TJREVERB

A High School CubeSat Story

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***Abstract*— High school CubeSat programs inherently face a unique set of challenges. Students enter high school with limited knowledge about programming, electronics, computer-aided design, and systems engineering. They work as volunteers and must balance time between the satellite team, school work, and other personal and academic commitments. Additionally, the team's most experienced members graduate after four years, creating a constant struggle to maintain club knowledge. Finally, high school labs are not set up for CubeSat development, with restricted building hours and school policies significantly slowing progress. The 2U CubeSat developed by students at Thomas Jefferson High School for Science and Technology, called the Thomas Jefferson Research and Education Vehicle for the Evaluation of Radio Broadcasts (TJREVERB), serves as a case study to explore these problems in depth and discuss their potential solutions.**

We found that mentors are crucial in addressing students' lack of expertise by providing guidance on technical problems and project management organization. Proper development procedures and documentation also helped alleviate the difficulty in maintaining continuity amid a four-year member turnover. Finally, a strong program culture helped increase student engagement and participation despite the time commitment challenges faced by high school students. We hope that the lessons learned on TJREVERB can provide other high school CubeSat teams with insight into navigating potential roadblocks during development to further streamline the process of educational CubeSat development.

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1. INTRODUCTION

Since the launch of the first high school developed satellite, TJ3Sat [1], there has been an increase in both the number of high school CubeSat programs (HSCPs) and the complexity of the satellites they can launch [2]. Programs have moved on from proving that launching a satellite as a high school is possible to conducting real scientific research in orbit. Driving this shift are knowledgeable mentors from the aerospace industry who led technical work, plug-and-play satellite kits that greatly reduce the technical complexity of launching a satellite, and direct partnerships with universities and corporate entities who handle much of the mission's design and many of its technical challenges. These resources have assisted HSCPs by simplifying the student role in CubeSat development [2]. The Thomas Jefferson Research and Education Vehicle for Evaluating Radio Broadcasts (TJREVERB), however, departs from this trend in the small satellite field by favoring a more student-centric and student-driven approach. Thomas Jefferson High School for Science and Technology (TJHSST) students designed the mission goals, selected commercial hardware components, developed computer-aided design (CAD) and assembly models, wrote and tested custom flight software, and CNC milled custom components as required. Students were also responsible for most organizational aspects of the project, from project management to searching for funding.

In this paper, we share the story of TJREVERB's seven-year development and highlight the largest issues the team faced in accomplishing their goals. We then discuss the team's methods of addressing those issues and put forward potential avenues for future research into HSCP organizational practices. We hope that the information in this paper can allow other HSCPs to preemptively understand potential roadblocks in CubeSat development and design solutions for those issues before encountering them during development.

2. OUR STORY

TJHSST's second satellite, TJREVERB, is a 2U CubeSat that began as a student-initiated research project in 2016. Its goals included testing the performance of an Iridium 9602N Short Burst Data modem as a communications system for satellites, producing documentation about how high school CubeSat organizations can best operate, and educating the next generation of engineers and leaders in aerospace. The team's original proposal was very ambitious for an HSCP: they aimed to compare the performance of three different radios in space (Automatic Packet Reporting System, S-Band, and Iridium), optimize solar energy generation by using a magnetorquer to control attitude, and track the satellite's position over the Earth in real time with GPS. Components were a mix of space-grade hardware, such as a Clyde Space Electrical Power System (EPS); Commercial Off-The-Shelf (COTS) hardware, such as the Raspberry Pi Zero flight computer; and custom components, such as the flight computer's interface board. These were not explicitly designed to function together and later led to hardware incompatibilities that stalled development.

