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Verification and Validation Methods for the Prox-1 Mission

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ABSTRACT

As the capabilities of small satellites increases and more academic institutions undertake the task of building such systems, student led missions are becoming more and more prevalent. This is aided, in no small part, by the University Nano-Satellite Program (UNP) sponsored by the Air Force Office of Scientific Research and the Air Force Research Laboratory. As these missions exit the design phase, and enter the fabrication, integration, and testing phases of the mission, student-led missions face unique challenges stemming from the academic environment and lack of experience. This is especially seen during the validation and verification (V&V) of the system architecture. This paper will serve as an overview of validation and verification methods used for the Prox-1 mission from the Georgia Institute of Technology and detail how they can be applied to other missions. Prox-1 brings together significant contributions from 10+ entities, further complicating the V&V process.

The Prox-1 mission will demonstrate automated safe trajectory control during proximity operations for on orbit inspection. Passive, image-based observations will be used for the navigation and closed-loop attitude control of Prox-1 relative to LightSail, a 3U CubeSat developed by the Planetary Society and deployed by Prox-1.

INTRODUCTION

The Prox-1 Mission

The Prox-1 mission, developed by the Space System Design Laboratory at the Georgia Institute of Technology is a student-led mission. The mission will demonstrate automated safe trajectory control during proximity operations for on orbit inspection. Passive, image-based observations will be used for the navigation and closed-loop attitude control of Prox-1 relative to LightSail 2. Lightsail 2 is a 3U CubeSat developed by the Planetary Society and California Polytechnic State University.

The mission will also serve as a technology demonstration mission for numerous components. Specifically, for MicroSat Control Moment Gyros developed by Honeybee Robotics (seen in Figure 1) as well as a Cold Gas Propulsion Unit designed by Dr. Lightsey at the University of Texas (seen in Figure 2). The Propulsion unit is 3D printed such that the tank and plumbing are one contiguous piece of Accura Bluestone material. This unit provides up to 5mN of thrust and 15 m/s of change in velocity. Finally, the visible and infrared imagers were developed by Michael Veto at Arizona State University.

Prox-1 will launch with an approximate wet mass of 75 kg and a flight envelope of 22” x 24” x 12” seen in Figure 3. Prox-1 will be launched into a 720 km circular orbit with a 24 ° inclination.

Project Development Timeline

The Prox-1 Mission was selected to compete in the University NantoSat Programs’s (UNP) 7th cycle in 2011, thus beginning system design. In January 2013, the mission was selected for flight by UNP. Following the completion of the detailed design phase and procurement of most of the flight hardware by early 2015, the project entered the verification and validation (V&V) phase. An initial step in the V&V process was the development of a table-top flat satellite (FlatSat), which incorporated both flight hardware as well as engineering unit hardware. The V&V process, partially dictated by requirements set by the University Nanosatellite program, was designed to verify all of the

Prox-1 requirements as specified in the project's Requirements Verification Matrix (RVM), and validate that the flight system was capable of meeting its mission objectives via flight-like scenario testing. Completion of the initial set of system-level testing using the FlatSat was completed prior to the PreIntegration Review (PIR) in February 2016. Following PIR, final integration of the flight hardware into the flight configuration was initiated. Following the integration of each subsystem into the flight structure, functional testing was performed. A Pre-Ship Review (PSR) was conducted with UNP program managers in May 2016.

