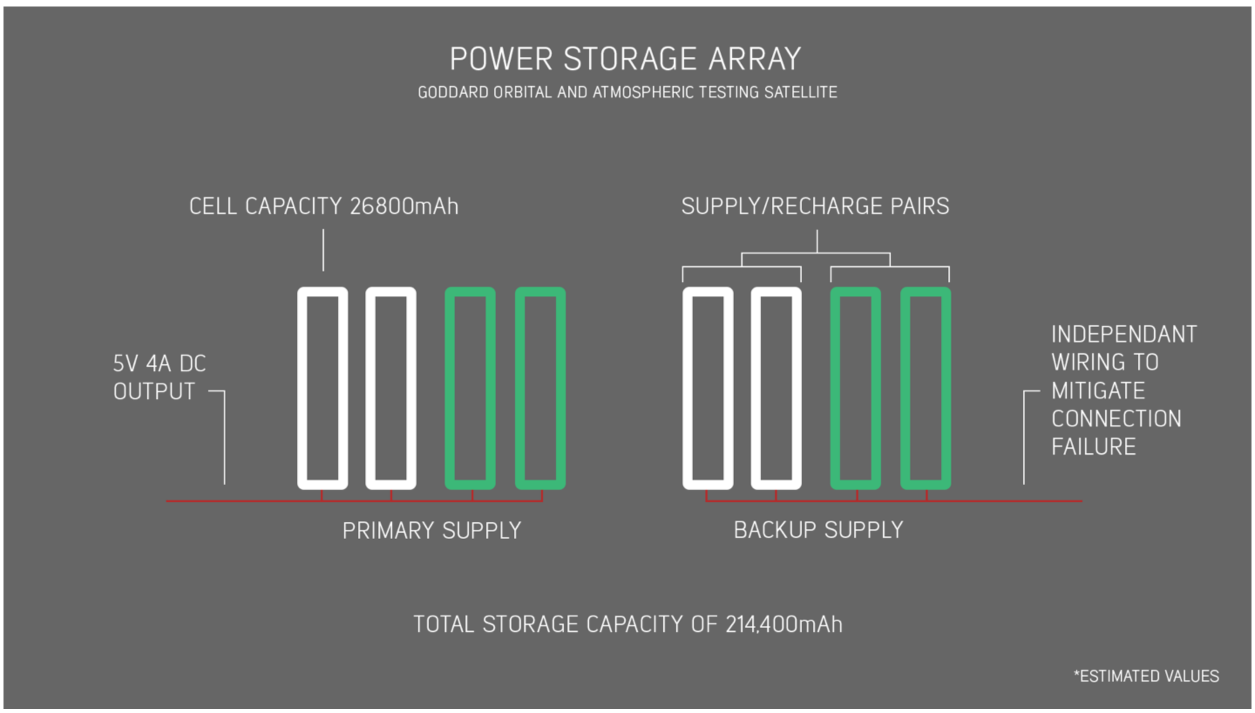


Figure 5: Power Storage Array

In order to supply constant power to subsystems, especially the main flight computer and radio, power banks composed of Lithium-Ion cells will be used. Given their power storage capability some banks will be embedded inside the CubeSat structure. It is expected that all power banks be used throughout the entire mission. At least three units will be installed and will take turns between acting as main power supply, immediate backup/redundancy, and being recharged. The choice for the model was made based upon technical specifications of maximum current output, a requirement of both flight computer PC and radio. Another decisive feature was the integrated circuit-based safety protection against short-circuit, overcharging, and current surge. The battery pack will automatic shutdown if a short circuit or overload output occurs while unit is charging. Also, high temperature protection (NTC), ‘plug and play’ like- no on-switch required. See the chapter three for more detail on the power supply. Below is the model and specification of the power bank chosen:

- Power bank: RavPower Lithium-Ion (RP-PB41)
- Power storage capacity 26,800 mAh / 99.16 Wh
- DC 5V 5.5A output
- DC 5V 2A input
- Product Information: http://www.amazon.com/dp/B012NIQG5E

5.2.3 Distribution

Power distribution will be controlled and prioritized by the flight computer. This includes managing the supply/recharge states for the power bank pairs, initiating redundancies and prioritizing the distribution of power between essential and nonessential subsystems. Communication systems are considered most essential in this mission. The power supply will output 5V at 4A DC, the required amount for system instruments and electronics. Primary and backup pairs will be wired independently to mitigate the effects of wiring/connection failure. Connectors unable to meet vibration standards will be replaced with reinforced directly soldered connections. All electronics will be appropriately shielded to protect against radiation.

