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Ut ProSat-1: A Platform for Testing Lightweight Deployable Composite Structures

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ABSTRACT

This paper details the mission, challenges during the design process, and lessons learned from the development of an upcoming 3U cubesat from Virginia Tech dubbed Ut ProSat-1, scheduled to launch in 2023 on NG-19. This student-designed, -built, and -operated flight is a follow-on from the VT ThickSat launch in February 2021, incorporating lessons learned and upgrading specific experiments. The mission science goal is to demonstrate the reusability of lightweight deployable space structures for solar sails, antennas, and other extended components as well as characterizing the dynamic properties of the deployed structure while in space. In addition, the team has set a goal for this mission to serve as a starting point towards developing a reliable satellite bus to host payloads for Virginia Tech researchers as a continuous learning and improvement program. The inclusion of multiple payloads necessitated a modular approach to spacecraft design that included the development of a standalone payload control module apart from the satellite flight computer. This allows future spacecraft using this design to host multiple payloads operated independently, helping to reduce the cost of a flight for any single payload. Several challenges made the design, test, and build process difficult for the team, including only a year of development time from first design to final delivery, a short operational window in space before de-orbiting, and uncertain launch and power parameters. This put the 20-person team comprised of graduate and undergraduate students to the test with fast-paced parallel development of both the satellite core unit and payloads. This study on the development and design process presents a retrospective of the project and highlights the upcoming mission goals from the perspective of the project manager and development team leads, with the aim to discuss how students can lead the development of small satellites and generate excitement around the mission.

INTRODUCTION

Virginia Tech's Ut ProSat-1 is a 3U cubesat built as a follow-on and upgrade to a previous flight attempt with ThickSat, a 6T ThinSat platform also performing a flexible structure deployment test.[1] ThickSat, flying on NG-15 in February 2021, suffered an early failure prior to release from the launch vehicle and did not return any data on the deployment of a tubular collapsible composite structure from a rolled configuration. This structure was developed at NASA Langley and was the impetus behind developing the original mission.[2]

Following the launch, a debrief was completed to reflect on the team and engineering performance as well as the failure. Though the failure originated in hardware outside of the scope of the team, it was a powerful motivator within the group to resolve to fly another mission. The team would get the chance several months later when development began on what would become Ut ProSat-1. This second-chance flight encompassed a much larger volume, a more complex system, and a shorter development timeline from the original ThickSat undertaking.

Slated to launch on NG-18 in August 2022, the Ut ProSat-1 mission demanded only a little over a year to go from initial concept to delivered cubesat. Though the launch slipped to NG-19 in February 2023, the pace was hardly less demanding of a team comprised of nearly all students. In addition, the team needed to provide both the research payload like it did for ThickSat and the core infrastructure of the satellite such as the power system, flight computer, and radios. Increased complexity combined with nearly tripling the available volume over ThickSat enabled a wider perspective on mission planning and setting mission priorities. As a result, Ut ProSat-1 sought to set the standard for ambition and capability in space for Virginia Tech.

MISSION REQUIREMENTS

The ThickSat mission was reviewed in full following the delivery of the satellite prior to launch and again after the failure. This post-flight analysis worked to state the facts and outcomes and attempt to find areas of improvement in both technical and management performance.

ThickSat took several different iterations, beginning as a senior design project in the 2018-2019 academic year before being overhauled and transformed into a more research-oriented program for the 2019-2020 academic year and the final work in the fall of 2020. Chiefly this meant that the program dealt with shifting priorities both in mission scope and design priority. This scope creep and other lessons learned are described in more detail in previous papers on the mission outcome.[1,3] In addition, similar reviews of the predecessor Virginia Cubesat Constellation uncovered management and design areas of improvement.[4] Taken together, these reviews helped shape the priorities and mission design for Ut ProSat-1 into two categories: Science Objectives and Program Objectives.

Mission Profile

Even though the team received more satellite volume to work with, which would increase capability for both data collection and longevity, the orbit lifetime and launch-constrained mission parameters were unchanged from ThickSat. These parameters included a low-altitude deployment from the launch vehicle, as well as an extended period of storage on the launch vehicle following integration and prior to liftoff. The mission lifetime was difficult to predict given that the low orbit altitude would be heavily influenced by atmospheric and solar conditions during the course of the mission. With this in mind, several analyses varying the atmospheric model were performed in STK to simulate best-case and worst-case mission lifetimes. The outcomes from these analyses are included visually in Figure 1. In general, predicted mission lifetime from deployment to re-entry was expected to be approximately nine to ten days, leaving very little time for mission operations to take place.

