Project Report: The Development of a CubeSat Program and Subsequent Business Implementation

By
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Arno Prinsloo
M.S., University of Kansas, 2020
B.S., University of Kansas, 2017

Submitted to the graduate degree program in Aerospace Engineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Doctor of Engineering.

Chair: Dr. Mark Ewing

Dr. Brian Kaplinger

Dr. Ray Taghavi

Dr. Craig McLaughlin

Dr. Bozenna Pasik-Duncan

Date Defended: 10 May 2022

The dissertation committee for Arno Prinsloo certifies that this is the approved version of the following dissertation:

The Development of a CubeSat Program and Subsequent Business Implementation

Chair: Dr. Mark Ewing

Date Approved: 12 May 2022

Abstract

Cube Satellites are a newer space innovation that aim to breakdown the prohibitive cost barrier of performing science objectives in space, an effort which has recently been bolstered by NASA's CubeSat Launch Initiative. The initiative aims to have every state in the country orbit a satellite, a task Kansas has yet to complete. Enter KUbeSat1, which aims to be the first fully built and successfully launched satellite from Kansas. To accomplish this task a new student run organization, KUbeSat, was created that features a unique organizational makeup meant to enable it to be a self-sufficient entity capable of launching a new satellite every two to three years. During the construction of KUbeSat1, nearly all of the components of the satellite were sourced outside of the US and there was a fundamental lack of inexpensive hardware in the US. The "small sat" market is expected to grow to be worth over $13B in the next decade with more than 9,000 small satellites being launched during that same time. The combination of the manufacturing vacuum in the US with the expected growth, means it is the perfect time to create a new startup focused on small satellite manufacturing. A vertically integrated small satellite manufacturer would need approximately $500,000 of capital investment to begin developing the hardware needed to meet the demand of not only KUbeSat, but also the growing small sat market.

Acknowledgments

I'd like to thank my parents for giving up everything in their lives so I can have the opportunity to pursue my dreams. I'd like to thank my brother for always being supportive and proud of me even when I am particularly grumpy. A huge thank you to my adoptive American family and my family back home for always being interested in what I am doing. Thank you to my friends for supporting and listening to me rant on about life and all the cool things I get to do. Thank you to my fellow KUbeSat colleagues for helping get this satellite to where it is now and making history. Thank you also to my professors for putting up with me for nine years and helping me grow and become a better person in this process. A special thank you to all the students I have ever taught for being one of the best parts of grad school and a thank you the KU AE staff for being my go-to source for venting. Lastly, I'd like to thank God for helping me get to this moment in life.

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1 Introduction

In recent years space accessibility has gone from being monopolized by world governments to high schools building and launching satellites. Part of this massive shift comes from the advent of reusable rockets thanks to the efforts of SpaceX and other rocket startups. The other half of this shift comes from smaller satellites that can compete with their larger counterparts at a fraction of the price. These small satellites have changed the dynamics of space-based research and with more entities interested in expanding on-orbit capabilities the solution is to increase the number of small satellites. With the large cost disparity between traditional and small satellites, companies are moving to "swarms" of small inexpensive satellites instead of one large costly satellite[1]. The problem with the massive increase in demand is a general lack of supply for these smaller satellites. As a result, the satellite market is grossly underprepared for the demand expected in the next decade alone. The simple solution to this problem is to increase the number of manufactured satellite parts and fill the market gap. Naturally, this is not a simple task and requires an understanding of how satellite components are made and the process that goes into creating a satellite from scratch to flight. Fortunately, The University of Kansas (KU) has recently begun a Small Satellite Initiative (SSI) and provides students with the perfect opportunity to build the required skills needed to compete in the growing market.

Table 1.1: Satellite Classification

Group Name	Wet Mass (kg)	Classification
Large Satellite	>1000	
Medium Satellite	500-1000	
Mini Satellite	100-500	Small Satellites
Micro Satellite	10-100	
Nano Satellite	1-10	
Pico Satellite	0.1-1	
Femto Satellite	<0.1	

1.1 CubeSats

These SmallSats have a variety of categories and in recent years have begun to break out of the neatly classified categories found in Table 1.1. For this paper, the nano satellite class will be the primary focus. Moreover, a specific design of nano satellites called Cube Satellites will take the spotlight in the analysis. These CubeSats, created in 1999, are the brainchild of Bob Twiggs and Jordi Puig-Suari[2]. Twiggs and Puig-Suari envisioned a small spacecraft of less than 5 kg that would allow their students to easily accomplish space-based research. The satellites derive the name from the simple cube-shaped unit size of 10 cm x 10 cm x 10 cm called a 1U. The benefit of such a standardized package is the ability to build on units and increase the size as needed for the internal components. By stacking a 1U on two other units, the satellite can grow to a 3U, and so on. This design standard eliminates one of the worst causes of price increases in any part and that is unique components. Having fewer unique components allows the same machine to create multiple copies of one part without needing special housing or dies that need to be changed after each part is made. While relatively new to the aerospace industry, these satellites are growing quickly, and more universities are employing them to accomplish unique space grants. NASA has pushed the development of these satellites with the CubeSat Launch Initiative (CSLI) which aims to have every state in the country launch at least one CubeSat. While Kansas has yet to do so, it still has a CubeSat history.

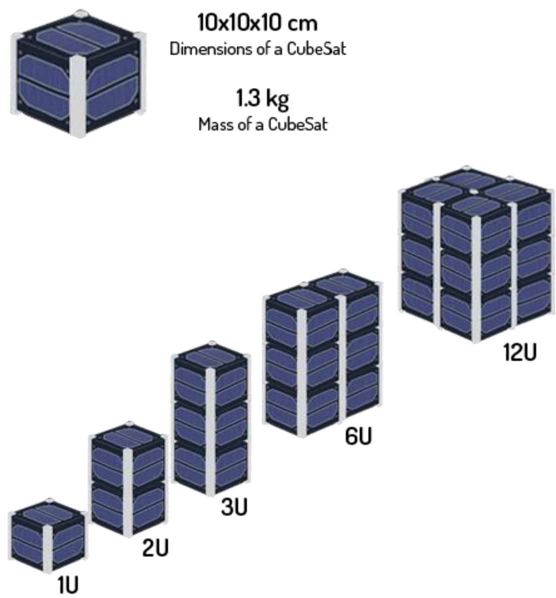

Figure 1.1: CubeSat Sizes

1.2 CubeSats at KU

The University of Kansas signed on to be a part of NASA’s CSLI in 2018 and launch the first satellite built in Kansas in the summer of 2022. Though this satellite has only had four years in development, it builds on decades of experience at KU. In 2002, Dr. Trevor Sorensen came up with the idea to have KU build a satellite. He stated, “*Kansas does have experience building satellite payloads, and we’ve done part of satellites*[3].” KU graduate student Marco Villa helped spearhead the project as the Pathfinder mission grew. In 2005 the satellite, named KUTEsat was slated to launch on a Russian rocket in Kazakhstan. Unfortunately, the rocket exploded on launch and the satellite never made it to orbit. Marco graduated from KU as a Doctor of Engineering and went on to work at SpaceX and eventually Tyvak Nano-Satellite Systems. Around 2017, an undergrad at KU reached out to Dr. Villa and began devising a way to restart the CubeSat program at KU. This included expert help from Tyvak, support from the Aerospace Department at KU, and participating in NASA’s CSLI.

Figure 1.2: Dr. Marco Villa and KUTEsat [3]

After being accepted into the CLSI program, students at KU began developing a new satellite. This time, with the full support of the department and university. The major difference in this development is the setup of a self-sustaining organization. Whereas the Pathfinder mission had the ambition to launch more satellites, there was no direct plan to ensure a future mission.

2 KUbeSat

To ensure that future students at KU would have the ability to continuously build satellites, the new SSI program had to be built out in such a way that it became a self-sustaining organization. This is where KUBeSat marks its entrance in the small sat history at KU. KUbeSat is a student-led organization that partners with a variety of organizations and businesses to design, develop, and build CubeSats at KU. The purpose of KU's Cube Satellite group is to create the infrastructure and opportunities for satellites to be built and launched through student-led projects. Building these satellites provides an opportunity to demonstrate, research, and test scientific equipment affordably in outer space. This process fosters leadership, communication, teamwork, and management skills for all involved members, thus contributing to educational and professional development. All of these goals start with the build-out of the needed infrastructure and the group's first satellite, KUbeSat1.

2.1 Organization Setup

To accomplish the monumental task of building a satellite and the ground equipment, KUbeSat needed a unique organizational setup. The organization is split into two groups with one half being run by the President and Advisors who oversee any projects currently in development. The main purpose of this group is to ensure that the program continues growing and has the needed funding for the projects currently under development. The president works with the VP to find funding and spread general awareness of the satellite. The Vice President leads the fundraising efforts of on-campus fund sources, like Student Senate or the Engineering Funding Advisory Council (FAC). The Secretary coordinates social gatherings and runs the program's social media accounts. The outreach chair handles interfacing with companies, schools, and organization materials while the treasurer tracks all expenses and incomes to ensure all projects have the needed funds.

The other half of the organization handles individual projects or satellites. Projects are handled by a Project Manager (PM) and a group of students dedicated to the success of that singular project. At the moment, KUbeSat only has one project and as a result, all members of KUbeSat are working towards KUbeSat1's completion. As the development of any satellite is a tricky endeavor, the team is divided into major satellite subsystems with two people leading each area. Each team lead works with the Chief Engineer (CE) to solve technical problems while the CE works with the Project Manager to tackle managerial tasks like scheduling, funding, and product procurement. The project manager interfaces with faculty mentors and the administration team to handle various tasks including industry contacts. The entire layout can be seen in Figure 2.1.

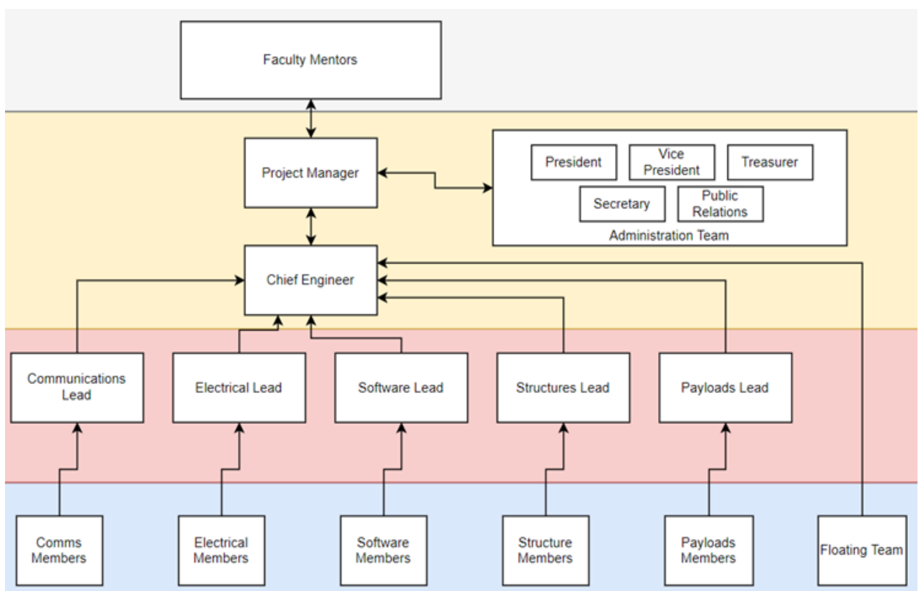

Figure 2.1: KUbeSat Organization Layout

With this setup, the team is divided into key areas and allows members to grow and focus on one set of problems at a time. At the same time, students who are interested in leading can do so. Moreover, the constitution written for KUbeSat clearly outlines the succession of lead members and the selection of the Chief Engineers and Project Managers. Beginning with the PM, the process is not unlike a job interview. Should a person want to be a PM of one of KUbeSat's projects, they must submit a resume to the advisors and the aerospace chair. These members will review the submission and select the appropriate person to fulfill the role. Similarly, the Chief Engineer must also submit their resume to the advisors and chair. This time though the PM will also have a say in selecting the chief engineer with the President residing as a tie break should it occur. One of the primary reasons why PM is involved in this process is because of how the PM and CE interact. While all subsystem leads have a co-lead to support the team, the PM and CE act as each other's co-leads. When one is unable to fill the role, the other does instead. Naturally, this means both leadership positions need to be able to depend on each other and form an inherently strong relationship to support the rest of the team. This organization is set up in a way to allow for multiple projects to be developed at the same time, provided there is enough funding.

2.2 Funding

At the inception of KUbeSat, the program worked on donated equipment and small amounts of departmental funding. As the program grew to include more people, and the scope of the project grew more funds were needed. At this stage, the President and Vice President began working with multiple university organizations to secure funding. While traditional satellites can cost upwards of $300 million[4], Cube Satellites on average cost about $50,000 per unit with a 3U hitting about $150,000[4]–[6]. The University Student Senate, FAC, PepsiCo, and Endowment Association were all approached with the desire to procure enough funds to purchase the off-the-shelf components needed to build KUbeSat1. To date, KUbeSat as an organization has raised over $100,000 in funds from several on-campus organizations, with about $13,000 in reserve. The full breakdown of what amount came from what source can be seen in Figure 2.2

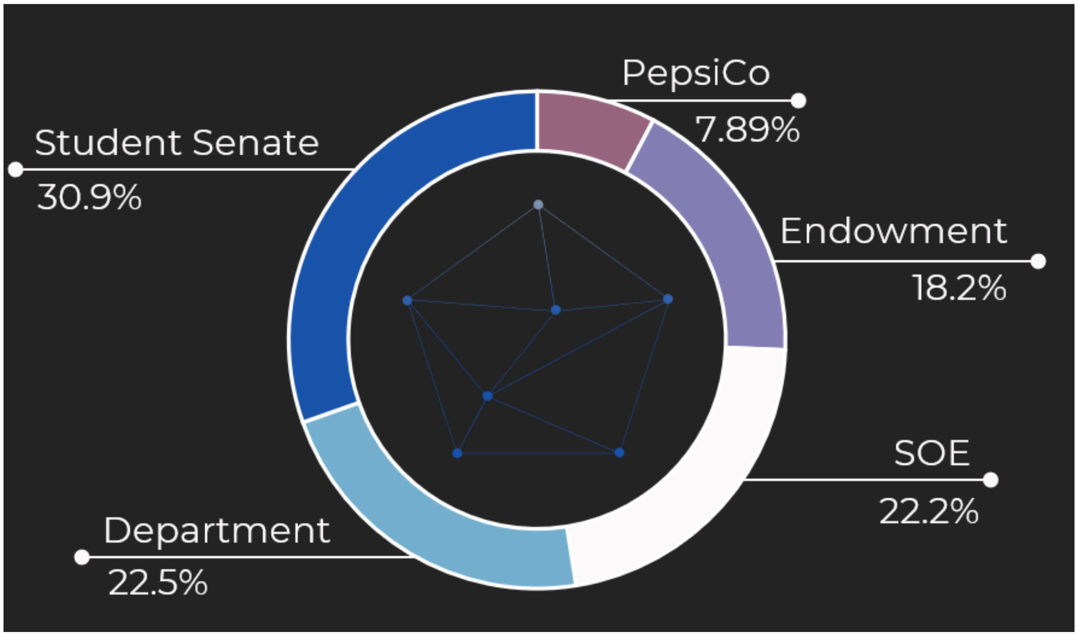

Figure 2.2: KUbeSat Income Breakdown 2022

While this funding is great at supporting KUbeSat1 it does not do much for future missions. As a result, efforts have been taken to ensure that KUbeSat can continue to build its business relationships with other organizations. This has led to an outline where KUbeSat can secure a minimum of $20,000 a year in funding with the chance to grow that total to $45,000 a year in the future. Furthermore, the organization is actively pursuing several multimillion-dollar space grants that could ensure sustained development down the road. Such a large increase in funding would even enable KU to partner with other universities in Kansas or the Midwest to co-develop satellites to reduce costs and increase participation. Not included in all the funding outlined above, KUbeSat has also been the generous recipient of several pieces of donated technology that help build out the unique infrastructure needed to launch and maintain a satellite.

2.3 Infrastructure

Figure 2.3: Hawksnest Ground Station

Once the satellite is in orbit, KUbeSat will need a way to communicate with it and downlink any scientific data. To do so KUbeSat had to build out a separate ground station (GS) called Hawksnest. This GS includes an Ultra High Frequency (UHF) antenna along with a rotator and controller to track the satellite as it passes over the university. These systems were donated by Research Concepts Inc and are currently installed on the roof of the Eaton engineering building. Moreover, to safely build the satellite, a clean room is needed to ensure no particulates get into the system that could damage sensitive components. Fortunately, Ron and Sue Hill, along with space and renovation donations from the AE department, donated the Hill Space Lab which is a Class 100,000 clean room meant for satellite development. Along with other smaller donated components, the total monetary value of donated equipment eclipsed $150,000. The GS and clean room can be seen in Figure 2.3 and Figure 2.4 respectively. With the infrastructure and donations KUbeSat has received, it is capable of fully building its first satellite KubeSat1.

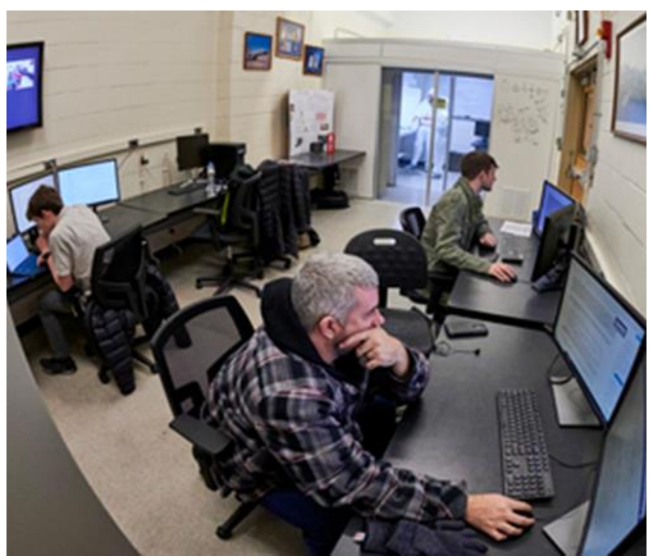

Figure 2.4: The Hill Space Lab

3 KUbeSat1

After being accepted into the NASA CSLI program in 2018, KUbeSat members began working towards the development of KUbeSat1. As this was the first satellite built by the KUbeSat group, an executive decision was made to take the development path that would ensure the highest probability of success. This meant that if there were available Commercial-Off-The-Shelf (COTS) components that fit within the scope and budget of the project they were acquired. Any components that needed to be built in-house would then be placed through rigorous design, development, and testing to ensure survivability in orbit.

3.1 Design

The design for KUbeSat1, like all CubeSats, is based on the standardized CubeSat design with the only variability being the general size of the satellite. To accommodate the payloads for this mission, a 3U satellite was selected and all other components were selected around that factor. The frame of the satellite was purchased from CubeSat component supplier Endurosat and is made from 6061-T6 Anodized Aluminum. This frame uses rails in the inner corners of the design to slot the other internal components into as a way of easing assembly. Continuing the design, the Onboard Computer (OBC), Radio Module, Antenna, and all Solar Panels were also purchased from Endurosat. These systems will provide command/data handling, communication, and power respectively to the satellite. The generated power is sent to a 40Whr battery and distributed by an Electrical Power System (EPS) both of which are manufactured by Clyde Space. Lastly, the satellite maintains its on-orbit orientation and direction by using a CubeSpace Attitude and Determination and Control System (ADCS). All these components, which can be seen in Figure 3.1, provide the backbone for the satellite to operate its payloads.

3.2 Payloads

To participate in the CSLI program, the satellite must have at least one payload that helps further NASA's Strategic Plan[7]. This meant that the payloads had to have some form of long-term benefit to the scientific community. The payloads developed for KUbeSat1, were designed, and developed by the KU School of Physics and not KUbeSat as an organization. This distinction is important for this document as these payloads were only integrated by KUbeSat. For more detailed information about the payloads including operation, it is recommended to look at Citation [8].

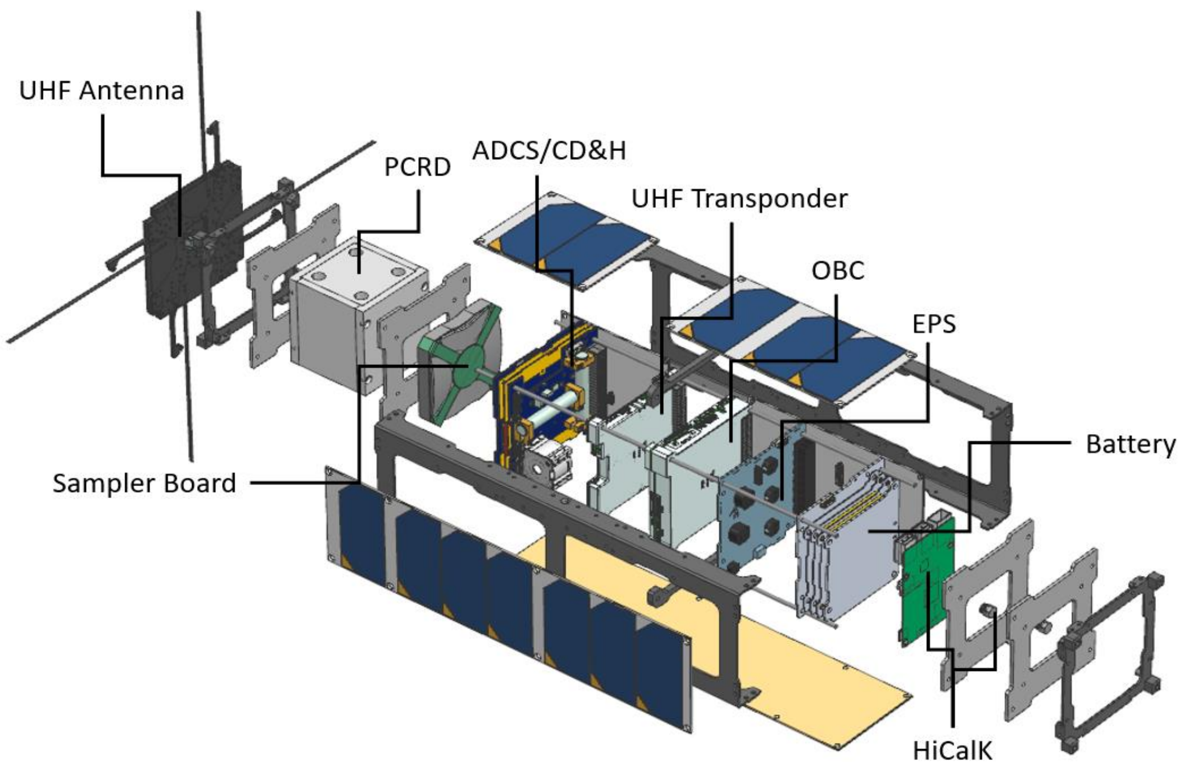

Figure 3.1: KUbeSat1 Exploded View

3.2.1 HiCalK

The first payload flying on KUbeSat1 is the High-Altitude Calibration for KUbeSat also called HiCalK. HiCalK is a proof-of-concept payload designed to provide calibration signals for ultra-high-energy cosmic ray ground experiments located in Antarctica. This system is the successor to previous HiCal systems designed for the Antarctic Impulsive Transient Antenna (ANITA) experiments. The pulses provided by the HiCal systems mimic Askaryan Radiation which ground equipment can then use to calibrate sensors looking for the Very High Frequency (VHF) signals from deep space. By comparing these signals, the ground equipment can be synchronized and provide an additional layer of sensitivity to radio events. Previous HiCal missions would use weather balloons to help calibrate these systems, but these missions had their shortcomings. The purpose of HiCalK is to prove that a system can reliably and accurately generate a signal over a specified location, while at the same time capturing the orientation of the satellite. If this is a success, future missions will have an upgraded HiCalK that will fully transmit signals to the ground. Lastly, the current design of HiCalK helps serve as a check for the second payload.