5.3 Command & Data Handling (C&DH)

5.3.1 Primary Flight Computer

Considered as the main mission computer, it is responsible for controlling the radio board. All the software used is open-source. The operational system is the latest stable version of the Linux distribution Ubuntu 15.04. Considering the radio board has a critical requirement for its communicating interface, minimum acceptable computer must have at least one USB 3.0. Currently, there are some off-the-shelf options on the market. Based on the USB requirement, processing power, size, weight and cost the final choice is to use the ODROID-XU 4 model, which has the following specifications:

- PC based: ODROID-XU 4
- CPU: Samsung Exynos-5422: ARM® Cortex®- A15™ Quad up to 2.1GHz + Cortex®- A7™ Quad up to 1.5GHz with 2GB LPDDR3 RAM
- GPU: Mali™-T628 MP6 (OpenGL ES 3.0/2.0/1.1 and OpenCL 1.1 Full profile)
- Interfaces: 2 x USB 3.0 Host; 1 x USB 2.0 Host; GB Ethernet; HDMI
- Product Information: http://www.hardkernel.com/main/products/prdt_info.php
- User Manual: http://magazine.odroid.com/odroid-xu4/

5.3.2 Backup/Redundant Flight Computer

Same configuration as the primary flight computer.

5.3.3 Data Storage (chips/cards)

For dealing with data storage such as ROM memory for storing the operational system and software to control the radio, data payload to be transmitted as the data for the main challenge, as well as byproducts from the secondary mission, eMMC chips and/or micro-SD cards will be used as both primary and redundancy storage units. It is not planned to build RAID with these devices, since they need to operate independently, and in case of emergency, to replace each other. Suggestions of supported models are described below, based on the flight computer manufacturer requirements:

- eMMC 5.0 HS400 Flash Storage
- iNAND 7030 or iNAND 5130
- Product Information: https://www.sandisk.com/oem-design/mobile/inand
- Micro-SD UHS-1
- Product Information: http://www.hardkernel.com/main/shop/good_list.php?lang=en

5.4 Guidance, Navigation and Control (GNC)

Guidance, navigation, and control (GNC) is one of the most critical parts of any satellites systems. Without it, the satellite will have no information in its position in space which can lead to a premature ending of a mission. GNC is an important system because it must be in constant communication with the onboard computer during the execution of maneuvers or attitude adjustments. Attitude Determination & Control Systems (ADCS) are responsible for controlling a CubeSats pitch, yaw, and roll. These two systems work to make together to make sure that solar panels are producing maximum power, communications are being accurately received / transmitted, and that Δv burns are being executed at the right time and in the right way.

5.4.1 Sun Sensor

The sun is the brightest object in our solar system, and we can use this fact to help orient our satellite in space. Coarse and Fine Sun Sensors can be installed into the satellite to help understand the satellites angle relative to the Sun. Multiple Coarse Sun Sensors can be located in multiple parts of the CubeSat to find the general direction of the Sun, and then be used to accurately pinpoint exactly where the sun. The use of this system is to help align the the CubeSat with the Sun such that the solar panels are running at peak efficiency.

Redundancy for sun positioning can be accomplished via comparing differences in solar panel power production. Given the dimensions of the solar panels and their positions relative to the CubeSat body, it becomes a simple matter of programming to then determine the exact location of the sun relative to the CubeSat. This procedure will be used in conjecture with Sun sensors to check for data consistency and accuracy to minimize the risk of misinformation and subsequent non-ideal maneuvers.

5.4.2 Reaction Wheels

The most reliable method of controlling the satellite in deep space is with using reaction wheels. Reaction wheels work by taking advantage of the law of conservation of momentum. By spinning wheels at various speeds mounted on multiple orthogonal axis relative to the CubeSat, the CubeSat has is given pitch, yaw, and roll capabilities. Reaction wheels require power to spin the wheels and must be in constant communication with the main computer during direction-specific tasks so that the system knows how fast to spin and when. They take up a relatively large volume of the CubeSat, given the physics of their design.

5.4.3 Blue Canyon Tech XACT Control System

The XACT Control System has the basic necessities for GNC capabilities and a small volume of 0.5U that make it the GNC system of our choice. For attitude control, the system has three reaction wheels and magnetic torquers. For sensors, XACT Lite is equipped with a micro star tracker. This system has not been flown but is flight-ready, and is rated with a TRL of 6.