Science Objectives

The ultimate goal for deployable structures like those flown on ThickSat and Ut ProSat-1 are their use in next-generation solar array structures and solar sails, among other microgravity applications where compactness is vital to mission success.[5,6] Working with the NASA Langley team, a parabolic bistable design was identified to serve as the basis for the Ut ProSat-1 deployer model. A bistable structure has two different stable orientations and "snaps" between these orientations when a force is applied. In this case the bistable boom has a stable rolled configuration and a stable unrolled configuration. To a certain extent the stable rolled diameter and parabolic profile can be customized depending upon the use case. An example of this structure is shown in Lee's paper on the design.[7]

While deploying a boom once under its own strain energy and returning photographic evidence of the deployment was the mission of ThickSat, the team determined that a larger satellite platform could deliver more opportunities for useful data collection. Through collaboration with NASA, the dynamic response of the boom to excitement and surface temperature along the length of the boom were selected as the new data products on top of motorless deployment testing and photos of the boom in space. In addition, experience in developing the ThickSat deployer provided a base from which to improve and further iterate. The deployer for Ut ProSat-1 would be capable of reeling the boom back in and redeploying as often as necessary. Redeployment would assist in collecting enough dynamic response and temperature data to draw confident conclusions on boom performance.

The available volume in the satellite as well as extra time predicted by the mission operations plan opened the opportunity to carry a secondary or even tertiary scientific payload. These payloads were selected from a variety of options by their implementation readiness and applicability to Virginia Tech as a whole. The secondary payload was selected as an S-band radio and antenna to qualify VT's S-band ground infrastructure and fulfill obligations for collaboration with Commonwealth of Virginia institutions. The operation and component selection of S-band hardware would be carried out by the team and the ground station group at VT.

The tertiary payload was selected on the basis of low-risk, low-power, and short operation schedules. This payload mounts a stick of Intel Optane computer memory within the avionics stack and periodically executes a memory reading script to examine the circuitry for single-event events and degradation as a result of exposure to ionizing radiation. The experiment serves as a proof of concept for the use of Optane memory in low-Earth orbit, short-duration applications where radiation exposure is elevated yet not to the level of requiring the use of extensive shielding.

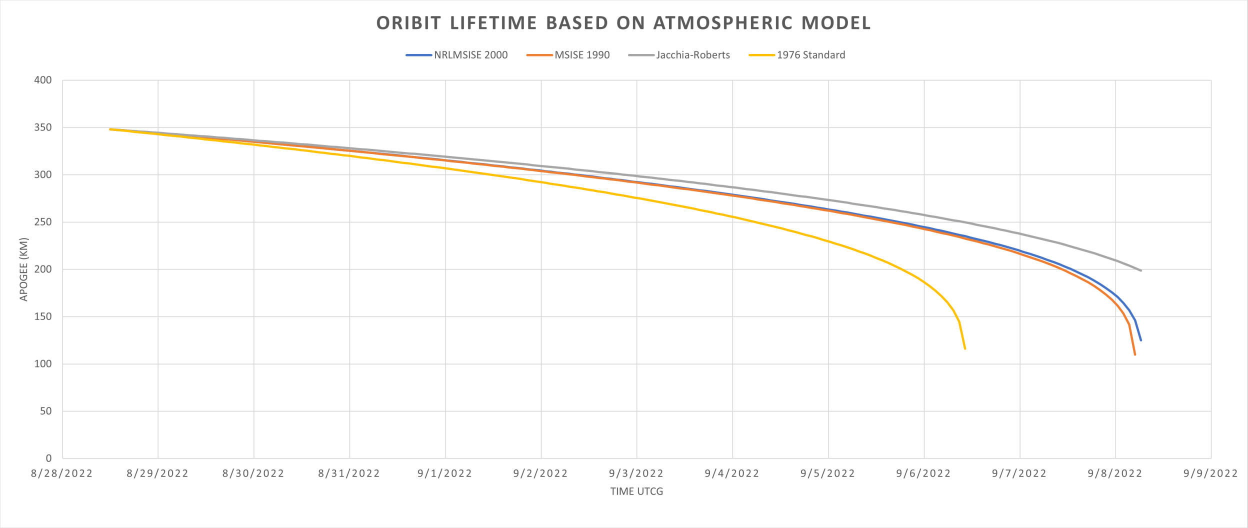

Figure 1: Mission Life for Ut ProSat-1 Based on ThickSat Deployment

Program Objectives

Alongside the science objectives, program objectives were set as a target to improve the satellite design and build process at Virginia Tech. Project management among student cubesat projects was recognized as a consistent failure point during the ThickSat debrief, documenting both loss of management continuity and uneven distribution of labor and accountability within the previous teams. This inconsistency interfered with effectively completing projects as well as documenting design decisions, leaving few common threads from one project to the next. With other large research universities developing robust cubesat programs, the team identified that an indigenous sustained cubesat program within VT would both reduce cost for future flights and empower students to better learn about space systems.