Due to the unique nature of what HiCalK is studying, it has some unique orbital requirements that need to be considered. Fortunately, there are no pointing requirements for HiCalK. The functional requirements are laid out below:

- KUbeSat1 shall have a polar or near-polar orbit that will enable it to operate over Antarctica.
- The satellite shall have the means to measure and catalog the orientation and position of the satellite during pulses.
- The onboard computer system shall be able to handle at least 5 B/s worth of data from the HiCalK software.

3.2.2 PCRD

The second payload on KUbeSat1 is the Primary Cosmic Ray Detector (PCRD). This payload represents a first in particle astrophysics as it uses a pulse shape discrimination calorimetry method to measure the energy and species of primary cosmic rays. These rays are stable-charged particles that have been sent flying in all directions by an unknown astrophysical source in the universe. Traditionally, detecting these rays is done on Earth using large scintillators and radio arrays. By moving such detection into orbit, the Earth's atmospheric influence is removed and the rays with lower cosmic energies can be analyzed as well. Unlike the HiCalK, PCRD is a fully developed system meant to gather new data that is often lost and not studied due to atmospheric intervention. The PCRD stands to be the first CubeSat payload of its kind launched by a public university in the United States. Its success will also pave the way for more advanced missions to follow. Both payloads are run by a Raspberry Pi4 and an Analog Discovery 2. These systems while not directly space tested have shown to be able to take the expected environment.

Unlike HiCalK, the PCRD has next to no orbit and operation requirements. As long as it is above the Earth's atmosphere, it is capable of conducting its mission accurately. Lastly, the onboard systems should be capable of handling 2 kB/s worth of data.

3.2.3 Camera

While not a payload meant to further NASA's Strategic Plan, KUbeSat1 will also include an HD camera onboard. This camera is a PiCam HD and plugs into the Raspberry Pi4 that is powering the payload systems. It is expected to be able to take 4K photos and over many downlinks send that information back to Earth. This payload was included as a source of marketing and campaigning meant to energize members and the public. Combined with the unique orbits KUbeSat1 expects after launch, the types of pictures are expected to be inspiring.

3.3 Launch Information

Table 3.1: Orbit Parameters

Altitude (km)	565
Period (min)	95.81
Day Period (min)	60.31
Eclipse Period (min)	35.51
Inclination (Deg)	97.61
Eccentricity (~)	~0
Longitude of Ascending Node (Hr:Min)	5:40
Right Ascension (Deg)	349.23

As part of the CSLI program, NASA will also partner with startups to provide funding to new launch providers. In this case, NASA has partnered with a Texas-based company, Firefly Aerospace which is building a new rocket system called Firefly Alpha. Alpha is a direct response to the growing small satellite market and takes aim at larger rockets with the biggest payload performance and the lowest cost per kilogram in its segment[9]. Capable of delivering upwards of 1,000 kg to Low Earth Orbit (LEO) and 630 kg to Sun-Synchronous Orbit (SSO), Alpha does stand out from other dedicated small sat launchers. Due to the need to fly over the Antarctic circle for HiCalK, KUbeSat1 will need to launch into an near polar orbit. As a result, Alpha is the perfect launch vehicle for the payload requirements. At this time, NASA has identified a launch opportunity for KUbeSat1 with Firefly which will occur No Earlier Than (NET) late summer of 2022, out of Vandenberg Space Force Base (VSFB). This launch will place KUbeSat1 into an SSO at 565 km in altitude. The inclination for this orbit is expected to be 97.61° +/- 0.05° and an eccentricity of approximately 0. Provided, the launch occurs on August 15th, the full suite of orbit information can be found in Table 3.1. Once in orbit, KUbeSat1 will go through a suite of actions to ensure deployment.

After reaching the correct orbit, KUbeSat1 is pushed out of a NanoRacks Deployer seen in Figure 3.2 [10]. This system uses a strong spring to push the satellite into orbit and away from the rocket. Once the satellite has been released, two electrical inhibit switches at the end of the frame are no longer depressed which allows the system to begin its general bootup phase. Ideally, 30 minutes after deployment, the satellite will open its mechanisms and begin orienting itself. Once it has done so, KUbeSat1 will begin projecting a homing signal meant to establish a ground station connection. After accurately communicating with the ground for the first time, the satellite begins its mission and activates the PCRD. Once the satellite enters the 66° 30’ S latitude the PCRD will switch off and the HiCalK will activate. This payload will only be active for one minute at a time. After it has completed its program, it will switch off and the PCRD will resume collecting data. Once KUbeSat1 gets close to Lawrence KS, it will take its first picture. After which the satellite will rotate and establish a downlink connection with the ground. After sending all collected data, the satellite will return to its normal operating mode and continue to

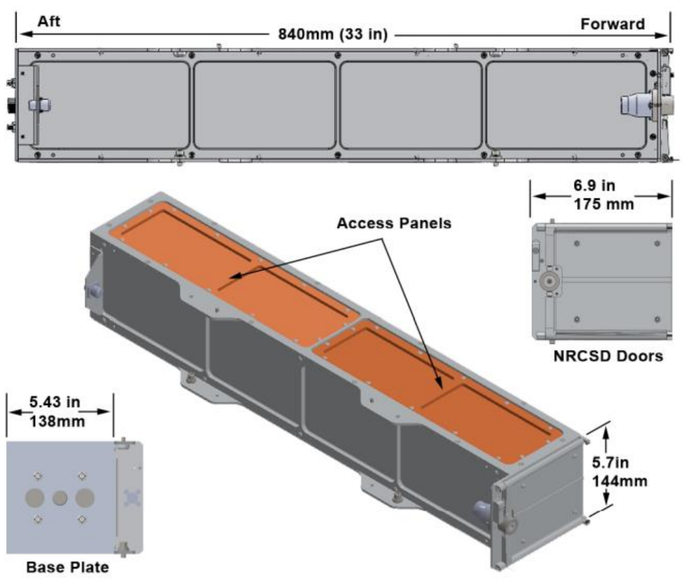

Figure 3.2: Nanoracks CubeSat Deployer Design Features

collect data as it orbits. The overall operation of the satellite requires that each system operates within the carefully choreographed routine and as such, it is important to understand what each subsystem brings to this dance.

3.4 Technical Breakdown

As with any complex project, KUbeSat1 has a unique set of subsystems that all come together to follow through with the satellite operations discussed above. There are many ways to split up a satellite, but for KUbeSat1 six teams would be dedicated to unique aspects of the project. They are Power, Systems, Communications, Software, Structures, Misc. While it is fairly straightforward what each section focuses on, the miscellaneous category is the catch-all for any other tasks not directly focused on the other teams. At the highest level, the structure of the satellite holds all the components together and ensures safe housing for the internal components. Power is generated by the solar panels which is sent to the 40 Whr battery. While the battery stores the power, the EPS distributes that power to all the other systems. This includes the Command and Data Handling System (CD&H) which houses the central processor of the satellite. This processor commands the payloads computers to execute commands and relay data to the respective boards. The CD&H system also communicates with the ADCS to ensure that the satellite is orbiting the way it is intended to. The ADCS and CD&H are both major systems in the satellite handled by the Systems team with the backbone of all the components being handled by the Software team. Lastly, the Communications team transmits all the stored data back down to the ground station. A full satellite architecture can be seen in Figure 3.3. Once again, the goal of all these systems is to ensure the PCRD and the HiCalK can accurately achieve the intended science objectives. At this point, a deep dive into each subsystem is needed to understand the complexity of the overall system, beginning with the backbone, Structures.

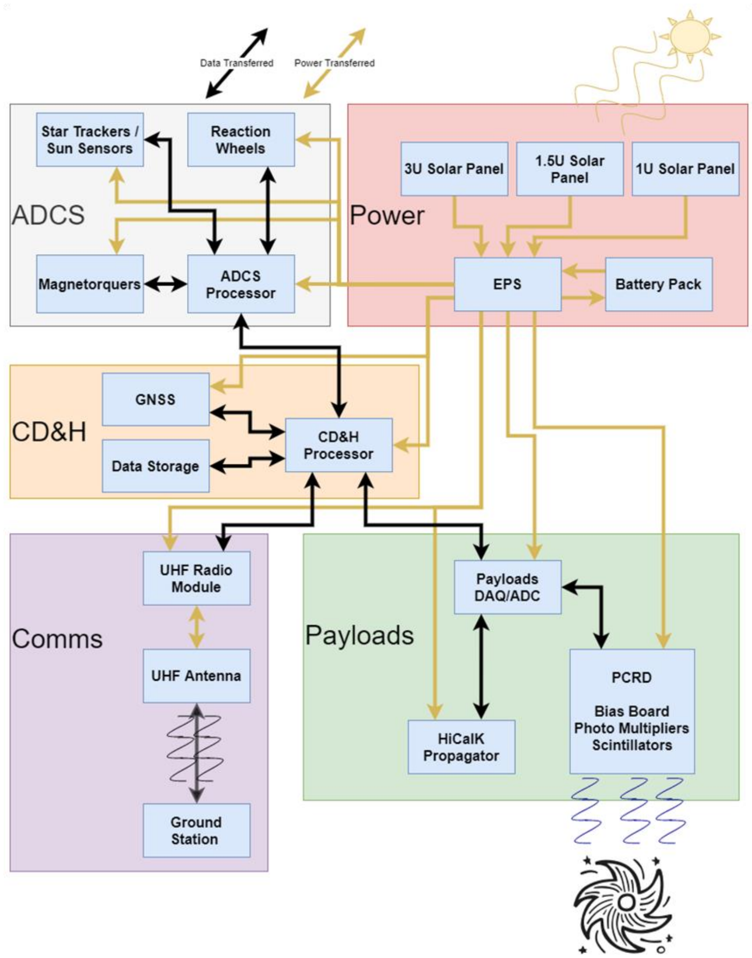

Figure 3.3: KUbeSat1 Satellite Architecture

3.4.1 Structures

As mentioned in Design, KUbeSat1 uses a 3U Endurosat Frame to contain all the internal components. This frame and the internal mounting mechanism are the core part of structures as it is responsible for the support of the satellite. The minimum requirements for the structures system are:

- The overall structure shall withstand the launch loads and environment from:
  - Dynamic Environment Testing
    - Expected vibration for 1 minute on each axis

Fortunately, the frame built by Endurosat is designed to meet both NASA and the European Space Agency's (ESA) General Environmental Verification Standards (GEVS) [11] [12]. Combined with proven flight heritage, this meant the frame did not need to go through rigorous stress testing on its own. When mounting components internally, the inherent design of the frame allows components to slide down rods and stack on the inside of the satellite. As this is a CubeSat standard, any off-the-shelf components would not need any specialized mounting mechanism to fit in the satellite. Since the payloads are built in-house, mounting them to the satellite needed the use of a mounting plate that acted as the interface between the payload and the frame. Since KUbeSat is a student organization and funds were limited the design of these plates had to be carefully considered and a balance between manufacturing and intricacy had to be struck. In the end, the Structures team designed "generic" mounting plates meant to provide a base for further customization. It was estimated that the tools and skills were available to drill any unique holes in the plates and custom fit them to the required components. The 2.54 mm thick aluminum plate was custom, it would need to be tested to ensure it could handle the loads expected on launch and more of that information can be seen in Section 4.

One of the final considerations the Structures team had to keep in mind was the mass and center of gravity (CG) locations of the satellite. It was stated earlier that all CubeSats conform to a standard and that includes overall weight. A general guideline for CubeSat mass is about 1.3 kg per Unit. As a result, a 3U

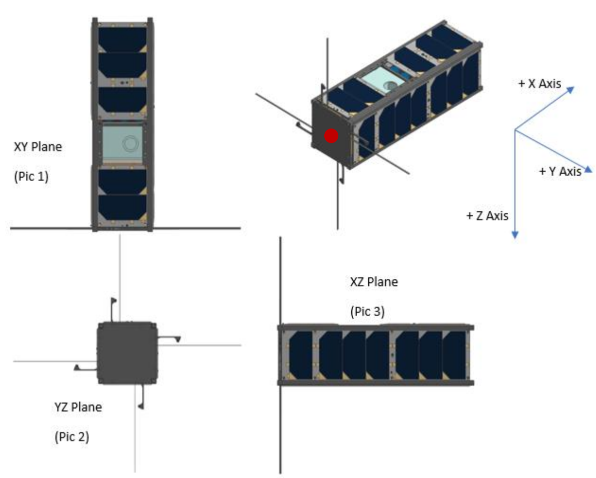

Figure 3.4: KUbeSat1 Coordinate Reference

satellite would not be allowed to exceed 4 kg, though newer launchers can handle 3U satellites upwards of 6 kg. Moreover, the CG locations of KUbeSat1 had to be kept as central as possible to ensure that the ADCS would be able to properly function. It is important to note the coordinate system when referencing the CG as this helps place the reader in the proper reference frame. For the entire paper, the coordinate frame for KUbeSat1 will be the one noted in Figure 3.4 with the CG defined from the negative X face, denoted by a red dot. The final CG location and mass of KUbeSat1 is listed in Table 3.2. More information can be found in Section 10.1.

Table 3.2: KUbeSat1 Physical Properties

Mass (kg)	***CG Location X (mm)***	***CG Location Y (mm)***	***CG Location Z (mm)***
2.89	163.175	0.016	4.858

3.4.2 Power

Arguably the second most important subsystem is Power as, without this team, none of the components would function. Like all the systems on the satellite, Power has a set of system requirements that it must meet so the whole satellite can accomplish its goals. The first of these requirements is the Functional requirements which state the power system:

- Shall meet power requirements for all the subsystems, during all modes of operation
- Shall have electronic mechanisms that protect from common circuit board failures

These requirements drive the overall functionality of the power system and generally do not differ from satellite to satellite. The second set of requirements, called Design Requirements, will most likely differ from satellite to satellite. These design requirements help convert ideas into design features. For KUbeSat1, the Power system:

- Shall be built using electrical components that have been tested for space-level applications
- Shall use proper documentation on all electrical components and electrical systems
- Tests shall be conducted on every electrical component
- The power subsystem team shall maintain a detailed power budget listing supply and demand for each of the subsystems as well as different modes of operation

Finally, the Power team must also deal with Safety Requirements which are often dictated by the launch provider or outside regulations to ensure a successful launch. Similar to power off devices during a flight, these requirements are aimed at keeping the satellite in an off mode until it has left the deployer. These requirements for KUbeSat1 state:

- No electronics shall be active during launch to prevent any electrical or RF interference with the flight dispenser and the primary payloads
- Rechargeable batteries shall be fully deactivated during launch or launch with discharged batteries
- Remove before the fight (RBF) pin shall be required to separate the CubeSat power system from the rest of the circuitry

With these sets of requirements, the Power system can be designed and in KUbeSat1's case, is split into three unique sections: Generation, Storage, and Distribution. The Power generation system is made up of five Endurosat Solar Panels. Similar to satellite

Table 3.3: Solar Panel Power Output

Panel Size	**Quantity**	**Max Power (W)**
1U	2	2.33
1.5U	2	3.61
3U	1	8.00

frames, the panels are sized based on units that represent the longest side of the panel. KUbeSat1 uses two 1U panels, two 1.5U panels, and one 3U panel all of which have an efficiency of 29.8% and an optimal current of 517 mA. The power output varies depending on how much sun the panels receive, though the max power output of each panel can be seen in Table 3.3. Any power generated is stored in the Clyde Space Optimus 40 Whr battery. The panels connect via several independent battery charge regulators (BCRs) and include several safety designs meant to protect the battery and satellite. This includes under-voltage, over-voltage, and over-current protection along with built-in heaters designed to keep the lithium cells above 1 °C. The BCR charging system has two modes of operation, Maximum Power Point Tracking (MPPT) and End of Charge (EOC). MPPT is when the battery voltage falls below the EoC voltage (6V), it will be charged at a constant current of 0.2A for maximum power transfer. On the other end, EoC is after the max voltage has been reached, a tapering current from the panels will be supplied to top up the battery until it reaches full capacity, drawing only the required power from the panels. Furthermore, the collected power is distributed by Clyde's EPS which includes a 3.3V, 5V, and 12V regulated power bus. BCRs output supply charge to the battery and the power conditioning modules (PCMs) and the power distribution modules (PDMs) inside of the EPS. Along with a 7.6V unregulated battery bus, these busses route power to each of the other subsystems. One important feature of the EPS and battery are power inhibit switches which stop power flow through the satellite until the switches are no longer depressed. This satisfies several safety requirements listed above and provides an overall safer power experience around the power system. Combining these three main areas creates a fully-fledged power system that enables all other systems to operate.

3.4.3 Systems

The Systems team tackles hardware-related tasks that the satellite as a "system" needs to function. Moreover, the Systems team focus on the highways of information on the satellite and how all parts of the satellite use these highways to complete the designated tasks. This includes a physical understanding of the ADCS, CD&H, and onboard camera.

The ADCS on KUbeSat1 is a CubeSpace Y-Momentum Wheel system that includes a single reaction along the Y-axis to allow for fine pitch control. As the payloads don't have severely restrictive pointing requirements, the less expensive Y-Momentum wheel setup was selected for KUbeSat1. The entire ADCS uses less than 600 mW of power and comes with a torque coil, torque rods, a deployable magnetometer, and other components. KUbeSat also elected to add an Earth Horizon Sensor to the setup as this would increase the measurement accuracy of the satellite to be within 0.6°. While the reaction wheel only allows a 3° control accuracy, the nature of the HiCalK systems required a system that could get smaller and more accurate readings. Like most systems built for CubeSats, the ADCS uses a standard PC104 header layout to plug into the surrounding components. This header stack, seen in Figure 3.5, will allow serial communication and power transfer without the need for loose cables. More importantly, the entire ADCS operates in

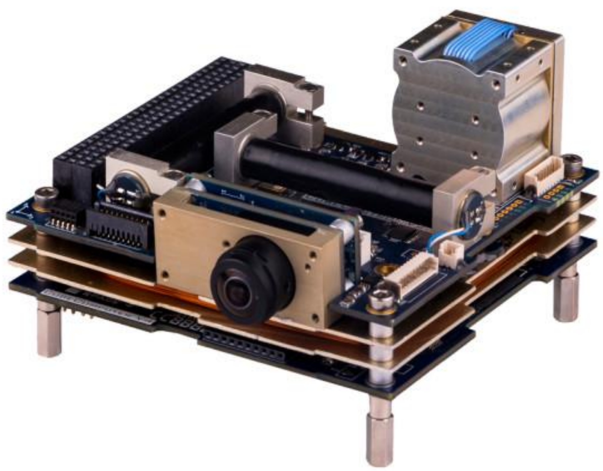

Figure 3.5: CubeSpace Y-Momentum ADCS

tandem with the CD&H system as the former handles orbit control and orientation, while the latter handles data crunching and satellite commands.

The CD&H system is made up of the Onboard Computer (OBC) built by Endurosat and is in charge of being the central operating system on KUbeSat1. The CD&H system runs off an ARM M7 processor with 512 kB of ram and 2 MB of programmable memory and includes a multitude of interfaces for varying plugins ranging from solar panels to cameras and other serial ports. While the ADCS has a built-in propagator, alone it cannot send the information anywhere. By combining with the OBC through the same PC104 header, the satellite can catalog where it is and verify with the built-in Novatel OEM 719 GNSS receiver. This GNSS receiver is capable of linking with Navstar, Glossnas, Galileo, BeiDou, QZSS, and IRNSS to offer sub-meter level positioning. In some cases, the GNSS receiver is capable of centimeter-level positioning which will be utilized as KUbeSat1 flies over Antarctica. As soon as the satellite passes the 66° S longitude, the GNSS will tell the OBC to send a signal to the HiCalK to begin its science collection. The other interfaces built into the OBC, shown in Figure 3.6, will be used to both power and communicate with the Raspberry Pi and the AD2 as neither have the PC104 header stack as the standard CubeSat components do. One of the other main goals of the OBC is to help coordinate when the

Figure 3.6: Endurosat OBC

satellite will pitch using the ADCS reaction wheel. These times usually include pitching for taking pictures of the Earth using the Pi Cam which was outlined and described in Section 3.2.3 and to allow for accurate downlink to the ground station based in Lawrence, Kansas.

3.4.4 Communications

As KUbeSat1 performs its science objectives, it will continually collect data and store it in the OBC's SD card. On each Lawrence flyover, KUBeSat1 will establish a downlink with the ground station at KU and begin transmitting the data. This means that the communications team has the difficult task of creating both the organization's communication infrastructure and getting KUBeSat1's comms working. To easily describe both, these facets of the team are split into two and detailed as the previous sections were.

KUbeSat's ground station, called Hawksnest, is a multifaceted approach designed to be expandable and upgradable from day one. It was important to the KUbeSat1 team that the GS communications adhere to several important requirements all of which are listed below.

