2010

TESTING PROGRAM FOR KYSAT-1

Jason Robert Bratcher

University of Kentucky, jason.r.bratcher@gmail.com

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Years of success in the aerospace industry has taught Kentucky Space several lessons. This thesis will summarize the accomplishments in an attempt to formulate a well-defined program for designing and testing small spacecraft in an environment with strict financial restraints. The motivation for producing this well-defined platform for testing small spacecraft arose when Kentucky Space became the liaison between NASA and its customers for the NanoRacks and CubeLab module program. Having a solid program for testing small spacecraft will allow future student programs to easily set standards for experiment payloads. Also by discussing obstacles for smaller programs such as restraints on funding, scheduling restrictions, and testing facility procurement, this thesis will provide a basis that other programs can use to start or expand a space research program that may be struggling due to mistakes that programs face in the early years due to the lack of experience and maturity of a veteran program.

KEYWORDS: KySat-1, Kentucky Space, Testing, Embedded Systems, Fault Tolerance
TESTING PROGRAM FOR KYSAT-1

By

Jason Robert Bratcher

Dr. James E Lumpp Jr.
Director of Thesis

Dr. Stephen Gedney
Director of Graduate Studies
June 9, 1010
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TESTING PROGRAM FOR KYSAT-1

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Engineering in the College of Engineering at the University of Kentucky

By

Jason Robert Bratcher

Lexington, Kentucky

Director: Dr. James. E. Lumpp, Jr., Associate Professor of Electrical and Computer Engineering

Lexington, Kentucky

2010

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Dedicated to my family who helped me through a tough academic career.

*I love them very much*
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1 INTRODUCTION

1.1 SMALL SATELLITE AND CUBESAT BACKGROUND

1.1.1 Small Satellites
Sputnik’s launch in October 1957 by the Soviet Union was the impetus for what became known as the “space age.” Besides initiating the U.S. – U.S.S.R. space race, the launch of Sputnik also sparked innovations in several fields, including political, military, technological, scientific, and commercial (1). At only 58cm in diameter (Figure 1 – Sputnik I), the world’s first artificial satellite was no larger than a common beach ball. In the years to come, satellites would grow larger and larger due to massive power and computational requirements. However, in the dawn of the digital age, as microprocessors became more sophisticated and electronics became smaller, small satellites not only became more affordable, but became powerful enough to provide a wider range of functionality.

Figure 1 – Sputnik I

In the late 1960’s, The Radio Amateur Satellite Corporation (AMSAT) was founded to increase the appeal for space research and communication for amateur radio operators. Its
mission was to continue the efforts started by Project OSCAR in the early 1960’s. Project OSCAR was a west-coast United States group that built and launched the very first Amateur Radio Satellite (2). From the early 1960’s to today, the majority of the time and resources required for the many OSCAR projects were all donated time and parts by volunteer organizations, primarily within the amateur radio community.

Figure 2 – OSCAR at the Smithsonian

There have been numerous satellites designed, built and launched using amateur radio frequencies such as the first OSCAR satellite shown in Figure 2. There are few qualifications to pass in order to use an amateur radio frequency, the most basic being to obtain a license. Thus, due to the ease of using amateur radio frequencies for Low Earth Orbiting (LEO) satellites, and the extensive use of those frequencies, the amateur radio community has been using LEO satellites as an easy means for communication for the last half century.

As previously mentioned, the smaller, cheaper and faster concept swept the space exploration community. Not only were government bodies building small satellites for their own purposes, but smaller, lesser funded organizations were able to participate in
space science for the first time. Private companies and universities were then able to enter
the space science arena. In 1990, the University of Surrey and Weber State launched
satellites along with AMSAT and some amateur radio operators from Brazil (3).

When universities and smaller companies obtained the capability to send payloads to
space, it renewed a surge of interest in space research. Before, universities and smaller
organizations primarily assisted larger corporations. Due to the pioneering efforts of
AMSAT these organizations began to build their own spacecrafts for their own research.
However, due to the increasing cost of launching a satellite, the concept was again
slipping out of the budget for even larger universities.

1.1.2 CubeSats
Small satellites changed the space exploration industry by merging the concepts of
smaller and cheaper. In 1999, Dr. Jordi Puig-Suari of California Polytechnic State
University (Cal Poly) and Professor Robert J Twiggs of Stanford University teamed up to
push the envelope. They wanted to make small satellites even smaller which led to the
development of the CubeSat standard. Their main goal was to standardize the form factor
of this pico-class satellite in order to reduce build and launch costs for space science so
more universities and organizations worldwide could participate in space exploration.

Figure 3 – Dr. Jordi Puig-Suari

Figure 4 – Professor Robert J Twiggs

Between 1980 and 1999, universities comprised less than 6% of small satellites
customers (4). Since then, the revolutionary CubeSat has allowed organizations to build
standardized payloads that can be launched from a variety of picosatellite orbital
deployers (PODs). This standardization has made it much easier for developers to design and build a CubeSat to fit in a standard POD or launcher, as opposed to a traditional satellite that has to be designed from the ground up to fit to the launch vehicle. Also, the small size of the CubeSat has recently been a big argument for riding along as a secondary payload on larger projects. In the past, this payload volume was wasted on ballast.

Cal Poly’s development of the Poly Picosatellite Orbital Deployer (P-POD) was one of the major advancements of the CubeSat program. Seen in Figure 5, it is the standard launching mechanism that can be used to deploy up to three 1U CubeSats\(^1\) from a launch vehicle. The P-POD provides a standard interface between CubeSats and a launch vehicle so that any group that wants to build a CubeSat can work with Cal Poly to interface with the P-POD, and Cal Poly can in turn interface with the launch integrator and their vehicle. This hierarchy of interface reduces the need for payload groups to interface directly to the launch vehicle and provider which in turn hastens the design process.

The CubeSat innovation was laughed at in the early years: “Too small to do anything,” quickly became the loudest complaint from several major players in the space industry. As the years passed however, several major milestones occurred to prove otherwise. GeneSat-1, launched in 2006, studied E coli bacteria as part of a genetics experiment (5) and PharmaSat, launched in 2009, studied the influence of microgravity upon yeast resistance to an antifungal agent (6). NASA heavily participated in the design and launch of both of these biosatellites. Also worth mentioning are NASA’s NanoSail-D and PRESat as well as Boeing’s CubeSat TestBed 1 (CSTB1). They all became proof that not only can meaningful research be done with such small satellites but also that the traditional major players in space exploration can benefit from CubeSats.

\(^1\) A 1U CubeSat is a standard CubeSat measuring approximately 10cm\(^3\). In a standard POD, you can also launch 2U and 3U CubeSats, which have volumes of 10x10x20cm and 10x10x30cm respectively.
1.2 **THE KENTUCKY SPACE CONSORTIUM**

1.2.1 **The Kentucky Space Consortium: The Beginning**

For years, the Space Systems Laboratory (SSL) at the University of Kentucky has produced major success in embedded systems technology and UAV development. In 2006, the University of Kentucky offered up the SSL, then known as the IDEA Lab, and teamed with the space science program of Morehead State University, the systems engineering of Belcan, and several other universities and companies throughout the state of Kentucky to create the first consortium in Kentucky dedicated to space research.

Today the consortium consists of the six universities: University of Kentucky (UK), Morehead State University (MoSU), the University of Louisville (UL), Kentucky Community and Technical College System (KCTCS), Murray State University (MuSU), and Western Kentucky University (WKU); and also Kentucky Space Grant Consortium (KSGC), Kentucky Council on Postsecondary Education (CPE), Kentucky Science and
Engineering Foundation (KSEF), Belcan Corporation, and Kentucky Science and Technology Corporation (KSTC). All projects are designed and built by students from the six universities with managerial assistance from the industry partners and faculty advisors.

The Kentucky Space vision is simple and includes several goals that are to be achieved through simple advancements in several areas.

[1] To produce an innovative and reliable space and technology research program in the state of Kentucky.
[2] To design, build, launch, and provide mission support for the duration of several space related research missions using a university based, student-led, state-wide consortium.
[3] To produce an interactive program for primary and secondary students to engage in space and technology-related research in order to foster the talent force needed for employment in-state.
[4] To establish a series of independent, technology-related business ventures derived from Kentucky Space research to promote economic growth and create job opportunities in-state.

Lead by the funding and managing leadership of KSTC (Kentucky Science and Technology Corporation), the first team of satellite engineers for Kentucky Space spent several weeks in Mountain View, CA learning about spacecraft, and the design and operation of CubeSats, in particular. The product after many long weeks was the beginning stages of KySat-1: Kentucky’s first satellite.

1.2.2 KySat-1
KySat-1 is the flagship mission of the Kentucky Space Consortium and will provide the case study of this thesis. It is a pico-class 1U CubeSat designed and developed by Kentucky students to adhere to Cal Poly’s CubeSat Design Specification (CDS). The main technological goal of KySat-1 is proof of concept. By developing a reliable and reusable CubeSat bus architecture for scientific payloads that can be designed and launched on future missions, Kentucky Space moves further toward its inaugural goal of growing the seeds of a space program in the state of Kentucky.
The other main mission goal included in the original design of KySat-1 was Science Technology Engineering and Math (STEM) education and K-12 outreach. In order to lay the groundwork for a space program in the state of Kentucky, a need exists to introduce younger students to the math and sciences needed to flourish in the space sciences field. Using a high power radio onboard KySat-1, simple outreach activities can be accomplished in a school’s courtyard or playground with just a simple handheld radio and antenna. KySat-1 is scheduled for launch in November, 2010 as a part of the ELaNa (Education Launch of Nanosatellites) mission.