In order to develop this indigenous program, the team needed to lay the groundwork for continuity between flights. This process involved establishing repeatable and reliable methodologies for the satellite design process from determining requirements through verification and validation prior to launch. These methodologies took shape in the documentation process covering both weekly interactions and design decisions as well as templates for test plans, inventory and cost tracking, interface control, and detailed milestone reports. Using examples from previous student-built satellite programs and thoroughly documenting the work, the team also targeted a critical weakness identified from previous missions.[8] Finally, the last key to developing team continuity is engaging a group that will continue to recruit new members. The crux of a student-led team is that the students leave quickly and onboarding new students is sporadic in nature. By developing a detailed organizational structure, involving new members in decision-making, and challenging team members to volunteer for assignments a clear path of promotion was built to encourage ownership in the success of the program.[9]

Success Criteria

With the previously discussed objectives in mind, mission priorities and success criteria could be determined. These high level priorities formed the core of both system requirements as well as a more detailed concept of operations.

Minimum Mission Viability comprised the minimal activity required to identify the mission as a success, even if not all objectives were achieved. This served as a benchmark for assessing risk and for assigning a priority on component reliability. The minimum success criteria were ordered as follows:

1. Establish communication with the satellite following deployment from the launch vehicle and automated start-up.

2. Determine the power margin of the satellite as well as checking solar panel generation against expected values.

3. Determine the location and orbit of the satellite.

4. Commission the satellite by switching all payloads into safe idle states.

5. Deploy the boom and return deployment confirmation via a low volume data source (shaft encoder).

6. Return a low-resolution image of the deployed boom to the ground station.

The minimum success criteria essentially encompassed a repeat of the ThickSat mission in scope, making good on the original intent of the mission - evaluating a deployment method for a flexible structure. Given the previous struggles with power reliability, a high priority was placed on documenting and measuring the available power from the satellite batteries as well as solar power generation. The focus on spacecraft commissioning also underscored the challenge of communicating with the satellite: at such a low altitude, radio accessibility became a concern relating to the number of viable passes over the extremely short mission lifetime.

Phase 1 Science comprised the actual full evaluation of the multiple-deployment deployer design as well as Ut ProSat-1-specific boom data collection. During Phase 1, the boom would be excited in order to measure the dynamic response of the extended structure. Following the measurement period, the boom would be retracted back into the deployer using in order to complete a second deployment. Once the boom was deployed again, another picture would be taken to confirm that it was fully extended and without any damage. This second deployment concluded Phase 1 and moved science operations into Phase 2.

Phase 2 Science captured extended science operations and the use of any secondary or tertiary payloads. During this phase, the boom would continue to be wound back into the deployer and released again and again until a stop command was issued or power failed. Other payloads would also be used during this phase, with the S-band radio used to send signals to the Virginia Tech ground station infrastructure and the memory radiation exposure experiment returning the results of the bit-flip detection algorithm. These payloads were prioritized last as completion of the boom deployment mission was considered of utmost importance both to the team as well as stakeholder satisfaction in the mission.

With these priorities in place, further requirements could be developed into effective system and component designs.

CORE DEVELOPMENT

Even though the focus of the mission is on the data collected by the science payloads, the development of the satellite core underpinned the success of the entire program. The core comprises both the hardware and software not directly used in carrying out the experiments. This includes the flight computer, power generation and delivery system, UHF and S-band transceivers and antennas, GPS receiver and antenna, and the structure of the satellite seen in Figure 2. The core software operates on the flight computer and is tasked with directing power, receiving and transmitting collected data and health information, and providing timing for the other payloads.

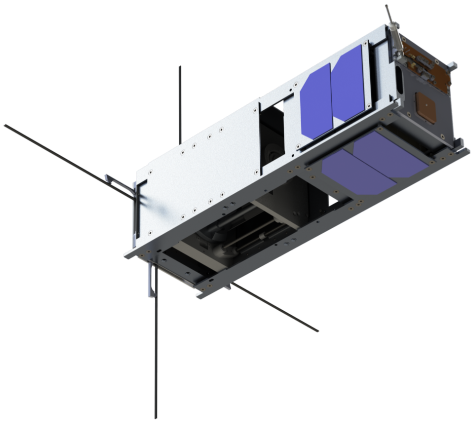

Figure 2: Full Satellite Assembly

The focus on successful commissioning as the highest priority dictated that even if a failure were to occur within one of the science payloads, the satellite would always be able to communicate with the ground and remain powered on. This heavily influenced the architecture design seen in Figure 3, the initial system block diagram. By separating the core hardware and software from detailed payload operations, commands and telemetry delivered over the Core/Payload interface could be tightly controlled. Such a separation necessitated the development of a payload control board, which is discussed in more detail in the Payload section of this paper.