- The communications sub-team shall design a communication system that reliably transmits information to the satellite and receives information from the CubeSat.
- The ground station shall withstand environmental factors, such as non-damaging weather events to maintain communication when the satellite passes over the ground station.
- The ground station shall comply with all state and local regulations, such as FCC, campus building regulations, and IARU.
- The ground station communication system shall be tested to prove fidelity, including functionality testing, anechoic chamber testing, and day-in-the-life testing.

Using these requirements, the communications team was able to set up an antenna mast with a circularly polarized UHF Yagi antenna on the roof of the Eaton Engineering building. This antenna can track any satellite as it moves over Lawrence via a donated Research Concepts Inc. controller. Operating at a frequency between 432-438 MHz, the antenna connects to a Low-Noise Amplifier (LNA) which helps amplify the low-power signal coming from the satellite. With an average gain of about 25 dB and a typical noise figure of 1 dB, the LNA is designed to pass along the signal with minimal degradation to the signal-to-noise ratio (SNR). Continuing along with the systems, a signal is next intercepted by an ICOM 7100 transceiver with a frequency range between 430-450 MHz. It is important to note that initially, KUbeSat used an ICOM 9700, but had to switch due to the 9700 not supporting a 9600-bps baud rate. The transceiver communicates with a modem operating under GMSK modulation and stores the data on a 128 GB SD card inside a Raspberry Pi. The Pi is also connected to KU’s network and automatically sends the data to the Hill Space Systems Lab for post-processing. The full design of the Hawksnest GS, seen in Figure 3.7, has several redundant cables installed that are meant for expansion as the KUbeSat organization grows. This includes the addition of an S-band dish antenna and other radio transceivers in the future.

On the other end of the communications equation, is the satellite side with its own set of complexities. Like the GS side of things, the satellite has its own set of requirements that it

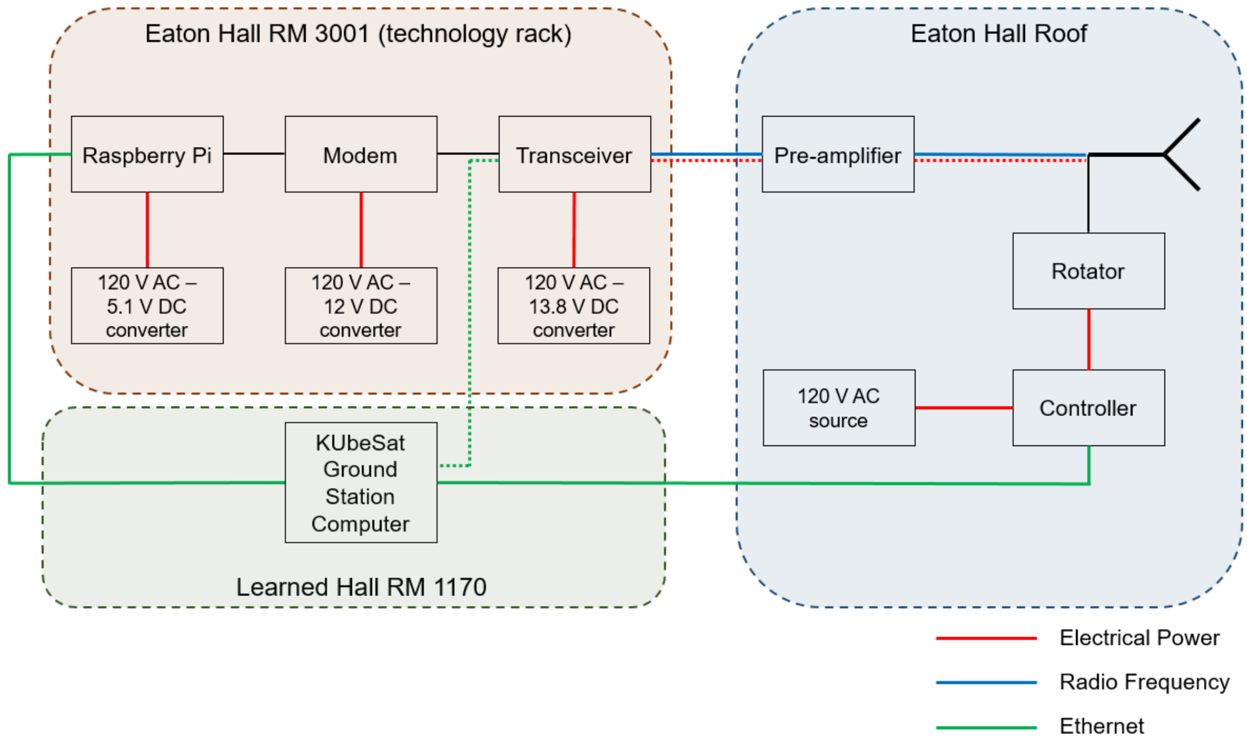

Figure 3.7: Hawksnest Ground Station

needed to meet.

- The satellite communication system shall be tested to prove fidelity, including functionality testing, anechoic chamber testing, and day-in-the-life testing.
- The satellite communications system shall withstand typical vibrations during launch.
- The satellite communications system shall be capable of at least 4800 bps with the preferred data rate of 9600 bps.

To meet these requirements, KUbeSat1 uses an Endurosat UHF radio module and deployable antenna both operating in the 430-440 MHz range. The radio module has a max transmit power of one watt with the option to go up to two watts on specification to the manufacturer. Moreover, the module is capable of 1200-19200 bps all while offering a variety of modulation types including the chosen GMSK. Like all the other standard CubeSat components, the radio module can stack to its other components via a built-in PC104 header. It also includes a few external ports meant for configuring and powering the module during testing. Lastly, the module includes an MMCX connection point that can support a cable and connect to the antenna itself. The Endurosat antenna is a circularly polarized deployable antenna meant to operate in the UHF spectrum. The antenna, seen in Figure 3.8, has four dipole arms that are deployed via a burn wire mechanism.

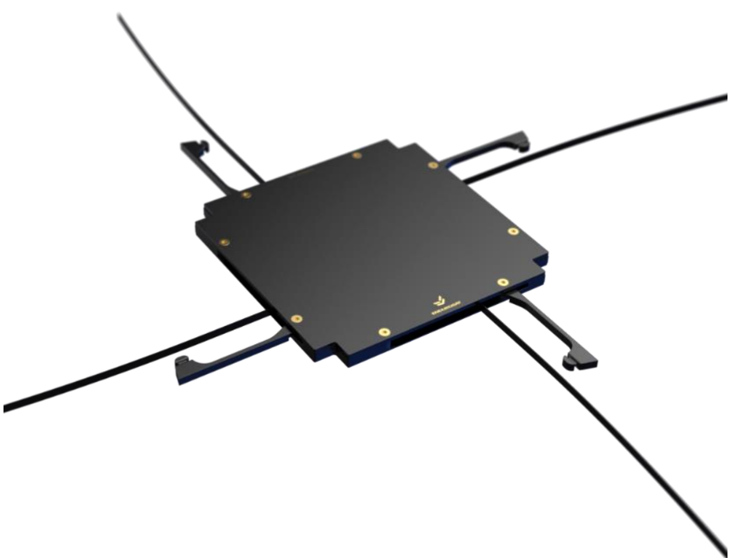

Figure 3.8: Endurosat UHF Antenna

This burn resistor mechanism also includes a redundant electrical path to ensure that all the arms deploy once in orbit. Endurosat does offer two varieties of UHF antennae, one with a solar panel and one without. The power team determined early in the satellite design this was not needed, and the standard antenna was selected. It is important to note that the antenna could not be tested much in its undeployed state and thus the rigorous testing that the manufacturer had set was relied upon. With the communications systems designed, the final team oversaw tying together the software needed for all the components to communicate with one another. Much like the Communications team, the Software team had to tackle the problem on two fronts.

3.4.5 Software

The final piece of KUbeSat1's puzzle is all the software that is needed to ensure all the components work together. This team has two main areas of focus: software for the satellite and software for the GS/post-processing on the ground. Like all other subsystems, the Software system is defined by its requirements and then designed around those requirements. For the GS side of thing the satellite shall:

- Display sensor readings from the satellite both as statistics and as a graph
- Be built with the future in mind and will support multiple satellites while being easily upgradeable
- Be able to view the location and flightpath of the satellite

The Hawksnest software, written in C#, is designed from the ground up meant to track satellite data. The location and subsystem information will be displayed in the KUbeSat lab for anyone to see, while post-processed information is stored on the KU Network. Under normal circumstances, Hawksnest will pull data from the GS Raspberry Pi outlined in Section 3.4.4, and then wrap the data in JSON containers. To identify where the satellite is regularly, the GS will pull a Two-Line Element Set (TLE) from online databases like Celestrak. This will then be fed into a propagator and displayed on a 3D visualization in Hawksnest. Moreover, as KubeSat1 orbits Earth, it will intermittently broadcast a beacon meant to identify itself. If this beacon is intercepted by HAM radio operators or other universities, it can be uploaded to a specialized Twitter account linked to Hawksnest software. This will in turn display location information inside of the KUbeSat Lab. Along with the location data, the post-processed payloads data will be stored in an accessible database meant for archiving all communication with KUbeSat1 and any future satellites. The general outline of how the Hawksnest GS software interacts with KUbeSat1 and users is shown in Figure 3.9.

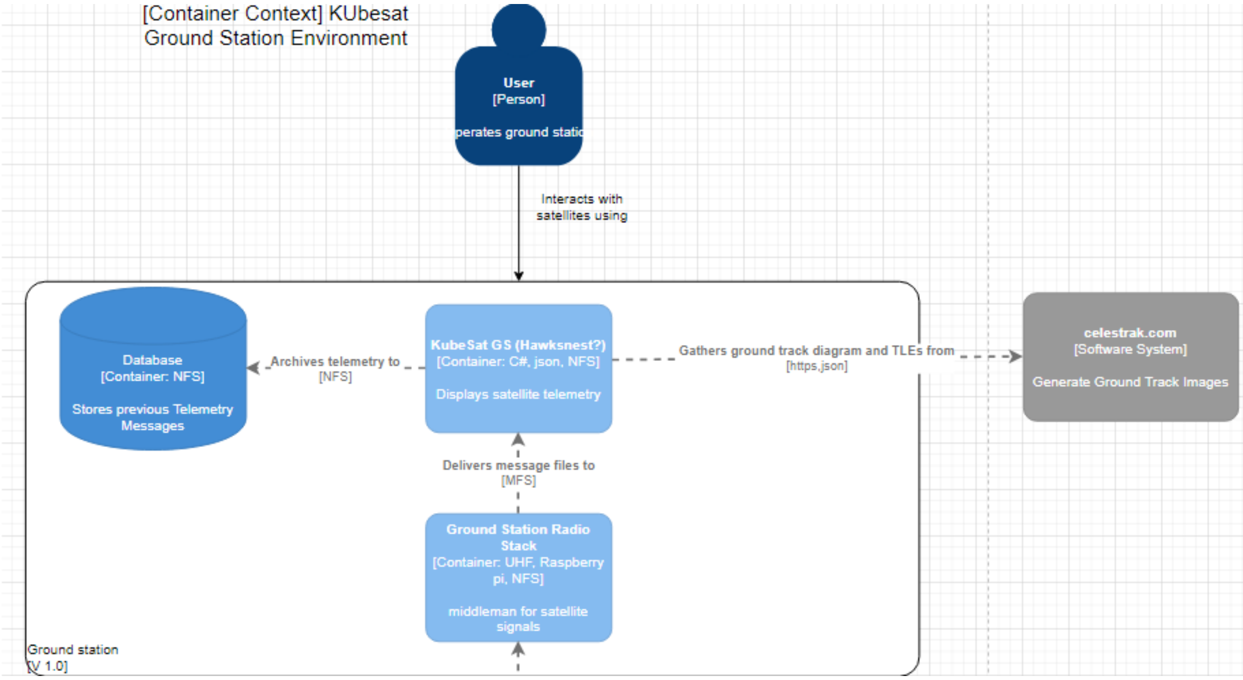

Figure 3.9: Hakwsnest Software V1.0

The GS software can be split into two sections. One that is considered active and one that is passive. The active side of the system is handling the heavy lifting during up and downlink communications. The process is outlined as follows:

- If the satellite is close to Lawrence, start sending handshake to raspberry pi
  - Use the TLE as a check to see if the satellite is close
- Once the satellite receives handshake, GS asks for health data
- The satellite sends health data
  - Ideally, the data fits in one packet
  - If not, each packet is 127 Bytes max and GS software will have to checksum after each packet has arrived and then ask for the next packet
  - If the health data check sum is not good, ask for that packet again
  - All health data is stored in a folder on a shared drive
- Once all health data is down, ask for the payload data
  - Like the health data, this will be in packets with checksums
  - If a checksum is bad, resend the packet
    - Else keep asking for the next packet

    - All payload data is stored in a folder on a shared drive separate from the health data
- Once all payload data is down, ask for picture data
    - Like the health data, this will be in packets with checksums
    - If the checksum is bad, resend the packet
        - Else keep asking for the next packet
    - This may not exist, or it may be left over from the last transmission
- Send command to Satellite to be in receive mode as it moves away from Lawrence

This process constantly interacts with the entire infrastructure outlined in Figure 2.3. The passive side of the GS software takes the data stored in the active end and displays it in the lab. This also includes pulling Two Line Element (TLE) sets from the internet and using that to display location data.

Unlike the GS software, the satellite side of the software is primarily developed by the suppliers of the respective components. This means the OBC, EPS, and ADCS systems all have proprietary software that KUbeSat as an organization must learn to work with. The satellite software, fortunately, was able to meet the requirements, listed below, outlined for KUbeSat1.

- Read and process telemetry and sensor data while in flight
- Write payload control services
- Write software to manage operations at different power states
- Interpret, store, and return to ground station data from PCRD payload
- Sense GPS position to trigger enabling and disabling HiCalK payload
- Determine and configure desired flight attitude

As this data is proprietary, little can be shared with the general public, and even then, some information may not be helpful. Nonetheless, it is important to document as much as possible in the chance that future missions could rely on legacy software. The majority of satellite software is written in C with the payload software being written in Python. To ensure communication between the OBC and the payload boards, the code must be converted to serial communication and passed to the OBC.

4 KUbeSat1 Results

4.1 KU Testing and Results

4.1.1 Structures

As was mentioned above, the entirety of KUbeSat1 is built using COTS components to avoid major operational issues once the satellite has been launched. This holds for all components except the payloads and their mounting plates. The mounting plates, pictured in Figure 4.2, were designed to be as generic as possible to allow for multiple uses and thus lower manufacturing costs. The plates are made out of 6061 2.65mm thick aluminum and have four predrilled holes to allow for the CubeSat rods to pass through. Any other holes would be hand drilled to the specification of the component that would be mounted to the plate. To ensure that these plates would be able to endure the launch loads (which are the peak loads) a PATRAN/NASTRAN analysis was done. Loads and boundary conditions were applied to the model that matched the anticipated launch loads. These include inertial loads in the Y and Z directions while the axial loads were applied through the X direction. Table 10.3 in

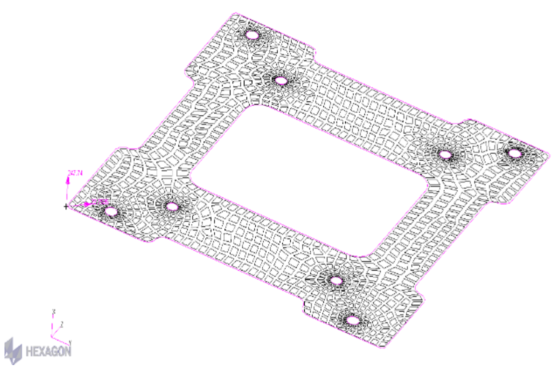

Figure 4.1: Mounting Plate 0.1 Inch Mesh

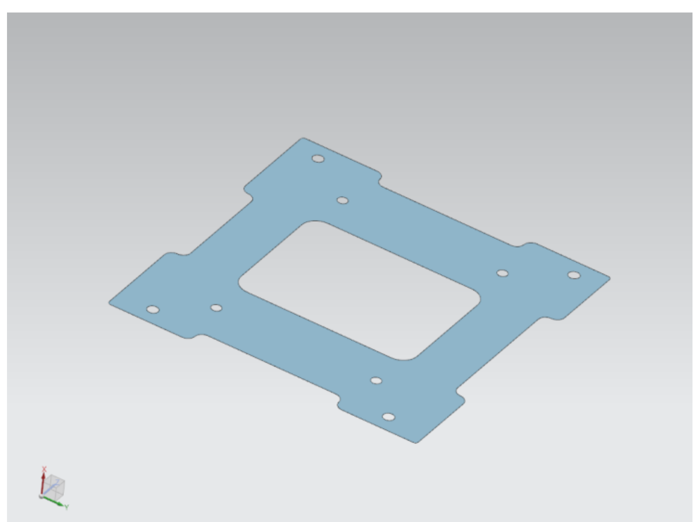

Figure 4.2: KUbeSat1 Mounting Plate

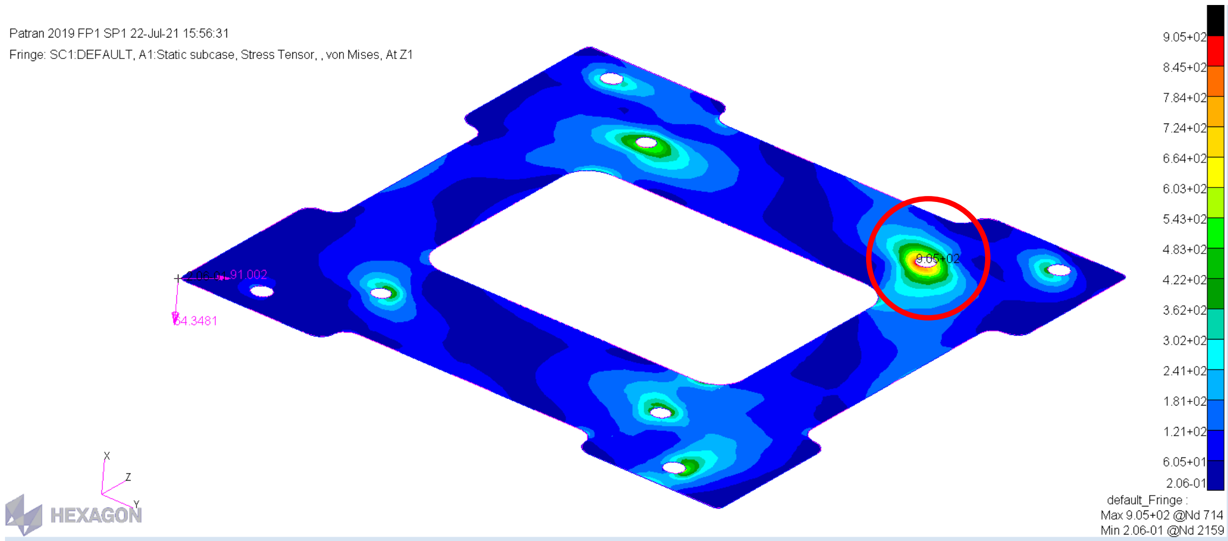

Figure 4.3: Mounting Plate Stress Hotspots

Section 10 outlines the exact boundary conditions and load values used. During testing, three different meshes were applied to the plates and used to find the location and max stress on the plate. One mesh, seen in Figure 4.1, used a 0.1-inch mesh seed while the other two went finer at 0.05 and 0.025-inch seeds. To ensure the plates were able to meet the required strength, the analysis primarily looked at the Von Mises Stress of the plates. This is generally considered a safe estimate for stress when tasked with testing a material's strength. If the max Von Mises stress induced in the material exceeds the strength of the material, then the part will fail. Looking at the highest fidelity mesh of 0.025-inch seeds shows that the highest expected stress occurs at Element 378, denoted as the hotspot in Figure 4.3. The load cases and their results are outlined in Table 4.1 with the highest value being 3658.95 psi. This in turn leads to a yield margin of safety (M.S.) of 1.733 which is above the minimum acceptable level of 1.5. From there all the other M.S. values are well above

Table 4.1: Test Results and Load Cases

Test #	Load Case (G's) [Translational, Rotational]	Location of Max Stress	Max Stress Value (psi)
3.1	[0.5, 7.7]	Element 378	3658.958
3.2	[2.4, 4.0]	Element 378	1889.174
3.3	[2.4, -1.0]	Element 378	490.066
3.4	[2.0, -2.0]	Element 378	962.626

the minimum acceptable value. In the end, all analysis of the mounting plate shows the plates are more than capable of handling the expected launch loads and were subsequently approved for manufacturing.

4.1.2 Power

Before flight, the power team had to work directly with the electrical components of the satellite to ensure they can perform the tasks needed in orbit. This meant connecting the EPS with the battery and running through a gamut of preflight checks. It was decided early on that whenever the battery was being used, it would be connected to the EPS as a way to prevent shorts and other technical problems. The EPS has a slew of over and under-voltage protection circuits built into the entirety of the system thus enabling safe testing and more importantly safe flight. To set the battery-ready state, the EPS is plugged in via the PC104 header stack and the n connected to both an external power supply and a multimeter. The external power supply is meant to provide a source of power to charge the battery while the multimeter reads out the information on the various battery voltage rails. Once all the leads have been connected and verified, the battery inhibits pin is pulled which allows for current to flow through the system.