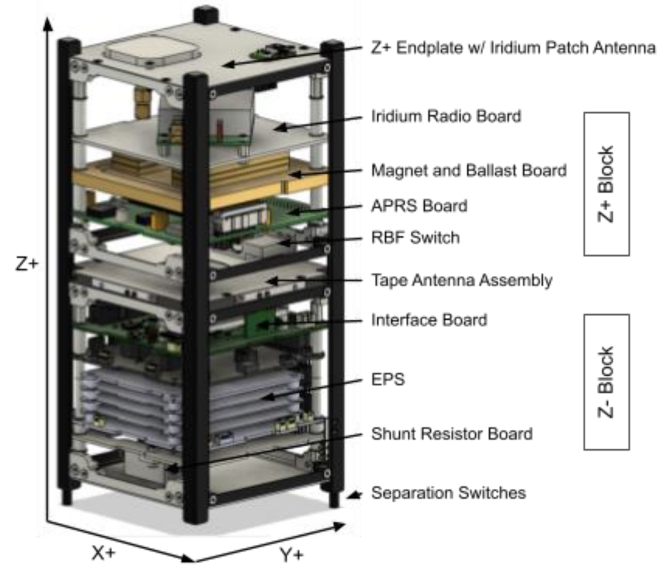

Figure 1. TJREVERB Final CAD model

Work on the satellite began slowly in 2016. Due to the amount of paperwork required to launch a satellite, it took one year to secure the required forms, approvals, and funding. Launch costs were covered by NASA's CubeSat Launch Initiative (CSLI) grant [3], which approved TJREVERB for a NASA-sponsored launch free of charge. Hardware costs were largely sponsored by the Thomas Jefferson Partnership Fund, a 501(c)(3) organization whose purpose is to support research at TJHSST. Corporate sponsors also donated a few components and provided additional funding, such as an EPS from Ragnarok Industries.

Technical work started in Q1 2017. The experienced seniors responsible for starting the project had already graduated high school, leaving inexperienced underclassmen with ambitious mission goals and hardware that they did not know how to use. It immediately became apparent how difficult the project would be. Due to the team's enthusiasm and lack of experience, they did not appreciate the scope of the project and how much work was required to complete the mission. As NASA's deadlines approached and work progressed slower than expected, questions arose about TJREVERB's ambitious and complex mission goals. This led to the gradual reduction of mission scope, first by removing the S-Band radio, then the GPS, and finally the Attitude Determination and Control System, which included the magnetorquer. Despite these cuts, the mission's initial readiness date in Q4 2017 passed without the project being anywhere close to completion.

Nevertheless, in 2018, the team started assembling a fully wired flat layout of the satellite's hardware (known as a FlatSat) and tested the radios using a weather balloon. Assembling the FlatSat proved problematic; due to poor systems engineering, the Iridium modem and APRS radio used RS232 and UART respectively, while the flight computer had one UART port and one USB port. This caused a year long delay due to confusion regarding the serial converters needed to connect them properly. The team ordered new parts and experienced manufacturing delays. The delays led to multiple deadlines being missed, and to repeated underreporting of the project's timeline. The situation improved in Q2 2019 with a turnover in the project's faculty sponsor. In Q3 of 2019, expert mentors with project management and CubeSat building experience were brought in to restructure and reorganize the project. The mentors helped to get the FlatSat functional and started working with students on flight software.

