DEVELOPMENT OF CUBESAT VIBRATION TESTING CAPABILITIES FOR THE NAVAL POSTGRADUATE SCHOOL & CAL POLY SAN LUIS OBISPO

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APPROVAL AND COMMITTEE MEMBERSHIP

TITLE: DEVELOPMENT OF CUBESAT VIBRATION TESTING CAPABILITIES AT THE NAVAL POSTGRADUATE SCHOOL AND CAL POLY SAN LUIS OBISPO

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ABSTRACT

DEVELOPMENT OF CUBESAT VIBRATION TESTING CAPABILITIES
AT THE NAVAL POSTGRADUATE SCHOOL
AND CAL POLY SAN LUIS OBISPO

MARISSA LOUISE BRUMMITT

The Naval Postgraduate School is currently developing their first CubeSat, the Solar Cell Array Tester CubeSat, or NPS-SCAT. Launching a CubeSat, such as NPS-SCAT, requires environmental testing to ensure not only the success of the mission, but also the safety of other CubeSats housed in the same deployer. This thesis will address the development of CubeSat vibration testing methodology at NPS, including subsystem testing, engineering unit qualification, and flight unit testing. In addition, the new Cal Poly CubeSat Test POD Mk III will be introduced and evaluated based upon comparison with the Poly Picosatellite Orbital Deployer (P-POD). Using examples from the development of NPS-SCAT and test data from Cal Poly's Test POD Mk III and P-POD, the current CubeSat testing methodology will be verified and an improved method for NPS CubeSat subsystem testing will be presented.

Keywords: CubeSat, Vibration Testing, NPS-SCAT, P-POD, Test POD Mk III.

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ABBREVIATIONS AND ACRONYMS

C&DH	Command and Data Handling
CFT	Comprehensive Functional Test
CONOPS	Concept of Operations
COTS	Commercial-Off-the-Shelf
CP	Cal Poly
CPT	Comprehensive Performance Test
EDU	Engineering Development Unit
EPS	Electrical Power Subsystem
ESP	Experimental Solar Panel
GEVS	General Environmental Verification Specification
IC	Integrating Contractor
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NET	No earlier than
NLAS	NanoSat Launch Adapter System
NPS	Naval Postgraduate School
NPS-SCAT	Naval Postgraduate School Solar Cell Array Tester
NRO	National Reconnaissance Office
ORS	Operationally Responsive Space
PCB	Printed Circuit Board
P-POD	Poly-Picosatellite Orbital Deployer

SCAT	Solar Cell Array Tester
SMS	Solar Measurement System
SpaceX	Space Exploration Technologies Corporation
SSAG	Space Systems Academic Group
STP	Space Test Program
TT&C	Telemetry, Tracking & Command
TVAC	Thermal Vacuum
USN	United States Navy

INTRODUCTION

1.1 CUBESAT BASICS

The CubeSat standard has now exceeded ten years of use in the small satellite and university communities. What started as a university-focused satellite development program has grown into an industry-wide phenomenon and global standard. At this point, CubeSats have been launched from all around the world, not only by universities, but also by high school students, government projects, and commercial aerospace companies.

The current CubeSat standard stipulates a single unit (1U) CubeSat is 10 cm in length, width and height and has mass no greater than 1.33 kg[1]. Two Unit (2U) and three unit (3U) spacecraft are also compatible with the standard. An example 1U spacecraft is Cal Poly's CP6 CubeSat, shown in Figure 1. The CubeSat standard is controlled by the CubeSat team at California Polytechnic State University (hereafter referred to as Cal Poly) where the co-creator of the standard, Dr. Jordi Puig-Suari oversees the CubeSat program. A drawing of the CubeSat standard is available in Appendix A.

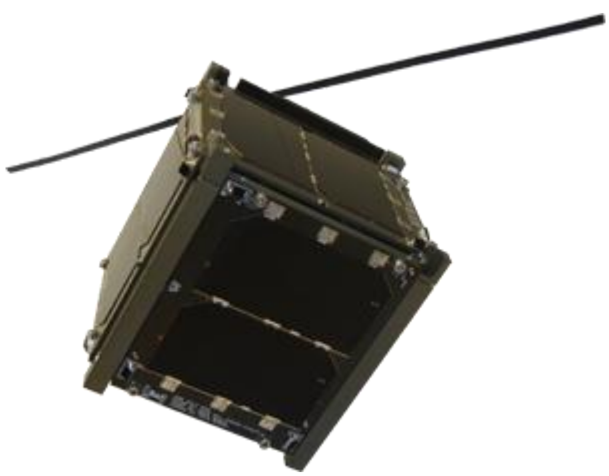


FIGURE 1: CAL POLY'S CP6 CUBESAT[2]

Multiple CubeSat deployers are available. The original is the Poly Picosatellite Orbital Deployer (P-POD) designed by Cal Poly. The P-POD is capable of holding three 1U satellites, a 1U and 2U, or a 3U. The third version of the P-POD, designated the Mk III, can be seen in Figure 2.