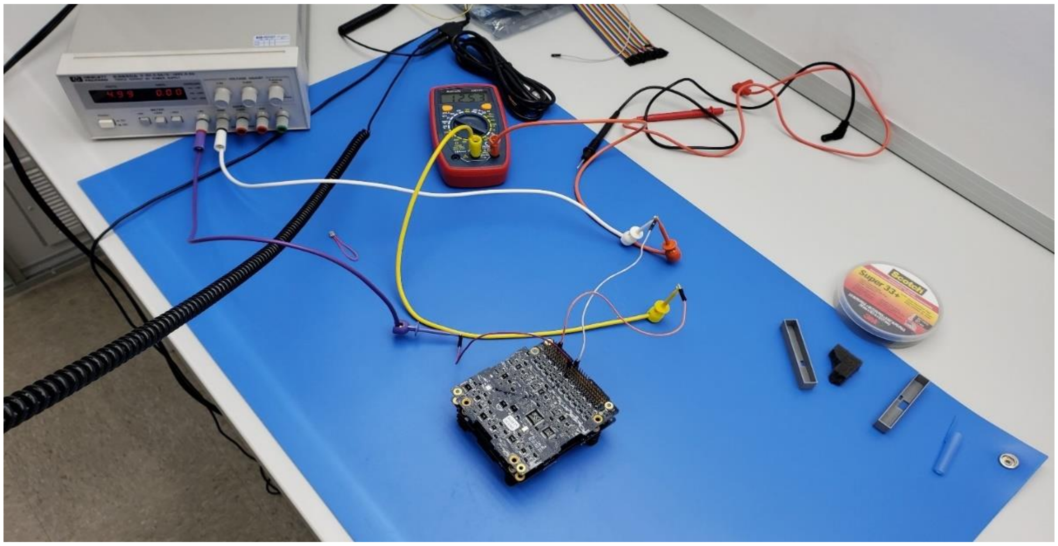

Figure 4.4: Power System Testing Setup

The anticipated voltage on the multimeter should hover around 7-8v and indicates a healthy battery and properly functioning EPS. The complete setup can be seen in Figure 4.4. It is important to note that the entire process must take place on a mat designed to prevent Electrostatic Discharge (ESD). To further prevent issues, the operator must also be wearing an ESD bracelet. KUbeSat1's battery and EPS have passed all the required checks and are ready for flight.

Testing the solar panels involved similar steps as the battery. The panels were placed in the clean room lab and connected to a multimeter to ensure some voltage was generated. It should be noted that while under the clean room lights the generated voltage does not necessarily match what will be generated when the satellite is in orbit. This was only to prove that all the panels were functioning. The other half of the testing with the panels was the creation of the wire harness of the system. While there were some provided cables for the wire harness, the end connectors did not work with the sourced EPS. To create a wire harness, Figure 4.5 was used as the primary wiring diagram. Each harness would have three connections, where one end goes to the EPS, and two plugs connect to the solar panel. Using a variety of tools, the wire harnesses were constructed and connected to the panels. Once attached to the panels, the same test with the multimeter was run to ensure that the wire harnesses made proper contact with the

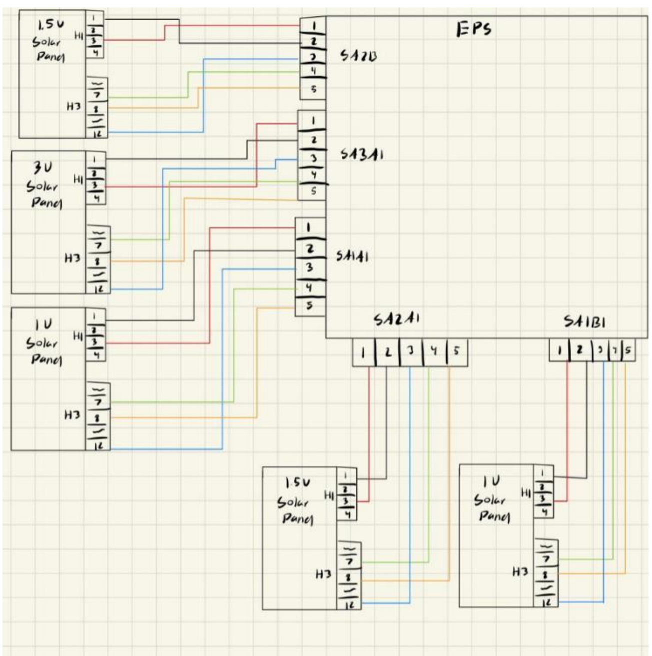

Figure 4.5: Wire Harness Wiring Diagram

pins on the panels and voltages still flowed through the system. Lastly, these wires were connected to the eps and one last test was done to ensure that the EPS was fed power generated by the panels.

4.1.3 Systems

As stated earlier, the Systems Team handles the physical parts of the ADCS, OBC, and camera systems. Fortunately, these three systems came with prewritten directions regarding preflight checks and testing. Unlike the other systems, the OBC did not have any physical hardware that needed to be verified ahead of time. The entirety of the OBC verification is discussed in Section 4.1.5.

The ADCS uses a configurator designed to calibrate and tailor the ADCS components to the specific location on the satellite. As KUbeSat1's ADCS includes an Earth-Horizon sensor and deployable magnetometer for attitude determination, the configuration program needs to be run to accurately predict the current orbit. The configurator can be seen in Figure 4.6. Moreover, the health checks involved running through a gamut of tests that included everything from checking boot status to getting temperatures of various systems. CubeSpace, the producer of the ADCS, outlined a step-by-step guide on how to perform these tests. Along with the health check of the main ADCS, there were several other tests for the "nodes" of the ADCS system. This included checks that would focus on the earth horizon sensor and the magnetometer.

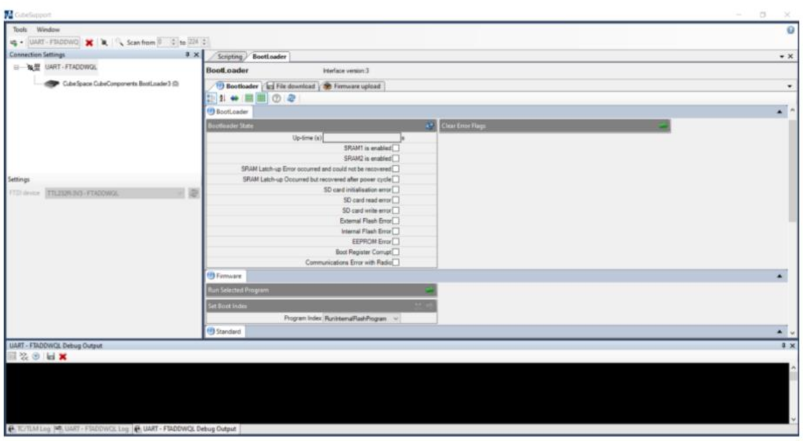

Figure 4.6: ADCS Configurator and Health Check

One of the more important issues surrounding the ADCS was the deployable magnetometer which shipped with a small defect. After the product had been shipped, the supplier reached and informed the team that there was a small manufacturer error. An issue with recently built, first-generation magnetometers where one of the soldered pins on the burn-PCB was in dangerous proximity to the aluminum mechanics. If contact does occur, then the magnetometer's mechanical body will be raised to battery voltage during deployment, which could in turn result in a short circuit. The recommended fix included placing a piece of Kapton tape between the body and the solder joint. The epoxy was used to secure the tape in place and to seal the whole system together. Figure 4.7 shows the magnetometer, its problem highlighted by the red circle, and the subsequent fixes applied.

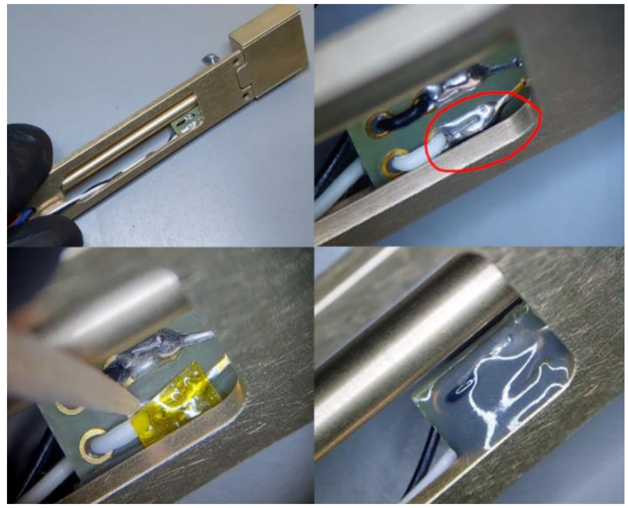

Figure 4.7: Magnetometer Issue and Fix

Another important component of KUbeSat1 is the Pi Cam camera kit. This system is meant to take pictures as KUbeSat1 orbits Earth uses the payload Raspberry Pi to run a program to take pictures intermittently. While the Pi Cam kit is capable of 4k photos, most of KUbeSat1's on-orbit pictures will not be at this resolution. This is primarily due to the communication constraints of KUbeSat1. Transmitting a 4k photo at 9200 bps, the baud rate for the UHF module, would take a minimum of 82 minutes which is nearly the entire 95-minute orbit of KUbeSat1. As such, the photos must be

Figure 4.8: Pi Cam Test Photo

compressed and condensed into smaller packages to ensure that along with valuable payload data, KUbeSat1 can send pictures from space. Before launch, the Pi Cam was connected to the Pi and a test photo was taken to determine the quality and more importantly the level of compression. The test photo, seen in Figure 4.8, was initially sized around 900KB. After being passed through a compression algorithm, the final size fell to 135KB.

4.1.4 Communications

Arguably one of the most critical components, the Communications Team had a full set of tests that needed to be performed before launch. Once again, these tests could be split into two subsections: Satellite and Ground Station.

On the satellite side of testing, the team had a full suite of tests to overcome. Since KUbeSat1 operates in the UHF spectrum, it needed to use a deployable antenna system. Unfortunately, this led to other another problem as the antenna could only be deployed once which is reserved for in-orbit flight. The antenna could not be deployed, tested in the anechoic chamber, and reset. After communicating with Endurosat, the team moved forward with testing the antenna in its undeployed configuration. While this would not give an accurate reading, it can be compared to a known working antenna with Endurosat. By testing both in an undeployed fashion and comparing

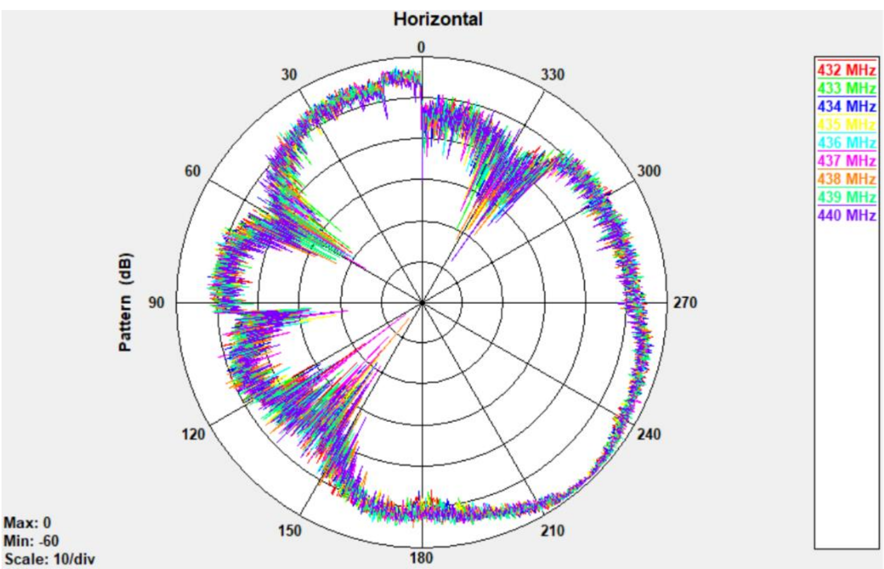

Figure 4.9: UHF Antenna Radiation Pattern

values, the antenna can be verified. To ensure that the antenna did not get contaminated and was safe during testing, it was sealed in a plastic container and placed in the anechoic chamber. An S11 and S21 radiation pattern test were performed and cross verified with Endurosat. The results, shown in Figure 4.9, show the antenna is operating at the expected values. Moreover, the results of the S21 radiation plot show that if the antenna does not deploy, KUbeSat1 holds the possibility of still being able to communicate with Hawksnest GS albeit at a significantly reduced capacity. This is because the S21 results showed a noticeable lobe indicating that even in an undeployed fashion the antenna has directivity. Combined with the results of the return loss test showing the minimum power received is less than -10 dB provides more proof that the antenna will be able to function regardless of its state. Still working on the satellite side, the Communications team also ran a gamut of tests that focused on the UHF radio module. These tests were mainly to gain an understanding of how the module worked, but also to verify the system was functioning properly. The team connected the UHF module to a configurator and a canted turnstile antenna meant for testing. The module was set to continuously beacon a signal which would be received by the transceiver at the other end of the room. In turn, the transceiver would use the attached modem to send the signal over the KU drive and decoded and displayed it on the computer. Show in Figure 4.10, the test setup on both the module side and receiving side can be

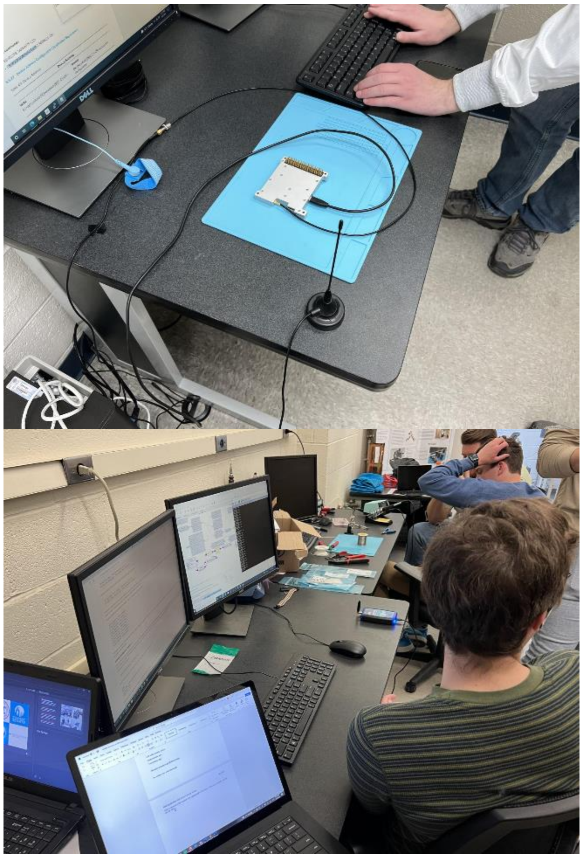

Figure 4.10: UHF Radio Module Testing

seen. Following through with all these tests, the team was able to confirm that the antenna and the radio module on the satellite were fully functional.

The other half of the communication testing involved working with the GS and ensuring it was ready for operation. This also included testing the Yagi antenna in the anechoic chamber to characterize its radiation pattern and prove that it matched the data sheet values. The testing in the chamber took place over several days and looked at the return loss graph of the antenna. Like the satellite antenna, the GS antenna had to display a return loss lower than -10dB in the frequency range that was needed for the mission. Fortunately, all tests indicated a working antenna with a good radiation pattern and better than expected return loss values, both of which can be seen in Figure 4.11. After verifying all values, the GS antenna was installed on the roof of the Eaton Engineering building and connected to the Hawksnest infrastructure outlined in Figure 2.3.

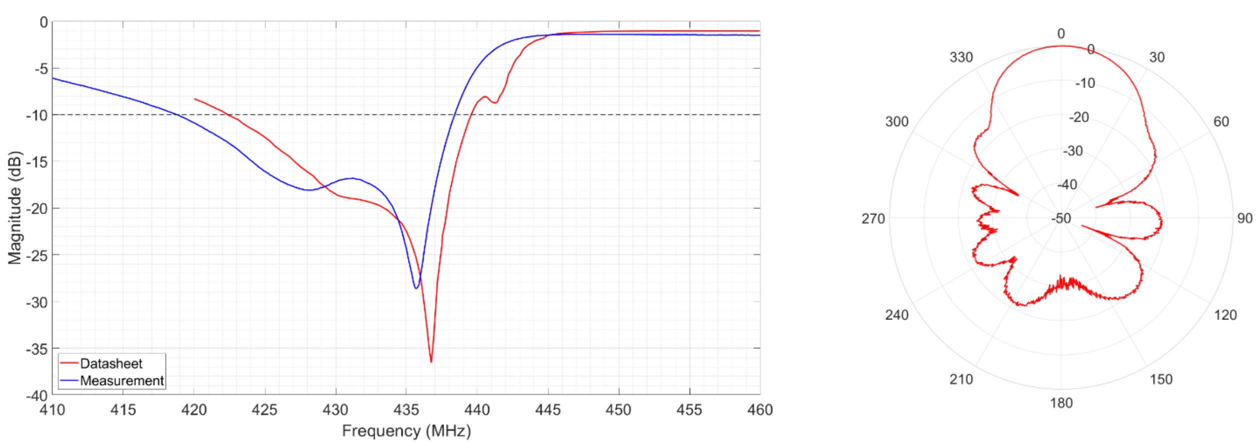

Figure 4.11: GS Antenna Test Results

Armed with the knowledge of a working system, the communications team created a link budget that would be used as the primary source in the accounting system of all the power gains and losses the system would experience during normal operation. Operating at 438 MHz at 565 km and the lowest available elevation angle of 10 degrees the budget is outlined in Table 10.4.

The team found a Signal-to-Noise Ratio threshold for GMSK BER of 10-5 is 9.6 dB with the Worst-case uplink and downlink margin to be 22.3 dB and 7.06 dB respectively.

4.1.5 Software

Similar to the communications team, the software team tackled testing on two fronts. The first of which is on the satellite side with the OBC. The OBC had no physical testing that it needed to go through and as a result, the software team did all testing in the virtual environments. Most of the testing involved writing code and communicating between different modules. This naturally is a trial-and-error process and took a substantial amount of time. The first set of tests involved getting status updates and pushing commands directly to the OBC. As the software was written in C, the main development environment for the OBC was Visual Studio seen in Figure 4.12.

Figure 4.12: Coding Environment Example

It should be noted that early on the team had to return the OBC to Endurosat as it was determined there was a fault with the system. Once the manufacturer was able to identify the fault and solution it was returned to KUbeSat and work proceeded. This fault arose from the inclusion of the GNSS module and a lack of clear instruction from the company. Once the team determined that the OBC itself was working properly, it was paired with the battery and EPS to provide external power and ask for information from the EPS. This included asking for battery health and status while simultaneously queuing the battery watchdog program to prevent the system from rebooting. After the battery and EPS test was deemed successful, the radio module was also connected and asked for similar data. Eventually, the OBC pushed data to the radio module which was transmitted via the antenna to the ground station and displayed on the ground station software.

Similar to the satellite side of software development the GS side went through a round of tests. The first test involved creating a program that would interact with the GS infrastructure developed by the communications team. This process used the data transmitted during a communications test and displayed it on the Graphics User Interface (GUI) the team had developed. It should be said that the first time this was done the data was received at one computer and then manually transferred via an email to the GS software computer. The next set of tests automated the process and had the Hawksnest software pull the data directly as it arrived. Finally, the team also evaluated the active part of the system by….

4.2 Licensing

Launching any satellite requires a variety of licenses with the two most common being a radio frequency (RF) license and a National Oceanic and Atmospheric Administration (NOAA) license. The RF license has different classifications depending on the operator with each having its own set of requirements and challenges. These classifications are:

- Amateur: Designed specifically for amateur radio enthusiasts and to serve the amateur radio community.

- Commercial: For commercial use, not applicable for non-commercial university-based CubeSats or CSLI selectees.
- Experimental: For radio frequency emitting systems on spacecraft containing experiments. A typical license for university CubeSats or CSLI selectees.
- Government: For spacecraft that operate radio frequency systems that "belong to and are operated by" any U.S. Government agency.

Despite most CSLI satellites falling under the experimental license, KUbeSat1 was advised to apply under the amateur license. As such, KUbeSat1 also had to work with the International Amateur Radio Union (IARU) which is an international agency run by volunteers. These volunteers are based all over the globe and help police amateur radio frequencies. The other major license required for KUbeSat1 is the NOAA license. While most CubeSats do not need a remote sensing license from NOAA, any satellite that flies with a type of passive or active imager will need regulatory approval. As KUbeSat1 is flying a camera in the form of PiCam, it did need to coordinate with NOAA and attain a license. KUbeSat1 was granted a Tier 1 NOAA license authorizing the University of Kansas to operate KUbeSat-1, a private remote-sensing space system comprised of one satellite with a small camera.

Fortunately, being part of CLSI enables KUbeSat to use various coordinating liaisons that help broker conversations and submissions with these regulatory bodies. Working with CLSI Liaison, KUbeSat1 was able to submit a proposal to the IARU and was granted an amateur frequency at 437.085 MHz. Once the IARU coordination came down, the Federal Communication Commission (FCC) was contacted and all the requested documentation was submitted. These documents include Orbital Debris Assessment Report, Stop Buzzer Control, NOAA license, and IARU coordination. At the writing of this section, the FCC has not yet responded to the submission, but it is anticipated that KUbeSat1 will have no issue receiving its license. With these licenses, KUbeSat1 is fully approved to operate in orbit when it launches in 2022.

4.3 Assembly

During testing the satellite was assembled several times to various stages of completion to understand how the system connects and fits together. Initially, this meant only connecting the "blocks" of the various systems, like the OBC and the UHF radio module or the battery and EPS. Once an acceptable comfort level was reached, the team moved to assemble larger pieces including the payloads, and the frame. Lastly, the team assembled all components including wiring and solar panels. The team discovered the best way to assemble the satellite was to begin with section blocks and then assemble the case around the internals. The process is as follows:

1. Assemble the Endurosat block which includes the Radio Module and the OBC
2. Assemble the power block which includes the battery and EPS
3. Assemble the ADCS block which includes the ADCS and all its subcomponents
4. Assemble the PCRD Scintillators
5. Assemble the payload computers
6. Assemble the bottom plate including the PiCam
7. Connect the three blocks and install the guiding rods along with spacers
8. Slide in the PCRD Scintillators with the bias board sandwiched in-between both housings
9. Cap off the one end of the satellite with the frame end piece
10. Slide in the Payload computers and the appropriate spacers on the other end along with the end piece

11. Attach all needed cables and mount the ADCS subcomponents
12. Assemble the frame around the satellite
13. Attach the bottom plate
14. Attach the GPS antenna panel
15. Attach the solar panels and UHF antenna to the outside of the satellite

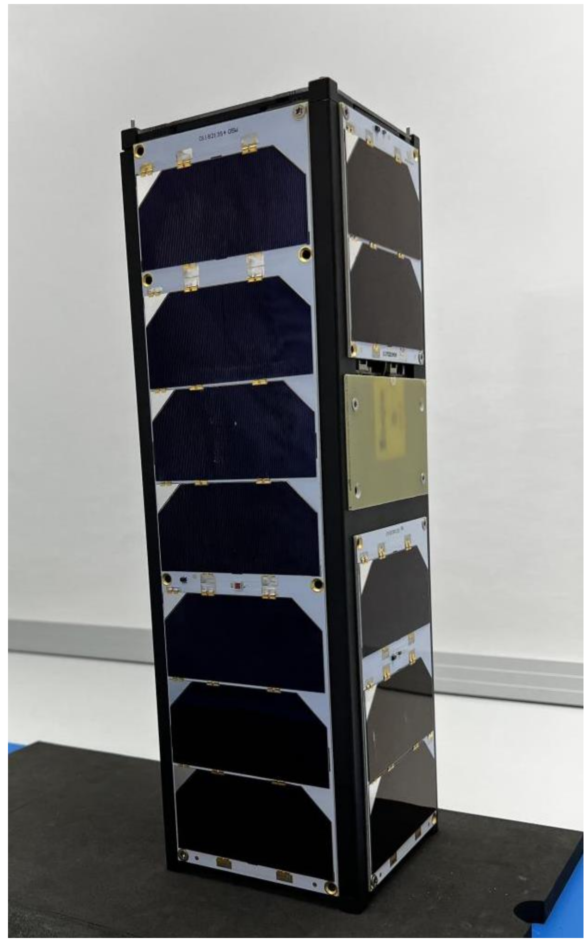

Figure 4.13: KUbeSat1 Full Assembly

In this process, several small adjustments were identified. This included things like sanding some custom plates to better fit in the frame, ordering flatter cables, or making small design adjustments to better account for wiring paths. The completed satellite assembly, seen in Figure 4.13, could now begin its testing with NASA

4.4 NASA Testing and Results

Once all internal testing had been finalized and the satellite assembled it had to go through a gamut of tests laid out by NASA. These tests are to ensure the satellite meets the strict requirements set by the launch provider which are often set to ensure the satellite will not be the primary cause for failure during launch.