Since the innovative CubeSat Standard was introduced to the space research community, hundreds of satellite missions exploded onto the scene. However, since launch opportunities are rare at this point, Kentucky Space decided to expand its research to include other mission types as well. Since the expansion, Kentucky Space has obtained at least minimum success criteria for sub-orbital sounding rocket missions and near space...
missions using high altitude balloons. This success provided several methods for testing KySat-1.

1.2.3 The Kentucky Space Consortium: The Missions
The original vision for Kentucky Space was to establish a reliable and reusable satellite bus architecture. Since the expansion to include other mission types, Kentucky Space has had the chance to create, reuse and revise many of the design and testing procedures that were used for KySat-1.

1.2.3.1 Space Express
The first mission Kentucky Space branched out with was a sounding rocket mission that launched from the White Sands Missile Range (WSMR) on December 5, 2007. Space Express was the first attempt to build Kentucky’s future in space. The mission goals were simple. Primarily, it was to test hardware and design philosophies that were to be used for the KySat-1 orbital mission. Secondary mission goals included gaining experience with launch integrators and sending Kentucky Space hardware to space altitude for the first time.

Lunar Rocket and Rover provided the Shadow 1 Dart/Super Loki Rocket that Kentucky Space equipped with a standard array of weather observing sensors connected to a simple Ham radio. Getting the opportunity to work with Lunar Rocket and Rover, the team gained valuable knowledge in launch integration and flight testing procedures. The Kentucky Space team was ill-prepared for launch day due to the lack of experience in mission planning. Preparations for launch went well into the morning of the launch. The lessons learned for this mission consisted of a long list of mistakes made by the group that would not have been made by a more experienced group.

1.2.3.2 Balloon-1
Seven months after Space Express came Balloon-1. Launched on Monday July 14, 2008, this high altitude balloon used software libraries developed for KySat-1 mission that had, until then, only been tested on a desk as well as other hardware that was planned for future missions. The team worked with Bill Brown, currently the VP of High Altitude Research Corporation, to gain some of his experience in high altitude balloon research.
Equipped with PearlSats, this mission marked the day that Kentucky Space began one of its visionary goals of reaching out to younger students. The PearlSat, innovative idea of Robert Twiggs, was a simple ping pong ball split in half so that younger students could place something inside such as candy, bugs, or whatever they wanted to experiment with. The PearlSats were all attached to a string and hitched a ride to near space. After the retrieval of the balloon, those students that participated with the PearlSats could examine their experiments and observe the affects space weather had on their experiments.

![Figure 7 – Picture taken from Canon Camera on Kentucky Space Balloon-1](image)

At an early age, these students were able to perform science experiments in the near space environment and discuss the affects of freezing cold temperatures and near zero pressure. Additionally, two high resolution Canon cameras provided a simple way to take high quality images of the curvature of Earth.
1.2.3.3 **Garvey Prospector 12A IMU Payload**

By the third mission, Kentucky Space had obtained enough man power and payload experience to attempt an extremely short turnaround mission. Garvey Prospector 12-A sub-orbital experimental rocket was built by Garvey Spacecraft Corporation with the assistance of students from California State Long Beach and launched from Mojave Desert on October 11, 2008. Kentucky Space did not participate in the design or build process of the rocket; instead the team built an Inertial Measurement Unit (IMU). Again the team used software and hardware from the upcoming KySat-1 mission, and had the opportunity to work with a payload integrator, Robert Twiggs, then at Stanford.

![Figure 8 - Garvey Payload Team with Recovered Payload](image)

1.2.3.4 **Sub-Orbital CubeSat Experimental Mission**

On March 27, 2010, the next mission, Sub-Orbital CubeSat Experimental Mission (SOCEM) marked the first time Kentucky Space put hardware into space. This mission gave Kentucky Space the opportunity to test some really small, custom built equipment
from KySat-1. This mission took careful planning to coordinate the combined efforts of Cal Poly, the universities of Kentucky Space, and the NASA Sounding Rocket Operations Contract (NSROC) at Wallops Flight Facility (WFF). This mission contributed quite a bit to the advancement of Kentucky Space due to the space qualification of the hand-made hardware. See Figure 9 - Model of SOCEM Ejection for a model of the two ejected CubeSats.

Due primarily to the success of SOCEM, Antenna Deployment And Monofilament Actuator Satellite (ADAMASat) returned information telling Kentucky Space ground stations, that the antenna deployment mechanisms survived launch and operated properly in space. This success increased the Technology Readiness Level (TRL) of the antenna deployment mechanism to a TRL of 7.

Figure 9 - Model of SOCEM Ejection
The TRL is a number between one and nine that represents the readiness of a piece of equipment to operate. If TRL is too low, then a mission could be jeopardized by delays or cost over-runs due to improper testing or unexpected failures. The increase of the antenna deployment mechanism to TRL-7 means a piece of equipment has had a prototype demonstrated in space environment and is a significant jump from TRL-6 (7).

SOCEM also marked the first time a CubeSat had been deployed in space from a sub-orbital rocket. Working with NASA Wallops Flight Facility, Kentucky Space obtained experience in acting as a launch integrator for Cal Poly who could not feasibly travel cross country to complete the launch themselves. Several other groups participated in the success of this mission: Cal Poly for the use of one of their orbital deployers; NSROC, for assisting Kentucky Space through all of the testing and integration stages into the payload section of the rocket; Dr. Bruninga, inventor of APRS, who helped spread word of the launch to the HAM community; and the HAM community who assisted in packet retrieval during the launch and deployment of ADAMASat. With all of the so many different groups involved, coordinating all aspects of this mission successfully was a true test for Kentucky Space.

Each of these missions contributed in different ways to the advancement of Kentucky Space’s cumulative experience over the years as well as its reputation. The biggest contributing factor, however, was that in each mission, there were several opportunities to test hardware, software, and testing methods themselves in preparation for the future of Kentucky Space.

1.2.4 Thesis Statement and Motivation
Creating a well-defined platform to facilitate small spacecraft testing and development will help Kentucky Space foster future small spacecraft missions. This platform can also aid smaller programs to generate valuable experience, information and technology at a fraction of the cost incurred by larger corporations.

Kentucky Space has accomplished much in four years of research in aerospace systems. The majority of these accomplishments can be classified as procedural, methodology, infrastructure, and lessons learned. The purpose of this thesis is to “summarize” the
accomplishments of the Kentucky Space program and to formulate a well-defined program for designing and testing small spacecraft in an environment with strict financial restraints. It will also address obstacles such as program procedures, location of testing facilities, program scheduling and restraints on funding which has hindered the growth of the program as compared to a larger aerospace program such as NASA.

As a university based program, Kentucky Space was forced to take several shortcuts due to testing procedures and facilities that weren’t available due to schedule and cost factors. Taking shortcuts can save resources such as time or money. However, there is some cost associated with every shortcut taken. This cost is generally some factor of precision. This thesis will discuss several shortcuts that should not be taken in order to avoid errors in precision that will compromise the integrity of the spacecraft. Avoiding these errors could reduce long term costs in budget or time.

In addition, this document will provide an excellent starting point for universities that are still in the early stages of their small spacecraft programs so that other groups can avoid making similar, costly mistakes that programs tend to suffer from in the early stages of development due to lack of experience or training.
2 TESTING KYSAT-1 AND SMALL SATELLITES

2.1 SOFTWARE TESTING PROCEDURES

One of the most critical systems in a spacecraft is the Command and Data Handling System (CDHS). It is important that the software running on the CDHS is completely tested, verified and validated. Software testing for a spacecraft is much different than other engineering projects. If software isn’t fully tested in a dishwasher, the customer may end up with unclean dishes. If untested software leaves the warehouse in a printer, customers’ documents may print abnormally. In either of these cases, the customer can return the defective product and get a new one. With a spacecraft however, after launched, there is no return or refund. A spacecraft has one chance to operate properly. If any subsystem is not operating properly, and there is no fail state to remedy the problem, then the spacecraft becomes orbital debris.

In the following section of this thesis, I will cover several ways that programmers from both small and large programs utilize testing techniques to verify and validate their software modules in order to assure that the CDHS will run properly once launched.

2.1.1 Component Testing

The simplest form of software testing that nearly every software engineer uses is component testing. Every function has a series of inputs and a series of outputs or results. This is by far one of the most important forms of testing because it allows testing of the software before the final product is put together. Component testing can be done at a lower level to ensure that every individual piece of code works properly by itself, which increases the probability that it will work later when incorporated into a larger project.

However, to exhaustively test each and every case will most likely be a very tedious, and in some cases, impossible task. Therefore larger companies save a lot of time by creating test benches to do the testing autonomously. Test benches are created by running each code component through a matrix of every possible input and comparing them to the theoretical results. In order to obtain the theoretical results, typically a separate group of engineers create a separate piece of code that does the exact same thing, however since every engineer has different coding styles, it is unlikely that both functions will be coded
similarly. See Figure 10 – Example Test Bench to test Module of Code for an example of a test bench for a module.

![Component Test Bench Diagram](image)

**Figure 10 – Example Test Bench to test Module of Code**

Smaller engineering programs, however, do not have the time or resources to commit two separate teams to code the same module in order to use a test bench for their component testing. Kentucky Space resorted to a less than perfect method for component testing. The team wrote scripts for each function to test boundary cases and a random number of other cases and then checked the results to see if they were logical results based on the inputs given to the function. This is not an ideal form of testing but is sufficient to “sanity-check” that the function is working properly and will work properly when called in a larger project.
2.1.2 Box Testing Method

2.1.2.1 White Box Testing

White Box Testing is a form of software testing that generally is done by the programmer himself. In order to do white box testing, the programmer will go through every piece of code line by line and executing them one step at a time and checking the variables to make sure the code is producing expected results. This is a very meticulous method of testing software. However it is nearly impossible to test the software completely due to variation of the code based on in the inputs.