Software

While the writing of functional code is the end result of flight software design, the team started the development process as soon as high-level requirements were completed. Software ultimately controls the states of the spacecraft and is intertwined with minute-to-minute planning, therefore the design of the concept of operations (CONOPS) for the mission

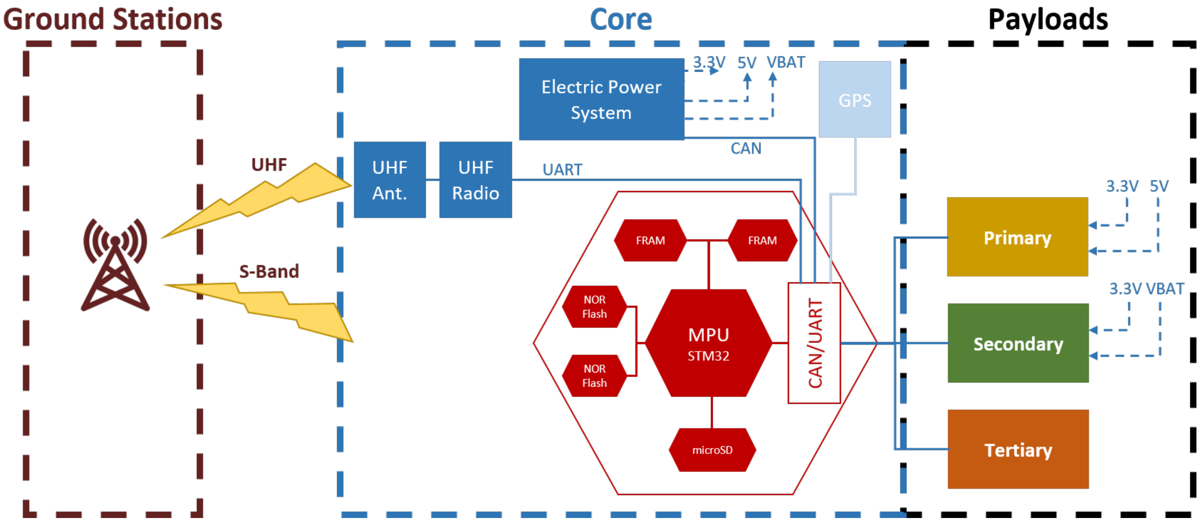

Figure 3: Core Avionics Block Diagram

was considered to be the beginning of the software effort.

The CONOPS were derived directly from the requirements and mission objectives. These included operations following deployment from the launch vehicle through commissioning using only the Core infrastructure and then moving into Phase 1 and Phase 2 science operations by communicating with the ground station and passing commands to the payload. Commissioning required the establishment of communication between the ground station and satellite followed by status checks of the electrical power system and solar panels. Once it was determined that the satellite was on and generating more power than it was consuming, a series of GPS-gathered coordinates would be passed to the ground so that the timing and exact orbit of the spacecraft could be determined. From this point, the ground antenna could more easily be trained on the satellite position, making the most use of the short windows of radio contact.

Following commissioning, the flight software and Core hardware would transfer science and satellite health data to the ground, and translate commands from the ground into ”Payload On” and ”Payload Off” commands for each experiment. One visual example of the CONOPS planning is included in Figure 4.

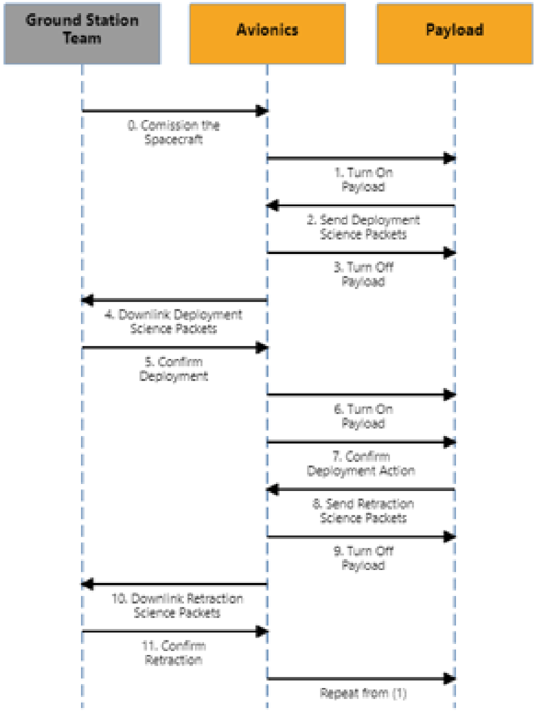

Figure 4: CONOPS for Science Downlink

The CONOPS were further augmented by mission analysis products for power consumption and generation, the number and duration of passes over the ground station, mission lifetime, and operations planning for each experiment. One such product is the expected data volume under different conditions, as seen in Table 1. This analysis included basic CONOPS for commissioning and nominal operations as well as expected orbit and atmospheric conditions. The data volume was then used to plan the software for building data packets and determining the resolution and size of experimental data.