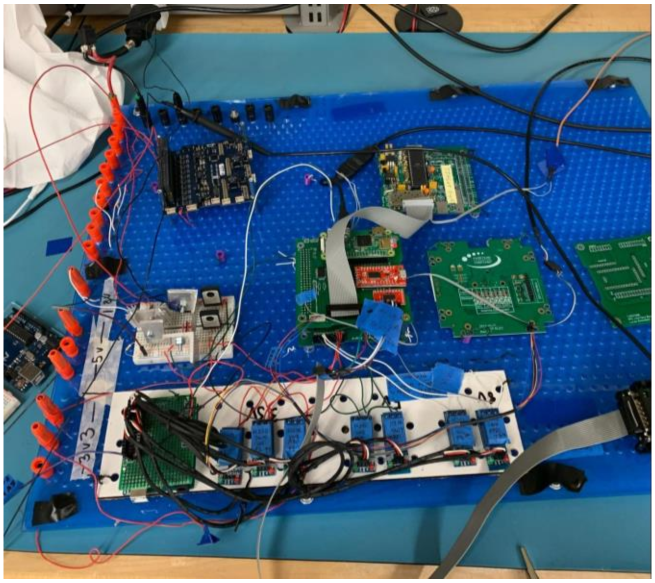

Figure 2. TJREVERB FlatSat circa. 2019

However, the COVID-19 pandemic shut down TJHSST in Q1 2020 and made it impossible for the team to access the hardware. This effectively stopped all work on TJREVERB, and the team's senior members, who were the last people on the team to be present at the project's initiation, graduated without having an opportunity to pass down their knowledge. This left the remaining members with little hope that the project would ever be completed. At its lowest point, the number of active members on the team was in the single digits. After 1.5 years of COVID-19 induced hiatus, quarantine protocols were lifted and the team was able to access the lab space to resume work on TJREVERB. NASA extended the CSLI grant's expiration date to Q2 2022, but made it clear that the deadline would be pushed back no further, leaving just one year for the team to finish the satellite.

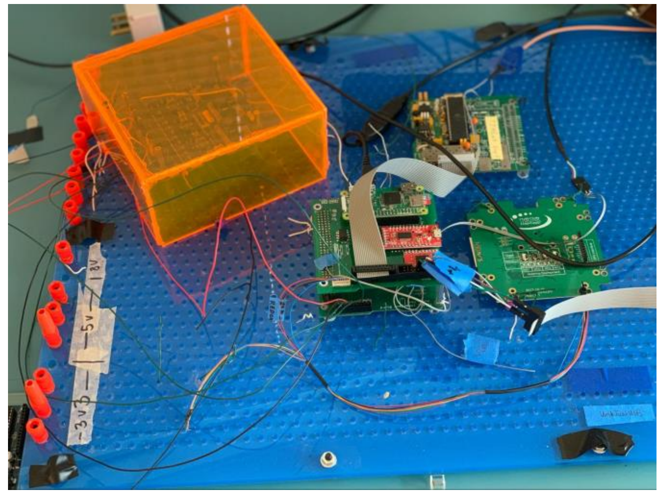

Figure 3. TJREVERB FlatSat circa. 2020

The new generation of students managed to break from years of historical delays and failures. The past group of students' primary focus had been on completing the project as fast as possible with the intent of getting a satellite into space, so documentation had never been a high priority. Consequently, the pre-COVID team had left very little documentation behind about the work they had done. Because contact with the previous team had been cut off so suddenly, the post-COVID team also did not fully understand what work had been done and what work was left to do. Because of this, the team opted to lay a fresh foundation by redoing much of the previous team's work. The electronics team reverse-engineered the FlatSat layout using the manufacturer's documentation, and from there developed their own interface board for the flight computer. The software team examined the poorly documented code and decided to rewrite the flight software with documentation and readability as priorities. The CAD team found that previously-machined components were outdated and of poor quality, and thus remilled all the custom hardware with better tolerances. The team also made major changes to the mission goals and concept of operations, addressing problems with TJREVERB's feasibility and timeline. Through thousands of hours of collective work, the project went from design changes to development to testing to final assembly. The team conducted a successful vibration test in Q2 2022, meeting NASA's deadline for mission readiness, and delivered the satellite for integration with TJREVERB's launch provider that July. TJREVERB is scheduled for launch on the NRCSD 25 spx-26 ISS resupply mission in Q4 2022.