White box testing includes but is not limited to Application Programming Interface (API) testing, code coverage testing, fault injection testing, mutation testing, and static testing. In code coverage testing, programmers create test arrays to use every statement in the program at least once in order to assure that each piece of code is being used and therefore should not have any bugs. However, code coverage testing does not take into account that software can be situational. This means that the same code can perform two
different actions based on the current state of the hardware. Since software is situational code coverage testing is not a complete method of testing software.

Fault injection testing plays a very important role in writing robust code that can withstand errors in calculations or faults in hardware. Programmers introduce faults or errors in the software during testing in order to test that the software is stable with or without the faults. The software tested in this method will not be used during normal operation but can cause major problems if reached and not tested properly (8).

Mutation testing is a common form of testing software to reach portions of code that are normally unreachable during normal operation. Some software is written to respond for instance to a hardware failure. This is hard to simulate in testing. Thus a programmer may change a portion of code so that an equation always results to zero or a certain branch is always taken. This way pieces of code that test failsafe conditions can be tested properly without posing a risk to any hardware during the testing stages. This is an unreliable method of testing mostly due to the fact that the code is changed every time the software is run. So consistency is lost between each test case (9).

Larger programs have experimented with several types of white box and condition testing over the years and have perfected their testing methods to the point where different types of software get tested to certain testing matrices. Kelly Hayhurst, a senior research scientist in the area of design correctness and certification at NASA Langley Research Center, along with several other authors have written several documents now in the NASA document repository that clearly explain scenarios and appropriate testing matrices to apply in order to test design correctness and functionality of software (10).

2.1.2.2 Black Box Testing

White box testing is a nearly impossible task for a programmer to accomplish in any feasible time. Thus, black box testing is also a widely used method for testing software. A larger advantage of black box testing is that anyone can do it. The programmer puts together a document with a set of inputs and instructions for a tester to perform on a certain piece of code along with the expected results. The tester takes that document and performs each test on the target code base. Generally the tester has no knowledge of the
code that is being tested. This way there is no bias of whether the code is working properly or not. If the tester does not receive the expected result(s) from the document, then the code is simply not working properly.

A major setback of black box testing is that since a tester is not privy to the code, generally the tester uses only 10-15% of the actual code. Programmers have safeguards and catchalls built into the back-end of the code and testers generally do not reach any of this code during black box testing.

The long and short of it is that specification-based testing such as black box testing is necessary because it will cover most of the test cases of a normal user running the code as it would normally be operated. However, since it only tests 10-15% of the actual code base, it is insufficient for testing purposes.

2.1.2.3 Gray Box Testing
Gray box testing is a form of testing that employs concepts from both white box and black box testing. A programmer will test at the gray box level when integrating two modules or functions that use each other, but may have been written by separate programmers. The programmer still tests at the black box or end-user level, but has knowledge of the data structures and algorithms implemented inside each function so that test cases that can ‘break’ the code can be performed in order to test the cohesiveness of the functions or modules. Gray box testing is widely used by programmers to assure that variable sizes and types are appropriate for modules that interact with each other.

2.1.3 Static Testing VS Dynamic Testing

2.1.3.1 Static Testing
Static testing is a form of white box testing that scans over an entire project, which may consist of several C or C++ files in order to find bugs, inconsistencies, and redundancies that are generally not found in the initial stages of testing. Compilers do an excellent job of finding syntactical errors. Static Analysis programs however perform precision tracking, initialization checking, value tracking, strong type checking and macro analysis that compilers do not do. A lot of compilers leave out checking these things either to save
time in compiling code or simply because the complexity to do so is out of the scope of the compiler.

Figure 13 – Cleanscape C++lint – An example static testing software suite

After research and comparing several different software suites capable of static analysis, Kentucky Space decided to purchase Cleanscape C++lint seen in Figure 13 – Cleanscape C++lint – An example static testing software suite. Not only did it allow the team to perform several arrays of static testing with different settings and features for different styles of coding, it also gave the ability to perform MISRA (The Motor Industry Software Reliability Association) compliance testing. The MISRA standard is a set of standards and guidelines aimed to assist the automotive industry in the creation of safe and reliable software for critical systems (11).
2.1.3.2 Dynamic Testing

Static testing, due to its simple task, is generally omitted in practice. Instead, dynamic testing is considered by many to be a much better testing tool in the early stages of development. Dynamic testing is a great way to check for code flow by confirming that the appropriate decisions are made at forks. Many times, programmers will use dynamic testing techniques before the code is completely finished to confirm that functions are being called properly within the program.

In practice, dynamic testing is relied on more heavily than static testing. However, the purpose of this thesis is to provide a set of standards for testing hardware and software for small spacecraft for smaller programs. Universities, for example, have much less talented software programmers due to lack of professional experience. From experience on the case study, KySat-1, nearly 80\% of the errors/warnings from Cleanscape C++lint were the same mistake over and over. These mistakes were common mistakes that young engineers make all the time, such as implicitly typecasting or changing precision of variables. Static testing provides an extremely beneficial result to younger engineers by showing the common mistakes they make that could produce unexpected results down the road.

2.1.4 A Different Approach to Software Testing

There are thousands of approaches a software engineer could take when testing his/her software. Some methods are more appropriate for larger programs and some methods are more appropriate for smaller programs. Some methods should be performed by any software engineer. In this section, I will briefly touch on a few methods that are suitable for a program of any size and can help software production depending on how much time is spent planning out testing.

2.1.4.1 Review Process

All companies and programs have some sort of review process set up for software testing in order to approve code that has been written by a particular software engineer. A larger company may resort to a more automated system like writing test benches for each function or module. Kentucky Space however set up a software team that consisted of a panel of engineers who read and reviewed each piece of code that each other wrote.
There were different levels of code readiness and several guidelines set in order for the process to go smooth for both the authors and the reviewers.

2.1.4.2 Bug Tracking List

Once the review process has taken affect, the module or code becomes ready for integration into the larger project and ready for use. If a bug was found later, it was entered into a bug list similar to the one seen in Figure 14 - Sample KySat-1 Flight Software Bug List.

![Figure 14 - Sample KySat-1 Flight Software Bug List](image)

Once a bug has been found, it is an open case on the bug list and is colored red. Once the bug has been resolved, it is marked as resolved on the bug list and colored yellow. Then that module is re-entered into the review process. Finally, once the module passes the review process again, it is marked as closed and colored green. It seems like a simple process, but when your code base is as big and comprehensive as the code base in KySat-1 for example, and when you have so many software engineers on the team, it is simple processes like these that help keep the software team well-organized.

2.2 Hardware Testing Procedures

The conditions a spacecraft will operate in from the day it is placed on the shelf to the day its operations are ended are extremely severe. Unless the hardware is fully designed and tested in preparation for these severe conditions, the day your spacecraft operations end may be sooner than planned.

Rocket vibrations, extreme temperatures, radiation and the vacuum of space all contribute to the harsh environment that any spacecraft will suffer from. Hardware must be designed and tested to resist each of these environmental factors so that a spacecraft will be able to operate nominally with little or hopefully no faults. To achieve a state of assurance that
your spacecraft will operate properly, it will have to pass an array of procedures that will test its endurance to the harsh climates of space.

In this section, I will discuss various tests that the case study KySat-1 underwent in preparation for its launch into orbit and compare testing strategies to other programs both larger and smaller.

2.2.1 Vibration Testing
The first thing a spacecraft suffers from is the vibrations from launch. Rocket motors aren’t exactly designed for the comfort and safety of the equipment they are transporting to space. They are designed to achieve the escape velocity required to escape Earth’s gravitational pull. The energy required to achieve this ΔV is so violent that spacecraft must be built so that they do not crush under the pressure or rattle apart.

Figure 15 – shows the NASA GEVS Qualification Profile. The P-POD from Cal Poly is shaken to these levels for each of the different launch vehicles.
Figure 16 - Random Vibration Qualification Graph for KySat-1 shows the random vibration qualification graph that KySat-1 had to pass in order to become eligible for launch in November. The values for this profile are listed in Table 1 – Random Vibration Profile. This vibration profile encompasses most launch vehicle qualification profiles (12).

### Table 1 – Random Vibration Profile

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>ASD Level (G²/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>30</td>
<td>1.15</td>
</tr>
<tr>
<td>75</td>
<td>1.15</td>
</tr>
<tr>
<td>125</td>
<td>0.08</td>
</tr>
<tr>
<td>600</td>
<td>0.08</td>
</tr>
<tr>
<td>3000</td>
<td>0.01</td>
</tr>
<tr>
<td>TOTAL</td>
<td>12.41 Grms</td>
</tr>
</tbody>
</table>

Figure 16 - Random Vibration Qualification Graph for KySat-1
In order to perform vibration testing, the Satellite was placed inside a containing mechanism that was connected to the base plate of the shaker. This mechanism was designed to decouple the resonance vibration of the satellite inside from the vibration of the base plate of the shaker so that the feedback measured through the accelerometers allowed the software to shake to the appropriate levels for the satellite to pass the test.

![Figure 17 - Fixture Designed for Vibration Testing](image)

Since the environment inside the launch vehicle is so violent, in addition to vibration testing, some launch providers may require pyrotechnic shock testing. In order to perform pyrotechnic shock testing, small explosives are placed near the spacecraft and fired to produce the controlled explosions that a spacecraft would endure during a launch into orbit. Figure 18 - Sample SRS Analysis of Ballistic Shock by Delserro Engineering Solutions shows a sample Shock Response Spectrum (SRS) for a dummy payload. The SRS can show how much acceleration or force is applied at each frequency in order to
determine if too much force is being applied at any natural frequencies which could damage a mechanical component (13).