Table 1: Expected Data Volume

Transmit Mode	Number of Passes	Total Bits	Total Bytes
Lower UHF	7	918k	114k
Higher UHF	40	40,983k	5,122k
UHF Mission Total			5,236k
Higher S-Band*	7	57,376k	7,172k

*S-Band mode is experimental and not added to budget

Following the finalization of the CONOPS and inclusion of the mission analysis, software architecture design could begin. The software architecture is the framework that the software will be written onto, so at this stage basic commands need to be defined and the CONOPS need to be translated into something akin to commands and changes in state. These state changes are defined and ordered by a state machine, a representation of the changing nature of the software and the satellite in response to different commands and situations. An example of the state machine for Ut ProSat-1 without command callouts is shown in Figure 5.

Following the definition of the state machine, individual commands could be defined and the software could move into the writing and testing phase. This phase comprised the longest duration of time on the road to launch and included integration with the specific hardware selected for the mission as well as ground control software. With the state machine and finished CONOPS, hardware could be selected.

Hardware

Core hardware development proceeded shortly after major requirements and CONOPS were realized. In an effort to reduce the risk and the time required to validate and verify subsystems, commercial-off-the-shelf (COTS) components were prioritized over in-house developed Core parts. The COTS parts were also stipulated to have prior flight heritage even if fully ground qualified by the supplier. This narrowed the field of acceptable components considerably and allowed the team to take cost into account for final decision-making.

One area of the Core deemed open for custom solutions was the satellite structure itself. The use of the Planetary Systems Corporation Containerized Satellite Dispenser (CSD) for the launch limited COTS options for chassis systems considerably. Utilizing experience from developing a chassis for the ThickSat mission that also used the CSD lent confidence that a reliable, cost-effective solution could be designed rather than selecting from a short list of commercial products.[10] This chassis solution with internal components mounted can be seen in Figure 6.

Figure 6: Core Hardware Assembly

The avionics stack, seen in Figure 7, required more input and requirements definition in order to settle on a final group of COTS parts. This included the mission analysis and data volume discussed in the previous section. Flight computer, electrical power system (EPS), and radio selections were performed according to software requirements, regulatory requirements, and a power analysis for capacity and capability. This power analysis tracked expected generation and consumption to ensure that the satellite could generate more power from the sun than it and consumed.

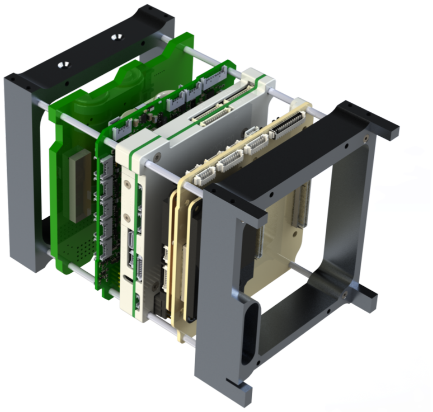

Figure 7: Avionics Stack

The power analysis was used to select the size and number of solar panels in addition to planning the specific operation of the science payloads. For the final solar array configuration, with each 1U

