

Ensuring Mission Success:
The Validation and Verification of
Academic Small Satellite Functionality

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Abstract. This paper will examine the necessity of an effective validation and verification program for small satellite projects. Specifically it will examine a minimal budget and manpower approach to small satellite system validation that was created to meet the needs of and constraints placed on academia. Testing methodologies, including subsystem specific testing as well as full systems testing of the spacecraft will be examined. The rapid development of an Internet based, cost effective, and user-friendly defect tracking system using readily available software will be discussed in detail. Such a system will allow the personnel leading the testing effort to quickly determine the status of the testing effort. As an addition to the testing effort, the testing of the human element of the mission, the operations staff, will be discussed. The Three Corner Satellite and Citizen Explorer 1 missions under development by the Colorado Space Grant Consortium at the University of Colorado at Boulder will be used to demonstrate the application of the afore mentioned aspects of a validation and verification effort.

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Introduction

The concept of validation and verification of spacecraft was first realized a half-century before mankind placed the first artificial satellite, Sputnik-1, in to orbit. In 1907 at Worcester Polytechnic Institute, a cloud of smoke suddenly filled the basement of the physics building. The source of this was perhaps the first recorded static firing of a rocket engine. Emerging from the cloud of exhaust was the student that had conducted the test, Robert Goddard. [1]

During the early years of the rocket age (1907-1957), many new developments in propulsion and guidance were produced and each had to be tested. Aside from static tests, the primary way to test the vehicle was an “all up” test. This would have the new hardware installed in a rocket and the vehicle subsequently launched. The beginning of the space age (1957-present) saw the beginning of laboratory test environments, but the “all-up” test was still frequently used.

Perhaps the most famous example of an “all-up” test is the flight of Apollo 4 in November of 1967. With the deadline of

achieving President Kennedy's goal just over two years away, it was decided that instead of testing each stage of the Saturn V using separate launches, an entire vehicle, AS-501, would be launched. The payload was a Block 1 command module and a lunar module test article to properly simulate the payload mass. This flight verified that all of the components for a lunar flight functioned properly. [2], [3]

After several decades of reduced funding comprehensive system and "all-up" testing was eliminated as the cost for the tests were preventing other missions from being developed.

The 1990's saw the evolution of the "faster, better, cheaper" mentality. Instead of comprehensive verification and validation procedures for the entire spacecraft subsystem specific validation was used. This cut costs by having the team developing the hardware and software later test the same system. The only problem was that each team only looked at their own subsystems, and little attention was paid to the interaction between the systems. The lack of comprehensive testing of the spacecraft as a whole has resulted in at least one major spacecraft failure in the past decade.

Unit testing is useful for verification of the functionality of a specific subsystem and validating the responses to various inputs. While unit testing is useful for verifying the functionality of the components of that subsystem only; comprehensive system validation is still necessary. Due to the budgetary and personnel constraints placed on spacecraft currently being developed by academia, a new methodology for validation and verification of spacecraft

functionality both on a unit and system level is required.

Methodologies

The unique constraints placed upon academia, including the rapid turnover in employees due to graduation and the summer holiday, as well as limited budget; require new validation and verification methodologies to be developed.

The first issue that arises when a project begins is who will be tasked with the validation of the spacecraft. Assembling a entire validation team to develop and execute all validation procedures for all aspects of the project will be personnel intensive, and require all members of the team to be experienced in test case development. On the other hand, having the various subsystem team leads conduct the testing will bring an inherent bias into the development of the validation procedures.

The solution to this quandary is fairly straightforward: designate one individual on the project as the Validation and Verification Coordinator and assign him or her to the Mission Operations team. The duties of this position will be take the data available from the Fault Mitigation and Effects Analysis (FMEA) for each subsystem, develop validation procedures for each subsystem and the spacecraft as a whole. This process will require extensive collaboration with the team leads for the various subsystems, as they are well versed as to the operation of their subsystems.

A second individual, preferably two academic years behind the Validation and Verification Coordinator, should also assist with all validation tasks. This will allow for "on the job" training of the

next Validation and Verification Coordinator to replace the current coordinator when he or she graduates.

Due to the complex nature of all spacecraft a method must be developed to track the progress of the validation effort. An elegantly simple concept is the completion matrix combined with multiple validation cases.

A unique validation case needs to be developed for individual or closely related sets of possible failures as outlined in the project's FMEA documentation. The step-by-step procedures contained within the validation case should be made as straight forward as possible so that any member of the project team that is familiar with the control interfaces will be capable of executing the validation procedures.