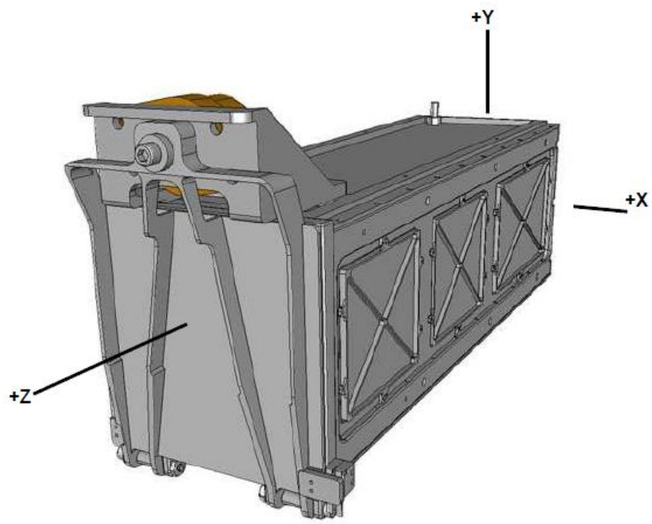


FIGURE 2: CAL POLY P-POD MK III[3]

With the growth in the standard, from 1 kg to 1.3 kg, the question has changed from "what even fits in a CubeSat?" to "what *can't* you fit in a CubeSat?" Companies see the opportunity to qualify space hardware, test risky architecture options, and fly single sensors without the need for a larger mission to purchase a launch. Professors, meanwhile, envision more capable payloads for students to operate after participating in the design, test, and launch of that same satellite – all before graduating from college. As more launch opportunities become available, greater possibilities will be demonstrated and higher levels of technology will find their way into space long before larger satellite programs will risk flying them.

1.2 EXPANDING CUBESAT CAPABILITIES

The maturity of the CubeSat standard is now reflected in the long list of satellites launched and the contributions those satellites have made to the aerospace and scientific communities. In their paper, "An Overview of Small Satellites in Remote Sensing," authors Kramer and Cracknell recognize that despite the limited objectives each CubeSat may have, the advantage of a picosatellite platform is the "very low cost and the speed of designing/building a satellite practically from off-the-shelf components."[4] A CubeSat that is launched with a limited objective still completes more valuable research than a larger satellite that never reaches orbit due to cost and schedule overruns.

Experiments that were formerly only possible in large spacecraft are now being accomplished by CubeSats. At NASA Ames Research Center, a fully capable biological research experiment took the form of a 3U CubeSat called GeneSat-1. One of the satellite's objectives and a main function of the payload was to "quantitatively detect levels of GFP expressed in living cultures (E. coli) as a means of evaluating technologies targeted at assessing human exploration risks."[5] The operation of GeneSat, after launching on December 16th, 2006, demonstrated that valuable science could be accomplished with a 3.5 kg satellite. As the CubeSat standard became more widely known, the National Science Foundation (NSF) recognized the future role of picosatellites in the study of space weather. In a recent launch on November 19th, 2010, the first NSF-sponsored CubeSat, the Radio Aurora Explorer (RAX), was launched from Kodiak, Alaska. The CubeSat will study large plasma formations in the ionosphere that can cause communication interruptions between orbiting spacecraft and earth.[6]

One further example of the vast capabilities of the tiny CubeSat form factor, is the NASA Nanosail-D 3U CubeSat managed by Marshal Space Flight Center. The satellite's mission is to demonstrate the use of a solar sail, as well as the ability to safely store and deploy the 100 ft^2 sail. As of December 6th, 2010, the satellite has been successfully launched, but has not yet deployed the solar sail.[7]

With advancing capabilities in such a small form factor comes new challenges, not only for the engineers involved in the design and development of the satellite, but for the testing teams as well.

1.3 CubeSat Testing Challenges

The growth and evolution of small satellite design has instigated an evolution in testing as well. To fly in the P-POD, CubeSat developers are required to meet specific vibration and thermal testing requirements for their integrated satellite, however, there are no pre-requisites for subsystem or unit testing[1]. These environmental testing requirements are designed to ensure the safety of the launch vehicle and the safety of the other satellites within the deployer without placing unnecessary constraints on the developer. With more advanced payloads however, CubeSats have now stepped into an arena where subsystem testing is often a necessity prior to integrated testing.

Even without the complications of subsystem testing, CubeSats face a number of testing challenges that are unique to picosatellites. Aerospace testing is not only time consuming, but also expensive, and the balance of these two factors is at the root of most CubeSat testing considerations.

First, the various standards and test plans that are followed by NASA and other large aerospace companies are tailored for large satellite programs with an emphasis on mitigating risk, while often times sacrificing cost and schedule. Blindly following testing standards meant for much larger spacecraft can severely hinder a CubeSat program by requiring extra tests or reviews that do not allow systems to progress in parallel. This applies to university and industry programs alike because it is often easier to follow protocols that are already set forth by previous projects, or refer to standard documents that are based upon testing space hardware rather than commercial off-the-shelf (COTS) products which can be replaced quickly and cheaply.

Another consideration for developers, is that the P-POD does not always have a desirable mounting placement on a rocket. This can impact both the shock and vibration environment as well as the thermal profile the satellite will experience on launch.

Additionally, CubeSat development schedules are compressed and budgets are limited, therefore testing is subjected to these same unique constraints. The MAST CubeSat, designed by Tethers Unlimited, is one example of this challenge. After the tether did not fully deploy on-orbit, the team outlined the earlier tradeoff they faced when they "had to choose between the options of redesigning and rebuilding the experiment hardware, and then not having sufficient funds to launch the experiement, or flying what we had and seeing if it would work."[8] Such a decision highlights the obstacles often faced by small satellite teams.