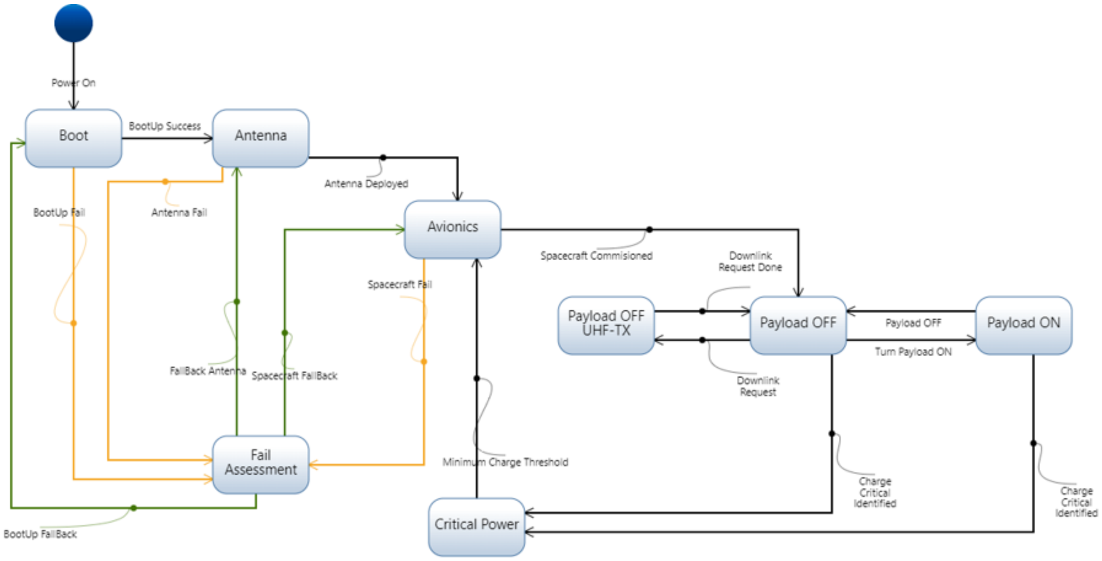

Figure 5: State Management Flowchart

panel delivering up to 2.4W with the solar incidence angle normal to the surface, the orbit average power range was computed to be between 1.4 and 2.0W. Using this value in the power consumption simulation in Figure 8 showed that if the payloads were shut off when not in use and during communication periods instead of moving to an idle state the power could be managed appropriately.

Using these simulations proved vital to making final, informed decisions on expensive equipment purchases. Once both Core hardware and software were defined, final preparations for both were undertaken to integrate them into one cohesive system.

PAYLOAD DEVELOPMENT

In contrast to the Core, the payload development process relied almost exclusively on in-house designed and tested components. Leveraging the experience earned during development of the ThickSat deployer and utilizing the skills available to the team, a deployer and payload control module board were developed from basic prototypes into flight-ready models.

Payload Control Module

The Payload Control Module (PCM) serves as the control board that interprets commands from the Core flight computer into specific operations for each science payload as well as organizing collected data for the flight computer and radios to transmit to the ground. This architecture helps to compartmentalize each payload from the others as well as the critical functions of the satellite. Even though it was not strictly necessary to add a layer of compartmentalization for this flight, the intention was to qualify the concept for future flights where multiple unrelated science payloads could be flown in a rideshare configuration, each with their own PCM and operations software.

The data collection for the boom deployment offered a unique challenge in the use of inertial measurement units (IMU). In order to measure the dynamic response of the boom, an IMU each was mounted at the root of the boom and at the tip, over one meter away from the spacecraft. The great distance required extensive analysis and testing to ensure that the signal strength, timing, and trace integrity along the boom would still enable data acquisition. Along with these instruments, a rotary encoder, camera, and thermopile all contributed data on the state of the boom throughout the experiment. The PCM block diagram can be seen in Figure 9.

Some of the instruments included on the PCM had heritage on ThickSat. The encoder and camera both flew previously and were utilized again as known quantities in order to make the design process of the electronics and software easier. The payload control software was developed in tandem with the flight software using the same processes and techniques. The similarity in software approaches at the Core and Payload level was a primary driver for microcontroller unit (MCU) selection. The STM32 MCU matched the MCU at the heart of the flight computer, reducing the complexity and learning

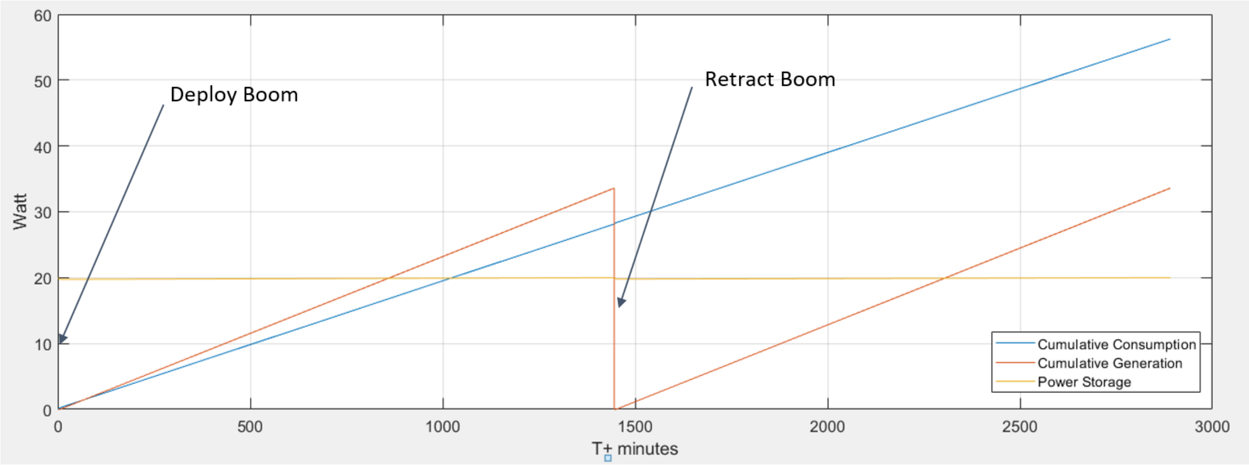

Figure 8: Power Simulation at 1.4W Average Orbit Power

curve of the software development.