Figure 1 is a sample of the validation procedures used to verify the functionality of the End-to-End Data System (EEDS) for the Citizen Explorer 1 spacecraft. [4]

the Power Distribution and Control Unit (PDCU) the command directly and verifying the responses to Task #1 and #4 based on laboratory conditions, all necessary systems are tested simultaneously. In this case the mission operations interface, an Ethernet or RF link to the spacecraft, the communications subsystem, the critical decoder, flight computer and PDCU are all tested for functionality as a whole.

The four columns in the procedure document are used to quickly document the outcome of each task as it happens. For example if the task successfully completes a "P" is placed in the "Pass/Fail" column. If the task is a failure, an "F" is recorded in the "Pass/Fail" column. The "Bug ID" column is filled in as the failed task is recorded in the anomaly tracking system, which will be discussed later in this document.

The completion matrix allows for the percentage completion of the validation and verification to be easily determined. Each subsystem will be given a two-digit

| # | Task Description | Pass/ Fail | Bug ID |
|---|---|---------------|-----------|
| 1 | Close Science Relay: " <u>cmd_sci_relay 1</u> " | | |
| 2 | <u>note</u> current draw on the power-supply in-line ammeter | | |
| 3 | Critical Power Sensors: Payload Volts: <u>mon_payload_volts</u> | | |
| 4 | Critical Power Sensors: Payload Current: <u>mon_payload_curr</u> | | |
| 5 | Science Relay Monitors: Science +5 V: <u>mon_sci_relay_five_volts</u> | | |
| 6 | Science Relay Monitors: Science +15 V: <u>mon_sci_relay_pifteen_volts</u> | | |
| 7 | Science Relay Monitors: Science -15 V: <u>mon_sci_relay_nifteen_volts</u> | | |
| 8 | Take science scan using 1000ms per channel integration times | | |
| 9 | Close Science Relay: " <u>cmd_sci_relay 0</u> " | | |

Figure 1 - Example Validation Procedures

As can be seen step-by-step instructions are written to be as straightforward as possible. Task #2 requires the individual conducting the test to physically take a measurement, which is later compared to the telemetry that is sent back after execution of Task #4. Instead of sending

designation. In the case of the Citizen Explorer 1 project at the two-digit designations will be identical to the configuration control number designation for the various subsystems. This is highly recommended for all projects with existing configuration

control numbers. The subsystem designation will be followed by a three-digit designation unique to each validation case for that subsystem. Figure 2 illustrates the concept.

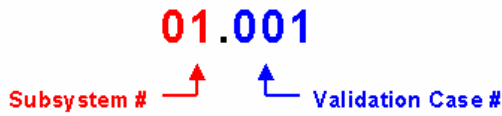


Figure 2 - Completion Matrix Numbering Scheme

Each validation case must be executed and regressed until all adverse anomalies have been eliminated. Once that criterion is satisfied the validation case may be considered complete.

Validation and verification can be considered complete at any point after 95 percent of the completion matrix has been finished, provided that the remaining five percent or less has been determined by the systems engineering lead, the mission operations lead and the project manager to be non-mission critical.

Execution & Regression

While the execution of the validation procedures should be straightforward to any individual experienced with the spacecraft; the determination of which individual should physically execute the test is another matter. Though the members of the subsystem teams are proficient with the spacecraft, they may not recognize potentially anomalous responses to commands as the specific response has reoccurred frequently for no known reason.

Therefore it is favorable to have either members of the Mission Operations

Team or System Engineering Team execute the validation procedures. Any responses that do not match the expected output will be recorded as anomalies and logged in the anomaly tracking system. The report that is filed will include a brief description of the anomaly, the name of the individual that discovered the anomaly, a detailed report of the anomalous response, and instruction detailing the procedure that was used, so that another individual may verify the anomaly's existence.

Once recorded in the anomaly tracking system, a hard copy of all anomaly reports will be given to the team lead for the subsystem(s) that had been tested. Once the anomalies have been repaired, the entire validation case in which they were discovered will be repeated to ensure that the repair did not adversely affect any other systems.

This regression testing is the most crucial portion of the validation and verification effort. Without regression testing a change to a single subsystem may render other subsystems useless. It is preferable to have the same individual that conducted the initial verification test conduct the regression test, as he or she will be familiar with the anomalies that were discovered.

Anomaly Tracking System

Several anomaly-tracking systems exist that satisfy the requirements for a small satellite project under development by an academic institution. However many have disadvantages that prevent efficient implementation. Two excellent packages are Bugzilla, an open source program, and Requisite Pro from Rational®.

(IIS 5.0). This allows any advanced Windows user to install and configure a basic BugBase in less than two business days.