With the completion of flight system integration, Prox1 will be shipped via FedEx van to the Air Force Research Lab at Kirtland Air Force Base for environmental testing. Prox-1 is currently manifested to fly on STP-2 in the early 2017 timeframe from Cape Canaveral. [1]

Figure 1: MicroSat Control Moment Gyros developed by Honeybee Robotics[1]

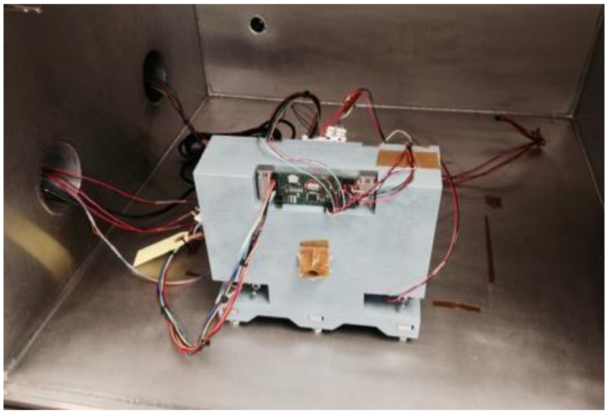

Figure 2: 3D Printed Cold Gas Propulsion System[1]

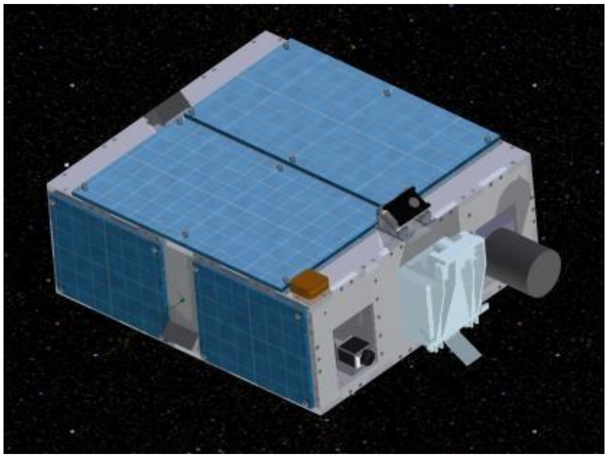

Figure 3: Rendering of the Prox-1 Mission[1]

VERIFICATION & VALIDATION APPROACH

To formally define V&V: Verification serves as the confirmation that Prox-1 meets all formal requirements outlined in the requirements matrix created for the mission. Validation serves as the confirmation that the system as a whole can carry out its mission and meet minimum and full mission criteria.

Overview of V&V for the Prox-1 Mission

The V&V process for the Prox-1 mission centered around preparation for four system level tests defined by UNP and a series of subsystem level testing in preparation for the system level testing.

In preparation for the tests, each subsystem carried out a series of confirmation tests outlined in the next section. These tests were carried out in a partial FlatSat configuration in the Space System Design Lab's Flight Hardware Lab at Georgia Tech. Once confirmation testing was complete, the team began the four major system level tests:

The first of the four tests, the Simulated Communication Test (SCT) demonstrates the ability for the system to communicate over radio frequency with our ground station.

The 2nd of four tests, the Complete Charge Cycle (CCC) Test, demonstrates the ability for the electrical power system (EPS) to charge the batteries using solar panels as well as discharge the batteries through depth of discharge, thus demonstrating full operation of the electrical power system.

The 3rd of the four tests, the Command Execution Test (CET), exercises all commands that are not part of nominal operations, but may be needed during flight. This includes serial commands to all subsystems.

The 4th of the four tests, the Day in the Life Test (DITL), represents an end-to-end simulation of the mission as accurately as can be done of the ground during a compressed time frame. This test begins with launch vehicle separation and goes through nominal operations of the mission through end of life. [2]

Once all tests are complete, the requirements outlined in the Prox-1 Requirements Verification Matrix should all be confirmed.

SUBSYSTEM CONFIRMATION TESTING

Before system level testing can be carried out, each subsystem must go through a series of confirmations tests proving that it is ready for system level testing. This includes the following general requirements:

- Ability to communicate with flight computer through command and data handling system.
- Ability to read sensor data.
- Ability to function from satellite electrical power system (EPS).

Anomalies found during confirmation testing

As Prox-1 prepared for system level testing, each subsystem was responsible for writing procedures that would rigorously testing their hardware. Further, confirmation testing allowed for a series of issues to be solved before the entire system was assembled.