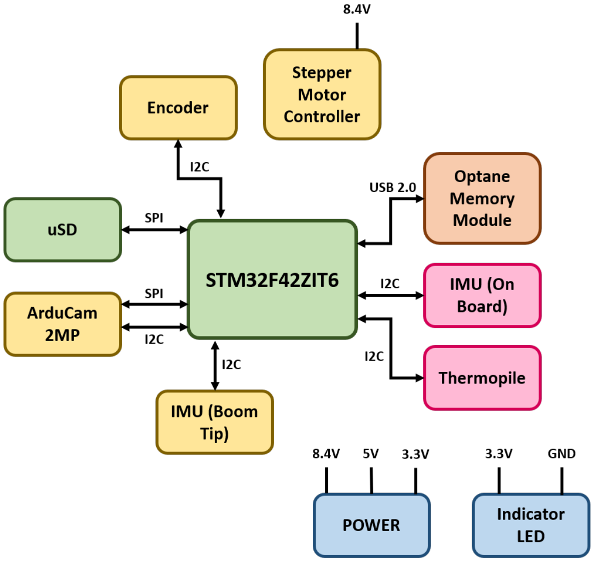

Figure 9: Payload Control Module Diagram

Bistable Structure Deployment

The core of the entire mission, the deployer was both the most complex mechanical system on the satellite as well as the most open-ended from a solutions perspective. The team determined that the ability to reel the boom back in and redeploy it was a crucial upgrade to be done immediately following the launch of ThickSat. From this concept, galvanized by the previous mission failure, the overall mission began to take shape. In addition to prioritizing redeployment abilities, the team met with a group from NASA Langley to narrow down what additional data products would be most useful to collect. Through this series of meetings, the in situ characterization of the dynamics of the boom rose to the top of the list.

Along with measuring the response of the boom when excited, the team sought to record other properties of the boom that would be difficult to replicate on Earth. The second data product was the boom surface temperature, measured by a thermopile mounted at the entrace to the deployer spool. Measuring the temperature on every deployment along the length of the boom could show a correlation between dynamic response and changes in temperature to the carbon composite.

With requirements in hand the team began to test and develop different concepts to enable multiple deployments, measure the surface temperature, and measure the boom response to excitement. The final design, seen in Figure 10, uses a cam-based clutch to disengage the reel motor for deployment and engage the motor shaft when the boom needs to be rewound. In addition, the thermopile for temperature measurement is mounted in front of the deployer spool, and the camera is mounted to the side to fit the entire boom in the field of view. The IMUs collecting the response data are mounted at the boom tip, bonded to the carbon structure with leads attached to the boom tracing back to the satellite. Material selection followed previous work done for ThickSat, selecting a combination of materials that are well-suited to the space environment and sufficiently budget-conscious to be readily available and easy to manufacture at Virginia Tech.

The deployer design and development campaign was the most familiar to the team of all the work done on the road to launch. With all members of the ThickSat team returning to work on this subsystem, the design progression closely followed where the previous design left off.[11] Development differed drastically from the rest of the satellite and relied on a highly iterative approach. Building and testing tens of prototypes, the team was able to come to a deep understanding on the mechanics of boom deployment and make quick adjustments for each successive build of the deployer.

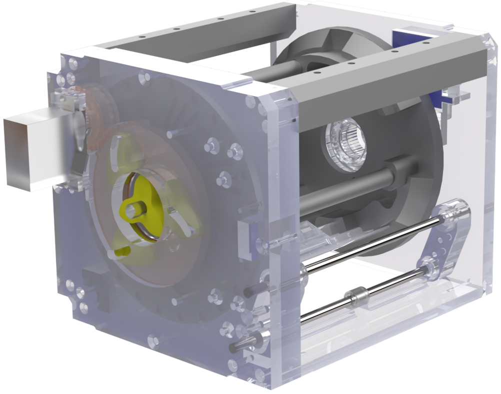

Figure 10: Deployer Assembly

Aiding the prototyping effort was the application of a variety of fabrication methods. Mixing together 3D printing when required and CNC router operations when possible produced parts quickly and directed the team into designing a deployer that was easily manufactured and simple in construction. Designing simple components was identified as a key lesson learned from the previous mission, and by applying that lesson from the start the team was able to build a first deployer prototype far ahead of any other subsystem. The drive for simplicity also kept the team from becoming obsessed over the design of exquisite parts rather than parts and a system that would just meet the need of the mission. As seen in Figure 11, many of the parts can be produced in one or two machining operations or one low-volume print.

By working closely with NASA and defining the problem to be solved by the deployer very early in the program, an effective solution could be designed quickly. The extensive testing undertaken on these custom components by the team applies directly to the overall objective of reducing risk for the mission and ensuring that useful data is delivered back to Earth.