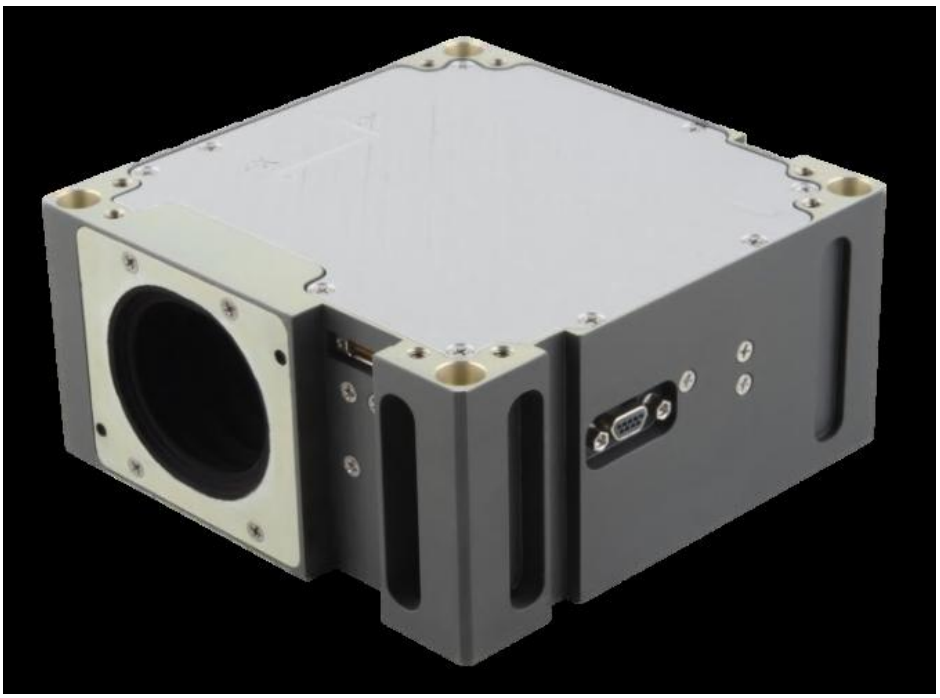


Figure 6: Blue Canyon Tech XACT Control System

Our basic needs of guidance, navigation and control are simple. One of the most important objectives is to maintain connection from the satellite to the ground base for communication. Another objective is to point the satellite where the solar panels receive the most amount of power.

Blue Canyon's XACT, satisfies the subsystem requirements by containing a multitude of different sensors and attitude control to help steer the satellite. The three reaction wheels will be able to maneuver the satellite to an accuracy of about .007 degrees that will allow the communication array to maintain precise communication with earth. The star tracker can communicate with the micro reaction wheels which can initiate changes in momentum to help align the satellite.

Operating the reaction wheels requires power from the battery and other systems of the satellite. This is taken into account and the power system contains sufficient amounts of power to allow the attitude control to shift the satellite. The XACT contains its own attitude determination system that uses all of the measurements. This grants more space for the onboard computer and also reduces the amounts of processes the onboard computer needs to compute.

Specification	**Performance**
Spacecraft Pointing Accuracy	± 0.003 deg (1-sigma) for 2 axes ± 0.007 deg (1-sigma) for 3rd axis
Spacecraft Lifetime	3 Years (LEO)
XACT Mass	0.91 kg
XACT Volume	10 x 10 x 5 cm (0.5U)
XACT Electronics Voltage	5V
XACT Reaction Wheel Voltage	12V
Data Interface	RS-422, RS-485 & SPI
Slew Rate (4kg, 3U CubeSat)	≥10 deg/

Table 3: XACT Specifications

Operational Case	**Power (W)**
XACT (low power standby mode)	0.03
XACT (5 Hz operation)	1.35

XACT + 3 TR (ON STATE)	2.14
XACT + 3 RW (@1.25mNms)	1.92
XACT + 3 RW (@2.5mNms)	2.47
XACT + 2RW (@1.25mNms) + 1 RW (@ 15 mNms)	3.23

Table 4: XCAT Operational Cases

5.5 Structures

5.5.1 Requirements

The structure requires that it needs to fit under the weight limits of 60 pounds, must have a center of gravity equal or less than 2 cm from the center of the structure, and all the element of the CubeSat has to fit within the 6U case (National Aeronautics and Space Administration, 2015). For the structure itself, we will be using an ISIS designed model that can survive launch and deep-space conditions (See Figure 2) (*6-Unit CubeSat Structure*). The antenna and other deployable pieces must be fixed to the chassis in such a way that they can reliably deploy and do not interfere with each other.