By utilizing SharePoint™ Team Services other aspects of the validation and verification effort can be easily managed. The added features include, a universal homepage for the Validation and Verification effort, a database of all personnel critical to the effort, and a document library where the test plans and procedures may be uploaded. [5]

As was mentioned in the Methodologies section of this paper, the “BugID” is assigned as the anomalies are logged. Simply the BugID is the record ID assigned by the database. As each project will have it’s own anomaly database, there will be no conflict for BugID numbers.

Three options exist in to manage the anomaly reports that corresponded to each sub system. The first option is to use the built in sorting capability included with the SharePoint™ site.

Figure 4 is a screen capture of the BugBase developed for the Three Corner Sat project at the University of Colorado at Boulder. As can be seen the defects are sorted based upon their entry date. This is very intuitive to experienced internet users, simply by clicking on the title of the column named “Severity”, all the anomaly reports will be sorted by their severity.

The second option is to have the Validation and Verification Coordinator create individual pages through SharePoint™’s management side that only displays the anomalies reported for each subsystem. Finally, a hard copy table that resembles the Completion Matrix may be created. Figure 5 demonstrates how this numbering system would work.



Figure 5 - Full Anomaly Tracking Number

It has been shown that due to the

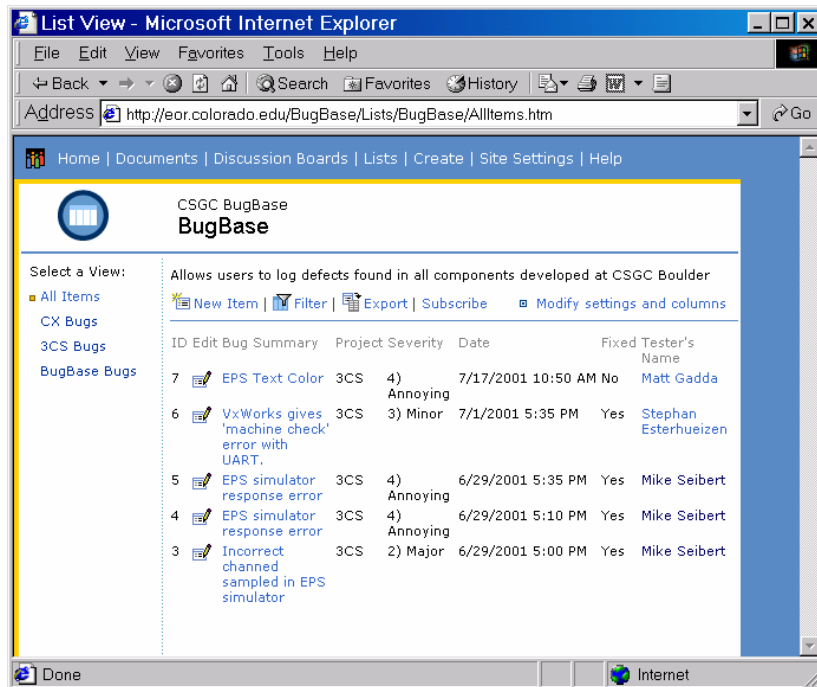


Figure 4 - An Anomaly Tracking System Database

interaction between subsystems during testing, BugID numbers cannot be assigned within the subsystem: i.e. BugID #0001 may fall under the communications subsystem and BugID #0002 will fall under science subsystem.

A system analogous to the BugBase used for the ground testing of the spacecraft could be developed using the same software to allow for the tracking of failures on orbit, concurrently logging the commands necessary to solve the problem or to work around the failures. This constant evolution of responses to the failures outlined in the project's FMEA documentation will significantly aid the mission operations staff in their task of ensuring the maximum mission life.

The Human Element

Once a small satellite project has completed the development, construction and ground testing phases, it is commonly thought that the mission is now completely ready for flight. The one exception to this rule had been manned spaceflight, where the crew and controllers would be put to the test in a series of simulations each more complicated than the prior simulation.

In the case of the small satellite projects in academia a similar set of simulations, minus the human crew, can be used as an effective measure of the preparedness of the Mission Operations Team. The purpose of verifying the readiness of the mission operations segment of the project, is that once on orbit, the functional lifetime of many academic small satellite projects is a matter of months and communications passes are extremely limited as universities and colleges do not have access to a network

of communication facilities even equivalent to the early manned spacecraft tracking stations utilized by NASA for Project Gemini.

Therefore the limited real-time operations of the spacecraft require a mission operations staff that is capable of quickly making critical decisions to ensure mission success. The verification of the readiness of the individuals involved can be determined to two ways: computerized simulations and simulations using hardware specifically designed for that purpose.