Figure 18 - Sample SRS Analysis of Ballistic Shock by Delserro Engineering Solutions

2.2.2 Thermal Bakeouts and Vacuum Testing

Thermal bakeouts are an important part of hardware testing for multiple reasons. First of all, this is a chance to test the cleanliness of the hardware. If a piece of hardware is too dirty, launch providers can deny launching that spacecraft. This is a big reason why if a program decides not to invest in a clean room, it should take serious consideration in adopting some sort of “clean space” in order to put together flight hardware in a hazard-free and dust-free area.
Thermal bakeouts are simple procedures that secondary payloads are required to perform in order to remove excess contaminants that may be harmful to the launch vehicle or primary payload. A thermal chamber that can reach high temperatures of $60^\circ$C or $70^\circ$C can follow the thermal bakeout profile seen in Figure 19 - Example CubeSat Thermal Vacuum Bakeout Profile in order to pass the thermal bakeout requirements for spacecraft payloads.

![CubeSat T-Vac Bakeout Profile](image)

**Figure 19 - Example CubeSat Thermal Vacuum Bakeout Profile**

Another requirement for testing under vacuum that some launch providers have is the venting requirement. There have been concerns that during rapid decompression of the interior of spacecrafts, pockets and blankets of varying pressures have caused mechanical stresses that may have damaged components (14). A vent test is a simple measurement that checks to see if there is sufficiently sized gaps in the frame of the spacecraft that allows for the pressure to equalize. This calculation is the volume of the spacecraft
divided by the area capable of venting. The ELaNa program requires a maximum of 2000 inches\(^3/inch^2\) for its payloads which includes KySat-1 in the November launch.

### 2.2.3 Antenna Testing and Tuning

Prior to the final integration steps of KySat-1’s engineering model, the Kentucky Space team performed antenna tuning and testing. The purpose of antenna testing is to measure the overall performance of the antennas and make sure that the ground stations will be able to close the communications link with the spacecraft while in orbit. Testing the antennas is a simple process that only requires a network analyzer. Ideally the test would be performed in an anechoic chamber to reduce reflected noise, but an open area is sufficient for a smaller program.

In preparation for tuning the antennas, the antennas were fabricated a little longer than the quarter wave they were supposed to be. Then, upon testing the antennas, the ends of the antennas were clipped off with pliers until the team reached the ideal matched antennas. In order to determine the return loss, each antenna was attached to a directional coupler. The input and reflection ports of the directional coupler were then fed into a network analyzer in order to measure the return loss of each antenna under test for its particular frequency. Figure 20 - Block Diagram for Antenna Tuning shows the block diagram for the testing setup. Also, Figure 21 - Measured S-Band Antenna Return Loss, Figure 22 - Measured UHF Antenna Return Loss and Figure 23 - Measured VHF Antenna Return Loss are the measured return losses for the S-Band, UHF, and VHF antennas respectively. The S-band and the UHF antennas had so little return loss for their respective frequencies of interest so they did not require a matching circuit.

![Figure 20 - Block Diagram for Antenna Tuning](image-url)
Figure 21 - Measured S-Band Antenna Return Loss
Figure 22 - Measured UHF Antenna Return Loss
In Figure 23 - Measured VHF Antenna Return Loss, you can see the return loss for the VHF antenna. This return loss was achieved only after matching the antenna with some series inductance. As it turned out, the VHF antenna needed to be a little longer than the quarter wave length in theory. The team thought that the frame of the spacecraft would provide a decent enough ground plane for the monopole antennas. However, the spacecraft body was too small compared to the larger wavelength of the VHF antenna. To alleviate this problem, the matching circuit added some series inductance and used shunt capacitors to better match the antenna with its frequency.
After the antennas were tuned and matched to their frequencies, the team needed to take measurements of the radiation pattern to determine if the antennas will be powerful enough to close a link with an Earth ground station from space. In order to take the radiation pattern measurements, the satellite was affixed to a non-conducting fiberglass fixture and suspended above the ground on top of a hill with the antenna pointing up at it from the bottom of the hill with the cold sky in the background. This setup minimizes reflection of signals bouncing off the ground.

A network analyzer would transmit a signal directly through the antenna under test which would be received by a ground antenna. The received signal from the ground antenna was then fed into the network analyzer. This measurement was saved, the satellite was rotated by $10^\circ$ and the test was repeated until the satellite was rotated all $360^\circ$. All three antennas were measured in this manner. Also a reference dipole was measured. Each antenna measurement was compared to the reference dipole which provided the team with the normalized radiation patterns for each of the three antennas on KySat-1. Figure 24 - VHF Antenna Normalized Radiation Pattern, Figure 25 - UHF Antenna Normalized Radiation Pattern, and Figure 26 - S-Band Antenna Normalized Radiation Pattern are the normalized radiation patterns for the VHF, UHF and S-Band antennas respectively.
Figure 24 - VHF Antenna Normalized Radiation Pattern
Figure 25 - UHF Antenna Normalized Radiation Pattern
Figure 26 - S-Band Antenna Normalized Radiation Pattern
2.2.4 A Different Approach to Hardware Design and Testing

Here I want to cover a few techniques that work well in industry that Kentucky Space expanded on to create a well functioning design and testing process for each stage of spacecraft development.

2.2.4.1 Flight Model VS Engineering Model VS Other Models

When building a spacecraft that has been designed from the ground up, it is unwise to build only one copy. With all of the harsh testing a spacecraft has to endure before it can be accepted for launch, it is better to start with a smaller less costly model and go from there. KySat-1 for example had several different models ranging from a mass model all the way to the flight model. Each model has its own function and thus role in advancing the project.

A mass model can help determine if the spacecraft will pass the mass property requirements of the launch provider and determine if the testing facilities that have been procured are sufficient. An antenna model can help determine if the spacecraft communication systems are working properly. A flat sat can integrate each of the systems components in a laid out form so that each piece can be seen as a functionally working whole but still have the advantage of easily reaching test points to debug system failures. In Figure 27 - Development Board and Flight Module, you can see the difference between the flight module that will fly inside the CubeSat frame and the development board used in constructing the flat sat model. The flight model will be the final product that will be shipped off to the launch provider assuming it passes all the required tests. However, before the flight model is built, an engineering model should be built. The engineering model is an exact duplicate of the flight model. Its purpose is to be a fully functioning model of the final product that can be tested and retested to assure that testing procedures are sound and that integration procedures are perfected.
2.2.4.2 Component Testing

At some point in the design process, component testing becomes a major focal point of hardware testing. Each of the testing methods I have described above should be performed on each component of the spacecraft. Ideally each component should be completely self-reliant. Otherwise, if two components rely on each other to operate properly, then a failure in hardware would have to be traced through the two components instead of just one. This makes debugging hardware easier.

Kentucky Space performed component testing on each of the sub-systems of the KySat-1 CubeSat: the Payload Interface Module (PIM), the System Support Module (SSM), the Electrical Power System (EPS), the Microhard S-Band Radio, the StenSat UHF/VHF Radio, and the Command and Data Handling System (CDHS). Each component had a piece of software that tested every driver for a particular component to see if it is working properly.
2.24.3 Functional Testing

Once the hardware has been integrated into an engineering model, it is extremely difficult and time consuming to test every piece of hardware. In most cases this is nearly impossible. The easiest way to comprehensively test the functionality of your spacecraft is to create a **minimal systems verification procedure.** This set of procedures should be a set of instructions a user can follow in order to test every piece of hardware possible whether it be through the communication systems or over a tether of some sort. This minimal systems verification should be performed before and after any suite of testing to determine if any of the individual components were damaged during testing.

2.3 Testing Facilities

Before a program can commit time to all of the testing required for a spacecraft in order to comply with launch providers and assure that a spacecraft will operate properly once in space, that program has to decide on facility procurement. If it is a small program that has no aspirations of fostering a long term aerospace program, it would be better to outsource facility procurement. On the other hand, if it is a program like Kentucky Space, investing money in testing facilities and equipment may prove advantageous in the long run.

2.3.1 Thermal Vacuum Chamber

Vacuum chambers come in all shapes and sizes from the glass bell jar seen in Figure 28 – Glass Bell Jar to the world’s largest vacuum chamber in Figure 29 – Vacuum Chamber Inside the Space Power Facility at Plum Brook Station. Inside the power facility at Plum Brook Station, NASA houses the world’s largest vacuum chamber. It was used to test the spacecraft Orion (15).
It goes without saying that the size of clean room required for a project depends on the size of the spacecraft. The chamber at Plum Brook is 100 feet wide and 122 feet tall. This is the perfect size for the 75 foot tall Orion crew exploration vehicle. This is the only facility in the U.S. that can perform complete environmental testing procedures under vacuum on a fully assembled spacecraft.

In Figure 30 - Thermal Vacuum Chamber in the Space Systems Laboratory at the University of Kentucky, you’ll notice that Kentucky Space has a much smaller and less grand vacuum chamber. This thermal vacuum chamber has a volume of 3.3 ft³ and uses both roughing and turbo pumps to achieve pressures as low as 10⁻⁸ torr. The thermal testing is accomplished with four resistive patch heaters and a liquid nitrogen cooling system. The heaters have the capability to raise the test article up to 90°C; currently the cooling system is in the final stages of construction but is projected to be able to cool test articles to -40°C. Presently the chamber is used for outgassing and bake out procedures.
but thermal cycling capabilities will soon be added to provide full testing for all CubeSat standard payloads.