A launch will never wait for a CubeSat, so it is up to each team to determine the amount of testing involved in the development and qualification of the satellite to ensure delivery at the correct time. Depending on the testing facilities available, another consideration is the cost of outsourcing the testing or travelling to Cal Poly for qualification.

University CubeSat programs have the additional challenge of high personnel turnover due to student graduations. Evaluating the trade-offs between time-consuming documentation and teaching new students through experience is a unique choice for every cube sat program. Based on these principles. a university will manage their student team in a way that optimizes the learning experience and satellite development process.

In contrast, the benefit of working on a CubeSat project is a higher tolerance for risk. Even prior to the CubeSat standard and the influx of university satellite programs, Michael Swartwout, of Standford University, pointed out that "Students have the 'luxury' to fail, something that most in professional space industry must avoid."[9] Most universities accept risk as part of the learning process, while companies are able to justify it solely on the basis of cost. For either part of the community, COTS components are a fraction of the cost of space-rated components, which also decreases cost and risk during development phases.

2 BACKGROUND

2.1 NAVAL POSTGRADUATE SCHOOL SOLAR CELL ARRAY TESTER CUBESAT

The Naval Postgraduate School (NPS) Space Systems Academic Group (SSAG) is currently building and testing the school's first CubeSat. The Solar Cell Array Tester CubeSat, or NPS-SCAT, will test solar cells on-orbit to record their degradation. The figure below shows the integrated satellite and the experimental solar cells that surround the payload sun sensor.

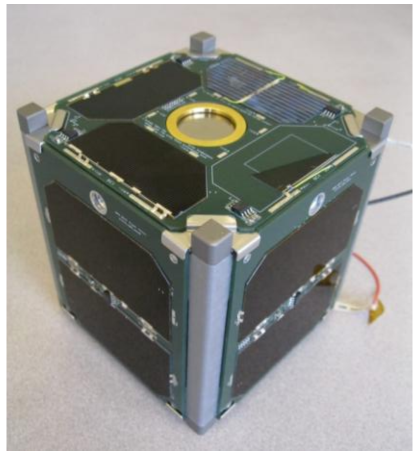


FIGURE 3: NAVAL POSTGRADUATE SCHOOL SOLAR CELL ARRAY TESTER

In addition to the design, build and test of NPS-SCAT, the CubeSat program also places a high level of emphasis on another goal – the education of Naval Officers and other students at NPS. The summer 2010 NPS-SCAT team is shown below.

FIGURE 4: NPS-SCAT TEAM, SUMMER 2010

2.1.1 Mission and Subsystems

The requirements for NPS-SCAT CubeSat are written as a set of Key Performance Parameters (KPPs)[10]. The KPPs are presented in Table 1.

TABLE 1 NPS-SCAT KEY PERFORMANCE PARAMETERS

#	NPS-SCAT Key Performance Parameter
1	*The satellite development program shall provide NPS students with an education in the satellite design process, integration, testing, and full life cycle of a space flight system.*
2	*The satellite shall utilize a 1U Pumpkin© CubeSat architecture*.
3	*The solar measurement system shall be capable of obtaining solar cell I-V data curve to include solar cell current, voltage, temperature and sun angle no less than once per orbit.*
4	*The satellite shall be able to communicate TT&C and Payload data to the NPS ground station using an S-band radio (primary transmitter) and/or UHF beacon (secondary transmitter).*
5	*The satellite shall transmit TT&C and Payload data continuously via the UHF beacon and transmit when commanded via the S-band radio.*
6	*The satellite shall be capable of being launched via a CubeSat deployer on a Falcon 1e launch vehicle.*
7	*The satellite shall operate continuously in orbit upon launch and have a mission duration of approximately 100 days to 1 year*
8	*The system shall utilize Commercial Off the Shelf (COTS) hardware whenever possible*
9	*The satellite development program shall establish the CubeSat program at NPS by creating a CubeSat working group, small satellite process and procedure development, and establishing an engineering support structure*.

To meet these requirements NPS-SCAT utilizes a combination of subsystems both designed in-house and purchased CubeSat subsystems that are compatible with the Pumpkin CubeSat structure.

The satellite bus consists of the Pumpkin FM430 Flight Computer, the MHX 2400 Radio, the ClydeSpace Electrical Power System (EPS), and the Cal Poly Beacon Board. A model of NPS-SCAT is shown for reference in Figure 5.