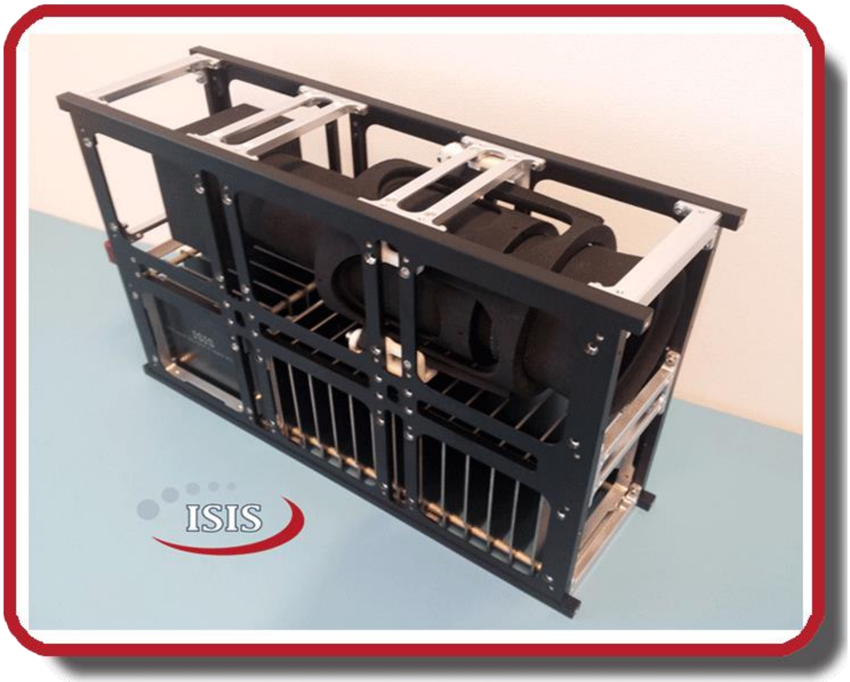


Figure 7: CubeSat Structure

5.5.2 Design

We have chosen to use the COTS ISIS 6-Unit CubeSat structure sold by CubeSatShop.com. On their website, the CubeSatShop describes their structure as:

> "The ISIS 6-Unit CubeSat structure is developed as a generic, modular satellite structure based upon the CubeSat standard. The design created by ISIS allows for multiple mounting configurations, giving CubeSat developers maximum flexibility in their design process. The stacks of PCBs and other flight modules can be build up first in the secondary structure and integrated with the load carrying frames at the end of the process, ensuring accessibility of the flight avionics. In addition, the use of a load carrying frame and detachable shear panels allows for access to all parts of the spacecraft avionics, even after final integration by removing one or more of the shear panels. The modular structure allows up to six 1-Unit stacks of PCBs, or other modules, to be mounted inside the structure in two rows of three. For example, a 3-Unit bus in combination with a 3-Unit imager." (*6-Unit CubeSat Structure*)

Using this COTS structure will give us many options for easy integration of other COTS parts, and will eliminate the possibility of untested failure from a structure that we could have designed. These are all good enough reasons to shell out the over 7000€ for a reliable structure, as it is housing our entire CubeSat.

According to the website, "No ISIS 6-Unit CubeSat Structures have flown in space yet, however, multiple units are slated for a launch in the upcoming 12 months."

The Structure will come with:

- Primary Structure:
  - 2x Side Frames, Black Hard Anodised
  - Ribs, Blank Alodyned
  - 2x Kill Switch Mechanisms
  - Supplied with inserted Phosphor Bronze HeliCoils
  - Fasteners
- Secondary Structure:
  - 6x Aluminium Shear Panels, Blank Alodyned
  - M3 Threaded Rods, M3 Hex Nuts, M3 Bus Spacers
  - Boards are supported using M3 Washers

5.5.3 Analysis

5.5.3.1 Mass Budget

The maximum total mass, according to the IDRD form given by NASA, is 60 pounds. Diving into the details, the IDRD notes that the 60 pounds includes, "the combined dispenser /payload unit and for features such as vibration isolation and thermal protection" (National Aeronautics and Space Administration, 2015). Therefore, we have set ourselves a limit of 20kg to the mass of our CubeSat and have set individual mass limits for each system and subsystem. According to CubeSatShop, the weight of the CubeSat, without any additional parts, would be 1100 grams. See Table 1: Subsystem Mass Allocations for specific mass distribution among subsystems.

5.5.3.2 Volume Budget

The CubeSat has to be able to hold all the other subsystems within its 6U chassis (about 4943 cm^3), so we have created limits for how much space each essential subsystem can take up (See Table 2). Each limit is an educated estimate based on the sizes of the components we have chosen or the sizes of similar off-the-shelf parts. We ended up with about 0.25U unused by anything, which is a good fudge factor for if one subsystem is more voluminous than expected. Otherwise, these estimates are all overestimates (to the best of our knowledge), so there is the possibility of having even more free space that can be given to additional subsystems or whatever is demeaned necessary. See Table 2: Subsystem Volume Allocations for details on volume distribution amongst subsystems.

5.5.3.3 Strength and Stiffness

The CubeSat structure we are looking at has the following design qualification loads (*6-Unit CubeSat Structure*).

- Static +21.6 [g], three axes
- Sine Vibration 4.0 [g], 5 – 100 [Hz]
- Random Vibration 14.1 [grms], NASA GEVS

Although these specifications do not meet the all of the qualifications of random vibration and shock set by the NASA IDRD's tables 3.3-3.6, these are just the specifications of the CubeSat Structure itself. The P-Pod will be designed to completely protect the CubeSat against possible vibrations and loads during launch.