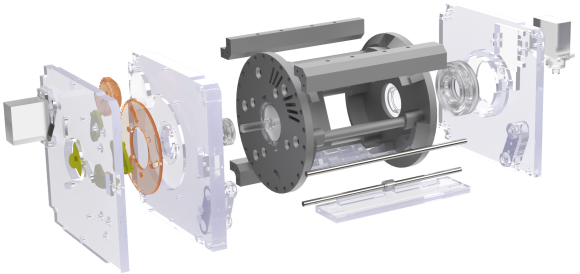

Figure 11: Deployer Assembly Exploded View

Memory Exposure Experiment

Through the use of a 3U form factor, additional space for other experiments was available for the flight. The team opened the opportunity to fly any experiment that had minimal overhead requirements in terms of volume, power consumption, and data transmission. The memory exposure experiment was suggested by a team member based on previous experience with solid state memory research and a desire to prove out high-volume, low-cost memory options for future flights.

The Intel Optane non-volatile memory, seen mounted in an M.2 form factor card in Figure 12, uses phase change memory materials and a unique memory cell selector to offer low-latency write times and drastically improved storage density over Flash and DRAM. These properties are especially useful in small satellite applications where power, speed, and size are typically balanced against each other. In the past, there has been an effort to qualify these memory modules on the ground through radiation testing carried out by the NASA Electronic Parts and Packaging Program (NEPP).[12] This experiment will be repeated onboard Ut ProSat-1 by running read and write operations and measuring bit error using a similar procedure.

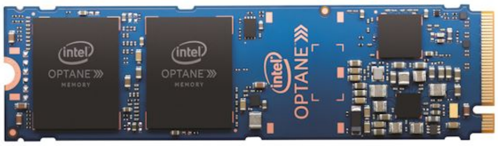

Figure 12: Intel Optane Module

The memory board was mounted onto the payload control module and will be controlled in the same manner as the boom deployer as dictated in the mission concept of operations. Radio blackouts on each orbit will offer ample time to run the read and write cycles and return data within one orbit with minimal power usage. In addition to evaluating the memory, the additional payload also puts the payload control module and the entire concept to the test. Proving out the satellite system architecture in a real-world application will enable more flights to be flown with higher confidence in their success.

LESSONS LEARNED

Throughout this program, many lessons were learned and incorporated into how the team operated and completed the mission. Ut ProSat-1 is the second satellite this team has developed throughout intermittent Covid-19 lockdowns, supply chain disruptions, and mixed attendance at meetings and in the lab. Flexibility and patience were required in equal measure to navigate toward success.

Expecting the Unexpected, even after the development of ThickSat during the pandemic, was absolutely required. Supply shortages as a result of disrupted integrated circuit manufacturing did not reach the COTS suppliers until well after the consumer market was beginning to show signs of recovery. The late turn into long lead times was relatively unexpected and cut into valuable development time. Taking the initiative and ordering parts as soon as they are decided upon would have mitigated most of these issues.

Virtual Work is an incredibly useful tool, however it is only as useful as the tools that team members have at home. Not all students had access to the resources needed to complete tasks, and it was much more difficult to build a cohesive and mutually accountable team when meetings were held in partially virtual environments. Using a model of accountability that both accommodates an individual's situation and fosters a culture of trust is important to keeping every team member engaged.

Systems Engineering can always be started earlier, and also has no end date. The team did generate requirements and used those to drive designs, however the systems work did not typically lead the design work throughout the program. More proactive systems work including pre-made document templates and a standard work process would have kept the requirements at the forefront of the program.

Stakeholder Relationships are vital to mission success and frequent, informal interactions as opposed to infrequent, formal check-ins do more to reduce miscommunications than anything else. Communicating on a weekly or bi-weekly basis with NASA Langley and VISA, the group responsible for launch vehicle integration and regulatory requirements, would have decreased the number of miscommunications and differences considerably.

Team Reorganizations can be very constructive if the current structure is not efficient. Halfway through development the team was reorganized from subteams for each payload and Core hardware and software into one Core team and one Payload team. This allowed members to work on mechanical, hardware, or software in either group and share lessons across the Core/Payload boundary much easier.

CONCLUSION

The development of Ut ProSat-1 will prove in time to be useful both as a scientific experiment and as a launchpad for future Virginia Tech cubesat missions. Improved documentation, systems engineering, software development, operations planning, and student learning have moved the standard of space missions further forward at VT and will allow future versions of the team to see success in space. The lessons learned build upon those encountered by the ThickSat team and reinforce that continuous improvement will bring about a better product and program.

The design and operation of the custom components onboard will deliver critical data to stakeholders and the team on future updates and iterations. The boom deployer is more capable than ever due to rapid prototyping efforts and a drive for simpler, more effective mechanisms. Future payload control modules will build upon this flight model and further improve on the modular cubesat concept. As a result of these technical achievements, notably the passive deployment and active recovery boom experiment, the team expects composite booms to become more prevalent in space missions in general and small satellite missions in particular.

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