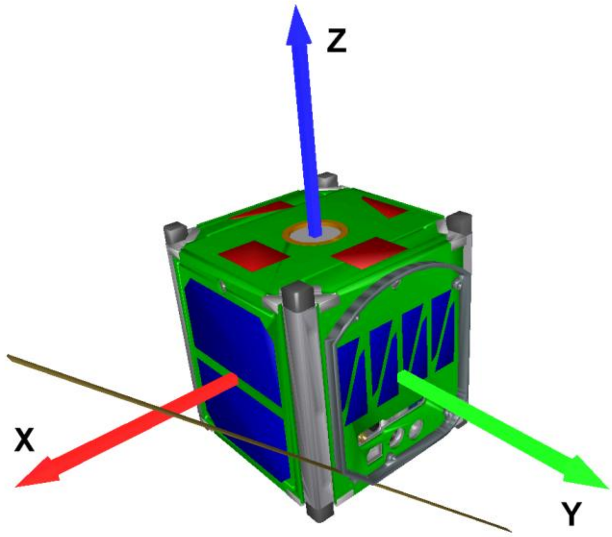


FIGURE 5: NPS-SCAT COORDINATE SYSTEM

The payload for NPS-SCAT is the Solar Measurement System (SMS) and the Experimental Solar Panel (ESP). The SMS printed circuit board is the structural component for mounting the Sinclair Sun Sensor and controls all payload measurements. These includes measurements taken from the four different experimental solar cells mounted on the ESP, which is on the +Z axis of the CubeSat and has a hole to accommodate the Sinclair Sun Sensor. Figure 6 shows the SMS and coordinate system for the payload board.

FIGURE 6: NPS-SCAT SOLAR MEASUREMENT SYSTEM (SMS)

2.1.2 CONOPS

Only a brief summary of the NPS-SCAT concept of operations (CONOPS) is described here. For a more detailed version please refer to Cody Mortensen's NPS Thesis titled "NPS-SCAT; Communications System Design, Test, and Integration of NPS's First CubeSat."[11] The CONOPS for NPS-SCAT was primarily driven by the CubeSat deployment requirements and the payload requirements.

Launch operations start with the CubeSat stowed in the deployer with batteries at the optimal storage level. At the point when NPS-SCAT is deployed, the switch on the foot of the CubeSat will no longer be depressed, turning on the FM430 and initiating a minimum 30 minute countdown. At the end of the countdown, the satellite will check the battery charge level. With adequate charge of 8.5 volts, the satellite will deploy the beacon antenna. On-orbit the satellite will execute a limited number of tasks to fulfill the mission of collecting solar cell data. These include the:

- MHX wakeup task
- Transmit MHX task
- Receive MHX task
- Collect data task
- Beacon transmit task
- Receive beacon task

Ideally, the collect data task is completed 3 times per orbit, while the spacecraft is in the sun. The measurements during the "Collect data" task include the sun angle and an IV curve for each solar cell.

2.1.3.1 LAUNCH VEHICLE

At the time of testing, NPS-SCAT was scheduled for a launch on the SpaceX Falcon 1e in fall of 2011. Previous SpaceX launches have had CubeSat payloads, including the RazakSat mission pictured below[12]. The Falcon 1e, shown in Figure 8 below, is capable of launching a 1010-kilogram payload into a 185 km circular orbit.[13]

FIGURE 7: LIFTOFF OF FALCON 1, RAZAKSAT MISSION

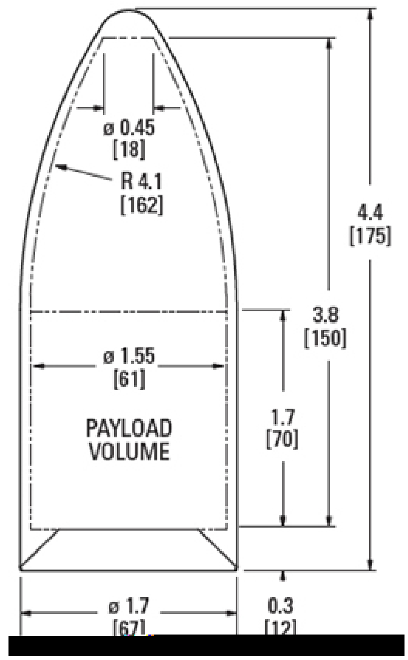


FIGURE 8: FALCON 1 FAIRING

The relevant information for CubeSat vibration testing was the Falcon 1 Random Vibration Maximum Predicted Environment PSD Values, listed in Table 4[13]. Unfortunately these values are from the Falcon 1, not the Falcon 1e, therefore they are still only an estimate and likely represent a minimum because of the enhanced performance of the Falcon 1e over the Falcon 1.

TABLE 2: FALCON 1 RANDOM VIBRATION ENVIRONMENT

Frequency (Hz)	ASD (g^2/Hz)
20	.003
100	.02
700	.02
2000	.0025
Overall	4.7 Grms

2.1.4 ENGINEERING DEVELOPMENT UNIT

The NPS-SCAT engineering development unit (EDU) was developed as an initial proof-of-concept and for qualification testing. It includes all of the subsystems identified in the description of NPS-SCAT except for the final version of the Cal Poly Beacon Board, which was not available for qualification tests. Instead, a prototype beacon board with similar characteristics was substituted for qualification testing. In the overall development plan, a second satellite will be built, which will be the Flight Unit. The second satellite will be tested at either proto-flight or acceptance levels, depending on any modifications that were made to the EDU after qualification.

There were multiple advantages to building both an EDU and a Flight Unit. Moving from the breadboard to an EDU provided an initial fit-check for the subsystems, identified interface issues before the flight unit integration, and allowed the payload SMS board and ESP board to be tested in a flight configuration. This follows the “test like you fly, fly like you test” philosophy, which results in risk mitigation through flight-like testing scenarios.[14] Building an EDU also allows the team to test the satellite at the higher qualification level because it is not intended for launch.