5.5.3.4 TRL

The TRL would be 5-6 since the structure is "fully compatible with ISIS mechanical ground support equipment for easy integration and assembly [and] fully compatible with ISIS deployable antennas and solar arrays," but has not flown in space yet.

5.6 Propulsion

The GOATS design currently calls for the use of electric propulsion to achieve the 4E6 km mission distance. Electric Propulsion is the clear choice given the limitations on pressure vessels and combustible materials laid out by the SLS. Additionally, this project acts as a learning experience for WPI students and must be safe to handle and store on campus. As such, no toxic or volatile substances can be used.

5.6.1 Delta-v Budget

Currently, the orbit has not been clearly defined making a Δv budget hard to estimate. Assuming the deployment from Orion allows the CubeSat to escape the Earth's sphere of influence, orbital adjustments will be made to ensure minimum contest distance and optimal communication ranges.

5.6.2 Thruster Choice

The team has specifically chosen a Pulsed Plasma Thruster (PPT) its compliance with SLS requirements, low power use, high technology readiness level, experience with the technology, and non-hazardous propellant. The technology readiness level of Pulsed Plasma Thrusters was documented as 5 in 2004 and is estimated to be 6-7 as of now, due to success on the FalconSat 3.

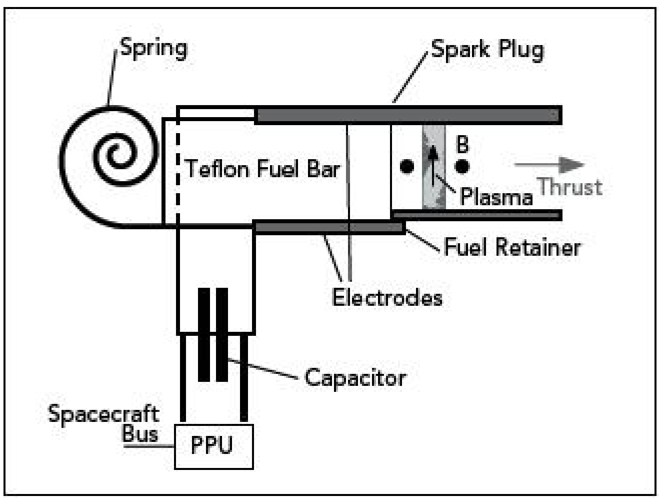


Table 5: Pulse Plasma Thruster Diagram, directory.eoportal.org

Due to the precision of the Pulsed Plasma Thrusters, detailed orbital alterations can be made via short firing periods. The propulsion will primarily be off, conserving energy and reducing thermal buildup.

5.6.3 Integration

The PPT will require interface with the power, command/control and thermal management systems for proper operation throughout the mission lifetime. In regards to other subsystem interaction:

5.6.4 Power Systems

The PPT will require a 2-4W nominal power draw (7.5W max) to ablate the PTFE and generate and accelerate the plasma. The required power is low enough to ensure little to no impact in the energy supply.