The satellite will be launching from an ESPA ring during STP-2. Consequently, a Lightband mechanism with inhibits that are flipped allows the system to separate from the launch vehicle. During confirmation testing, a design error in the inhibits board was found and allowed for a revision of the board to be made while other confirmation testing occurred. Had this error been noticed during full system testing, it would have resulted in all work ceasing until the issue could be resolved.

Also during confirmation testing, the interface connector to the Honeybee microsatellite control moment gyroscope unit was found to have been damaged. This confirmation testing allowed time for the component to be sent back to Honeybee and be brought back to full functionality. As a result of this experience, the Prox-1 team implemented more stringent procedures with regards to connector protection.

Another example of validation and verification occurred when the thruster controller did not respond commands with specific identifiers. This software issue was resolved, and a retest showed the desired command capability prior to system-level testing.

Lessons Learned from Confirmation Testing

During early confirmation testing it became clear that asking a single team member to solve the specific issue was not sufficient. The problem needed to be fully documented in order for all relevant students to understand the issue without miscommunication. Consequently, a formal system of Problem Reports was implemented. This one-page form allowed for the student who found the problem to write a brief summary, include any relevant data, and quickly send the report to the team. This also formalized the process of creating a historical log of all problems that had been solved; this allowed for the documentation of solutions to be referenced when the problems arose again, as they have since done.

As components successfully went through confirmation testing, the system was assembled into the FlatSat configuration, pictured in Figure 4. Since the assembly of the FlatSat only occurred as confirmation testing was complete on each component, the flat satellite served as a physical representation of the preparedness for system level testing.

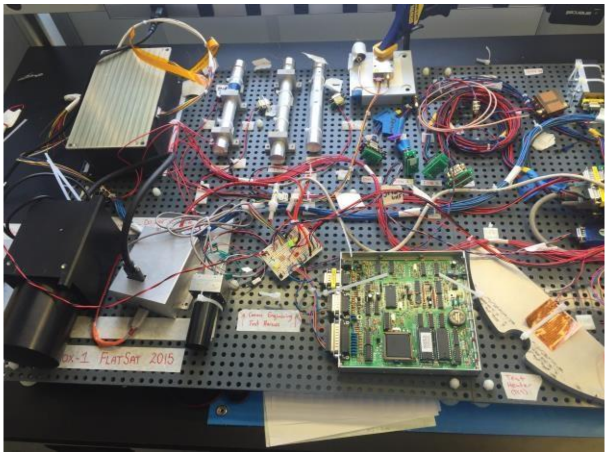

Figure 4: Part of Prox-1 Flat Satellite

Flat Satellite configuration

Ideally all V&V should be done on engineering unit hardware. However, low-cost and technology demonstration missions may only have a single unit to test and fly. This is true for the Prox-1 for many components, including electrical power subsystem batteries and control moment gyros. Thus, the FlatSat system used for V&V carried the risk that testing may damage flight hardware. With this consideration, special care was taken in grounding the FlatSat. Further, cycling of connectors could become an issue with non-standard connectors, and the project used connector protectors on the FlatSat to minimize the wear on flight connectors.

Harnessing for the FlatSat was composed completely of non-flight harnessing. Though this allowed for quick and easy assembly of the harnessing by students, harnessing errors led to numerous anomalies during confirmation and system level testing. These issues could have easily been avoided with good test harnessing. Many universities do not teach students the value and best practices of quality fabrication: work that is often completed by skilled technicians in the professional practice. Consequently, student-led teams often do not place priority on ensuring that the hardware that is built 'just for testing' will function as well as it should.

The Prox-1 mission originally planned to fly many electronic boards that were completely fabricated by students. However, during the early stages of flat satellite testing, it became clear that the fabrication and soldering skills of students presented a mission risk if the soldering joints did not withstand the rigors of the launch environment and space. Consequently, the decision was made that all custom boards designed by students would be remade by professional technicians. These boards were still designed by students, the fabrication was over seen by students, and the testing was conducted by the Prox-1 team. These boards were later integrated into a FlatSat configuration and tested prior to final integration.