4.4.1 Dynamic Environment Testing

As the satellite rides the launch vehicle (LV) to orbit it will encounter the highest loads it will experience during its usable life. The only exception to this rule could be reentry, though many satellites have failed by the time reentry begins. There are currently two main types of

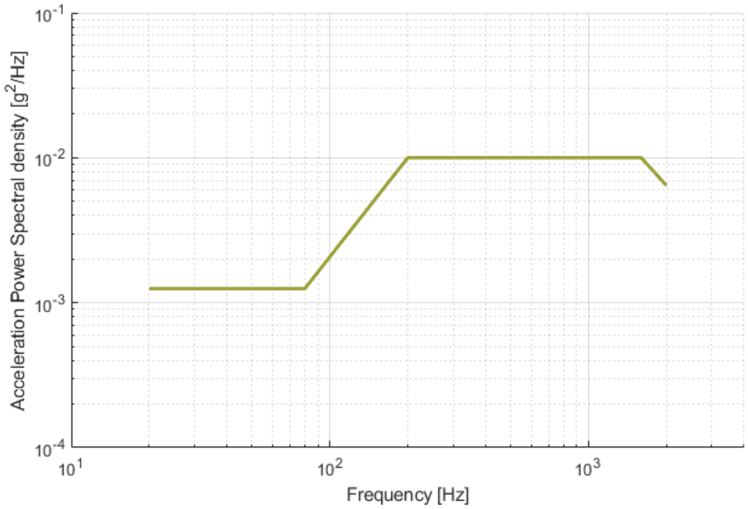

Figure 4.14: Firefly Alpha Random Vibration Environment [7]

dynamic testing: vibration and shock[13]. For all launches, satellites are expected to go through vibration testing, often shortened to vibe testing while shock testing is dependent on the launcher. This test uses a dispenser, typically built by the Launch Service Provider (LSP), and a vibration table to simulate the vibration loads of the LV. As mentioned, KUbeSat1 will fly onboard a Firefly Alpha vehicle and be dispensed by Firefly's custom-built dispenser. Given the availability of the facilities at KU, the KUbeSat team elected to do the vibe testing on campus. This meant the satellite had to be 100% fully assembled including all cables and wires that would fly on the satellite. The main goal of the testing would highlight any weak connections or imperfections in the satellite design. As a result, Firefly sent the expected launch environment, seen in Figure 4.14 with a discrete breakdown seen in Table 10.5, ahead of the actual test so the KUbeSat team could prepare for testing. Once the team determined the facilities could perform the test, Firefly would send a group of representatives from Nanoracks to KU to perform a fit check and vibe test. It should be noted that the dispenser itself falls under the restriction of the International Traffic in Arms Regulations (ITAR). This meant that only US citizens were allowed to be in the same room as the dispenser, let alone perform the actual vibe test. As a result, the actual vibe test along with images from the procedure is not allowed to be shared with the public and will be omitted. What can be stated is that KUbeSat1 is expected to pass both its fit check and vibe test, certifying it for the next stage in the verification process known as the readiness review.

4.4.2 Readiness Review

Once the satellite has passed its vibe test, NASA expects it to undergo a readiness review. This process involves meeting with several NASA, Firefly, and Nanoracks officials who will perform a full analysis of the satellite in its current state. Once that is complete, the officials will interact with the team to identify what has been done, what still needs to be done, and how ready the team is for launch. It should be noted, that during the Venture Class Launch Service (VCLS) contracts NASA does not consider the rideshare CubeSat as the primary payload. Instead, the newly developed rocket and its success are considered the most important objective. This in turn means that should a CubeSat team fail its readiness review; NASA will not hesitate to move the satellite off the launch and continue according to schedule. As such, passing the readiness review is the final stage for a satellite to achieve flight heritage. The readiness review typically takes place about one month from the turnover date, which is the date the satellite is shipped to the launch facility.

4.4.3 Integration

One of the last steps before the launch of any satellite is integration. This occurs once all testing is complete, all paperwork has been submitted, and the satellite is ready to go. The integration site is determined by the launch pad, which in the case of KUbeSat1 is Vandenburg Space Fore base (VSFB). During integration, KUbeSat1 will be responsible for positioning and handling the satellite while a Firefly integrator takes final measurements and reviews the deliverables of the satellite. Most of the verification occurs on day one of integration with day two being reserved for one final vibration test to ensure the system is a go[13]. Members of the

KUbeSat team are expected to be on-site during integration to ensure that any issues can be handled in real-time. The end of day one represents the last time the team will see KUBeSat1 as the dispenser is sealed with the satellite inside. As mentioned above, during the second day of integration the entire dispenser unit is placed in one last vibe test. After this point, the team will no longer have access to the satellite unless special permission is given. With an identified turnover date of NET of June 28th, 2022, KUBeSat1 is estimated to integrate into the LV around the first week of August. The last step of the integration takes place without any outside help and only Firefly personnel. Like many aspects of Aerospace, the vehicle and full integration under ITAR and further company restrictions. The team will not be involved in this process as the integrator will hand over the satellite to the LV technicians and leave the launch site. At this point, KUbeSat1 is ready for launch.

4.4.4 Launch

Launching anything into orbit is often a chaotic but well-scripted dance of events that involve weather and other factors. As such, launch delays or scrubs are not impossible and often have to be accounted for. For the launch of KUBeSat1, the team has chosen to have as many members as possible at VSFB to commemorate the moment Kansas reaches space. It should be noted that CubeSats on VCLS launches are often not the primary payloads and as a result have no say in the launch date of the vehicle. The submission of this paper will occur before the launch of KUbeSat1, and as a result, the information presented above is all that is known at this time.

4.5 Operations

Once KUbeSat1 has been launched, the next phase of its life begins. The mission segment will enable the payloads to execute the needed commands and collect the science data in orbit.

Directly after launch, the LSP will provide the first estimated state vectors of the LV to enable the teams to begin scheduling operations. After the satellites are ejected into orbit the actual state vectors can be converted into Two Line Element (TLE) sets. These sets, typically produced by the United States Air Force's Joint Space Operations Center (JSpOC), are an efficient way of encoding orbital data for a given point in time called the epoch. Initially, the TLEs will be rough in estimate as there are several other satellites on the launch with KUbeSat1. Over the next few days, the satellites will spread out and JSpOC will generate a more refined TLE used for tracking and thus communicating.

The operation of KUbeSat1 can be divided into phases of operation. These phases correspond to the various objectives the satellite needs to complete as it obits and are outlined as follows:

1. Detumble and deploy antenna. Expected duration: 24-72 hours
2. Beaconing and establishing first contact. Expected duration: 12-24 hours
3. Check out and commission onboard systems. Expected duration: 12-24 hours
4. Begin operation of HiCalK and PCRD. Expected duration: 1-4 weeks
5. Shutdown primary HiCalK operation and focus on PCRD. Expected duration: 1-2 years
6. Intermittently use PiCam to take photos in orbit. Expected duration: Satellite Life

It is of course expected that there may be some form of deviation from the outlined satellite operation and as a result the plan above is meant as a guide for normal operation. Anytime KUbeSat1 is above the Hawknest GS it will follow the procedure outline in Section 3.4.5. Should any uplinks be needed to adjust software and provide new instructions to the satellite similar operations protocol will be followed.

4.6 Business Opportunity

As the KUbeSat1 team worked toward launch, it continued to run into consistent supply issues that highlighted a much larger issue with the small satellite industry. All of the COTS components on KUbeSat1 came from foreign companies with all parts being less expensive and more readily available to buyers. While some companies in the US charge nearly $150K for a combined ADCS/CD&H system a comparable system from foreign entities would cost closer to $75K including shipping and import fees. None of this includes other problems with foreign transactions including customs difficulties, wire transfer problems, or settling a problem in a foreign country. As a result, a deep dive in literature and market analysis was begun to understand if there truly is a gap in the US COTS market and what could be done about it.

5 Satellite Market

5.1 Market Summary

The small satellite industry is relatively new with the first CubeSats being launched in 1999. In just under 20 years of flight, the smallsat industry has grown from obscurity to a $3.25 Billion industry[14]. With just over 1700 CubeSat launched since 2003, the industry is poised to explode with growth[1]. Currently, there are just under 50 companies in the US alone dedicated to small satellite manufacturing. Of those 50, about five provide a full suite of components with only one providing a COTS solution for customers[15]. These 50 companies provide the components needed to fully build a small sat and launch it into orbit to achieve the intended mission target. Of the 1700 satellites launched since 2003, their mission targets have fallen into five main categories with a sixth small category encapsulating all other mission types seen in Figure 5.1.

More than half of all satellites flying are satellites designed for remote sensing (RS) or Earth Observation (EO). These satellites take pictures, perform radar measurements, and other Earth-focused measurements. Technology studies make up just over ¼ of current satellites with most of these dedicated to proving new technologies on a smaller platform, often considered the R&D of the small satellites. The remaining satellites focus on communications and purely scientific studies[1].

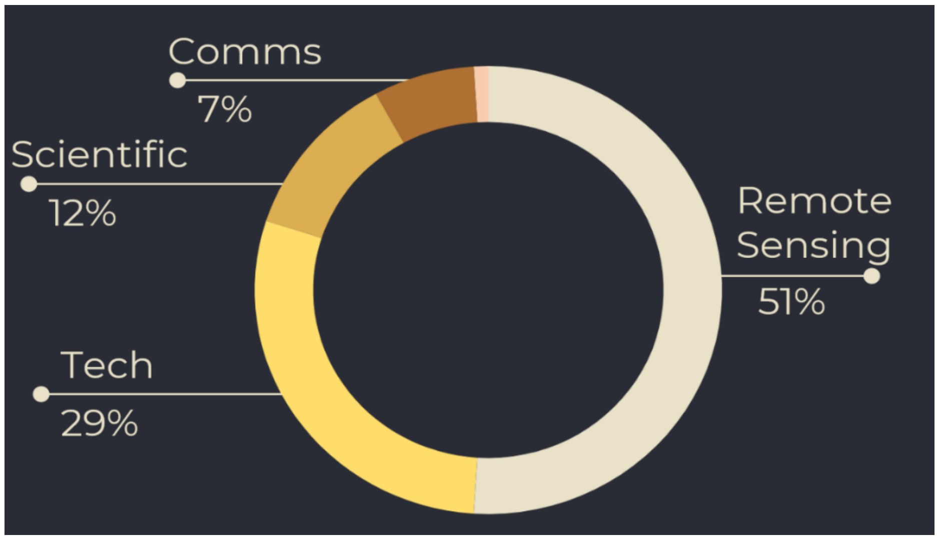

Figure 5.1: Current Small Satellite Uses

Another hallmark of the current satellite market/industry is slow and specific satellite design. While cars today roll off the assembly line thousands a day, a satellite can take years and at times decades to make only one. A satellite is capital intensive by nature, and this requires the firms producing them to make several long-term forecasts into capital expenditure decisions. Couple that with a very tightly run supply chain, and satellite manufacturers often run on a razor-thin margin of capital. The recent COVID-19 pandemic has shown that global supply chains are a tricky business, and the backlog has decreased the amount of small satellite production by 10% in 2020[16]. All these factors show that the current satellite industry is ripe for disruption and in need of a more modular approach. The modular system can have a variety of benefits that include faster time to orbit, reduced upfront capital expenditures, and increased opportunities for new tech insertion.

5.2 Market Trends

A major market trend in the small satellite world is the increasing use of constellations. More and more customers are planning constellations of satellites with some estimates placing 20,000 more satellites in orbit in the next ten years. Of those 20,000, just under half would be CubeSats[17]. If the definition of smallsat is expanded to not only include CubeSats (to 500 lbs),

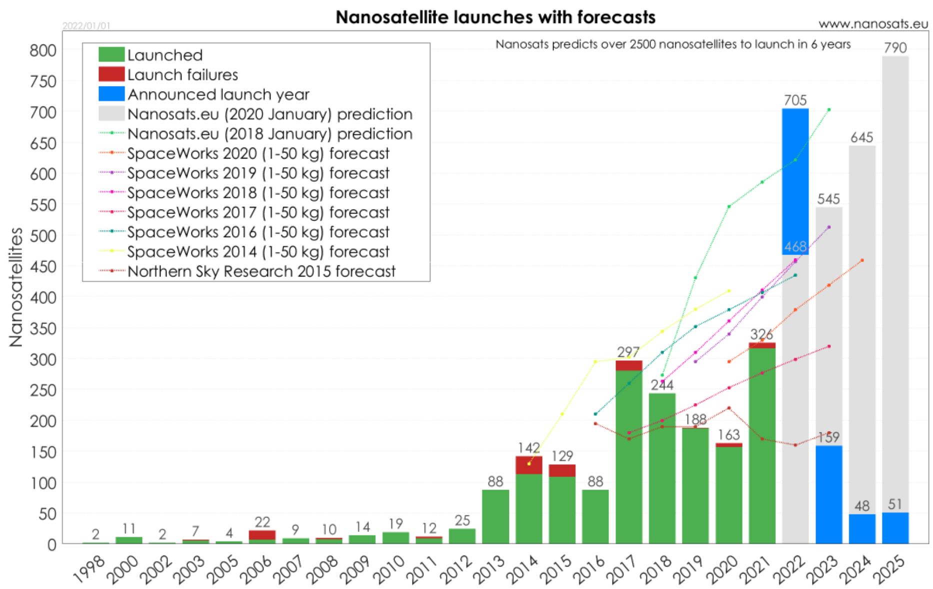

Figure 5.2: Nanosatellite Launch Forecasts

then it is estimated that 80% of all satellites launched in the next decade will be small satellites. A variety of organizations have begun forecasting long-term data to identify what the smallsat market will look like in the next few years. As seen in Figure 5.2, the anticipated number of small satellites launched is expected to be nearly 800 by 2025 [18]. It is important to note that this data considers announced missions as well as projections from various sources and includes projections as far back as 2014. By taking the data in Figure 5.2 and applying various trend lines a broader picture can be seen. Highlighted in Figure 5.3, the worst-case scenario shows just under 400 satellites launched by 2030 while the best-case scenario has nearly 2000 satellites. Given that there are more than 20+ projects focused on constellation development and launch, the lower value of 400 satellites a year seems less likely to be accurate. These swarms will have a variety of functions that range from remote sensing to satellite imagery, to communications[1]. This sharp increase in demand has left many customers waiting on suppliers to play catch-up to their needs and thus represents a whole in the current market.

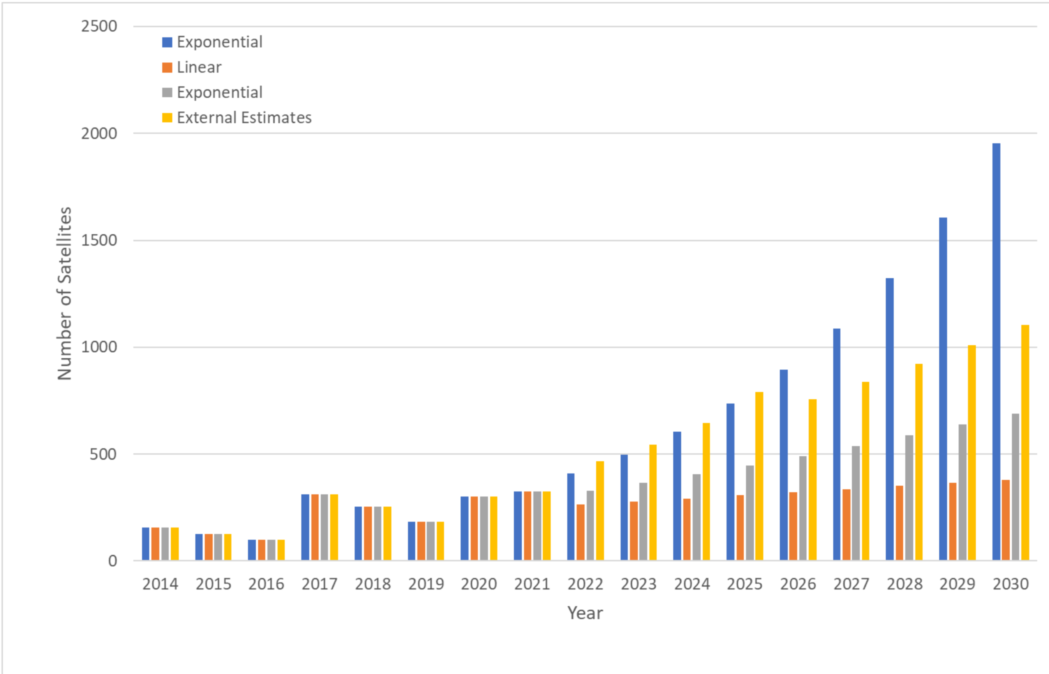

Figure 5.3: Launch Forecasts to 2030

While more customers are looking to launch satellites, new customers are looking to clear the orbital highways satellites operate in. Ironically, the mega-constellations some customers are proposing require even more satellites with some operating as space tugs used to pull orbital debris back to Earth. Currently, there are more than 20,000 pieces of orbital debris the size of a softball or larger being tracked with millions more that are smaller[19]. Unlike on Earth where traditional impacts leave controlled impact zones, on-orbit impacts lead to a cascade of dangerous particles that can snowball into worse and worse events. There is a growing trend aimed at solving this debris issue with several companies proposing ideas on how to clean up space.

Lastly, the rapidly decreasing cost of getting to orbit has emerged as another major trend in the space industry. More than 35 public projects are working towards small satellite launchers all aimed at decreasing the cost of space access[1]. With NASA’s Space Shuttle, it cost nearly $54,500 per kilogram to get a satellite into space[20]. With new rideshare programs, Rocket Lab has been able to drop that cost down to $25,000 per kilogram and SpaceX dropping it a full order of magnitude to only $2,700 per kilogram[20], [21]. New companies are developing rockets to lower that another order of magnitude making space highly affordable. With this newfound affordability and the desire to increase the number of satellites in orbit, there is an immediate need for new satellite components.

5.3 Market Growth

Although new, the current small satellite market is rapidly growing with a 16.4% Compound Annual Growth Rate (CAGR). This means the industry is expected to be worth $13.7B in less than 10 years with more than 9,000 CubeSats being launched in the next decade[16]. Most of these satellites, as stated previously, would operate in a constellation style with some swarms measuring in the 10s of thousands. The uses of these satellites are expected to change rapidly as well, with communication satellites making up nearly 1/5th of all small satellites by 2024[1]. This rapid change from only 7% currently is another testament to planned swarms and market growth. Another quantifiable metric for communication satellites is the amount of broadband capacity passing through the satellites. Currently, only about a terabyte of data is passed through all small satellites. In the next 3 years, this number is expected to triple and reach 3TB of data representing a CAGR of 29%[22].

It should be noted that while communications and scientific payloads will increase in the next few years, RS and technology development must decrease. This is not to say that these fields will become less lucrative by any means. With a CAGR of nearly 50%, the satellite imagery market will hit nearly $8.8B in 2030[22]. The US represents the largest player in this market as they are the most interested in the monitoring of agricultural fields, detection of climatic changes, disaster mitigation, meteorology, and several other resources. Since the US is the single largest purchaser of these images, most companies US-based and international consider the US government a stable long-term customer.

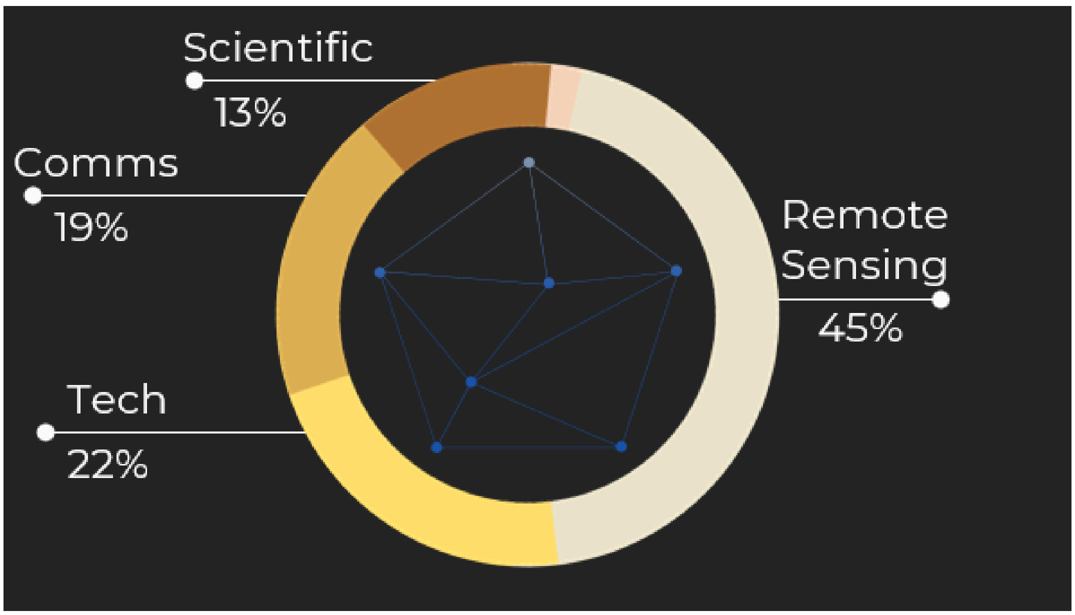

Figure 5.4: Projected Small Satellite Use by 2024[2]

6 Competitive Analysis

6.1 Current Competition

As mentioned in Market Research, in the US alone there are about 50 small satellite companies currently operational. These major players include behemoths like L3 Harris, Lockheed Martin, Northrop Grumman, Planet Labs, Sierra Nevada Corporation, Thales, Tyvak Nano Satellites, York Space, and Pumpkin Space. While not an exhaustive list these 50 companies only a few focus on direct-to-consumer solutions with only one operating in a COTS spectrum. If the lens is expanded outside of the US, the number of companies grow very quickly. These include major players like Clyde Space, Endurosat, Gomm Space, CubeSpace, and Innovative Solutions in Space (ISIS). In the United States, three companies can be considered major component providers. York Space, Tyvak Nanosatellite Systems, and Pumpkin Space. From a global perspective, Endurosat, CubeSpace, and Clyde Space will be analyzed.