The integration and functional testing of the EDU was an iterative process with these tasks often taking place in parallel. The original integration procedures for the EDU were written in 2009 and further refined as the final boards were manufactured. Between the fall of 2009 and summer 2010, the NPS-SCAT subsystem configurations were finalized, which allowed the test engineers and systems engineer to work collaboratively to find an optimized integration sequence. Consequently, integration of the NPS-SCAT EDU takes approximately three days and includes all necessary torque values and staking compound placement.

2.1.4 ENVIRONMENTAL TESTING

The development of environmental test plans and levels for NPS-SCAT was based upon the expected launch environment and the CubeSat Design Standard (CDS) because the satellite was not officially manifested at the time environmental testing took place. Although the CubeSat had an assigned Falcon 1e launch, it was in the best interest of the program to test at higher levels to allow launch flexibility in the future.

Thermal vacuum testing will be discussed in Commander Kerry Smith's thesis completed for the Naval Postgraduate School.

2.1.4.1 DERIVED TEST REQUIREMENTS

Defining testing levels for NPS-SCAT involved two challenges that are typical of CubeSat programs. First, NPS-SCAT was not officially manifested on the Falcon 1e at the time it was necessary to complete qualification testing. Second, the Falcon 1e has not flown before, so the vibration levels are based upon the previous Falcon 1 flights. In addition, due to contract delays, NPS-SCAT was not given any information regarding the deployment device that would be used for launch.

Due to these uncertainties, NPS-SCAT was essentially tested independently of the launch vehicle and deployer. The disadvantage to this testing methodology was the necessity to always choose the worst-case environment despite a high probability the satellite would not be exposed to the extremes it was tested to.

It was known that an Integrating Contractor (IC) would be chosen eventually, and that organization would be responsible for setting forth the requirements for CubeSats participating in the launch. In discussions with a NASA facility, it was suggested the NPS-SCAT team test based upon the NASA GEVS testing standard (which is utilized in the CubeSat Design Standard) or the Falcon 1e levels.

The NASA GEVS random vibration levels, including the lowest level of component workmanship, all encompass the Falcon 1e profile.[15] Conveniently, the NASA GEVS levels are designed to encompass most of the common launch vehicles used.[3] For this reason, the CubeSat Design Specification (CDS) uses NASA GEVS when the launch vehicle environment is unknown. In order to ensure the satellite would not require further testing if a different launch vehicle was available, the GEVS vibration testing levels were adopted for NPS-SCAT environmental testing. The NASA GEVS levels are shown with the Falcon 1 levels for comparison in Figure 9.

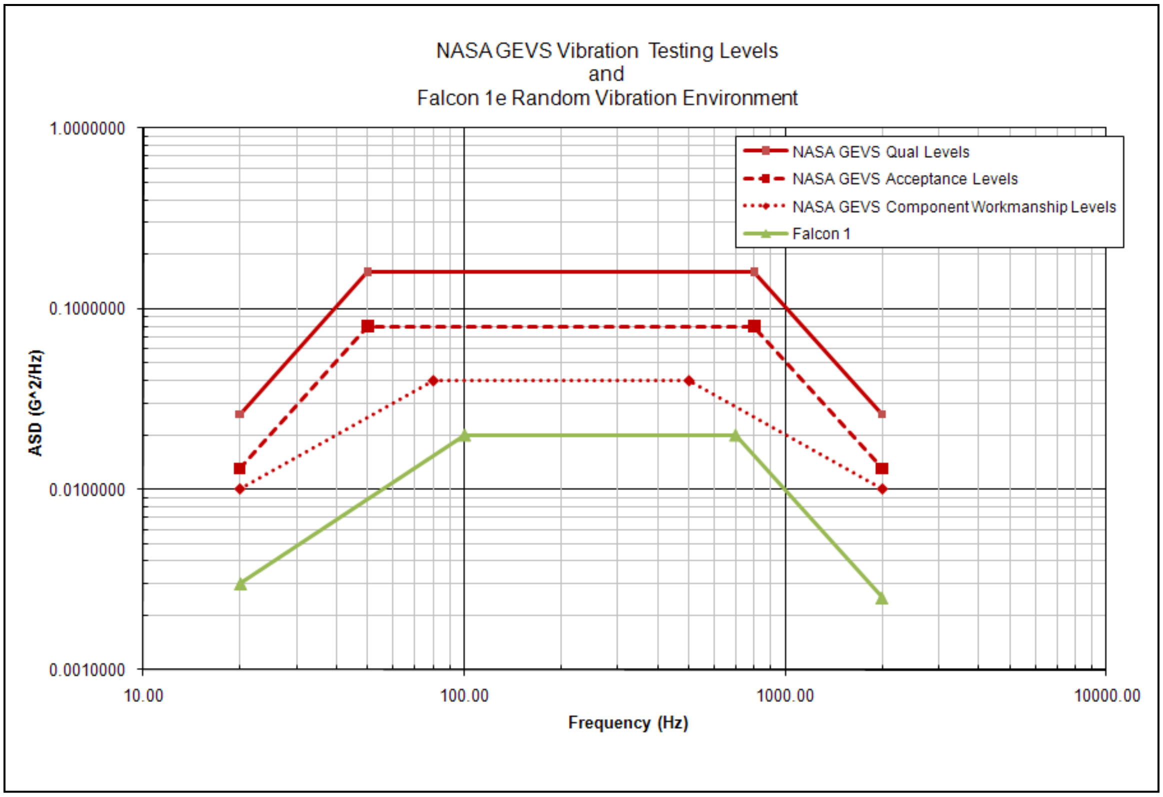


FIGURE 9: NASA GEVS AND FALCON 1E RANDOM VIBRATION PROFILE

The following tables call out the values for the NASA GEVS Qualification, Acceptance and Component Workmanship profiles that are shown above.