![Figure 30 - Thermal Vacuum Chamber in the Space Systems Laboratory at the University of Kentucky](image)

2.3.2 Clean Room

Previously, Kentucky Space had utilized a “clean space” approach to keeping space hardware clean. However in the attempt to foster a growth-oriented program, Kentucky Space recently acquired a 10x18ft, class 100,000, soft wall, laminar flow clean room.² This is a little more than most university based programs spend on clean rooms. Most university based programs forgo the clean room expense altogether and either rent the services of a clean room or rely on the cleanliness of a clean space.

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² Class 100,000 clean room corresponds to a clean room that has 100,000 or less particles ≥0.5µm per cubic ft
NASA Goddard has a much larger Clean Room called the High Bay. It is a class 10,000 clean room that can hold much larger equipment. The cleaning system consists of 9,000 square feet of HEPA filters along one of the walls. Figure 32 - NASA Goddard, High Bay Clean Room shows a panorama view of the High Bay from the viewing deck. Inside you can see equipment for an upcoming 2014 project, the Webb Telescope, which is a joint project between NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA).
2.3.3 Shaker Facility

During the launch, due to extreme shock and vibrations, the environment is extremely harsh inside the rocket. These environmental factors present a need for vibration testing to assure that the mechanical integrity of a spacecraft can endure the launch, the shaker facility is probably one of the most important facilities for spacecraft testing. Kentucky Space procured a MB dynamics C10E electro-mechanical shaker that can provide 1200 lbs force. It is not the most common shaker for a small spacecraft in that it has a vertical setup and the effects gravity has on the spacecraft during testing may skew measured results. However, this is a good example of how smaller programs can improvise to obtain Most small spacecraft programs invest in a horizontal shaker with a table. The table rests on bearings and lubricant to lessen the affects of friction due to gravity.

![Kentucky Space Vertical Shaker](image)

Figure 33 – Kentucky Space Vertical Shaker

The two shaker systems pictured here (Figure 33 – Kentucky Space Vertical Shaker and Figure 34 – Cal Poly Horizontal Shaker Table) are suitable for performing vibration
testing on nano and pico-class spacecraft for the majority of vibration profiles corresponding to different launch vehicles. Unfortunately, the Kentucky Space shaker does not have the appropriate software to accurately run the proper levels and the Cal Poly shaker does not have the capability to shake to the levels required for the ELaNa launch in November. Therefore, the Kentucky Space team will have to outsource the shaking of KySat-1 in order to qualify for launch. Shaker Facilities require an extremely large initial investment and are generally an outsourced resource for smaller programs.

![Figure 34 – Cal Poly Horizontal Shaker Table](image)

### 2.3.4 Anechoic Chamber

The purpose of an anechoic chamber is to test antennas and other communication equipment. It is essentially a room lined with RF absorbent material that mimics the electromagnetic environment of space. Kentucky Space recently acquired an anechoic chamber that measures 15 x 45 x 15 feet, seen in Figure 35 – The Morehead State University Space Science Center Anechoic Chamber, through Lockheed Martin Global
telecommunications. The anechoic chamber allows empirical measurements of antenna parameters such as radiation patterns, gain, system temperature profiles, astronomical radio source gain-to-noise temperature ratio (G/T), cross-polarization isolation contours, and Effective Isotropically Radiated Power (EIRP) stability.

Figure 35 – The Morehead State University Space Science Center Anechoic Chamber

The acquisition of the anechoic chamber is impressive for a university based program. Only a handful of universities in the world have access to their own anechoic chamber for testing purposes. Nonetheless, this chamber is small compared to those used elsewhere in the aerospace industry. Edwards Air Force Base is home to the world’s largest anechoic chamber that measures 250 x 264 x 70 feet. It supports ground testing of electronic warfare systems on full size aircraft.
3 THE BASIC PLATFORM FOR TESTING SMALL SPACECRAFT

Here I will discuss the basic platform for testing a small spacecraft in a limited budget environment. First I will discuss the major differences between a limited budget company and one that has a little more leniency, with respect to their budget, to design and test mission payloads. Then I will discuss what can and cannot be sacrificed by a smaller company in order to achieve the maximum performance for a mission payload.

3.1 LIMITED BUDGET VS. GOVERNMENT FUNDED BUDGET

Like most university based aerospace and space systems laboratories, Kentucky Space is restricted to a limited budget. The three constraints of any project are time, money and performance (16). You can constrain any two of these, but there must be an unconstrained portion. For limited budget corporations, money is definitely one of those constraints. Generally, time is also a constraint due to mission schedules and launch windows. Therefore, performance is the unconstrained aspect of the three and can sometimes hinder what can be done in a particular mission.

![Figure 36 – Three Constraints of a Mission](image-url)
Corporations such as NASA, Northrop Grumman, and several others however make their own schedules based on the performance they want to achieve. As well, they are less concerned with spending on design and testing, so the final product will be much more advanced in technology and readiness for operation than in a limited budget corporation.

It would be comforting to say that this section would be the same for every company that may read this document. However, that is simply untrue. Kentucky Space started as a fledgling entity in the aerospace industry designing KySat-1 from the ground up with little to no experience in small spacecraft design. Since then, Kentucky Space has expanded its infrastructure in order to complete several different missions per year. The scope of this section will be limited to programs that are just beginning a space science payload department or are tasked with one or two aerospace projects.

3.2 WHAT CAN BE SACRIFICED IN A SMALLER COMPANY

As I mentioned earlier, programs can take certain shortcuts in order to save time or money when designing or testing a small spacecraft – or doing anything for that matter; but every shortcut taken contributes to some amount of loss in precision or performance.

3.2.1 Testing Facilities

The first thing I will discuss is the need for testing facilities. Depending on the future of a program, it could forgo testing facilities altogether. For instance, if working on just the first project, most programs would be uncertain of their future. This case, which is very similar to the early years of Kentucky Space, the best financial decision would be to outsource testing facilities.

There are several different avenues for outsourcing facilities. Most universities already have some sort of clean room that could be used to assemble electronic parts and most Mechanical Engineering departments have some sort of machine shop that could fabricate parts that do not need extreme precision. It would be in a university program’s best interest to explore local opportunities like these because they will most likely be much cheaper, if not free, than outsourcing to another company or university.

If a university program does not have its own facilities available for testing, it could try exploring other universities in its geographical area. Most university facilities are
underutilized most of the time. Kentucky Space, for instance, is willing to share its facilities under supervision and reasonable circumstances (17). Larger universities are more likely to provide facilities for testing as well as contacts at other locations that could help.

If all other options are unavailable, visiting a larger company and using their resources is a viable option. Quite a bit more expensive than previous options, there are NASA facilities in all corners of the United States that would be willing to loan time of their testing facilities again under supervision and with reasonable circumstances. Even non-aerospace companies have options to explore. Local to Kentucky Space is a Lexmark facility that has antenna testing facilities that are suitable for small spacecraft.

For teams such as Kentucky Space, however, which are interested in fostering a long-term growth-oriented space program, independent investments in infrastructure such as thermal vacuum chamber facilities and clean rooms, can be beneficial.

### 3.2.2 Testing Strategies

Most small spacecraft such as CubeSats are secondary payloads on larger missions. This is unavoidable due to the large cost associated with sending them into orbit. It is much more cost efficient to launch as a secondary payload on a larger mission in which case you would be replacing ballast and subsequently paying much less for a ride into orbit (18).

This inevitable situation leads to a smaller program conforming to someone else’s scheduling constraints, which means delivery dates will be months in advance of the actual launch. So, the question remains – What testing will be required for a spacecraft in order to fly and what can be bypassed in order to save time and money and deliver on time?

Unfortunately, since launch providers require mandatory environmental testing of secondary payloads in order to protect the primary payload and launch vehicle, you are limited here to foregoing some of your own testing that may not be required by the launch provider. For KySat-1, there was an extensive testing platform put together in order to test each and every aspect of KySat-1 from every line of code to every nut and
bolt used. However, this may not be a feasible option for every program. In the case of Kentucky Space and KySat-1, there were several setbacks and delays in the launch provider’s timeline that allowed for every test case to be performed. This will not always be the case.

3.3 **What Will be Needed in Any Program**

As I mentioned early, as a secondary payload, most launch providers will require a certain amount of environmental testing to be performed before you can be integrated into the launch vehicle so they are sure you are not a liability to the launch vehicle or the primary payload.

3.3.1 **Vibrations and Thermal Bakeouts**

The two most important environmental tests that launch providers are concerned with are vibrations and thermal bakeouts. Therefore, obtaining access to facilities that can provide these services is definitely a requirement for a small spacecraft program.

Different launch vehicles will provide different environments during launch. For instance, the case study, KySat-1, was shaken to one set of vibration levels that corresponded to the Taurus XL launch profile, while hardware from another Kentucky Space project, ADAMASat, was shaken to a completely different set of vibration levels because it flew on a Terrier-Improved Malamute. The same goes for thermal bakeouts. Where one launch vehicle may require a payload to bake in a thermal chamber for one hour at 70°C, another may require a bakeout period for two hours at 60°C.

3.3.2 **Clean Space**

The ambient air outside in a typical environment contains 35,000,000 particles per cubic meter that measure greater than 0.5μm. This number of particles can cause hazardous effects to microelectronics such as shorting or opening a circuit, eroding away at a coating, causing buildup of loose particles that can shake loose and damage a circuit, and several other adverse effects (19).

Although an actual clean room could help foster the cleanliness of electronics and prevent the possibility of failing an off gas test, one is not exactly necessary for smaller programs. If the clean room option is not taken, however, any program will still want a
“clean space” free of clutter and laboratory traffic. Somewhere in the back of a lab or office that doesn’t get used often should be chosen in order to mitigate accidents. The “clean space” should be equipped with static preventative gear, for example, static straps, mats and tools. Kentucky Space relied on a “clean space” for the first few years of operation because they were busy procuring other facilities at the time.