5.6.5 GNC

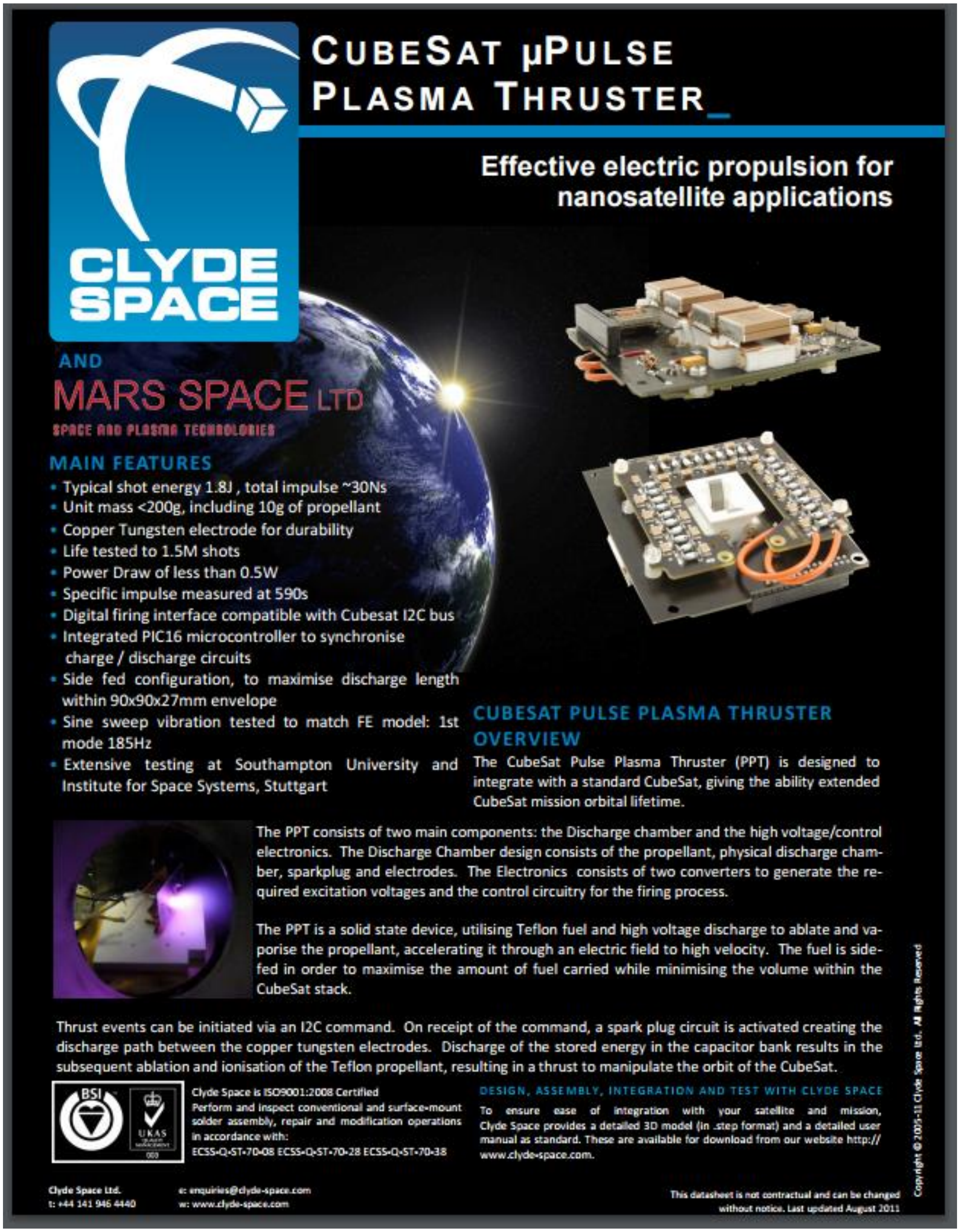
I2C digital bus interface to command circuit to allow for digital firing of the PPT. A PIC16 microcontroller will manage the charge/discharge circuit of the PPT.

5.6.6 Thermal Management

The PPT may require interface with the thermal management systems to dissipate heat resulting from charge/discharge of the PPT. The model selected will include thermal management systems included in the COTS part. Radiation sinks will release excess heat build up to the environment to minimize internal build up. The exhaust plume will be located in an area that will not infringe on any other subsystems.

The Propulsion subsystem was allotted ⅓ unit space and 0.8 Kg mass for use. The PPT selected was the Clyde Space CubeSat Micropulse Plasma Thruster. This requires 9cm X 9cm X 2.7cm volume and 300 grams of mass. The propulsion system can be resized to incorporate more propellant for more intensive orbital alterations.

The COTS unit data sheet follows:



CubeSat µPulse Plasma Thruster_

Effective electric propulsion for nanosatellite applications

CLYDE SPACE

AND

MARS SPACE LTD

SPACE AND PLASMA TECHNOLOGIES

MAIN FEATURES

- Typical shot energy 1.8J , total impulse ~30Ns
- Unit mass <200g, including 10g of propellant
- Copper Tungsten electrode for durability
- Life tested to 1.5M shots
- Power Draw of less than 0.5W
- Specific impulse measured at 590s
- Digital firing interface compatible with Cubesat I2C bus
- Integrated PIC16 microcontroller to synchronise charge / discharge circuits
- Side fed configuration, to maximise discharge length within 90x90x27mm envelope
- Sine sweep vibration tested to match FE model: 1st mode 185Hz
- Extensive testing at Southampton University and Institute for Space Systems, Stuttgart

CUBESAT PULSE PLASMA THRUSTER OVERVIEW

The CubeSat Pulse Plasma Thruster (PPT) is designed to integrate with a standard CubeSat, giving the ability extended CubeSat mission orbital lifetime.

The PPT consists of two main components: the Discharge chamber and the high voltage/control electronics. The Discharge Chamber design consists of the propellant, physical discharge chamber, sparkplug and electrodes. The Electronics consists of two converters to generate the required excitation voltages and the control circuitry for the firing process.

The PPT is a solid state device, utilising Teflon fuel and high voltage discharge to ablate and vaporise the propellant, accelerating it through an electric field to high velocity. The fuel is side-fed in order to maximise the amount of fuel carried while minimising the volume within the CubeSat stack.

Thrust events can be initiated via an I2C command. On receipt of the command, a spark plug circuit is activated creating the discharge path between the copper tungsten electrodes. Discharge of the stored energy in the capacitor bank results in the subsequent ablation and ionisation of the Teflon propellant, resulting in a thrust to manipulate the orbit of the CubeSat.