PROX-1 REQUIREMENTS VERIFICATION

Prior to the start system level testing, a thorough Requirements Verification Matrix (RVM) was constructed specifically for the Prox-1 system. This included 400+ requirements that the system must meet before being fully verified. Many of these requirements were dictated by the Nanosat-7 User's Guide.[3] The RVM was structured in such a way that all requirements not dictated by UNP stemmed from the Prox-1 mission statement and could be traced back. This was done so that no requirements could accidentally and arbitrarily be placed on the system, thus restricting design or capability. The traceability is very important as responsibility for requirements is handed down from student to student when personnel graduate or cycle through the team. Table 1 articulates the mission success criteria the stem directly from the Prox-1 mission statement. Figure 6 shows the flowdown of requirements, starting at the mission statement and going all the way to the subsystem level.

Table 1: Minimum Mission Success (MMS) and Full Mission Success (FMS) Criteria for Prox-1

Identifier	Description
MMS-1	Prox-1 shall successfully detumble
MMS-2	Prox-1 shall perform initial Acquisition & System Checkout
MMS-2.1	Prox-1 shall successfully complete flight check-out of Honeybee Control Moment Gyroscopes
MMS-3	Prox-1 one shall successfully deploy Light-Sail-2
FMS-1	Prox-1 shall perform automated identification and tracking of the CubeSat.
FMS-1.1	Prox-1 shall observe CubeSat within instrument field of view 10 times per orbit.
FMS-2	Prox-1 shall rendezvous with CubeSat into a stable trailing orbit between 100 - 200m (along track distance).
FMS-3	Prox-1 shall perform relative orbit determination for Prox-1 with respect to the CubeSat.
FMS-4	Prox-1 shall validate relative orbit estimate using GPS measurements and ground based observations.
FMS-5	Prox- 1 shall perform proximity operations relative to the CubeSat.
FMS-5.1	Prox-1 shall use automated maneuver planning to maintain a maximum separation distance from the CubeSat of 200 m and minimum separation distance of 50 m (along track direction) for a minimum of one orbit.
FMS-5.2	Prox-1 shall implement a natural motion circumnavigation about CubeSat for one orbit.
FMS-6	Prox-1 shall image Lightsail-B in deployed configuration and downlink image.

Constraints placed on the system were also included in the RVM. Though not formal requirements, these constraints included limits that the system must meet and therefore were deemed relevant for tracking. For example, one constraint reads:

"Use of glass shall be minimized. Where glass must be used, it shall be non-pressurized and subject only to inertial loading, as required by NASA-STD-5003, Section 4.2.3.6."

Care should be taken when writing requirements that reference outside documents. Student team members often lack the experience to understand formal NASA standards. All efforts were made to minimize external references within the RVM. However, the source of the requirement should be kept intact as questions may arise as to the source of a certain value.

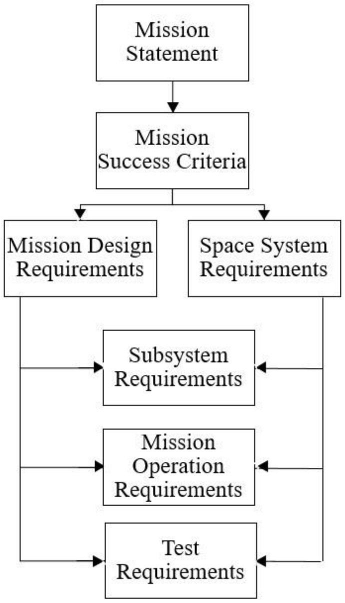

Figure 6: Flow-down for requirements generated from the Prox-1 Mission statement (not from the Nanosat-7 User's Guide)

System level testing ultimately allowed for verification of the majority of requirements. However, some requirements were verified simply through structure design and other methods that do not require stringent V&V methods. The RVM should be considered a 'living document' in that requirements do change in small and significant ways. For example, during the Prox-1 V&V process, power draw calculations brought concern about the ability to operate components with high power consumption while in the eclipsed portion of the planned orbit. Consequently, requirements regarding when components could be used were discussed and implemented.