TABLE 3: NASA GEVS QUALIFICATION AND ACCEPTANCE

	Qualification	Acceptance
Frequency (Hz)	ASD (g^2/Hz)	ASD (g^2/Hz)
20	.026	.013
20-80	+6 dB/oct	+6 dB/oct
80-500	.16	.08
500-2000	-6 dB/oct	-6 dB/oct
2000	.026	.013
Overall	14.1 Grms	10.0 Grms

TABLE 4: NASA GEVS COMPONENT WORKMANSHIP

Frequency (Hz)	ASD (g^2/Hz)
20	.01
20-80	+3 dB/oct
80-500	.04
500-2000	-3 dB/oct
2000	.01
Overall	6.8 Grms

2.1.4.2 TESTING SEQUENCE

With the determination of the testing environment, the team went forward with defining a test plan and test procedures for the satellite. These included the NPS-SCAT Test Plan, the NPS-SCAT Vibration Testing Procedures, and the NPS-SCAT Thermal-Vacuum Testing Procedures. In addition, Test Readiness Reviews (TRR) were conducted prior to each test.

The original test sequence and the final testing sequence were slightly different, therefore the final test sequence is shown to encompass all additional tests and modifications that were included. The rational for each test is further addressed in the subsequent sections of this document.

NPS-SCAT subsystem testing was completed first to qualify the payload SMS board. This was completed using an interface plate and NASA GEVS Workmanship testing levels.

Next, it was recognized that the payload test levels should actually be based upon the environment experienced within the satellite, so an additional test was added. A Mock Satellite was built to replicate the NPS-SCAT satellite and the responses within the satellite were recorded for comparison with the subsystem testing. This testing was completed at both NASA GEVS Workmanship and Qualification levels. The results verified the NPS-SCAT SMS board had survived qualification levels based upon the response within the satellite, and therefore was ready for integrated testing.

At this point the EDU was integrated and the qualification test at NASA GEVS Qualification levels was completed. The only modification was the substitution of a board similar to the Cal Poly Beacon Board.

Flight Unit testing is the last portion of the test plan which has not been completed. This is dependent on flight unit subsystem testing and the arrival of the Cal Poly Beacon Board. Test levels for the Flight Unit will be determined at the time of testing depending on any modifications made after EDU qualification. Further details are presented in section 4.3.

2.1.3.3 NPS VIBRATION TESTING FACILITY

The Space Systems Academic Group at the Naval Postgraduate School has an impressive array of spacecraft testing capabilities that are available for use by the NPS-SCAT team.

For NPS-SCAT vibration testing, a Ling Electronics electrodynamic shaker was used. The shaker can be oriented vertically or horizontally for use with a slip table, allowing 3-axis testing without an additional test adaptor or bracket. The system is rated for a maximum of 6,000 pounds force (26.7 kN). Both the vertical and horizontal configurations are shown in Figure 10.

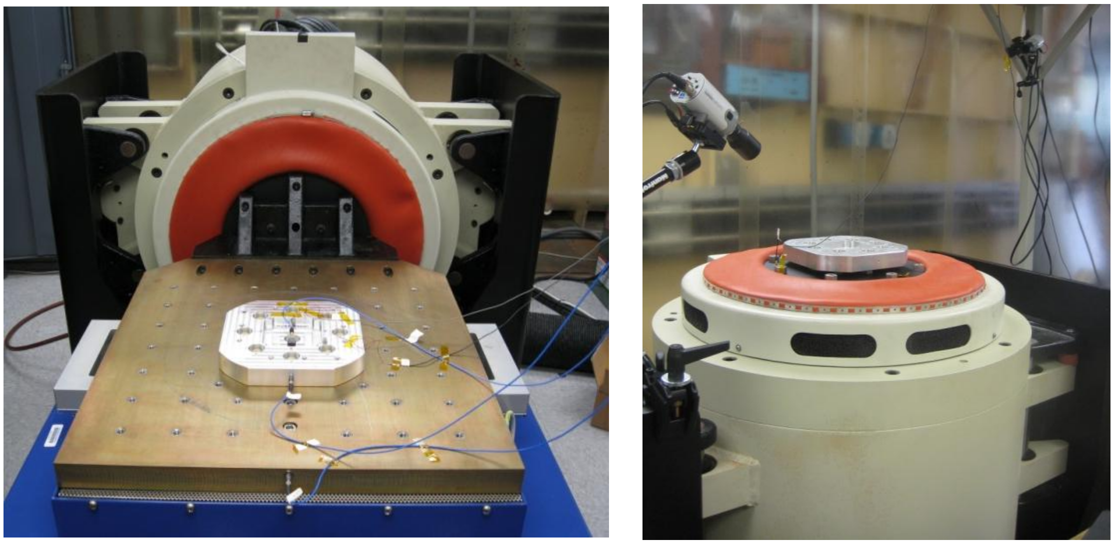


FIGURE 10: NPS VIBRATION TEST FACILITIES, LING SHAKER

The full configuration for vibration testing includes[16]:

- Ling 612VH Electrodynamic Shaker
- Dynamics Solutions GT600M Stand-alone Slip Table
- DMA-6XE Solid State Amplifier
- Agilent VXI Data Acquisition Unit and Function Generator
- Vibration Controller PC with m+p brand software

This set-up allows up to 16 measurement channels to be recorded during a test. In addition, the vibration test facility is also equipped with a digital video monitoring system. The four cameras are positioned in the test area to record the test item from all angles.