6.1.1 US Based Companies

6.1.1.1 Tyvak Nano-Satellite Systems

Tyvak (based in Irvine, CA) is a wholly-owned subsidiary of Terran Orbital and was founded in 2011 by the co-inventor of the CubeSat design Jordi Puig-Suari[23]. In 2012, they unveiled the Intrepid Platform which was the most compact and low-power avionics suite for 0.5U to 3U satellites. They continued to iterate on designs focusing solely on avionics systems until about 2017[24]. At this point, Tyvak moved away from offering a COTS solution to components and instead shifted toward custom fully built satellites for individual customers. As of 2020, Tyvak has launched nearly 220 satellites and has about $53.1M of annual revenue[25], [26]. Currently, Tyvak offers three fully built solutions that feature an allowable payload volume further cementing their move away from the COTS solution. They have shifted their main strategy away from offering individual components to solely offering a completed satellite.

6.1.1.2 York Space Systems

Founded in 2014 York Space Systems is a company based in Denver, CO to improve spacecraft affordability and reliability[27]. Unlike Tyvak, York has never focused solely on components and instead dedicated itself to payload platforms for its customers. Their S-Class platform is a “proprietary design” meant to reduce the cost of space access by “orders of magnitude.[28]" York currently employs about 61 people and has had a yearly revenue of about $5M[29]. They have also partnered with other major corporations like Lockheed Martin to produce a new larger satellite platform meant to fill a hole in the market. By York's admission, they need to expand their production facilities to achieve the "high-rate production" needed to meet "the demand that we're seeing in both the commercial and government markets now." Their overall goal is to bring down the overall time frame from three months to 30 days[30].

6.1.1.3 Pumpkin Space

While the other competition tends to be younger, Pumpkin Space Systems was founded in 1995 in San Francisco to make COTS components for a variety of customers and enable them to succeed in their missions[31]. Unlike the previously discussed companies, Pumpkin does not offer a satellite bus instead they offer components and even sell completed kits. While these systems do lead to a "some assembly required" philosophy, they also allow for a more unique and modular approach to mission design. Pumpkin offers a variety of components including, Power, GNSS Communications, Solar Panels, Structures, and CD&H systems. To date, Pumpkin has turned a yearly revenue of just under $5M with about 50 employees[32]. It should be noted that finding financial information on Pumpkin is difficult with most numbers being estimates. The key difference in providing components and not busses makes Pumpkin one of the very few if not the only company in the US that offers a wide variety of COTS components. There were only 2-3 other companies that offered singular systems such as Blue Canyon Technologies (Avionics). This means that when it comes to COTS components in the US, Pumpkin has a form of a monopoly on the industry and can set the price of its components. Often these prices are much higher than their global competitors. Pumpkin gets away with this increase as they get to avoid import tariffs and international shipping delays. This means that a massively growing market has very few domestic players and is ripe for disruption.

6.1.2 International Companies

6.1.2.1 Endurosat

Endurosat is a small company based in Sofia Bulgaria founded in 2015 by Raycho Raychev[33]. This startup has quickly moved to capitalize on the growing need for small satellite components and currently provides more than 35 products and offers custom-built modules[34]. The company prides itself on providing COTS components that can be easily and modularly integrated into other satellite components or buses. It is estimated that Endurosat has raised between $12.2M and $13M in funding with $11M of that happening in August of 2021[35], [36]. This funding comes from the European Investment Bank (EIB), which acts as the long-term lending institution of the EU. This financing falls under the venture debt financing category and will be backed by European Guarantee Fund (EGF). It is estimated that Enudrosat earns about $1.2M in profit annually and uses that to pay its 50-70 employees and fund its R&D operations[33]. There are two main areas where Endurosat does fall short in comparison to the companies based in the US. The first is an obvious one with Endurosat being based in Europe and as a result, must deal with the tariffs and import duties is a huge counterpoint. Secondly, Endurosat does not currently offer an ADCS system and has no public plans to do so.

6.1.2.2 CubeSpace

Information on CubeSpace is difficult to find as it is a newer company based in South Africa, though plenty of information can be garnered through its online presence alone. CubeSpace almost exclusively focuses on ADCS components and flew its first system in 2014. To date, they have launched more than 80 missions and have over 120 ADCS systems in orbit[37]. They provide components meant to orient and adjust the satellite on orbit and as a result, they offer individually purchasable ADCS components as well. This has led to them delivering more than 400 reaction wheels since their inception with plans to introduce their next generation of control systems in 2023. CubeSpace prides itself on rapid learning and modification meant to allow for quick iteration of components. They work hands-on with customers and provide a solution as customized or not as the customer needs. Their entire goal is to be able to work with any other companies' components and let their customer not worry about integration challenges. Finding any financial information is difficult, but it is known how much CubeSpace approximately charges for its components. While most American companies are charging nearly six figures or more for a complete ADCS solution, CubeSpace has a fully built system for about $28,000[37]. This massive price drop provides a tantalizing product for anyone looking for a full ADCS system along with the option to customize the hardware. While the US-based company would eventually compete with CubeSpace, providing an ADCS solution for customers may not immediately be available. Instead, a company could partner with CubeSpace and provide their solutions in the US as an authorized reseller. This would allow CubeSpace to provide components to US customers without having to deal with tariffs and import fees. At the same time, the US company, could offer a small upcharge to handle those tariffs and take the load off of customers.

6.1.2.3 Clyde Space

Clyde Space is an older company than the other two discussed above as it was founded in 2005 in Glasgow Scotland. By 2017, Clyde Space had supported between 30%-40% of all current and past CubeSat missions and solidified its role as a market leader[38]. In 2017, Clyde Space sold 100% of its shares to AAC Microtec in a nearly $35M deal. Since then AAC Clyde

Space has continued to be a dominant player in the market with nearly $7.3M in sales in 2020[39]. These sales come from Clyde Space offering a full suite of COTS components that range from ADCS, Batteries, Communications, Solar, and ADCS Systems. While Endurosat and CubeSpace offer unique but specific components to their customers, Clyde Space offers nearly everything one would need to build and assemble a satellite. The publicly-traded company also has an easy way to raise money by selling its shares to other investors and having the general public behind them in support. Of the international companies, Clyde Space represents the biggest threat to US-based companies as they offer nearly everything that a US business would. Their components are competitively priced and with the full satellite suite they offer, customers can design a satellite with ease. The biggest advantage a US company has over Clyde is once again, its location. This avoids long ship times and import fees which are often passed onto the customer. By not having those fees, it could undercut the prices Clyde offers and help fill the supply for the growing demand.

6.1.3 Future Competition

After reviewing the current competition that a US Company would go up against, it is important to identify any possible future competitors that might rise to fill in the lack of supply. There are undoubtedly many startups focusing on various parts of the cube satellite infrastructure. One such startup is Plutonics Technologies.

Plutonic is a new startup that prioritizes modular designs meant to dock to a Reusable Satellite Bus (RSB) that is already in orbit. This would allow customers to forgo the cost of developing a full satellite and would only require them to design a payload that can integrate into the RSB[40]. Once the payload is launched into the correct orbit, the RSB would move to attach to the payload and being mission operations. Once the payload has served its purpose and the mission is at its end, the payload is jettisoned while the RSB stays in orbit waiting for the next payload. The idea has many merits and addresses a major orbit debris concern with small satellites. At the same time, many logistics issues would need to be worked out beforehand. The most obvious of which is the docking maneuver and mechanism of the satellite. This is a difficult maneuver for large satellites and could be even trickier with smaller targets such as CubeSats. At a high level, Plutonics does not directly compete with other satellite manufacturers as it seeks to provide a service rather than a product.

Another potential competitor in the US arrives in the form of Analytical Space. This startup once again seeks to provide a service rather than a product but offers a compelling argument, nonetheless. Analytical Space focuses on the development of fast-acting data relay networks with continuous low-latency links to the ground[41]. Using this network would help monitor global food and water scarcity, climate change, and even geopolitical tensions. Recently, Analytical space won a $26.4M contract to build out an optical network on a CubeSat swarm[42]. As with Plutonics, Analytical Space presents another opportunity for a COTS company to help provide components for their satellite network.

7 Business Plan

Based on the research outlined in previous sections, the small satellite industry is ripe for disruption. The following section will outline a potential path for a small satellite company to follow to become a successful player in the small satellite field. Section 7.1 outlines the executive summary and can be seen as the abstract of the entire business plan. While the Executive Summary gives a general overview, more in-depth details follow in later sections.

7.1 Executive Summary

7.1.1 Mission Statement

A mission statement outlines the guiding principles for a company to follow as it grows and provides products. As outlined in Section 5, the biggest area lacking competition is the Commercial-Off-The-Shelf (COTS) component market. As a result, a successful company would do its best and focus attention in this vacuum. For the remainder of this Section, the following mission statement will be the guiding goal.

To provide quality space-rated COTS solutions for use in the small satellite sector.

7.1.2 Product

A company would manufacture small satellite components for commercial and academic customers looking to deploy their solutions to space. All components would be manufactured using aerospace-grade hardware and fully meet all regulatory requirements. The components available include both hardware and software meant for easy modular assembly and rapid development.

7.1.3 Objectives

The recommended objectives would include the following:

- Provide quality space rated commercial-off-the-shelf (COTS) products for the small satellite industry
- Provide modular hardware and software solutions meant to easily interact with industry components
- Execute Objectives 1 and 2 while based in the United States

- Operate under a vertically integrated methodology to not only iterate but scale production as needed
- Become a domestic-based resale partner for international companies

7.1.4 Customers

The target customers for such a company can be separated into two categories: Educational and Commercial. On the Educational side, the company will operate in tandem with universities and schools to provide components and platforms for research projects. By using the education industry as a platform, it can test and qualify its hardware in a low-cost environment while also supporting new payloads. This also provides an opportunity for the business to recruit new employees and develop new offerings for other customers. On the Commercial side, it would provide modular platforms and solutions for private customers with an emphasis on swarm and constellation flight. It should be noted that at its inception the primary focus of customers should be US-based, due to a lack of competition in the US.

7.1.5 Viability

As stated in Competitive Analysis, in the US alone there are less than 50 companies currently developing products for satellites, with only three companies in the US market competing with the general objectives outlined above[15]. Of those three companies, only one, Pumpkin Space, offers a COTS philosophy effectively creating a US-based monopoly. As a result, Pumpkin can set the prices for nearly all its products as there are no real competitors here in the US. For the CubeSats that do not use Pumpkin hardware, they are forced to rely on foreign components which come with transport risks and import tariffs often raising the cost dramatically. This has led to an obvious gap in the market that has yet to be exploited.

7.1.6 Future of the Company

While the small satellite industry represents a small portion of the global space sector, it is quickly growing with a 67% growth in small satellites launched in 2020 compared to 2019[1]. It is expected that small satellite constellations will soon outnumber traditional satellites in orbit while taking more of the communications workload in Low Earth Orbit. The small satellite market is expected to grow to $13.7B by 2030 with a CAGR of 16.4%[16]. Moreover, the number of small satellites is expected to be launched in the next ten years sitting just below 10,000. Eventually, a company should aim to be a major player in the small satellite field with potential expansion into beyond Earth orbit applications. Moreover, strategic placement in the Midwest would allow for an expansive amount of growth due to the lack of immediate co-located competitors and business-friendly regulations. Combined with direct access to many academic institutions in the area, there is significant growth potential.

7.2 Products and Services

7.2.1 Products and Phasing Structure

A company should provide a variety of products aimed at the small satellite sector. Naturally, at first, the range of available products will be small, but as it grows with the market so too will the products. In order of availability, the expected products and their introduction phases are listed in Table 7.1. It is important to note that the designated phase's corelate to the start of design not the start of sale.

Table 7.1: Suggested Products and Introduction Phases

Component	Subsection	Phase
Structural Frame		

	1U	1
	2U	1
	3U	1
	6U	1
	12U	3
EPS		1
Battery Module		
	30 Whr	1
	40 Whr	1
	80 Whr	3
Radio Module		
	S	2
	UHF	2
	X	3
	GNSS	3
Antennas		
	S	2
	UHF	2
	X	3
	GNSS	3
CD&H		
	Without GNSS	4
	With GNSS	5

ADCS		
	Base	
	One Reaction Wheel	5
	3 Axis Reaction Wheels	

7.2.2 Product Lifecycle

A company should be vertically integrated, initially focusing on backward vertical integration. This focuses on the components and material suppliers first while placing the operation and end-user in the hands of its customers. The lifecycle of a component starts at the material stage where materials are processed and manufactured into subcomponents. Once the subcomponents are ready, they are assembled into the final component and shipped to the customer. At this point, the customer integrates the components and proceeds to launch the satellite into orbit. Furthermore, the product can have a variety of end-of-life sequences with most ending in the product burning up on orbital reentry.

7.2.3 Research and Development

As the space industry can be difficult to develop, it is recommended a company implement a tiered strategy when it comes to RD. The products offered will move from the easiest manufacturing to the hardest. This means the first products recommended for construction include frames, EPS systems, and Batteries. Once a solid foundation has been built on those systems, R&D will begin developing the other systems listed in the order they appear. It should be noted that there is some level of general R&D that will go into all systems with a few outlined below:

- Since CubeSats are standardized, their general shape is fixed, but their loads tend to vary based on the launch vehicle. Using a genetic algorithm to find an optimal shape for CubeSat frames would allow for a tailored result.
- While S and X band antennas are typically patch antennas, UHF antennas are dipoles that are deployed from one end of the satellite. Any deployable system represents an inherent risk for any satellite as failure to deploy could jeopardize the mission. R&D will look into the design of a body-mounted UHF antenna.
- A recommended component for any COTS company to pursue is a high-energy particle detector. This system will monitor on-orbit particles and interact with the system's EPS to shut down the satellite in case of damaging particles.

As with any company, there is a significant amount of R&D that needs to be done and these represent a small amount of what can be explored.

7.3 Marketing & Sales

7.3.1 Brand

As with any company, a brand will need to be developed to sell its products and grow its business. To define the brand for a company, inspiration is often drawn from a variety of sources including competitors, modern industry, history, and mythology. The brand of a company is crucial as it defines how the customers see the business, which in turn reflects on sales. As a result, brand clarity is often derived from the inside out. Once again, the focus of the recommended company is to provide high-quality COTS components to the aerospace community while operating under a vertically integrated business. To highlight these traits, the brand should emphasize a modern and sleek aesthetic that highlights a simple experience with cutting-edge equipment. To further drive home this intent the predominant colors for a company were chosen based on decades of research in color theory. The color theory states that colors can elicit an emotional response in the viewer, who in turn often attributes that emotion to the item they are looking at[43]. Most companies rely on a three-way scheme for their brand split between the base, accent, and neutral color[44]. The base color represents the brand trait most important to the core of the company and, in this case, a dark blue which symbolizes professionalism and trust is used[45]. The accent color is used as the second most important trait and must compliment the base color. For the accent color, white evokes simplicity and modern design. Finally, the neutral color is a dark grey which itself represents neutrality and a mature sense of stability[46]. These three colors can be seen below.

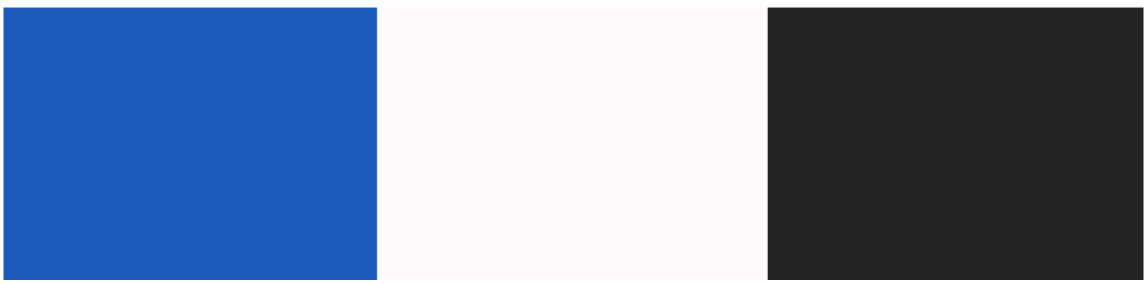

Figure 7.1: Suggested Company Colors

7.3.2 Differentiation

Any company needs to differentiate itself from its competitors. Based on the literature review, it is recommended a company differentiates itself in three key areas.

1. Location
2. COTS components
3. Vertical Integration

Each area stacks on the following area to build out a unique company that should have little to no difficulty in carving out its section of the market. The first area of differentiation, location, is a key factor in company development. As was discussed in Section 5, the biggest competition is located outside of the United States and as a result, customers of those companies must pay import duties, deal with international shipping, and in the case of legal disputes potentially international law. Placing a company in the US can help alleviate those issues for US consumers. As a result, it can offer lower prices than its international competitors as those tariffs are often baked into the purchase price. Moreover, placing a company in the Kansas City Residential area provides with it a strategic benefit as well. The next closest satellite component provider is in Denver and most are based in California. This means that by establishing a company in KC, there are no immediate competitors in the area allowing a company to truly stand out. In turn, surrounding universities can become partners as a way to develop new components and thus lower R&D costs. There are many more factors to the general benefits to KC and just a few are listed below.

- Low overhead[47], [48]
  - The average office space cost is $19.94 per sq ft
  - Compared to $42.41 per sq ft in LA
- Sense of collaboration[49]
  - Heavy tech industries tend to have a cutthroat business philosophy
  - This leads to job jumping employees and a less motivated workforce
- The highest average internet speeds in the country[50]
  - As of 2018, KC clocked in at 159 and 127 Mbps for download and upload respectively
- Venture capitalist influx[51]
  - In 2019, more than $900M worth of venture funds were invested in the city, up nearly 90% from the prior year.

  - The average venture-backed firm raised $17.46M in 2019
- Growing tech force[51]
  - Kansas City witnessed the 6th largest growth rate for North American tech talent over the last five years
  - Kansas City experienced more tech job growth than Los Angeles, Boston, New York, Dallas, Philadelphia, and Washington D.C. between 2012-2017

The second point of differentiation pulls on the gap left in the current market with the ability to produce COTS components. Since Pumpkin Space is currently the only COTS component provider in the US, they get to control the US market and set their price. By also producing COTS components in the US, a company can become the only competitor to Pumpkin and thus be an easy stand-out in the field.

The third point of differentiation is not something that will be immediately implemented but rather a guiding philosophy that will be integrated over time. More research is showing that a vertically integrated company can reduce several key costs when compared to a standard company. Vertical integration refers to a firm bringing additional elements of the industry value chain under common ownership[52]. There are different types of integration and more will be discussed in Operations. The general benefits of vertical integration are listed below.

- Enable Economies of Scale
- Improve Quality Control
- Increase Market Power
- Eliminate supplier risk
- Lower transaction cost

The COVID 19 Pandemic highlighted how fragile the global trade ecosystem is by bringing many industries to a screeching halt. By vertically integrating, a company would be able to hedge against massive transport issues while at the same time improving its quality control. As stated by Space Works, "*With the rise of the small satellite sector has come to an industry-wide shift towards disaggregated, constellation architectures with the name of the game now being efficient manufacturing*.[52]" This means organizations now think in weeks or months not years and decades as some seek to launch as many as 50 satellites a year. Moreover, ongoing tension between suppliers and OEMs in the aerospace sector has resulted in the need to prioritize other metrics over the cost of a component[53].

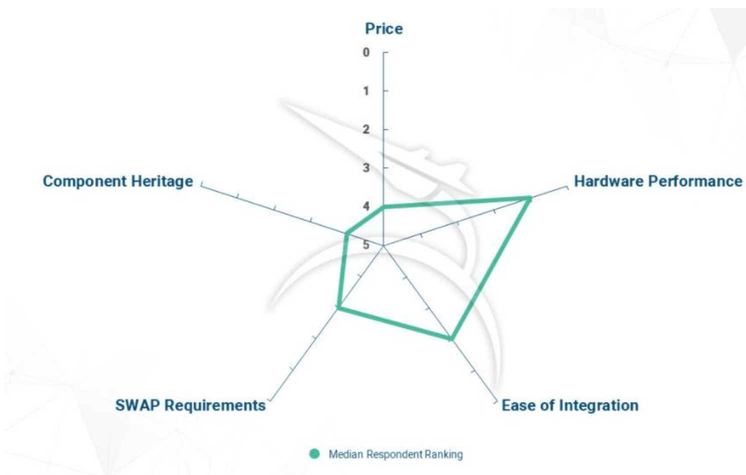

Figure 7.2: Factors Considered when Purchasing Hardware Components[53]

It comes as no surprise that traditional component suppliers are better equipped to scale the production process but cannot rapidly iterate. The opposite also holds for a standardly integrated startup, where they can iterate rapidly, they cannot scale products due to a lack of control in their supply chain[52].