SYSTEM LEVEL TESTING FORMAL DEFINITIONS

As mentioned previously, the crux of the Prox-1 V&V process centers around four system level tests mandated by the UNP's process. Below are the definitions as outlined in the UNP User's Manual for the 8th cycle of competition.

Simulated Communications Test (SCT)

The Simulated Communications Test should verify the design of the telecommunication system. This should be done by successfully having the satellite communicate with a ground station over a substantial distance. Per UNP guidelines "The radio must be in the satellite so that the effects of the structure and other components can be accounted for. The test should verify the radiation pattern of the antenna as well as verify the received power." [2]

Complete Charge Cycle (CCC)

The Complete Charge Cycle Test is a full system test of the satellites ability to charge and discharge itself. The batteries must be drained to depth of discharge during the test using satellite operations and then be fully charged. Charging must occur at least partially using solar panels.

At the point when batteries reach depth of the discharge, the system must demonstrate the capability of turning itself off and enter some safe mode. Also, the system charging must "auto shut-off" once batteries have been charged fully. [2]

Command Execution Test (CET)

The Command Execution Test is a formal test of every command that may be sent to the spacecraft. This is done to ensure that all commands are safe for the satellite and do not cause any unknown errors physically or digitally. The command and data handling system should be fully tested, demonstrating "all internal commanding"[2] This should include voltage and current thresholds for various spacecraft modes on the electrical power system. [2]

Day-In-The-Life (DITL) Test

The Day-In-The-Life test represents a simulation of the entire mission of the spacecraft. This is to include "satellite initialization (i.e. a satellite separation and turn-on scenario), executing modes and appropriate commands, as well as a turn off command from the ground."[2] Only commands nominally required for mission operation should be included in DITL. However, all phases and modes of the satellite should be fully tested. The test should take special care to simulate launch vehicle separation and system initialization. Further, the full experiment plan for the mission should be simulated as realistically as possible.

DITL should mimic an accelerated mission. However, all necessary changes should be made to ensure the safety of the hardware and personnel. Tests should also span no less than 24 hours. [2]

PROX-1 SYSTEM LEVEL TESTING

Once confirmation testing was completed, the Prox-1 team entered the system-level testing phase. This included developing mission specific procedures for each test. The procedure development was instrumental to ensuring that each test truly tested functionality as realistically as possible.

However, oversights were made during the procedure development. For example, the ability to track and measure power draw from all components should have been a fundamental outcome of system level testing and integrated appropriately into the procedure. Though this was not a fundamental goal of the test, the information was vital to verifying the design of the system. This oversight resulted in the need for further testing.

Further, clear communication about procedures needed for testing of components supplied by collaborators should also be given special attention. For example, confusion arose about the procedure for fully testing Honeybee's MicroSat Control Moment Gyros because automation of the component checkout was not clearly communicated to the Mission Operations team who were operated the system level tests.

Simulated Communications Test (SCT)

SCT allowed for the ideal link budget to be experimentally confirmed, further confirming link margin. The test also confirmed the ability to encode and decode data. Testing was done across the Georgia Tech campus between two roofs, approximately 1 km apart from each other. The ground station was placed on one roof, and the telecommunications system was placed on the other. Because of the size of Prox-1 and the desire to keep all flight hardware in the clean room, only required telecommunications hardware was taken to be tested. However, the engineering structure was used for this test to help create realistic communications, with antennas mounted in a flight like configuration. Systems that are small enough to be easily carried should be tested as a whole. Because the test was carried out over a relatively short distance, signal was appropriately attenuated.