BSI UKAS

Clyde Space is ISO9001:2008 Certified
Perform and inspect conventional and surface-mount solder assembly, repair and modification operations in accordance with:
ECSS-Q-ST-70-08 ECSS-Q-ST-70-28 ECSS-Q-ST-70-38

DESIGN, ASSEMBLY, INTEGRATION AND TEST WITH CLYDE SPACE

To ensure ease of integration with your satellite and mission, Clyde Space provides a detailed 3D model (in .step format) and a detailed user manual as standard. These are available for download from our website http://www.clyde-space.com.

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Figure 8: PPT Data Sheet, http://www.clyde-space.com/documents/2409

5.7 Thermal Management

5.7.1 Thermal Considerations

Because we have not chosen all of the specific components that will be in our CubeSat, we cannot yet perform a full thermal analysis to determine all the necessary passive and active thermal management systems. Based on the components we have chosen, our operational temperature range spans from 0°C to 30°C. Our lower temperature limit corresponds to our chosen batteries, and our upper temperature limit corresponds to our solar arrays. Also note that our operational temperature range will likely change as we specify more components with potentially narrower operational temperature ranges to the system.

Component	**Part Number/ Name**	**Min Op Temp**	**Max Op Temp**
Solar Panels	VINSIC 22W	0C	(+) 30C
Sun Sensor	General	(-)25C	(+)50C
Chassis	ISIS model	(-)40C	(+)80C
Flight Computer	ODROID-XU 4	(-)10C	(+)45C
Battery	RavPower Lithium-Ion (RP-PB41)	0C	(+)45C
Data Storage	eMMC 5.0 HS400 Flash Storage	(-)40C	(+)85C
Radio	USRP B200mini	Unknown*	(+)40C
Storage	16GB eMMC 5.0	(-)40C	(+)85C
SMA Cables	NA	(-) 65C	(+)165C

Figure 9: Operational Temperature Ranges of CubeSat Components

*We have requested this information from the manufacturer and are waiting for a response

In comparison to the ideal temperature range of our CubeSat, the actual temperature of a CubeSat in space without any thermal regulation system could range anywhere from about -125°C (behind the earth's shadow) to 150°C (in full sun) (Dunmore, 2016). In addition, while the CubeSat is inside the MSA, it will experience a temperature range of -

97°C to 93°C (NASA, 2015). Hence it will be crucial for us to regulate the temperature of our CubeSat, through either passive or active measures.

A note regarding our current solar panels is that they have a minimum survival temperature limit of 0C. We chose these particular panels because they fit within our monetary budget, so one of our challenges for thermal management will be to make sure they can tolerate the cold of space. Obviously we cannot insulate the panels themselves, but we hope to be able to modify the electronics system rather than the panels themselves so that they can withstand cold temperatures. These panels also have a fairly low maximum operating temperature of 30C, so we will need to determine a way to increase this if possible. We may, however, just end up needing to choose different solar panels that can withstand the extreme temperatures of space.

For the time being, we will only discuss passive measures. Because we have not chosen some components, nor have we actually designed our CubeSat (e.g. placement of components), there is no reason for us to look into active systems, as we do not know whether they will be needed, and in addition we would be unable to analyze their effects. However, we recognize that we will almost definitely need an active system of some sort, because during the times when our CubeSat is in “sleep mode” there will be no heat generation from the electronic systems. In the future, once our CubeSat is fully designed, we hope to use COMSOL Multiphysics Simulation Software, or something similar, to model and analyze our thermal management system as it develops and becomes more complex. SolidWorks will be sufficient if we are unable to obtain a license for another software, but it is not preferable as it requires us to make many simplifications of our model.

5.7.2 Thermal Management Options

Currently we know we will be using Multi-Layer Insulation (MLI) on our CubeSat; MLI can be used as a passive thermal management system to maintain a particular component’s temperature at a range of -23°C to +40°C, if used properly (Dunmore, 2016). We plan to use this insulation for our some of our electronics to protect them from the cold. However, because our CubeSat’s overall temperature needs to be above 0°C, we will need to determine an additional method of maintaining that temperature. The main source of heat generation is actually internal heat generation (from circuit boards, batteries, etc.) after a certain distance from the earth is reached (Peake, 2014). In many CubeSat systems, this heat generation is enough to mitigate heat loss from the CubeSat, and a passive system is sufficient to maintain the system within its operating temperature range (Peake, 2014). However, as stated before, a purely passive system will not be sufficient for our CubeSat, as the CubeSat will generate little to no heat when it is in “sleep mode.” Hence we will not be able to rely on this heat generation to maintain the CubeSat above the minimum survival temperature, as we could if the CubeSat was actively functioning during the entirety of the mission, so we will need an active system.