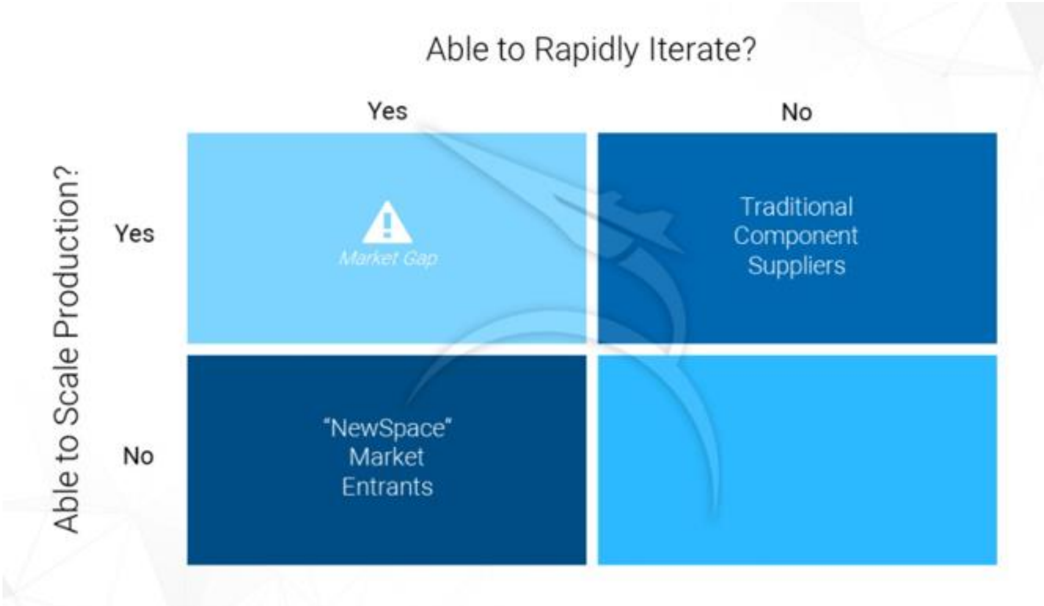

Figure 7.3: SmallSat Component Market Gap[53]

By integrating vertically over time, a company could differentiate itself by being to scale production, while iterating rapidly. This will allow for greater control over the entire lineup of components and in the end, provide a higher quality product in the end.

7.3.3 Growth Strategy

To grow a company, one could do the following:

- Create relationships with universities and sell to them directly
  - Ideally aiming at universities that are part of the NASA CubeSat Launch Initiative (CSLI). This allows a company to create its flight-proven hardware with minimal launch costs while at the same time acting as R&D
  - This will also double as a method to hire new talent
- At the same time, it should establish relationships with international competitors and act as a regional distribution center for them

- It is recommended the company follow the outline listed in Products and Services as these are ordered from difficulty to the engineer from least to most
    - Starting with a frame presents a simpler challenge and allows the company to achieve an economy of scale accordingly
    - Once a component has achieved the flight heritage, the next component will begin development
        - This does not mean only one component will be developed at a time
- As the business grows, advertise in target markets, especially in areas where other competitors are already active
    - This includes all sectors minus defense
    - With this growth, it is recommended a company begin to vertically integrate by slowly moving to build more components in-house.
- Once a company can support half of the proposed products consistently, it will begin to expand to defense contracts and European customers.
- Eventually, the company should begin offering components built alongside its international partners
    - This marks a shift from being a regional reseller to being a joint venture between two companies
- Once a company can support nearly all its proposed products it will expand its vertical integration further backward in the supply chain and exercise greater control over its products
    - At the same time, a shift to support all international customers is recommended

- Having filled out most of the general-purpose product line, a company can begin exploring unique concepts to continue to differentiate itself from its competitors
    - This could include modular satellite architecture that builds off one another in orbit
    - Expanding forward and offering more services post-launch
    - Propulsive components
    - Deep space contracts

This growth outline is not set in stone and should naturally evolve with the environment that a company develops in.

7.3.4 Communicate with the Customer

As with most businesses in the digital age, communication with the customer through digital media is the expected norm. There are many ways to effectively communicate with customers and grow a company's base and a few recommendations are listed below.

- Providing an email newsletter with company news, product information, and production schedule.
- Using targeted Google and Facebook advertisements.
- Utilizing social media such as Twitter, YouTube, Instagram, and LinkedIn,
- Providing contact information on the company website.
- Eventually providing an app meant for placing and following orders

7.4 Operations

7.4.1 Facilities, Equipment, and Supplies

Any company will need space, equipment, supplies, and other operational items to reach its potential. The following section outlines these components and provides recommendations for a company to follow based on the guiding Mission Statement.

7.4.1.1 Facilities

In the table below, the expected facilities that are used to manufacture components are categorized by phases. These are the business phases of the company and are designed around the tiered approach to providing components to clients. In Phase 1, the company is producing the frames and electrical components like the batteries and EPS. It should be noted that during Phase 1, a company could begin research and design into Phase 2 components with the general understanding those components will begin extensive testing after Phase 1 is complete. As with any company, a small satellite startup will need a general base of operations. For the sake of this report, the company will be based in the Kansas City Missouri/ Kansas metropolitan area. After looking at a variety of offices spaces available, the Aspiria office location was selected which has a yearly square footage cost of about $12.75[54]. Aspiria offers the flexibility of various divisible floor plans and has options as small as 5,000 square feet and some as large as 50,000. Based on the facility needs and equipment outlined below, approximately 7,500 square feet will be needed in Phase one. As the company expands, the office space used can expand as well, filling in upwards of 50,000 square feet. In Table 7.2: Recommended Facilities and Cost, the cost of the facilities and the respective phases can be seen.

Table 7.2: Recommended Facilities and Cost

Equipment	**Amount**	**Cost ($)**	**Phase**

Office Building	1	$95,625/year	1
Clean Room	1	~$18,550.00[55]	2
Anechoic Chamber	1	~$500k[56]	3

7.4.1.2 Equipment

As can be expected the type of equipment needed will differ as a business grows and expands its portfolio of offerings. The equipment needed is also driven by any required testing for that component. This testing can ensure flight worthiness before delivery to a client and is based on the strict NASA GEVS: GSFC-STD-7000A standard[11]. These tests include Thermal Cycling, Thermal Vacuum, Sinusoidal Vibration, Random Vibration, Pyroshock, and Physical Properties Test. The following list of components has been identified as vital to production. Note that all equipment listed follows a similar phased approach as the facilities table.

Table 7.3: Recommended Equipment and Cost

Equipment	Amount	Cost ($) per Unit	Phase
4 Axis CNC	2[57]	20,000	1,3
Drill Press	2	110	1,6
Shake Table	1(Quote)	15,000	1
Vacuum Chamber	1	2,000	2
Vacuum Pump	1 [58]	4,923	2
Clean Flow Enclosures	2[59]	4,000	1,3
Thermal Cycle Oven	1 (Quote)	5,700	1,4
Laser Cutter (Quote)	1	4,000	2
Solder Reflow Oven	1	500	1,4

Soldering Robot[60]	1	11,875	2,4
Soldering Irons	6	150	1,6
Multimeter	6	50	1,5
Oscilloscope	2	759	1.6
Network Analyzer [61]	2	8,390	1,6
Power Supplies	2	70	1,5
Air Bearing	1	3,000	5,6
Helmholtz Cage	1	5,000	5

7.4.1.3 Supplies

Once the components have been procured, the needed supplies can be bought. The supplies category covers items that are more easily replaced and are needed to complete work, not so much needed to manufacture components. Unlike the other sections, the supplies do not have a business phase designation as they are needed immediately and are not as dependent on the manufactured components. The list of base supplies is shown in Table 7.4.

Table 7.4: Recommended Supplies and Cost

Equipment	Amount	Cost ($) per Unit
Desks	10	800
Chairs	15	275
Worktables	5	300
Clean Suits	25	50
Computers	10	849

Monitors	20	249
Electronics Hardware Tool Set	5	50
Calipers	4	50
Shipping Containers	~	
Misc Tools	~	
Raw Metal	~	
Nuts and Bolts	~	
PCB	~	
FR4	~	

7.4.1.4 Software Licenses

One of the often-overlooked aspects of an engineering-focused company is the various software licenses that are needed to develop the desired product. Software licenses typically act as a legal instrument governing the use of some software. In the US, that, in turn, translates to a copyrighted system in both source code and object code. For most engineering-focused companies these licenses can be expensive and are usually one of the largest portions of the budget. In Table 7.5, the appropriate licenses, amount, cost, and phase are listed. It is important to note that some software is acquired in a limited number at the start to avoid overspending and allow the budget to be allocated in other places. Once the company has grown and has substantial income, the number of licenses will be increased.

Table 7.5: Required Software Licenses and Cost

Software	**Number of Licenses**	**Cost ($) per Unit**	**Phase**

Ansys Mechanical[62]	2	30,000	1,5
Siemens NX[63]	2	6,000	1,4
MATLAB[64]	5	2,200	1,5
Ansys EMAG[62]	2	29,000	2,4
Ansys Mechanical	2	30,000	2,6
Altium[65]	2	3,850	1,4
ADS	2	6,000	1,4
Ansys EMAG[62]	2	29,000	3
Altium	2	3,850	3,5
Siemens NX[63]	4	6,000	3,6
ADS	2	6,000	5

7.4.2 Organization Structure

A small satellite startup should follow a decentralized organizational structure with an emphasis on team-based organization. This means that the company is organized by sets of teams that will ideally focus on the specific subsystem tasks, this includes groups such as structures, electrical, communications, and so forth. Moreover, the decentralized organization will empower teams to make their own decisions and arrive at the best results without always needing approval from "up top[66]." The obvious benefit of this setup is rapid iteration with a focus on scalable growth. As mentioned in Differentiation, this will allow a business to target a specific gap in the satellite manufacturing market. While there are still built-in hierarchies with positions like Chief Executive Officer (CEO) and Chief Technology Officer (CTO), the decentralized structure allows employees to be self-sufficient while enabling newer members to learn management skills in a less critical environment. A comparison of centralized vs decentralized structure can be seen in Figure 7.4[67].

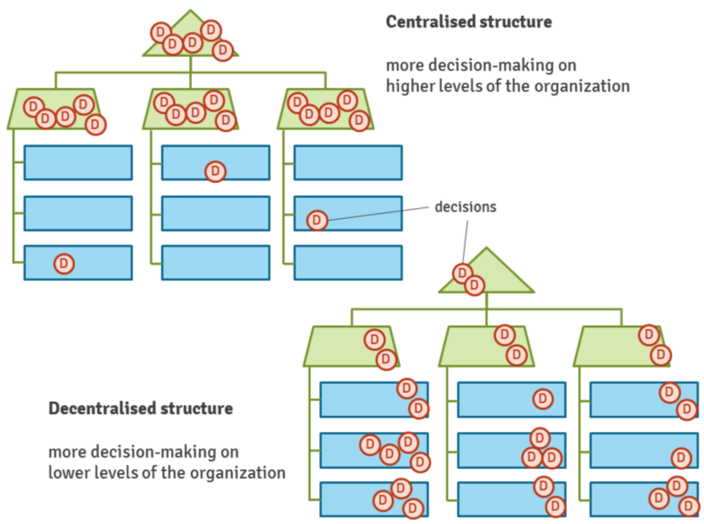

Figure 7.4: Centralized vs Decentralized Company Structure[67]

While the overall organization will be focused on decentralized teams, the entire company will be focused on vertical integration. As stated earlier, vertical integration refers to a firm bringing additional elements of the industry value chain under common ownership. Currently, there are two forms of vertical integration, Backward and Forward. While backward focuses on moving away from the end-user and closer to the raw material, forward moves in the opposite direction. Initially, it is recommended a business integrate backward and exercise greater control over its supply chain to avoid the massive supply chain issues that have been plaguing the world. As stated earlier, this is not the case at inception, but a change that is recommended for general implementation over time as a business grows.

Research has shown that the average per-unit cost (APUC) for a vertically integrated satellite company is initially high, reflecting the upfront costs associated with the building of new facilities, processes, etc[53]. As the company grows and achieves economies of scale, the APUC drops significantly and at a faster rate than traditional manufacturing. The break-even point is around 88 operation 3U satellites. While this number is high it pales in comparison to a standard CubeSat constellation of 150+ satellites. This break-even point for a larger, 300 kg, the satellite is only around 49 satellites[52], [53].

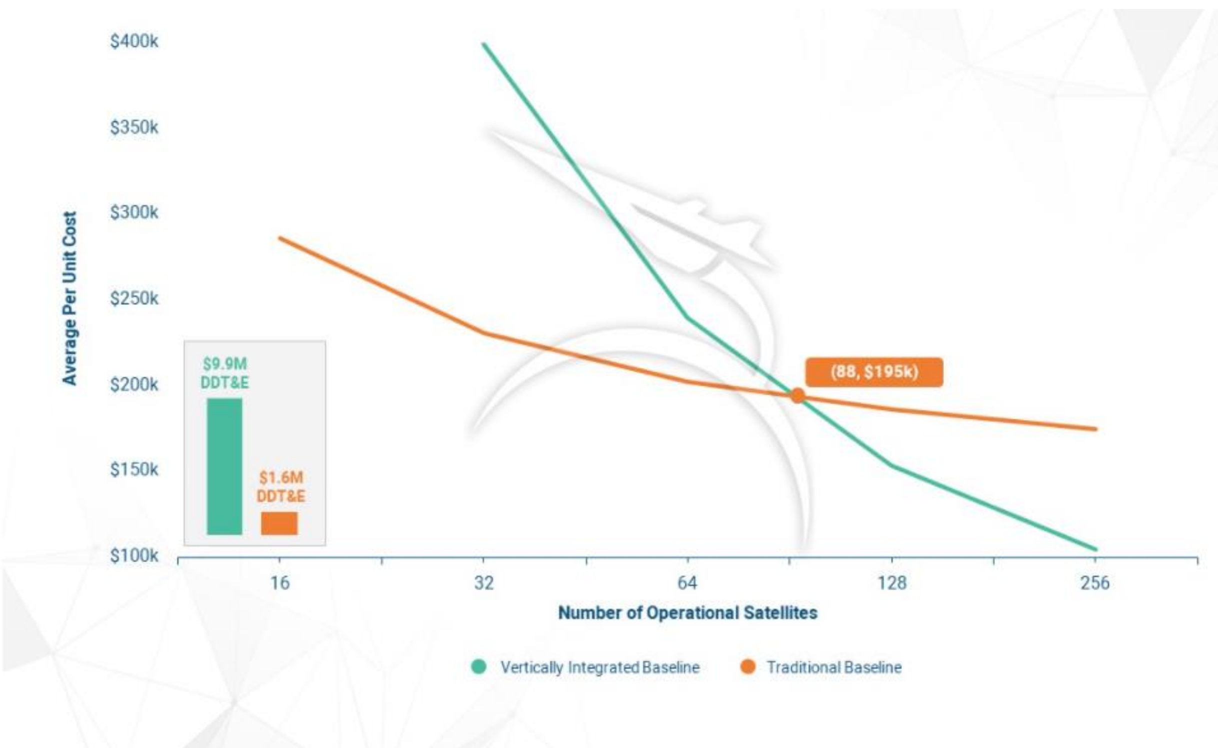

Figure 7.5: Average Per Unit Cost Comparison

Ideally, a business will be able to remove unneeded nodes in the supply chain by vertically integrating while simultaneously enabling faster design cycles and quality improvements. Spaceworks has found that "*If manufacturers can improve upon satellite* *reliability by adopting a vertically integrated approach, there could be substantial cost savings*.[52]"

7.4.3 Establish business relationships

To start any business, several business relationships need to be forged that help fulfill the overall goal of the product. As mentioned in previous sections, a company needs to start by developing relationships with universities as they provide a unique opportunity to get qualified flight heritage. As an example, The University of Kansas can be approached to be an immediate business partner. The fledgling Small Satellite Initiative (SSI) at KU could allow a company to work with students to place their payloads into space while at the same time developing its products. Keeping with the above example, a business could begin to approach other universities in Kansas and forge new relationships at the same time. Coupled with the built-out infrastructure at KU, this would give other schools a low-cost entry into the CubeSat world. Simultaneously, the company would benefit from general income and reduced R&D costs. Eventually reaching out to other states who have not yet competed in NASA's CubeSat Launch Initiative (CSLI) to follow a similar process as Kansas.

During the above scenario, a startup should aim to work with international component supplies to set up a US-based reseller of their components. These offerings would be sold to the customer at a slight markup, but with the added benefit of avoiding import costs and shipping issues. Eventually, the co-development of more complex components with international partners will reduce the inherent risk of complicated components and unique parts.

When it comes to manufacturing relationships, it is recommended to build those out as a company gains more experience in the industry and understands supply chains in a greater capacity. Ideally, a relationship with raw material suppliers would also be built out as the company transitions to vertical integration.

7.4.4 Potential Change as the Company Grows

As with any company, none of the mentioned details are set in stone. As the company takes shape and grows, the offered products and focus of the company could change. One way a company could change is the slew of products offered and how they are offered. Dependent on regulations and demand, the second set of components offered may not be a communication devise as this involves the FCC and other regulatory bodies.

Another major potential change is the vertically integrated aspect. As stated before, the cost of setup and per-unit cost of a vertically integrated company is higher than a traditional company. This could force a company to abandon the idea for a given time until a stronger business has been built up. Once that occurs, a company could shift again to embrace the vertically integrated business.

As of right now, it is not recommended to create a company outside of the Midwest, but as the company grows, it may become more profitable to shift manufacturing to another location. This is entirely dependent on tax breaks, cost reductions, and customer demand. Many other companies place themselves at the heart of the space industry at the cost of high operation costs. As a result, moving the company to another location would only result in increased profits without lowering quality.

Lastly, another potential change currently being considered is the order of company stages. It is recommended a business begin the development of its structure and other components first. As the company grows it will then offer international components as a reseller. This may happen first as it could be seen as an easier entry into the market while providing a lower entry cost while allowing the business to generate capital without a huge upfront investment. This is still being researched and could change the scope of the business plan.

7.5 Management

7.5.1 Key Leaders

While it is stated in Section 0 that a company focuses on a decentralized organization structure, it will still have key leaders that help spearhead the charge into new technology and territory. These positions are often difficult and require a special set of skills and determination needed to ensure the company is successful. The following lists these roles and their descriptions.

Table 7.6: Key Leader Descriptions

Position	Description
Chief Executive Officer	The CEO's role is responsible for making top-level decisions that include gathering resources and providing support for the company. This role often drives operation and structural changes that influence the overall growth of the company. This role has the final say in the company.
Chief Operating Officer	The COO's role focuses on managing the daily operations of the company and ensuring processes run efficiently. Oftentimes overseeing the various departments to ensure employees are completing their work on time.
Chief Financial Officer	This position is responsible for the cash flow and financial success of a business. They focus on finding funding and external investors meant to grow the business.

Chief Technology Officer	The CTO manages all technology functions of the company and focuses on integrating new tech trends into the company portfolio. This role often leads the R&D division.
Chief Marketing Officer	The CMO role directs the marketing campaigns and plans budgets while overseeing the marketing department of the company. They often make the final calls on marketing projects.

At the inception of any company and into its first few years of work, some of these roles may be co-occupied by one person as many people will need to hold many jobs. As a business grows into new phases and markets, these roles will be diversified and filled out by a variety of people.

7.5.2 Positions

Outside of the Key Leaders, there are a variety of positions that need to be fulfilled to ensure the needs of the customers can be met. One important item to note is that these jobs are organized by sub-teams in the company with phases denoted to show when those jobs would be pursued and fulfilled.

Table 7.7: Career Positions

Sub Team	**Job Title**	**Phase**
Hardware		
	Design Engineer	1,4
	Hardware Engineer	1,6
	Manufacturing Engineer	1,6

	Electrical Engineer	1,4
	Communications Engineer	2
	FPGA Design Engineer	3
	Systems Engineer	3,5
	Propulsion Engineer	
	Advanced R&D Engineer	5,6
Software		
	Communications Software Engineer	2,6
	Embedded Serial Engineer	3
	Embedded RTOS Engineer	2,5
	Embedded Software Engineer	3,6
	Javascript Developer	4
	Middleware Software Engineer	4
	Software Engineer	2,5
	UI/UX Developer	3,5
Quality Assurance/Testing		
	AIT Engineer	1
	Hardware QA Engineer	3
	Embedded Systems QA Engineer	4,5
	Software Test Engineer	2,6

Sales		
	Sales Technician	1,5
Support		
	Customer Support Engineer	2,4
Manager		
	Program Manager	4,6

7.5.3 Salary Levels

The positions listed above are also entitled to fair compensation for their time and effort. Extensive research was done to offer competitive salaries to employees. This includes research into competing companies and adjusting the anticipated wage to the Midwest-based cost of living. It is important to note, that the listed salaries offer a range from entry-level to highly experienced professionals. The values were derived by finding industry averages and adding a 2.5% boost to attract talent. Those positions and their salaries are listed below[68].