The biggest challenge for this test was finding a distance over which to test over in an urban area. Interferences caused the test to be carried out at four different locations until test distance was found with acceptable interference. Often interferences were not immediately obvious and should be carefully monitored.

Complete Charge Cycle Test (CCC)

Though the CCC is only a test of the electrical system of the satellite, it is considered a system level test because it includes simulating launch vehicle separation as well as discharging and charging the system. Once launch vehicle separation has been simulated, the EPS is allowed to turn on. For CCC, the batteries are discharged using a dummy load. Ideally, this test would be conducted using components from the system itself. Once, the system reaches depth of discharge it begins charging. The CCC test requires proof that solar panels can successfully be used to charge the batteries. Ideally this should be done for as long personnel are available for. However, charging the systems batteries using only solar panels inside of a clean room will generally be time prohibitive, even when using strong lighting. Therefore, the test allows the majority of battery charging to be done from a desktop power supply.

Challenges faced by Prox-1 during CCC testing included batteries never fully charging. After close inspection it was concluded that the EPS system itself had a nominal power draw that prohibited the system from ever fully charging. This was characterized and taken as a lesson learned. Such an issue is a good example of system idiosyncrasies that students with little experience would not easily be able to identify.

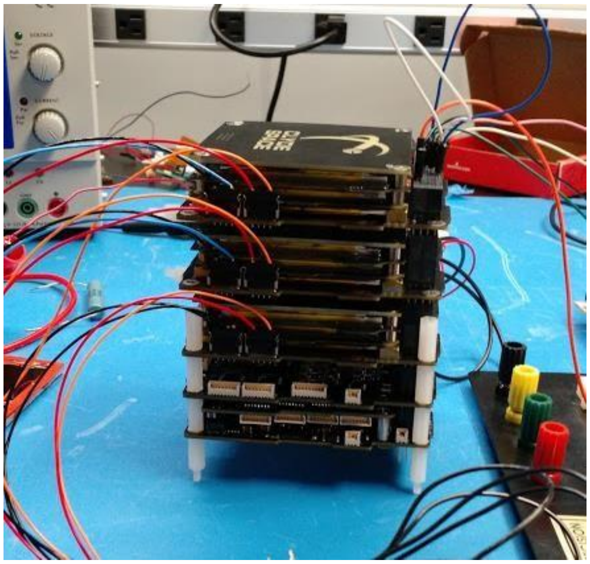

Figure 5: EPS components tested during Complete Cycle Charge Test

Command Execution Test (CET)

The CET test is a true system level test in that all components of the satellite are needed for the procedure to be carried out. This tests include all commands that may be needed during the mission that are not tested during the DITL test. However, for the case of serial commands, of which there are many, at least one serial command is sent to each subsystem to test the ability for the flight computer to communicate with each component and subsystem successfully.

Prox-1 CET testing was very successful with all commands behaving as expected and not causing any potential harm to the spacecraft for any components.

Day-In-The-Life Test (DITL)

The DITL Test was easily the largest challenge that the Prox-1 Team faced during the V&V process, and the test was guided by a highly detailed procedure which also serves as a starting point for a flight operations procedure. Because the DITL test simulates the mission as closely as possible on the ground, every effort is made to carry out mission operations realistically, in adherence to the "test as you fly, fly as you test" principle. Consequently, the test procedure included detailed information about all commands sent to the spacecraft, and in what order. Further, expected responses and consequent actions were also included in the procedure.

Once the procedure was defined, the system had already undergone confirmation testing and some system level testing. However, this did not fully mitigate for issues seen during system level testing.