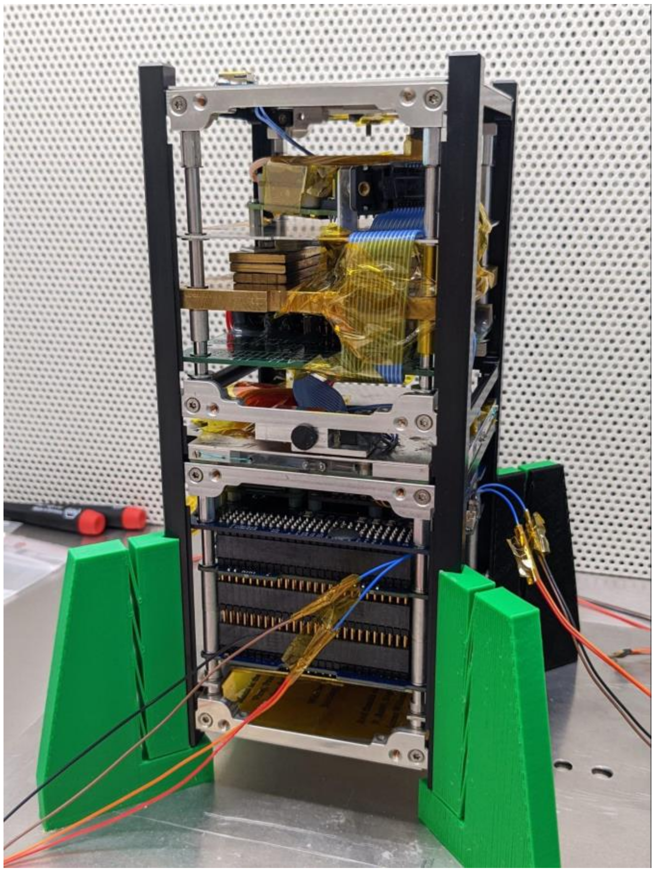

Figure 4. TJREVERB Final Assembly without Solar Panels, circa. 2022

3. PROBLEMS FACED

Throughout TJREVERB's story, the team faced a litany of problems that caused delays and threatened the existence of the program. Here, we summarize the team's experiences into four fundamental challenges with running a high school CubeSat program that we had to address to have a successful mission.

Lack of Expertise

The most glaring challenge with operating a high school CubeSat program is that its members have elementary knowledge and experience in engineering CubeSats. As freshmen, they are not expected to have any prior knowledge of electronics, programming, CAD, robotics or prototyping. Foundational courses such as Computer Science, CAD, Electronics, Fabrication and Manufacturing, and Robotics are taught at TJHSST as elective classes. However, specific skills essential to building a CubeSat, such as systems engineering and professional development procedures, are not taught in school.

Member Turnover

In addition to a lack of technical expertise, high school students graduate after four years. Each student has a short amount of time to learn CubeSat development and contribute to the project before moving on to study at a university. TJREVERB was a large-scale multi-year project, and the members starting the project were not the same as the members finishing it. This opened up the prominent issue of knowledge transfer, and figuring out how to pass down the knowledge gained and progress made by graduating seniors to future generations of students. Members' responsibilities became twofold: directly making progress on the CubeSat, while also training the next generation of students to continue their work in the future.

Time Constraints

Compounding these problems is the fact TJHSST high school students spend the majority of their time on their academics. For every student, 8 hours each weekday is spent in school, additional hours in commutes, and even more hours doing homework and studying for tests. Extracurricular projects such as developing a CubeSat must fit within the relatively small amount of time students have left, and often come at the expense of other personal time commitments. These time constraints encouraged short-term thinking, leading to lack of documentation, lack of organization, and a defocusing of efforts on new member training. Senior members spent their limited time contributing whatever they personally could directly to the project, instead of addressing issues like transferring crucial knowledge to enable future generations to continue their work. This led to the gradual reduction of the mission's scope until even central mission goals had undergone feasibility cuts by the project's final year. As the deadlines approached, the team started prioritizing basic satellite functionality over the scientific mission.

High School Working Environment

Developing TJREVERB at TJHSST differed from a commercial or university organization. TJHSST is unique for a high school because it has lab space for engineering projects. The students have access to an electronics lab, a robotics lab, laser cutters, 3D printers, and CNC mills for metal and wood working. TJHSST is also well funded, allowing students to purchase components and tools to support their projects. While the school provided support for their program, certain policies, such as the requirement for direct adult supervision while students are in the lab, greatly hindered development by limiting the amount of time that students could work. Faculty sponsors are not financially compensated for staying after school, and thus the team could only meet in the lab once or twice a week for a couple of hours. The limitations on time in the lab contributed to slow project development.

Additionally, school policy restricted what funding was spent on, even if it was money donated by an external organization. School policy does not allow funding to be spent on student travel, even for project-critical trips such as CubeSat delivery for final integration. To fund the trip, the team was forced to request special concessions to accommodate the project. While students had the ability to make purchases that supported the project, hardware orders took weeks due to the approvals needed by many layers of school administration.