Table 7.8: Career Salaries

Sub Team	Job Title	Entry	Average	Experienced
Hardware				
	Design Engineer	$ 63,000.00	$ 84,000.00	$ 113,000.00
	Hardware Engineer	$ 71,000.00	$ 95,000.00	$ 128,000.00
	Manufacturing Engineer	$ 65,000.00	$ 84,000.00	$ 108,000.00

	Mechanical Engineer	$ 65,000.00	$ 88,000.00	$ 119,000.00
	Communications Engineer	$ 79,000.00	$ 110,000.00	$ 153,000.00
	Electrical Engineer	$ 68,000.00	$ 92,000.00	$ 122,000.00
	FPGA Design Engineer	$ 76,000.00	$ 108,000.00	$ 153,000.00
	Systems Engineer	$ 71,000.00	$ 98,000.00	$ 134,000.00
	Propulsion Engineer	$ 78,000.00	$ 102,000.00	$ 131,000.00
	Advanced R&D Engineer	$ 55,000.00	$ 93,000.00	$ 160,000.00
Software				
	Communications Software Engineer	$ 69,000.00	$ 93,000.00	$ 126,000.00
	Embedded Serial Engineer	$ 73,000.00	$ 98,000.00	$ 130,000.00
	Embeded RTOS Engineer	$ 73,000.00	$ 98,000.00	$ 130,000.00
	Embeded Software Engineer	$ 73,000.00	$ 98,000.00	$ 130,000.00
	Javascript Developer	$ 56,000.00	$ 94,000.00	$ 158,000.00
	Middleware Software Engineer	$ 76,000.00	$ 112,000.00	$ 162,000.00
	Software Engineer	$ 70,000.00	$ 98,000.00	$ 123,000.00

	UI/UX Developer	$ 63,000.00	$ 88,000.00	$ 125,000.00
Quality Assurance/Testing				
	AIT Engineer	$ 65,000.00	$ 94,000.00	$ 136,000.00
	Hardware QA Engineer	$ 68,000.00	$ 95,000.00	$ 132,000.00
	Hardware Test Engineer	$ 66,000.00	$ 87,000.00	$ 114,000.00
	Embedded Systems QA Engineer	$ 60,000.00	$ 101,000.00	$ 173,000.00
	Software Test Engineer	$ 68,000.00	$ 93,000.00	$ 128,000.00
Sales				
	Sales Technician	$ 22,000.00	$ 37,000.00	$ 66,000.00
Support				
	Customer Support Engineer	$ 59,000.00	$ 85,000.00	$ 125,000.00
Manager				
	Program Manager	$ 91,000.00	$ 132,000.00	$ 190,000.00
Average		$67,167	$95,083	$134,833

7.6 Minimum Initial Capital Investment

After identifying all the equipment, facilities, software, and personnel needed, the minimum investment initial capital investment can be found. This value represents the initial amount of money needed to get the company off the ground based on the product plan and cost outlined above. As stated earlier, it is recommended that a company develop in stages/phases. In Phase One the company focuses on easily manufactured components like the frame and critical components like the power systems. This in turn means that the needed equipment, material, and personnel for frames are less expensive and represent an easier ask to investors. While at the same time, the batteries and power system are something all satellites will need regardless. Having this more complicated system in phase one will in turn yield a higher profit as early on as the frame and the battery can be sold together. This is similar to buying a car with a motor vs just a car frame. Moving to Stage Two has the company focus on more RF-focused devices and thus needs more complicated hardware, whereas Stage Three will offer more differentiated components of products already be offered. The product lines are divided into six stages, with some hardware/personnel getting acquired more than once in different stages. Of these six stages, there are four different scenarios to consider each with varying costs.

Two scenarios involve the use of KU’s Innovation Park (KUIP) which is an independent non-profit economic development organization on KU’s campus. The sole purpose of KUIP is to support innovation and entrepreneurship through the commercialization of new technologies. By working with the university, KUIP leverages the regions strengths and campus’ facilities to help startups get off the ground. This is done through a variety of means but includes, initial market assessment, company formation, talent sourcing, identifying grant opportunities, and more.

Importantly, KUIP does not require or accept equity in any of the companies they support. Moreover, they do not directly invest in companies or take partial control of individual property.

The other two scenarios use a standard startup trick to save money early on by paying the employees in equity in the company. Instead of paying the salary levels described above in Table 7.8, the salary for all employees would be capped at $65,000 with additional equity in the company. The amount of equity would depend on the experience level and role the employee is hired into. This would save the company significant money early on, while still rewarding employees to work hard as the company success is directly tied to their work. Eventually the pay cap is removed and people are moved to a more traditional salary range.

Combining these scenarios gives a wide range of data that can be interpreted as the minimum initial investment needed to start.

- The first of these scenarios is a company that forms out of its own work and seeks investments through traditional means while playing traditional salaries.
- The second scenario has the company working with KUIP and offering traditional salaries.
- The third has no support from KUIP, but with capped salaries with equity
- The fourth has support from KUIP and capped salaries with equity

These scenarios all have varying investments at certain times but can be split into two main categories, lifecycle costs and acquisitions costs. The acquisition costs represent the cost of one-time purchases while the lifecycle costs are recuring. In Table 7.9, the acquisition cost of the various phases can be seen. Without the support of KUIP, Phase 1 is the minimum acquisition cost needed to start and is a bit more expensive than the other stages. In Phase 4 some components are purchased a second time to expand the capability of the team and manufacturing output. Phase 5 is a significant increase in cost as the company begins to bring more of the supply chain under its control. This is primarily highlighted in buying more stock metal and the purchase of an anechoic chamber for testing RF hardware. Compared to the scenario where KUIP supports the company the costs are only shifted to a different phase. Initially the investment cost is significantly lower an it stays that way until Phase 4 where ideally the company would begin to move away from university resources. In Phase 6, an anechoic chamber would potentially be purchased driving the cost much higher for that phase. As a note: office space is not included as this is a recuring cost

Table 7.9: Acquisition Cost Divided by Phases

Scenario	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Total
No KUIP Support	$181,442	$129,599	$128,638	$108,722	$594,017	$100,670	$1,243,089
KUIP Support	$113,104	$76,545	$75,322	$164,797	$155,385	$657,935	$1,243,089

Using the data from Section 7.5.3, the yearly recurring costs can be calculated for the company. This time the cost of the office space is also included and can be seen in Table 7.10. For the scenarios including the use of KUIP, the office space cost was dropped drastically as that is one of the of the services offered. KUIP charges about $500 a month for office space plus access to university facilities thus significantly dropping the cost of rent. At about Phase 4, it is assumed the company would grow out of the KUIP offices and begins renting their own. Thus there is a sharp increase in cost around this phase.

Table 7.10: Lifecycle Costs and Phases

	Phase 1 ($)	Phase 2 ($)	Phase 3 ($)	Phase 4 ($)	Phase 5 ($)	Phase 6 ($)	Total ($)
	$561,750	$642,750	$716,750	$764,750	$788,750	$760,750	$4,235,500
	$504,000	$585,000	$659,000	$764,750	$788,750	$760,750	$4,062,250
	$453,750	$453,750	$518,750	$518,750	$518,750	$518,750	$2,982,500
	$396,000	$396,000	$461,000	$518,750	$518,750	$518,750	$2,809,250
No KUIP + Base Salary		KUIP + Base Salary		No KUIP + Capped Salary + Equity		KUIP+ Capped Salary + Equity	

By combining the values in Table 7.9 and Table 7.10, the full initial investment can be found. This includes all values that have thus far been discussed and are shown in Table 7.11.

Table 7.11: Initial Investment Values

	Phase 1 ($)	Phase 2 ($)	Phase 3 ($)	Phase 4 ($)	Phase 5 ($)	Phase 6 ($)	Total ($)
	$743,192	$772,349	$845,388	$873,472	$1,382,767	$861,420	$5,478,589
	$617,104	$661,545	$734,322	$929,547	$944,135	$1,418,685	$5,305,339
	$635,192	$583,349	$647,388	$627,472	$1,112,767	$619,420	$4,225,589
	$509,104	$472,545	$536,322	$683,547	$674,135	$1,176,685	$4,052,339
No KUIP + Base Salary		KUIP + Base Salary		No KUIP + Capped Salary + Equity		KUIP+ Capped Salary + Equity	

Based on the data presented above, a small satellite manufacturing company could enter the market with a minimum investment of around $525,000 which includes a small amount of margin as well. However, it should be noted that this outline does not include every single component, cost, or other monetarily intensive items. There are some items such as IT, ITAR control areas, and utilities that are not outlined above. Another important detail to consider is that nearly 66% of the initial investment is for salary alone in two of the scenarios. On top of that, if the company grows out of the university it can save even more money by potentially using university resources until it can purchase its own equipment. Other companies in this field have followed a similar path and were profitable from day one without having to give up equity outside of the company employees. By combining all these aspects, a much clearer picture of what the minimum investment can be found. Despite there being some information missing, the foundation for what would be Series A, B, and C funding has been supplied and can be built upon to get an even more accurate picture. Based on the analysis done here, it is recommended that such a company partner with KU's Innovation Park and initially cap the employee salary at $65,000 while offering direct company equity. This is the least expensive and potentially most direct path to being profitable as soon as possible. This path only requires about $500,000 investment which is in line with many Small Business Innovation Research (SBIR) grants. Moreover, this path would allow for minimal outside equity holders allowing more control of the company to remain with the employees. Should KUIP, not be a suitable path, the next best recommendation would be normal growth, but capped salary plus equity. This time the investment rises to about $650,000. A graph of the minimum initial investment can be seen in Figure 7.6. If all else fails, then the minimum investment cost rises $750,000.

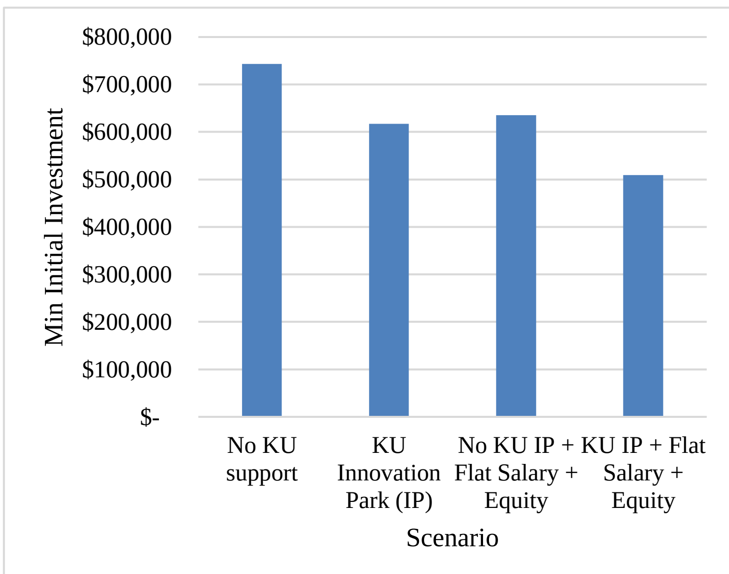

Figure 7.6: Minimum Initial Investment Scenarios

8 Conclusions

Nearly 20 years ago, KU entered the new world of small satellites with the development of KUteSat. Despite not making it to orbit, KUteSat was supposed to represent the start of the next generation of space research at KU. However, nearly a decade later the drive and research behind CubeSats at KU had fallen by the wayside and was in desperate need of new life. With submission to the CubeSat Launch Initiative, the small sat initiative at KU was restarted. This time, a uniquely designed student organization was tasked with not only creating a new satellite but the development of a self-sustaining program that could create a new satellite every few years. The organization, known as KUbeSat, worked with the KU Department of Physics to develop two payloads for the first satellite, KUbeSat1. The KUbeSat team began work on designing, assembling, and testing the various components on the satellite with a focus on commercial the-shelf components. It was during this process the team realized that since the majority of components came from foreign sources and despite growing industry needs, there was not enough component manufacturing in the US. The result is a business plan that a potential company could follow to fill the economic gap. As such deliverables for this report can be divided into three main sections:

- A framework for a self-sustaining Cube Satellite program
- A satellite produced by that organization
- A business plan meant to outline the potential entry into the small sat market

8.1 Deliverables

As stated above, this report delves into three main areas of deliverables, with the first being the creation of a university small sat program. KUbeSat as a program has undoubtedly been successful in its initial goal of getting selected to develop and fly a satellite through NASA's CLSI. With KUbeSat1 nearing completion, the organization has already started developing KUbeSat2 and is in the process of procuring a significant amount of recurring funding for the next three years. Moreover, the organization has outlined clear procedures for nearly all the processes involved in the development of this first satellite. This includes things like funding allocation, outreach events, officer election, development cycles, lead selection, and overall succession. This represents a stark contrast from the original team at KU developing KUteSat who may have started small satellite development at KU but were unable to create a self-sustaining organization.

Figure 8.1: KUbeSat Logo

The biggest immediate result of KUbeSat's efforts is KUbeSat1 which is scheduled to fly no earlier than August of 2022. This satellite features two School of Physics payloads one of which will be the first time primary cosmic particle research is done on a CubeSat. KUbeSat1 is scheduled to pass its first vibration test on May 1st of 2022 and will move on to a readiness review on June 7th of the same year. Once it has passed that final milestone it will be handed over to NASA on June 28th with integration coming later and flight launch in August. Throughout the development of KUbeSat1, the team realized that there is a significant lack of components in the US for these CubeSats. As a result, the final deliverable arrives in the form of a business plan meant to provide guidance on a possible path of entry into the small sat market.

A business plan is meant to be a blueprint or guideline for the development of a new company in a specific area, in this case, the aerospace industry with small satellites. The business plan outlined above begins with the mission statement "*To provide quality space-rated COTS solutions for use in the small satellite sector."* This mission statement leads to the ideal products for such a company being small satellite components for commercial and academic customers looking to deploy their solutions to space. These components would be manufactured using aerospace-grade hardware and fully meet all regulatory requirements. The components available include both hardware and software meant for easy modular assembly and rapid development. To accomplish this rapid development, the company would focus on bringing additional elements of the industry value chain under common ownership in the form of vertical integration. While initially an expensive endeavor, this integration allows for a company to fill a gap in the market between new space entrants and old legacy companies. After a literature deep dive and communicating with industry experts, it was found that the initial capital investment would sit around 1 million US dollars with the ability to scale that up or down depending on the availability of various facilities to the company. Like with any business plan, the results are fluid and constantly changing as the market does as well. As the company learns more, it can adapt to the environment and apply its lessons learned. As with any project, there were a substantial number of lessons learned which helped push the team into new directions

8.2 Lessons Learned

One of the biggest lessons learned early in the process of KUbeSat1's development was the need for professional industry contact. KUBeSat1 initially began life with donated equipment that was no longer being supported and as a result, the industry support was minimal. This led to nearly a year delay in development which could have been used to create more robust systems. A similar issue arose with some of the final component suppliers of KUbeSat1. Though this time, instead of not supporting the equipment, the equipment had little to no supporting documentation. This of course also lead to severe delays as the team had to learn as they went and grow homemade solutions where there were certainly plenty of professionally available ones. The primary takeaway from those interactions was that any company operating in this field would need to be able to supply the documentation needed to take the hardware and develop at a breakneck pace. Initially, KUbeSat operated as one team with leads often taking multiple roles. When it became apparent that this was not a sustainable option the organization was reformulated into what it is today and has thrived since. There are countless other lessons to be learned as a satellite is built from the ground up but in the end a combination of enthusiasm, effort, and drive led to the creation of an organization that not only spawned a new satellite from KU but a new aerospace startup.

8.3 Original Contribution

As was discussed in Section 2, the makeup of the KUbeSat organization is uniquely divided into sections while being run by students. One section focuses on the technical projects of the individual satellites, while the other handles the more administratively challenging aspects of an organization. This includes funding generation and allocation for each of the satellites under development. This setup allows the organization to seek funding from sources only limited to students, while at the same time allowing technically dedicated students to focus on areas of interest. Based on interactions with other schools and literature reviews, it seems that this is a unique setup that is not openly prevalent elsewhere. Moreover, the organization's constitution is so written to ensure there is a constant line of succession as the members of the team graduate or move on to the next stage of life. The author claims this framework as one of the major original contributions of his dissertation. Without the guidance of the author, the organization would not have developed the unique structure it currently. That structure is a direct result of seeking to maximize funding opportunities while at the same time allowing non student led projects to exist under the organizations umbrella. The managerial/organizational layout while unique allowed the University of Kansas to build KUbeSat1.

KUbeSat1 represents no small feat of engineering for any a school that lost and rediscovered its passion for satellite design. The satellite went from design to a fully built model in less than three years and has taught the team working with it an innumerable number of lessons. Furthermore, the original payloads will enable the Department of Physics at KU to study deep space particles in a way no other institution has ever had the chance to do. When KUbeSat1 launches in the August of 2022 it will also capture images from orbit that can be used for university recruitment and community-building at KU. Without the support of the author the satellite would not have made it to its current point. Most of the authors support was through the management of the team. This included holding members accountable to certain tasks and breaking down communication silos. This was primarily done through guided team meetings, but also through the development of mutual respect among members. Understanding not only the problems members faced on KUbeSat1, but also those faced in life helped fortify the team and the success of the project. It is

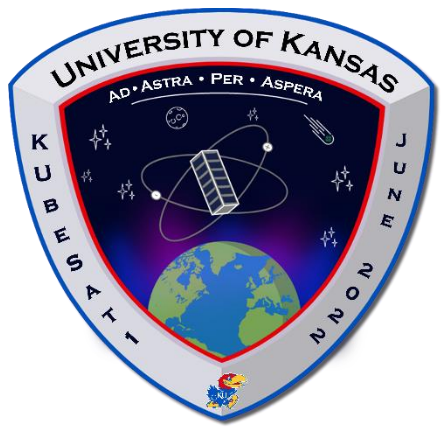

Figure 8.2: KUbeSat1 Mission Patch

through this managerial approach; the author was able to lead the team getting KUbeSat1 where it is today. Indirectly, KUbeSat1 has also inspired a deep dive into the economics and market of the small satellite world, which in turn could lead to the formulation of a new aerospace startup not far from KU.

The final original contribution presented here is a business plan and the subsequent prospective implementation of said plan. As was discussed above, there is a rapidly rising demand for satellites as more and more companies look to launch swarm/constellation architectures. In the next decade alone nearly 8,000 small satellites will be launched with the number growing even higher in the 2030s and beyond. This means that there is an immediate need for satellite hardware, components, and software. There is only one identifiable company in the US that sells COTS components to solve these problems whereas the rest are all located outside of the US. Moreover, the industry is seeing a noticeable shift in manufacturing requirements, and instead of thinking in terms of years, the timetable has moved to months and in some instances weeks. This is where a new startup could enter the market with a specific emphasis built on vertical integration and rapid iteration. The outlined business plan in Section 7 details the recommended steps and even outlines a suggested minimum required capital investment required to start such a company. The author claims this business framework as the primary contribution of his defense. Combined with the skills learned during the development of KUbeSat1 and the creation of the KUbeSat organization, the foundation of an original aerospace startup could lead to exciting new developments in the small satellite world.

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10 Appendix

10.1 Tables

Table 10.1: KUbeSat1 Mass Margins

Item	Mass (g)	Margin (%)	Margin (g)	Mass + Margin
ADCS Y-Momentum Wheel	300	1%	3	303
CD&H/OBC	130	1%	1.3	131.30
3U Solar Panel	127	1%	1.27	128.27
1.5U Solar Panel	65	1%	0.65	65.65
1.5U Solar Panel (Top)	65	1%	0.65	65.65
1U Solar Panel	40.7	1%	0.407	41.10
1U Solar Panel (Top)	40.7	1%	0.407	41.10
40 WHr Battery	354.7	1%	3.547	358.24
Starbuck Nano EPS	55	1%	0.55	55.55
UHF Antenna	77.1	1%	0.771	77.87
UHF Radio Module	94	1%	0.94	94.94
HiCalK	40	1%	0.4	40.40
PCRD1	187	1%	1.87	188.87
PCRD2	187	1%	1.87	188.87

PCRD1 Mounting Plate	41	1%	0.41	41.41
PCRD2 Mounting Plate	41	1%	0.41	41.41
3U Frame	308.8	1%	3.09	311.89
GNSS Antenna	40	1%	0.00	0.00
Bottom Plate	193.05	1%	0.40	40.40
Magnetometer	11.4	1%	1.93	194.98
Earth Horizon Sensor	30	1%	0.11	11.51
Discovery 2	79.5	1%	0.30	30.30
Camera	10	1%	0.80	80.30
Pi (with Heat Sink)	46	1%	0.10	10.10
End Plate	40.7	1%	0.46	46.46
Wiring	150			
Totals (g)	2630.69			2780.69

Table 10.2: KUbeSat1 CG locations and Margins

	Center of Gravity (mm)	**+ Margin (mm)**	**- Margin (mm)**
X	163.175	8.159	-8.159
Y	0.016	2.000	-2.000
Z	4.858	2.000	-2.000

Table 10.3: Mounting Plate FEA Analysis

PCRD Mounting Plate FEA Analysis				
Test #	**Mesh Seed Length (in)**	**Boundary Conditions**	**Inertial Loads** (*Rotational <0 0 0> & Translational <0 0 0> ^values in ft/sec^2)	
			Translational^ <x y z>	Rotational^ <x y z>
1.1	0.1	Static*	<0 16.0870245 16.0870245>	<247.7401733 0 0>
1.2	0.1	Static*	<0 77.2177176 77.2177176>	<128.696196 0 0>
1.3	0.1	Static*	<0 77.2177176 77.2177176>	<-32.174049 0 0>
1.4	0.1	Static*	<0 64.348098 64.348098>	<-64.348098 0 0>
2.1	0.05	Static*	<0 16.0870245 16.0870245>	<247.7401733 0 0>
2.2	0.05	Static*	<0 77.2177176 77.2177176>	<128.696196 0 0>
2.3	0.05	Static*	<0 77.2177176 77.2177176>	<-32.174049 0 0>
2.4	0.05	Static*	<0 64.348098 64.348098>	<-64.348098 0 0>
3.1	0.025	Static*	<0 16.0870245 16.0870245>	<247.7401733 0 0>
3.2	0.025	Static*	<0 77.2177176 77.2177176>	<128.696196 0 0>
3.3	0.025	Static*	<0 77.2177176 77.2177176>	<-32.174049 0 0>
3.4	0.025	Static*	<0 64.348098 64.348098>	<-64.348098 0 0>

Table 10.4: KUbeSat1 Link Budget

Uplink		**Downlink**	
Ground Station		Satellite	
Max. transceiver output power	18.75 dBW	Radio module output power	0 dBW

Total transmission line loss	6.41 dB	Total transmission line loss	1 dB
Antenna Gain	13.3 dBic	Antenna Gain	1.5 dBic
Effective Isotropic Radiated Power	25.64 dBW	Effective Isotropic Radiated Power	0.5 dBW
Total path loss = 156.21 dB			
Satellite		Ground Station	
Isotropic Received Power	-130.57 dBW	Isotropic Received Power	-155.71 dBW
Antenna gain	1.5 dBi	Antenna gain	13.3 dBic
Total transmission line loss	1 dB	Total transmission line loss	0.33 dB
Gain to Noise Temperature	-23.3 dB/K	Gain to Noise Temperature	-13.3 dB/K
Receiver Noise Power	-161.5 dBW	Receiver Noise Power	-159.4 dBW
Received Signal Power at LNA	-130.07 dBW	Received Signal Power at LNA	-142.74 dBW
Signal-to-Noise Power Ratio	31.9 dB	Signal-to-Noise Power Ratio	16.67 dB

System Link Margin	22.3 dB	System Link Margin	7.06 dB

Table 10.5: Random Vibration Breakpoints

Freq [Hz]	**ASD [g^2/Hz]**
20	0.00125
80	0.00125
200	0.01
1600	0.01
2000	0.00644
g_{RMS}	4.23