Figure 37 - Clean Space used to build KySat-1 Engineering Model

3.3.3 Organized Teams

Depending on how large and how specialized a payload group is, there should be strong consideration for organized teams. If there are more than ten or so members designing and building a spacecraft, the group should be split up into smaller teams such as software design, software testing, hardware design, mechanical design, ground operations, antenna design, payload science, and so on. When forming teams, it would be beneficial to do so, based on the strengths of the employees/students. If there aren’t any
computer science/software students on your team, it would not be very beneficial to have a software design team because no one group will be better equipped for the task than another. The whole idea here is to lessen the burden of some tasks on the whole and place those tasks on a smaller more equipped group that can handle the task in a more efficient manner.

If there is a significant number of members on any given team, assigning a team leader to help keep that sub team organized is also a very beneficial plan for success. Just as breaking a larger group of students/employees into a team helps focus overall productivity, assigning team leads helps focus individual productivity by coaching the team and providing goals and objectives set by the main payload group (20).

In a smaller atmosphere, you have to make a judgment call as to whether or not to break a program into teams to represent smaller subsystems of the project. NASA however has a clearly laid out plan of leadership developed in order to maximize personal production through a system similar to a chain of command. At the top of the Leadership and Management Development Model are the Executive and Manager positions. This is where most of the heavy decision making begins. Below these positions are the First Line Supervisor, Team Leader, and Influence Leader. Each position has decreasing decision making ability and increasing project output as well as team member interaction. This model was developed by NASA over years of research and validation. It works because they have the personnel to foster the various links in the chain of command. However, for a smaller company, this extravagant model may not be necessary (21).

### 3.4 Validating Testing Strategies on Supplemental Missions

#### 3.4.1 Kentucky Space Balloon-1

The first project I worked on from start to finish was the first Kentucky Space Balloon. The smooth flight of the balloon and decent of the parachute allowed us to ignore most vibration testing on the balloon payloads. Our biggest worry dealing with vibrations was how the bottom facing camera would react to landing on the ground after its flight. In order to alleviate the shock of landing on a camera lens, the bottom side of the balloon
payload was equipped with an inch thick foam block to pad the landing and prevent cracking the camera lens.

Thermal testing on Balloon-1 was a much simpler task than the testing suite performed on KySat-1. Instead of a cycle that our payloads would have to endure over and over, simulating an orbit, the balloon-1 payload only had to be tested at extremely cool temperatures in order to prove they could endure the coldness. The high altitude balloon was expected to reach altitudes of 80,000 to 110,000 feet (24-34km). You can see from Figure 38 - Average Temperature Versus Altitude that the payloads would experience temperatures down to -50°C.

![Figure 38 - Average Temperature Versus Altitude](image)

The testing on the electronics package of the payload proved that it and the batteries in particular would endure at least a 5 hour flight of the payload, which was much longer than the anticipated 3 hour flight time. Thermal testing on the cameras produced condensation on the camera lenses. However, this was attributed to not allowing the temperature inside the chamber to equalize completely before opening the chamber door. The test was redone allowing the temperature inside to equalize with the temperature outside and there was no condensation in the second test.
In order to test our ground stations and chase team equipment, two weeks before the launch, the team loaded the balloon payload into the back of a truck and drove around the city of Morehead, KY while a ground station on top of a building followed the payload’s radio signals. The ground station successfully used the equipment to map the GPS signals transmitted to them over the payload’s radio and successfully mapped the trip around the city (with the exception of a particular area covered with trees that prevented the transmission).

3.4.2 Garvey Prospector 12-A Payload – IMU

The next mission Kentucky Space worked on was an IMU payload for the Garvey Prospector 12-A sub-orbital sounding rocket. Due to the short mission duration, thermal testing was ignored for this mission. The length of time the payload would spend in a reduced temperature environment was insignificant for the temperatures it would see.

The Garvey P12-A IMU payload was an extremely low-cost, quick-turnaround mission for Kentucky Space. The mission, from brainstorm to delivery, took less than six weeks. Thus, we didn’t have the time necessary to perform the vibration testing on the payload using our own system, whose setup would require at least a week. Also, the cost to outsource the vibration testing was outside of the mission budget. So regrettably we had to forgo the vibration testing. Instead, we focused what little time we had to test the system on software acceptance testing.

The IMU payload was required to “turn-on” and begin taking measurements based on an incoming signal from outside the system. To perform our testing, we had to create switch to simulate turning on the system and connect it to the payload. Measuring the performance of the system was split into two parts. First we tested the 3-axis accelerometer system by turning the system on and positioning the payload so that each accelerometer would read 1G while the other two would read 0G. The data from the SD card after the tests confirmed that the accelerometer system was working properly.

The second half of the acceptance testing required the team to validate that the 3-axis gyro system. This test was a little more difficult. The team could not simply position the payload and study the results. In order for the gyros to produce data, the team had to
place the payload in a chair and spun at approximately 1Hz. This test, although creative, was not ideal. However, considering that only two days were left for testing before delivery, it was the cheapest and quickest method of confirming that each gyro was operating normally.

3.4.3 ADAMASat
The main goal for the SOCEM mission was to space-qualify the antenna cutting mechanism for the KySat-1 orbital CubeSat. In order to build our confidence that the testing platform that will perform this qualification in space would work properly, the team had to sufficiently test the system here on Earth but in as close of an environment as possible to that of space.

To simulate the environment of space, we inserted the payload section of the CubeSat into the thermal vacuum chamber and reduced the vacuum and temperature in order to simulate the space environment. The thermal vacuum chamber is setup with a harness that allows us to send electrical signals inside the chamber. Once the appropriate levels were reached, we used the harness to turn the system on by shorting the footswitch of the satellite that keeps it turned off while inside the launching mechanism. During the test, the experiment ran and successfully cut all four lines holding the switches closed. We also successfully received the transmission from the payload confirming those results.
Antenna testing was performed by taking the satellite to the top of a large hill and adding a significant amount of series attenuation to the antennas that simulated the distance between the satellite and each ground station. This test proved rather unsuccessful. Somehow, there was a mistake in the originally calculated link budget and the ground stations that were selected did not have enough gain to receive the signal and properly decode the packets. Also, the tree line may have caused some signal disturbance. This problem was solved by creating a higher gain antenna capable of performing to the specification of the new link budget. The test was repeated with the newly created ground station and was successful.

The 2U CubeSat went through two sets of vibration testing. The first set of vibrations took place in the Kentucky Space lab. The payload was shaken to see if it was mechanically sound for the mission’s extreme vibrations. The second set of vibrations occurred at the Wallops Flight Facility in Virginia. After the CubeSat was fully integrated into the Rocket, The rocket performed an array of several different tests; the first of
which was the vibrations testing. The NSROC team shook the entire rocket payload section to the levels that were expected for flight.

CubeSats are normally deployed on orbit from a launch vehicle that isn’t spinning. The sub-orbital rocket in this mission, however, had a predicted rotation of about 3-5Hz. The centrifugal force created could prevent a payload inside the launching mechanism from deploying. In order to overcome this obstacle, the team had to make sure the launching springs were much stronger than normal, as well as move the center of gravity of each payload closer to the door so the centrifugal force would help the payloads escape rather than prevent them from escaping.

The next day, The NSROC team put the entire rocket onto a table that would spin the rocket in order to determine if the rocket was appropriately balanced. Once the balance was approved the rocket was sent a signal that allowed the door to deploy and send our dummy payloads shooting out onto a padded wall. This test gave the team reasonable assurance that the launching mechanism would work properly.
4 HURDLES FOR SMALLER PROGRAMS

In this section I want to cover several hurdles that smaller programs face that prevent extensive, long term projects from being feasible. This lack of capability to foster long term projects directly affects the funding available and in turn makes most university based programs nothing more than a training ground for the future engineers of larger companies. In discussing the several hurdles that university based programs endure, I want to explore solutions that have the potential to turn university based research programs for space science into something more than a breeding ground for future employees.

4.1 MISSING EQUIPMENT OR RESOURCES

One of the biggest problems that university based programs are faced with is the lack of resources to complete a mission. The engineering model for KySat-1 was built in a “clean space.” Kentucky Space had no other choice at the time. Scheduling did not permit enough time to procure time in another clean room before testing had to move on. Since the University of Kentucky’s Space System Laboratory shaking facility did not have the appropriate software to run the levels covered earlier in chapter 3, the flight model of KySat-1 will have to be sent to Florida in order to complete vibration testing. Shock testing would have been a whole other problem to solve if it weren’t a package with the vibration testing.

If a university based program wants to fulfill a commitment to fostering a growth oriented program that is capable of producing results for not just quick turn-around projects but also long term programs and missions, then that program must begin to acquire the facilities and capabilities necessary to grow into a mature program. One of the goals Kentucky Space set for itself was to gain the ability to produce one CubeSat every
year. In an effort to meet this goal, Morehead State University began a complete overhaul of their space science program. Starting with the 21 meter dish, primarily used for radio-astronomy, in just a few years they added a 20 foot antenna, an antenna test and measurement range, an anechoic test and measurement chamber, an advanced computing facility, RF and electronics laboratories, and clean rooms (micro-nano laboratory, space systems development laboratory). All of these facilities are housed in the brand new Space Science Center, a 45,000 square foot, $15.4 million facility that was built in partnership with NASA to study space science research.