2.1.5 Flight Unit

The NPS-SCAT Flight Unit subsystems are currently in the manufacture and testing phases. Subsystems purchased from other vendors require acceptance testing prior to integration with the rest of the satellite. Subsystems manufactured in-house require parts bake-out and clean room population before individual acceptance testing.

Integrated testing of the satellite will take place prior to conformal coating and environmental testing. This decreases the risk of finding physical incompatibilities and/or operational anomalies after the conformal coating has been applied. Further testing at the subsystem level and satellite level after conformal coating is applied and cured.

Upon passing the initial functional tests, the satellite will be fully integrated in preparation for vibration and thermal-vacuum testing at acceptance or proto-flight levels.

2.1.5 Future NPS Satellite Development

One of the goals of the NPS CubeSat program is to develop a satellite bus that can be used with any given payload. Future use of NPS bus will build heritage and allow the team to focus on payload development. In the case of NPS-SCAT, the satellite bus consists of the Pumpkin FM 430, the ClydeSpace EPS and battery board, the MHX 2400 radio, and the Pumpkin CubeSat structure. As will be shown subsequently, the current bus was successfully qualified when the NPS-SCAT EDU was tested at NASA GEVS qualification levels. The integrated payload, which is the Solar Measurement System (SMS), was also qualified at that time.

Although system integration and testing will be required for each new satellite, the process can be dramatically simplified if the payload is qualified separately from the bus. With a standard bus and a qualified payload, the satellite could be integrated and tested at proto-flight levels. This does however require a specially designed payload testing configuration and payload test levels, which will be addressed within this thesis.

2.2 Cal Poly Test POD Mk III and P-POD Mk III

During the same time frame that NPS-SCAT was approaching satellite qualification, testing, Cal Poly San Luis Obispo completed the manufacture of a new CubeSat Test POD, the Test POD Mk III. The combination of advanced testing facilities at NPS and further interest in evaluating the standard CubeSat testing process allowed the Test POD Mk III to undergo qualification level testing at NPS. With a greater number of measurement channels and new 1U mass models made by Cal Poly, the Test POD Mk III was instrumented to record the actual CubeSat response in addition to the response of the outer structure. With additional support from Cal Poly, a P-POD with three 1U mass model was instrumented in a similar fashion; each 1U mass model had an inner accelerometer to record the CubeSats' responses.

Three main goals were accomplished with these tests. First, the Cal Poly Test POD Mk III was tested at qualification levels and the response of the mass model was recorded. Second, the CubeSat response measurements from the Test POD Mk III were compared to the response measurements of the Cal Poly P-POD to understand how the testing method and deployer environments compare. And lastly, the CubeSat responses from the P-POD were examined to understand the dynamics of the individual satellites when exposed to environmental testing and ultimately, launch conditions.

2.2.1 Cal Poly Test POD Mk III

Cal Poly originally designed the CubeSat Test POD as a stand-alone testing apparatus for 1U CubeSats. Multiple Test PODs were manufactured to lend to other CubeSat teams and facilitate satellite qualification at other universities with vibration testing capabilities. A picture of the Test POD is shown in Figure 11.