Another unexpected obstacle while developing TJREVERB was the school's strict security measures on WIFI. Students used the Secure Shell (SSH) protocol to access the Raspberry Pi flight computer to remotely upload and test flight software. When the TJHSST WIFI security certificate system was updated in January 2022, it completely disabled the remote access features the team had set up, halting most of the flight software testing scheduled for that month. This significantly delayed the completion of the flight software, and testing would not return to its initial pace until the certificates were updated and access was restored.

4. SOLUTIONS

In this section, we seek to summarize some of the measures the team took to mitigate issues, explain the rationale behind those decisions, and evaluate their end result.

Mentors

Having expert mentors working with the team helped with many of the major issues. Some mentors helped address gaps in the team's technical knowledge, such as setting up the APRS ground station with poorly documented hardware that none of the students were familiar with. Others helped get the team through the process of launching a CubeSat, provided program management, organizational and financial support, and access to manufacturing and testing facilities. Others still helped connect with potential sponsors and guided us towards opportunities to get the word out about the team's work. Students were still responsible for the vast majority of technical work, but asking expert mentors when there was a difficult problem saved a lot of development time. Without that guidance, a successful launch for TJREVERB would not have been possible given the timeline constraints.

Documentation

Documentation has been a persistent issue throughout the program's history, often being set aside due to time constraints. However, it is crucial for recording technical specifications and designs of the project, and transferring experience and best practices to future generations. To address this shortcoming, the team took many steps to create a solid, project-agnostic foundation for future work. Chief among these was the creation of a CubeSat best practices GitBook which serves as a quick guide to the process of designing, building, programming, and launching a CubeSat.

In addition to writing documentation, the pre-COVID students did not appreciate the necessity of reading hardware documentation. To address this, post-COVID students made sure to read all the hardware manuals and documentation. This significantly increased developmental efficiency, as students would not have to waste time discovering on their own how hardware operated.

Proper Development Procedures

In addition to documenting, proper procedures for development were put in place. This ensured that work was reviewed by different people to catch design oversights. It became apparent that there had to be a clear development pipeline, from proposing features, to implementations, to finally testing and integration, so that members were not rewriting and debating in circles about new features. This was most evident on the software team. After years of poorly-documented and difficult-to-read software, documentation and clarity were high priorities for the team's rewrite. The team made extensive use of internal comments, standardized method headers, and high-level flowcharts to clarify and communicate their work. The team also held regular code reviews with most of the team present in order to minimize bugs and to brainstorm new features and better implementations. This system was possible due to the small size of the software team, which made a pull request system impractical and inefficient.

Program Culture

The program's strong culture helped solve the time commitment and technical knowledge problems. The team found that the most effective way to get students to willingly spend their free time on TJREVERB was to ensure that the project was enjoyable. When students actively chose to spend their time working on TJREVERB, it was no longer necessary to constantly press members about overdue tasks or missed meetings.

Another aspect of program culture was the tolerance for mistakes. Even the most senior members had stories of comical errors during their time as inexperienced new members, and this served to prevent a toxic and pressure-filled environment where members would quit. By recasting mistakes as something necessary for learning instead of something shameful, team members were free to make mistakes and learn from them without fear. In the long run, this created an environment where members were always curious and experimenting with new ideas, which helped development greatly. Avoiding rigid leadership structure, rules, and bureaucracy also gave members the freedom to be curious and explore their interests, feeding into the team's spirit of self-driven exploration.

5. CONCLUSION

While there were many obstacles surmounted during the project, such as member turnover, lack of expertise, time constraints, and the COVID-19 pandemic, TJREVERB was successfully completed within the NASA CSLI extended deadline. The successful completion of TJREVERB can be attributed to a dedicated team of exceptional students, strong program culture, proper development procedures, support from its faculty sponsor and mentors, and access to excellent lab facilities. It should be noted that while we had appreciable success applying these solutions to TJREVERB's development, some HSCPs have unique problems which cannot be solved by the solutions presented. Nevertheless, we expect that these solutions can still generalize to most HSCPs. We hope that the story of TJREVERB can serve as an inspiration to aspiring HSCPs, and we believe that the lessons discussed in this paper can allow future HSCPs to develop more ambitious CubeSat projects more efficiently.