Figure 40 - Morehead State University's Space Science Center

Seventy miles west, at the University of Kentucky, Kentucky Space partnered with NanoRacks LLC to form a joint venture in order provide rapid and affordable access to science on the International Space Station. NanoRacks is a Houston-based aerospace company that, in the Fall of 2009, signed a Non-Reimbursable Space Act Agreement with NASA that provides a unique opportunity for NanoRacks to design, coordinate and
conduct research on the International Space Station (ISS) for itself as well as on behalf of national educational and commercial clients.

The revolutionary CubeLab standard will allow aerospace programs from all over to obtain rapid access to the ISS where their experiments can spend time in micro-gravity for thirty days. NanoRacks is a space proven technology and the University of Kentucky’s Space Systems Laboratory is already in the works for a new an improved version, NanoRacks 3, which will be a completely autonomously, pc-based system that will not require as much astronaut interaction.

![Figure 41 - NanoRacks 2, CubeLab 3 and CubeLab 4](image)

In order to foster the growth of this new program, the University of Kentucky has converted an old room of student offices and created a brand new CubeLab Operations Station. The CubeLab Operations Station is dedicated to the operational support of NanoRacks and CubeLabs onboard the ISS. The station consists of six flat panel monitors
run by three redundant computers each with the capability to coordinate information about the management, science, and testing of every NanoRacks and CubeLab payload.

Figure 42 - CubeLab Operations Station

In both situations, when Kentucky Space was presented with an opportunity to begin a longer term program to study space science, advancements and investments were made, in facilities in particular, in order to foster that growth. Facilities are not only the most important asset in order to foster long term growth for a program, but they are also the most expensive asset. Facilities require a large initial investment to acquire. So where does an up-and-coming program get the money to invest in facilities for the future?
4.2 SUPPLEMENTAL PROJECTS

Cal Poly began their research in CubeSats over a decade ago. It wasn’t until years later that the concept began to emerge as a worldwide topic of interest. Kentucky Space began in 2006 as an embedded systems oriented team from the University of Kentucky and a Space Science oriented team from Morehead State University. Several years and partnerships later, the program is now on the horizon of a new age in space research with the NanoRacks program.

For a university based program, it is virtually impossible to just start a long term oriented program like those discussed here. It took several years of mistakes and milestones before anything of that nature was achievable. Sub-orbital and near space projects are quick turnaround, low cost missions that can help supplement the growth of a program.

Several smaller missions that help supplement some sort of flagship mission are critical in getting attention from the media. The more success a program creates for themselves, the greater opportunity they will have at receiving private or government grants. Kentucky Space spent time and resources on several side projects, while maintaining the flagship mission, KySat-1. The first mission, Space Express failed to reach altitude and thus didn’t receive the press that was expected. Balloon-1 was an extremely successful mission in terms of both the press and outreach. Regarding the Garvey payload built by Kentucky students, not all aspects of the mission were a complete success, but the payload designed by the SSL worked just as designed. SOCEM was a completely successful mission that received quite a bit of press. Each of these missions helped bolster the confidence of the Kentucky Space team as well as secure funds for future missions from the state as well as other partners in the consortium.

Another advantage of the supplemental projects for programs is that they help young engineers grow into mature workers that will sustain the program for years to come. Most undergraduate students understand the theory behind systems, but have little experience in the design, build or test process. It takes time for these students to learn the skills of space systems design. So, once team members learn the trades, all is well right?
4.3 **Team Member Turnover**

The only problem with growing young engineers into mature workers is that they eventually graduate. The average graduate student finishes classes in two years and a thesis or project in another semester. What this means is that by the time an graduate student enters a program, takes the time to learn about the program, learn what their role will be, and actually participate in a mission, it could be a year or more into their graduate careers. This is a big problem. By the time a graduate student is acquainted well enough with the program to help teach the new students, they are almost ready to leave the program. Keeping experience in a program is an extremely difficult thing to do.

Recently Kentucky Space has resorted to recruiting more undergraduate students to participate in the program. At first, this effort was an experiment to see if the overall experience would pick up throughout the program. Due to the success of the experiment, the team even started recruiting freshman. Although freshmen have even less experience – that is, a freshman electrical engineer likely doesn’t even have a basic knowledge of circuits – the idea of recruiting younger talent was still an overall increase in knowledge and experience retention. Learning things such as documentation standards and program history can be one of the toughest things for newcomers and can be learned regardless of preexisting technical knowledge. In turn, since having hands on experience makes learning the theory behind things easier, the undergraduate recruits will do better in their classes due to the knowledge and experience they learn in the lab working on aerospace projects.

Knowledge retention can be a problem regardless of the countermeasures taken. Another method for retaining knowledge is to hire a research associate to the university. This assures that you will have a permanent employee to act as program manager and help coordinate the efforts of the team. Knowledge retention is difficult when every four years the team turns over completely with all new students. With the research associate the source of the knowledge changes much less frequently which can help minimize the effects turnover rates have knowledge retention.

As programs grow, another big problem that has to be faced is coordination efforts. Even with a program manager to coordinate engineering efforts, the task of coordinating
meetings, travel, conferences, presentations, students’ classes, and so on can be a
extremely daunting task. Kentucky Space recently acquired an assistant to the team that
has been a great help in coordination efforts. Now even organizing websites and
maintaining team member contact information is a one-man effort. In turn these tasks are
done much more efficiently.
5 DISCUSSION

5.1 LESSONS LEARNED

Kentucky Space has had its fair share of success in the last five years. However, at times, mistakes were made. It’s been said that mistakes are only truly costly if they are repeated. So, I thought it would be beneficial to discuss some of the more costly mistakes made while designing and testing spacecraft by programs and how they could have been prevented.

5.1.1 Documentation and Organization

Working with Kentucky Space was a thrill. It was a fast-paced environment and I learned something new nearly every day on the job. The majority of what I learned about the program was through its documentation called the wiki. The wiki was a documentation and organization tool similar to Wikipedia. It was a great tool to organize thoughts, documents, and mission planning. The problem was that there were a lot of holes in the documentation that I had to have filled in by other employees who worked before me. There was no real documentation policy other than “everything is supposed to end up on the wiki. If it’s not on the wiki, then it never happened.” However, after years of improper upkeep, the wiki became an unorganized cluster of ideas. There were pages and stubs of pages that were incomplete, in the wrong place, out of date or even contained incorrect information. If there had been a better policy for documenting work, procedures, equipment lists, etc., it would have increased the overall effectiveness of the wiki.

NASA has developed an effective document control system that is widely used called NASA Headquarters Library (22). It is an extensive archive of NASA publications. There are also a few other document databases: NTRS (NASA Technical Report Server) (23), NASA GALAXIE (only accessible by NASA employees and contractors) (24), and also the Scientific and Technical Information databases (25). NASA’s extensive documentation databases are certainly great examples of how to set up and organize a document control center. Electronic documentation is the best way to go since it can be downloaded from anywhere. The only disadvantage is keeping track of written or signed
documents. Larger documents will take a lot of time to have to be scanned into digital format to preserve them.

Kentucky Space decided to begin a video documentation library to help train new recruits on procedural activities such as how to run the thermal vacuum chamber or proper soldering technique. It has proven to be a more effective method of passing on procedures and techniques that were confusing to follow from instructions written on paper.

Another area where Kentucky Space lacked proficiency in the beginning of the program was lab organization. Tools and lab equipment were rarely returned to where they belonged. Most tools never had a place where they belonged in the first place. Recently, improvements have been made to the lab in order to help organize cabinets into mission hardware, equipment shelves, and toolboxes labeled for particular tool sets. These improvements in tool and equipment organization were accompanied by adding a dedicated soldering station, a reflow oven, and the CubeLab operations station. These improvements will help streamline the CubeLab and NanoRacks programs in the future.

5.1.2 Handling Procedures
When building a satellite, careful precautions should be taken to avoid damage. However, completely eliminating the possibility of accidents occurring is impossible. The proper handling procedures should prevent most accidents. Kentucky Space has very few procedures documented for its missions. Even the procedures that were documented were not ideal. Some were written in notepad with little detail. Some were even written in shorthand. Handling procedures should always be descriptive and accurate.

It is regrettable that a university lab may not be very well equipped to work on projects with the same care that NASA and such companies give to their projects. The funding and expertise are just not available. But, some actions are inexcusable, such as carrying a payload from one lab to another, in one hand, with its documentation in the other, while talking to a colleague, in a crowded hallway. This is definitely not a very cautious approach to transferring a payload from one lab to another. I’ve seen several instances of
distraction in the last two years that could have caused major setbacks; and in some cases did.

One day, KySat-1 was sitting on a foam block that protected it from scratching the solar panels. Because it was sitting too close to the edge of the desk and a hurried employee stood up, bumped into the CubeSat and knocked it from its foam block onto the desk. The System Support Module (SSM) was damaged beyond repair and a replacement had to be made which required retesting the new module and the integrated payload. Had that payload been further from the edge of the desk, the employee not been so hasty around payload hardware, and proper handling procedures were implemented and enforced, this incident may have been prevented.

Handling procedures are a necessary precaution when building spacecraft or anything with high value. Mitigating risk of unnecessary accidents or mistakes ensures that time and money do not have to be wasted fixing the problem.

5.1.3 Limited Access
Lab resources are hard to manage even with a decent document control system to help the process. In order to prevent tools from “walking off,” there should be a system in place to allow limited access to particular laboratories. The newly designed CubeLab Operations Station has access limited to only CubeLab Operations staff. This was a NASA security requirement given to us by our partners in the NanoRacks program before they would allow access to the resources that will allow us to work with the CubeLabs and NanoRacks.