The computerized simulations for mission operations training is perhaps the easiest route. A health and status downlink can be simulated with any combination of values for each sensor. A series of scripts can be constructed to simulate everything from nominal operations to a complete failure of the spacecraft. A second set of scripts can be developed to monitor the responses from the mission operations center. This second set of scripts will be programmed to adjust the simulated health and status data based on user input. The determination of correct user input will be developed during the validation of the actual spacecraft hardware.

Computerized simulations are advantageous as they reduce the potential that a new controller may enter a command that could damage the spacecraft.

As comprehensive as the computerized simulations may be, they cannot simulate the sudden loss of a subsystem. To do this simulation hardware must be developed. The Colorado Space Grant Consortium at the University of Colorado at Boulder is currently developing the Sister Sat program to aid in the training of the mission operators

for the Three Corner Sat mission. These Sister Sats will allow for many different mission aspects to be verified. An example of this is solar panel output. A Sister Sat can be placed in direct sunlight to simulate the actual illumination on the solar panels due to the sun. Since the Sister Sat was never intended to fly in space, it may be used in normal work areas instead of a clean room.

During mission operations simulations commands can be sent to real hardware to ensure proper responses. The testing team can simulate hardware failures to verify mission operations readiness. For example, during simulation part of a solar panel may be covered to simulate loss of electrical output by a micrometeorite impact. Likewise an entire solar panel may be disconnected to simulate the complete failure of that panel.

To compensate for these computerized or simulated failures the mission operations team must employ the correct responses to ensure continued mission success. Due to the limited real time communications with the spacecraft, split second decision-making is necessary to ensure seamless operations.

The verification of mission operations readiness should take place in three phases: nominal, typical, and critical. The nominal phase will simulate mission operations where all components of the spacecraft are performing exactly as designed. This phase is designed to familiarize the operators with controlling the spacecraft.

Once the operators are comfortable with controlling the spacecraft, a more typical scenario is used. The simulation supervisor will send status values that are either perfectly normal or abnormal

but within tolerable limits. Over the course of several simulated passes, the values could fluctuate forcing the mission operations team to react accordingly.

The most difficult stage in the verification of mission operations readiness is the critical phase. It is necessary that the simulation supervisor send data that shows highly abnormal readings in one or more of the telemetry channels. For the first critical phase simulation, only one channel may be displaying telemetry which is outside the tolerable parameters. Follow on sessions will include multiple sequential and simultaneous failures. By the end of the training simulations the mission operations staff should be capable of solving or working around any problem short of any issues that would constitute a complete spacecraft failure, such as a flight computer failure or communications system failure.

Conclusions

With the rapid increase in academic institutions undertaking small satellite projects, the need for a validation and verification program that addresses the unique monetary and personnel constraints placed upon these organizations has forced new methodologies and protocols to be developed.

The methodologies and practices outlined in this document reflect current developments developed to simultaneously support the needs of two separate academic small satellite programs under development at the University of Colorado at Boulder. This approach to validation and verification reflects a paradigm shift from similar

efforts undertaken in industry. As with any well conceived engineering effort, the methodologies and their associated protocols are flexible to permit adaptation to any academic small satellite program.

The validation and verification of an academic small satellite should be regarded as one of the critical phases in the satellite project, as one overlooked anomaly may cause the spacecraft to inoperative on orbit. This is especially important to academic programs, as the distribution of funds for future programs is performance oriented. If an educational institution's first spacecraft is a complete failure the potential to receive funds necessary for the development of a second satellite is reduced.

It was the intent of this paper to provide the project leaders for the next generation of academic small satellites a reliable method with which to validate and verify the functionality of their spacecraft without sacrificing resources critical to the development and construction of the spacecraft. If these methodologies are implemented, the reliability of the spacecraft will be improved, reducing the potential for failure. And "failure is not an option" for academic small satellites.

Acknowledgements

The author would like to acknowledge the following individuals for their invaluable contribution to the creation of the methodologies and practices outlined in this paper.

Andrew Bussbee, Citizen Explorer Program Manager, for initial development of the Colorado Space Grant Consortium management website

upon which the SharePoint™ Team Services based anomaly tracking system was developed.

Jalane Daily, formerly with SysTest Labs, LLC, for introducing the author to skills necessary to effectively coordinate a validation and verification effort.

Elaine Hansen, Director Colorado Space Grant Consortium, for continually supporting the creation of a validation and verification program, despite the occasionally radical changes in methodologies leading up to this design.

Jen Michels, Three Corner Sat End-to-End Data System Program Manager, for her input as to how to adapt the original software validation and verification methodologies to the entire spacecraft.

Steve Wichman, Software Advisor, Colorado Space Grant Consortium, for his valuable input into the development of the validation and verification methodologies beginning in Fall 2000 when the current validation and verification effort only pertained to the software element of the Three Corner Sat project.

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