Initially, DITL testing was only carried out for minimum mission success criteria. This allowed for the majority of the mission's functionalities to be tested with the major exception of proximity operations. Nevertheless, issues that arose during DITL were numerous and varied. For example, the command and data handling system recognized an issue with managing data allocation within the ADCS subsystem with regards to GPS data. Further, logic errors within the thermal control system were found and corrected, and logic errors with the Prox-1 system that interfaces and triggers the PPOD mechanism that deploys LightSail 2 were found. This issue would have resulted in a failure to deploy the cube sat on orbit.

Integrating proximity operations into the testing of the satellite also proved to be a major challenge because of the reliance on simulation. Running the simulation on the flight computer as the flight computer also maintains the operations of the satellite proved to be too computationally intensive for the system. Consequently, another computer must be used to feed the flat satellite with simulation data. Even so, the system can only test software responses as much of proximity operations relies on propulsion and attitude control which cannot be fully tests on the ground in a lab environment.

The DITL test is also requires a serious commitment from the personnel of the team. The test is required to run for at least 24 hours by UNP. Therefore, shifts must be scheduled in such a way so that students may attend class as well as be present to support relevant portions of the test. Furthermore, successfully conducting 16 hours of the test only to hit a problem can result in significant morale issues with the team. This can only be mitigated with thorough preparation for the DITL test.

SYSTEM V&V LESSONS LEARNED

Ultimately, the Prox-1 system level testing resulted in significant student learning as well as successful V&V of the system. Through the process, many lessons were learned that may be useful for other university based satellite projects.

Major challenges arose from limits in student experience. This was especially seen as students struggled to adequately recognizes errors that arose from hardware issues. Consequently, students struggled not only to fix such issues but also to communicate them to others. Formalizing the process, and asking students to write down issues in Problem Reports greatly aided the Prox-1 Team.

Many issues arose from a lack of experience in computer and electrical engineering. Basic training in circuits and microcontrollers would greatly aid the teams, especially students in the first two years of their education. Furthermore, teaching specialized skills with regards to FlatSat operation would also be very useful. All team members involved with testing should have a good understanding of all hardware involved in the testing.

For a mission with the complexity level of Prox-1, engineering mentors from the aerospace industry provided needed guidance, and professional engineering technicians provided hands-on support in targeted areas. Collaboration with professional engineers on high-criticality tasks such as flight circuit board assembly and the fabrication of flight harnessing, was beneficial to student training while ensuring that the hardware was fabricated at a high level of quality.

Procedural challenges also arose, as creating test procedures is not a skill often taught or learned outside such experiences. A significant adjustment period was needed to train the team to realize that all tests needed to be fully documented. Further, creating thorough test procedures with collaborators from across the country caused delays and sources of error. These issues were partially remedied when the collaborators were more easily available for real time problem solving; however, this is often not possible because of the schedule of students.

SUMMARY AND CONCOLUSION

Ultimately, the Prox-1 V&V program was very successful. Students learned about validating a system as well as the challenges of system level testing. The

Prox-1 system was found to have many errors, but all errors were resolved or mitigated. More work will be done to simulate proximity operations, but enough work has been done to prove that hardware and software design is capable of successfully fulfilling both minimum and full mission success.

Generalized Implications

Students partaking in the V&V of university led satellite projects would greatly benefit from seminars in the following areas:

- Procedure development for thorough testing.
- Best practices with regards to Engineering Unit and Flight Hardware.
- Data collection from system level testing.

However, struggles that result from lack of experience are challenges well worth the learning experience students get from the experienced gained when understanding the entire V&V process.

The V&V process is also streamlined with increased documentation in the university setting. Student teams have a very high rate of personnel churn which is especially significant when students are working on individual small pieces of the project. Documentation will ensure knowledge be passed efficiently.

The four system level tests described provided a great format for design V&V of the Prox-1 satellite. It began training the team for operations by formalizing the testing process and requiring the team to acclimate to working shifts occasionally. Finally, it also showed students that no matter how perfect a design may seem, nothing replaces testing. These test can be implemented for other student-led satellite missions.

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- To The Planetary Society for their support and collaboration.

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