During some periods of the mission, cooling the CubeSat may pose a bigger challenge than keeping it warm, as the electronics will generate a lot of heat. In addition, depending on where our CubeSat is in relation to the earth, there will be considerable external heat transfer from direct solar radiation, albedo (solar radiation reflected off the earth/ moon), and direct radiation from the earth. In order to prevent overheating due to internal heat, we will need to incorporate radiators as well as conductive paths from electronic components to the exterior of the CubeSat. These will be determined in greater detail once our CubeSat has been completely (or almost completely) designed and component placement determined. To create an effective thermal management system, we will need to calculate the heat generation in every component, how this generation will affect other components, and how we can most efficiently transfer excess heat to the exterior of the CubeSat, if needed. Note that although some of the electronic components chosen have fans for temperature regulation, these will be useless in space because there is no medium through which convection can take place.

We will also provide protection against external heat transfer due to the sources of thermal radiation mentioned above. One of the easiest ways to do this is to use a surface coating with high reflectivity (thus low absorptivity). This coating, if used, would obviously have to be applied only in areas without solar cells, as we want the solar cells to absorb as much solar radiation as possible. In addition to a surface coating, the MLI mentioned above will help keep the CubeSat warm by preventing conduction out, and also help keep it cool by creating a higher resistance to any heat flux into the system resulting from thermal radiation.

Overall, once all components chosen and placed within the CubeSat structure, we will complete a comprehensive thermal analysis. This analysis will take an iterative approach to balancing all positive heat transfer to the CubeSat (solar and albedo radiation, direct radiation from the earth, internal generation) and negative heat transfer (radiation from the CubeSat). To do this we will need to determine the absorptivity, emissivity, and thermal conductivity of all components, as well as the view factors between components to determine their thermal interaction (hence we could not possibly complete the analysis at this time). As previously stated, we plan to use some type of software- whether COMSOL or SolidWorks- to avoid having to do this analysis by hand (this would be almost impossible). We will ultimately analyze the worst-case-hot and worst-case-cold scenarios to ensure that the thermal systems in place are sufficient to keep the temperature of the CubeSat within its operating temperature range.

5.8 Mission Description

Our team, GOATS, is building a CubeSat intended to compete in the Deep Space Derby for the Best Burst Data Rate and Farthest Communication Distance prizes. As the competition will take place in deep space, the environment will be filled with space debris and subject to the effects of solar winds. This type of environment will prove challenging because of the effects of a vacuum environment, radiation, and varying temperature extremes on the electronics and physical structures of our CubeSat.

Following is a general overview and description of the major phases of our CubeSat operations. The first stage is the launch and deployment from the Secondary Payload Deployment System (SPDS). Shortly after being deployed, the CubeSat will power up then perform a self-diagnostics test to determine if all of its systems are functional, and to determine whether it is ready to begin transmitting data. After this has been completed, the CubeSat will make contact with our ground station, then begin transmitting data according to the operational protocol, starting with status reporting and then data transmission related to the challenge itself. After Best Burst Data Rate trials are complete, the CubeSat will transmit data on varying modes, depending on which stage of the trip it is in. Additional details of operations can be found in the Mission Concept Registration Data Package.

At WPI we have access to an amateur radio station that can act as our base of operations. It is currently equipped to communicate with satellites in LEO. We plan to use our own station for approximately the first few days of the mission in order to establish that our CubeSat is working properly. Once we know the CubeSat is communicating as it should, we will rely on the DSN for deep space communications.

Each element of the design process has been distributed amongst team members with varying technical backgrounds to match design tasks with individuals best suited to fulfill each requirement. In this regard, each aspect of the CubeSat is developed with a degree of autonomy that is critiqued and verified by the group collective at meetings. This selective group structuring will play to the strengths of each participant and allow our CubeSat to be the sum of these collective efforts.

6 Appendices

6.1 Acronyms

ACK - Acknowledgement

ADC – Analog to Digital Converter

CC - Command and Control

DAC – Digital Analog Converter

DBPSK - Differential Binary Phase Shift Keying

DSN- Deep Space Networking

EMI – Electromagnetic Interference

FEC - Forward Error Correction

FPGA – Field Programmable Gate Arrays

HET - Hall-effect Thruster

LEO – Low Earth Orbit

LOS – Line of Sight

MAC – Media Access Control layer

OSI – Open Systems Interconnection

PHY – Physical Layer

P-POD - Poly-PicoSatellite Orbital Deployer

QAM - Quadrature Amplitude Modulation

QPSK - Quadrature Phase Shift Keying

RF – Radio Frequency

SDC - Satellite Development Club

SDR - Software Defined Radio

SMA - SubMiniature Version A (Cable)

SPDS - Secondary Payload Deployment System

TT&C - Telemetry, Tracking, and Command

WPI - Worcester Polytechnic Institute

WPIWA - Worcester Polytechnic Institute Wireless Association

5.4 Authorship and Team Roster

5.5.1 Subgroup Roster

The following team members are associated with the specified technical subgroups:

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