6. FUTURE DIRECTIONS

While we discussed solutions using the team's experience on TJREVERB, future research using other HSCPs as case studies could identify more solutions to HSCP inherent issues. Additionally, implementing TJREVERB's solutions from the beginning of a project could serve as a better guide to the generalizability of the lessons discussed. Since both the organizational and scientific research dealing with HSCPs is still minimal compared to more established university and commercial sectors, we hope that this paper can spark more research and development of HSCPs.

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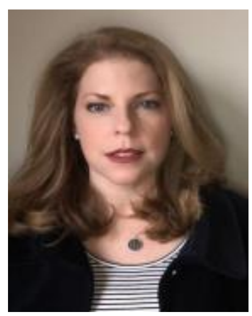
BIOGRAPHY

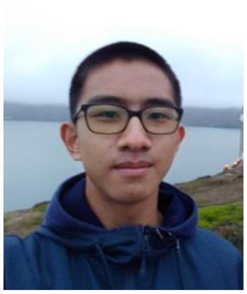
Khoi Dinh *is a student at Thomas Jefferson High School for Science and Technology (class of 2024). He is the Project Manager at TJ Space Program, the organization which developed TJREVERB. He is passionate about aerospace and plans to pursue a career in aerospace engineering and computer science.*



Kristen Kucko *received her B.S. degree from The Pennsylvania State University in 1996. She is currently the Director of the Automation and Robotics Lab at the Thomas Jefferson High School for Science and Technology in Alexandria, Virginia. She is the faculty sponsor of TJ Space, the high school's CubeSat team. She is also the principal investigator on TJREVERB. Prior to her current role, she worked at Apple. Additionally, she has worked as an application developer, test engineer and systems engineer.*

Nikhil Kalidasu *graduated from Thomas Jefferson High School for Science and Technology in 2022, and is currently studying Computer Science at the University of Texas at Austin. He was a member of the Thomas Jefferson Space Program for four years in high school, and led a team that completed a 2U CubeSat in 2022. He currently works in the Texas Rocket Engineering Lab, helping to build the first university-developed liquid-fuel rocket capable of reaching the Karman line. His additional interests lie in* *artificial intelligence, bioinformatics, and general systems engineering.*

Nicolas Makovnik *studies at Thomas Jefferson High School for Science and Technology ('23). Worked on TJREVERB 2U CubeSat as programming team co-lead with the TJ Space Program. Team lead for TJUAV team in developing autonomous fixed wing aircraft.*



Alan Hsu *is a senior at Thomas Jefferson High School for Science and Technology. He is a technical lead for the school's Avalon project, an autonomous aircraft that competes in the Student Unmanned Aerial Systems competition, and the Research and Education Vehicle for the Evaluation of Radio Broadcasts, a 2U CubeSat. He also worked on the school's weather balloon project, which was to collect 5G wireless signal strength data at various altitudes.*

Zichang (Amanda) Wang *attends 11th grade at Thomas Jefferson High School for Science and Technology. She is currently the program manager for TJ Space Program and Vice-President of TJ Rocketry. As a student, her goals include sharing her passion for space with others and exploring the possibilities of technology and scientific research. Amanda plans to pursue a major in Aerospace Engineering and Business.*

Lucas Ribeiro *is a student at Thomas Jefferson High School for Science and Technology. He worked as one of the leads for TJREVERB (Thomas Jefferson High School for Science and Technology Research and Education Vehicle for Evaluating Radio Broadcasts), where he was the main author of the research paper "Identifying and Overcoming Challenges in High School CubeSat Clubs," published under SmallSat conference proceedings in 2022.*

Jin S. Kang *(Suk Jin Kang) is an Associate Professor in the Aerospace Engineering Department at the United States Naval Academy, and serves as the Director of the Naval Academy Small Satellite Program. His main research area is in small satellite technology development and was involved in development of four micro-satellites and numerous CubeSat satellites. He received his B.S. from the University of Michigan, M.S. from Stanford University, and Ph.D. from Korea Aerospace University (KAU) in Aerospace Engineering. After working for General Electric for two years, Kang taught at Korea Air Force Academy, KAU, and Drexel University before joining the Naval Academy faculty.*