There are plans for the future to allow only a certain few people access to the clean room area where the flight hardware is kept. Currently, all flight hardware is kept in a locking cabinet inside the clean room. This should be helpful in protecting hardware from unauthorized personnel. However, since so many different people work on different projects, too many people have access to the locking cabinet. This, in turn, defeats the purpose of limiting access to flight hardware. In an ideal world, each project would have its own locking cabinet to ensure that each group of engineers would have access to only their hardware and nothing else.
As well as limiting hardware access to certain staff, Kentucky Space requires that each engineer be accompanied by two people whenever working with flight hardware. One person is to sit and watch. This person will redundantly make sure everything is done according to the procedures and checklists. The third person should be taking pictures. Photo documentation creates a record of what was done and facilitates solving problems should they occur. It also provides good shots of the hardware for future reference, media and outreach.

5.1.4 Analysis and Avoiding the Testing Bottleneck

As any proficient programmer will tell you, no software can be completely bug-free. Every piece of software uses other software, drivers, compilers, and a particular set of hardware which if changed, could produce a bug (26). Since no software can be bug-free, what is the point of software testing? Kentucky Space took several different approaches to software testing – namely, those described earlier in chapter 3. However, even those methods would have left KySat-1 tested incompletely. Time was running short before the flight model had to be built and tested for mechanical integrity.

At this point, the satellite was in a perfectly working order and all systems have been tested and were working properly. However, bugs were still being found on a weekly basis. So there was fear that there could be a bug in a critical module somewhere. From here, the software team decided to avoid the testing bottleneck. What that means is that the team decided to focus the efforts of the testing on the mission critical parts of the software such as communications, system restore, and system safe mode operations. Completely testing this portion of software would ensure that the satellite would always be alive and able to communicate with a ground station. Next, the software team focused on removing bugs from software that dealt with the file system and also software that checked for errors and failures. This would ensure that all our errors and failures were correctly logged. In turn, Kentucky Space would be able to use the earth ground stations to properly acknowledge errors that occurred on the satellite.

After each successful round of removing bugs and testing components, the software team expanded its search to less critical sections of the software. In the end, the software team was unable to fully test all components of the satellite software because of time
constraints, but since time wasn’t wasted fully testing sections of code that were less critical, the satellite will survive through the projected mission lifetime with reasonable assurance of operating properly.

5.1.5 Equipment Hour Logs

Accidents happen. KySat-1 had a few mishaps that may have put a hold on the mission altogether. In some cases, there was uncertainty as to what caused the problems. One strategy that could have helped Kentucky Space was to keep a time log of every piece of hardware used. The fact is, electronics wear down over time. Knowing the lifetime of hardware is key to understanding how long a mission will last.

NASA uses a system of logging every minute a piece of hardware is being used. This ensures that if a piece of equipment fails, it can be determined whether that piece of hardware broke early or late in its life. If a piece of purchased hardware breaks early in its life, then a program with proper documentation could return that hardware to the vendor for a free replacement. A piece of hardware in Kentucky Space’s possession broke. There was no apparent cause. I believe that piece of hardware sat in a cabinet without being used from the time it was acquired until the day it was installed and malfunctioned. However, since there was no record of how much that hardware was used, the program was forced to settle for buying a replacement piece of hardware.

5.2 Future Missions

As a student led program, Kentucky Space has endured its share of mistakes in the last five years. Mistakes are beneficial as long as they are used to help your program. If documented properly and discussed with the team, mistakes can help a program learn what they are doing wrong and how to improve. Is Kentucky Space repeating the mistakes they’ve made? There is no room to repeat mistakes that have already been made. Another huge advantage of the side projects is that the processes required to run a space systems laboratory are refined and perfected. There are quite a few missions coming to completion in the next year for Kentucky Space.

Since the first NanoRacks assembly has been installed into the ISS, and the second assembly is onboard ready to be installed, Kentucky Space will be focusing its efforts on
CubeLab Operations. In November, KySat-1 will be launched and the ground station operations will begin for the orbital mission. Also this year, Balloon-2 and Balloon-3 will be completed. Next Year, another orbital mission will begin.

KySat-1 was designed to have a reusable satellite bus that can be used on future satellite missions. The first of three proposed missions that will use the reusable bus is the Polarization Observation Satellite (PolOSat). PolOSat, seen in Figure 43 - PolOSat Model, is a spin stabilized satellite that will study the polarization of bright gamma-ray bursts (GRBs). The data collected from PolOSat will allow scientists in Kentucky Space and partnering laboratories to better understand the models of radioactive mechanisms associated with GRBs as super-massive stars undergo collapse into black holes.
The next mission proposed to reuse the bus from KySat-1 is the Kentucky Outreach Satellite (KOSat). KOSat will be very similar to KySat-1 but will have upgraded functionality to make outreach a little easier and more enjoyable.

Finally, another mission that is proposed to reuse the KySat-1 bus is the Danjon CubeSat. The purpose of this 2U CubeSat is to measure Earth’s albedo. Using the four lunar telescopes surrounded by the magnetic attitude control system, seen in the payload section of the CubeSat shown in Figure 44 - Danjon Model, Danjon will measure the brightness of the dark side of the moon – This is the light reflected from the Earth’s albedo.

NanoRacks and CubeLab modules will become the next major focus of Kentucky Space after the launch of the orbital satellite, KySat-1. The CubeLab standard is a new, small form-factor payload standard for the International Space Station (ISS), similar to the CubeSat Standard, providing mechanical support, power, and data transfer capabilities for a variety of payloads. The system is designed in such a way that after the NanoRack platforms are installed in the ISS, only small payload modules need be carried to the station in standard Cargo Transfer Bags (CTB) aboard any of the existing and planned cargo vessels that service the station (e.g., Progress, ATV, HTV). At the end of the
operating life-span of a CubeLab module they can be disposed of in Progress vehicles or returned on Soyuz and DragonLab. Once the station is outfitted with the first two NanoRacks on 19A (STS-131) and ULF4 (STS-132), the ISS will have the capacity to operate 32 CubeLab modules.

Figure 45 - NanoRacks1, KyLab1, and KyLab2

With all of the experience that Kentucky Space has gained from interacting with various launch providers and integrators, it has an opportunity to become a dominant presence in the space research community. Similar to Cal Poly and the P-POD, Kentucky Space has become the liaison for any CubeLab modules requesting space on the International Space Station.
6 CONCLUSION
Kentucky Space has designed, tested, launched and operated seven experiments. With several more projects sitting on the shelf and in various stages of development, making sure that the design and testing processes used to perfect each spacecraft is a critical part of the program. As Kentucky Space grows and gains experience, it becomes even more critical that mistakes are not repeated.

Whether fostering a long-term goal oriented space science program or taking on a one-time project, having the ability to balance the cost, performance, and time spent on each project is extremely beneficial. Throughout this thesis, I’ve described testing procedures for software and hardware that Kentucky Space has performed on the case study KySat-1 and its various supplemental missions. The Kentucky Space team learned quite a bit about how to run a space science program including design procedures, testing techniques, organizational techniques, and even a little about the hurdles for a space science program and what it takes to succeed.

With the testing procedures, lab equipment and facilities ready to handle CubeSats, CubeLabs, and payloads for near space, sub-orbital and orbital projects, Kentucky Space is ready to open a whole new chapter. Using the research gathered and first-hand experience given in this thesis, small spacecraft programs such as Kentucky Space can continue to grow and continue producing results that university research programs has brought to the space science community for years to come.
ACRONYMS

ADAMASat: Antenna Deployment And Monofilament Actuator Satellite
AMSAT: The Radio Amateur Satellite Corporation
ATV: Automated Transfer Vehicle
Cal Poly: California Polytechnic State University
CDHS: Command and Data Handling System
CDS: CubeSat Design Specification
CPE: Kentucky Council on Postsecondary Education
CSA: Canadian Space Agency
CSTB1: CubeSat TestBed 1
CTB: Cargo Transfer Bags
EIRP: Effective Isotropically Radiated Power
ELaNa: Educational Launch of Nanosatellites
EPS: Electric Power System
ESA: European Space Agency
GRB: Gamma-Ray Burst
HTV: H-II Transfer Vehicle
ICD: Interface Control Document
IDEA: Intelligent Dependable Embedded Architectures
IMU: Inertial Measurement Unit
ISS: International Space Station
K-1: KySat-1
KCTCS: Kentucky Community and Technical College System
KOSat: Kentucky Outreach Satellite
KSEF: Kentucky Science and Engineering Foundation
KSGC: Kentucky Space Grant Consortium
KSTC: Kentucky Science and Technology Corporation
LEO: Lower Earth Orbit
MISRA: The Motor Industry Software Reliability Association
MoSU: Morehead State University
MuSU: Murray State University
NASA: National Aeronautics and Space Administration
NSROC: NASA Sounding Rocket Operations Contract
NTRS: NASA Technical Report Server
PIM: Payload Interface Module
POD: Picosatellite Orbital Deployer
PoOSat: Polarization Observation Satellite
P-POD: Poly Picosatellite Orbital Deployer
SOCEM: Sub-Orbital CubeSat Experimental Mission
SSL: Space Systems Laboratory (University of Kentucky)
SSM: System Support Module
STEM: Science Technology Engineering and Math
STS: Space Transportation System
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<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
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<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
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<td>University of Kentucky</td>
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<td>UL</td>
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VITA

Jason Robert Bratcher was born on October 17, 1985 in Louisville, Kentucky. He completed the requirements for his bachelor of science in electrical and computer engineering in May of 2008 at the University of Kentucky. He was a graduate research assistant for the Space Systems Laboratory at the University of Kentucky for the duration of his master’s degree. He was a contributing author for an Institute of Electrical and Electronics Engineers (IEEE) conference paper.