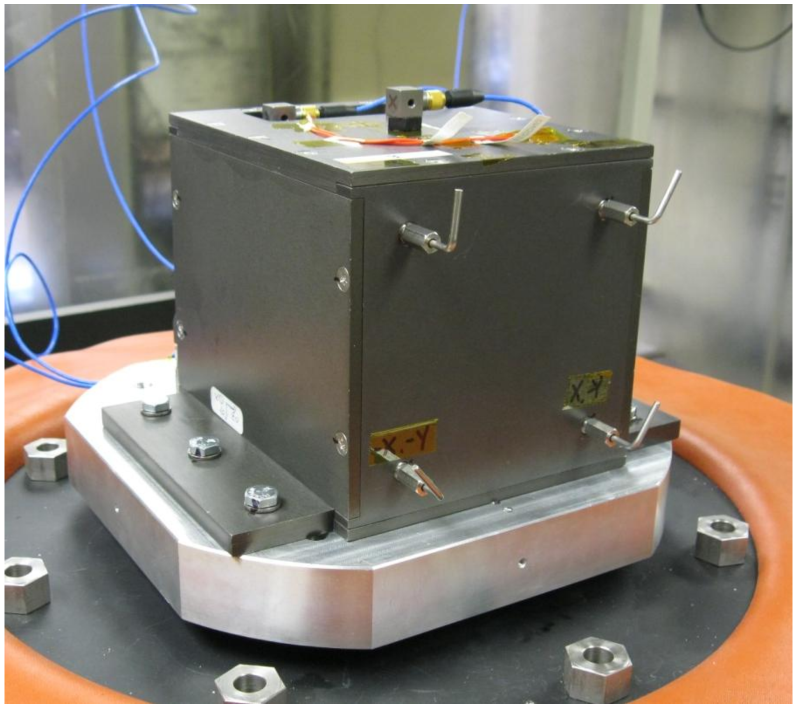


FIGURE 11: ORIGINAL CAL POLY TEST POD

Although the original Test POD is still in use, a number of changes were identified to improve the design. The result of those improvements is the Cal Poly Test POD Mk III. A member of the Cal Poly CubeSat team completed the design modifications to the original Cal Poly Test POD and produced a proto-type for qualification purposes. Though it is only the second revision of the Test POD, it is called the Test POD Mk III because it was designed to mount similarly to the PPOD Mk III.

The Test POD Mk III is different from the first Test POD in three main features. First, the pusher plate located inside of the Test POD, which mimics the pusher foot of the PPOD, is restricted by the rails from moving freely within the Test POD Mk III. Second, there are no flanges for connection to the vibration table. This means a vibration interface plate is necessary to connect to the Test POD and then to the vibration table. Finally, the Test POD Mk III uses set screws instead of helicoils to hold the spring plungers in place. This specific change was made because the helicoils are difficult to replace when a Test POD returns from a CubeSat program and is refurbished before being sent to another location.

The empty Test POD Mk III and the integrated configuration are shown in Figure 12 to illustrate the testing configuration.

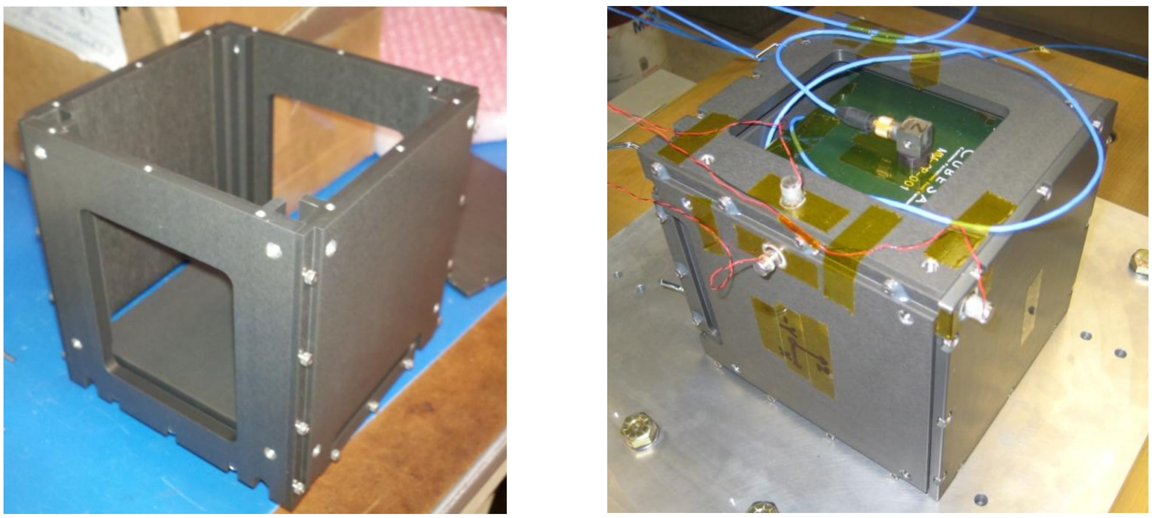


FIGURE 12: TEST POD MK III PRE AND POST INTEGRATION

As mentioned, the Test POD Mk III must be qualified before it is manufactured and sent out to developers. For this portion of the testing it has been agreed with Cal Poly the Test POD will be tested at NASA GEVS Random Vibration Qualification levels with a pre and post-sine sweep. There was also interest in seeing if the response of the CubeSat would change after the first random vibration test, therefore a second GEVS Random Vibration was completed, followed by a final sine sweep.

The instrumentation for this testing will include an accelerometer inside of the CubeSat mass model for measurement of the CubeSat response and comparison with the P-POD response levels.

2.2.2 Cal Poly P-POD Mk III

As previously described, the Cal Poly P-POD Mk III is the third generation design of the Poly Picosatellite Orbital Deployer produced by Cal Poly. The deployer acts as a secondary payload adapter to hold three CubeSats during a launch. There is a standard hole pattern for interfacing with launch vehicles, however some modifications are possible based upon the specific launch vehicle and position of the P-POD.

The P-POD is essentially an aluminum box with a large spring to eject the three CubeSats simultaneously. The deployer uses an NEA to release the door and separation between the CubeSats is accomplished with two small springs in the feet of each satellite (refer to the CubeSat specification in Appendix A for further details).

The P-POD Mk III has completed extensive qualification testing and characterization, as documented in Wenschel Lan's thesis[17]. However, the previous testing did not document the CubeSat response within the P-POD, so it was necessary to take those measurements using standard CubeSat mass models and controlled accelerometer placement. Cal Poly's vibration testing facilities only support the recording of four response channels, one of which is necessary for the control accelerometer attached to the shake table. Therefore, the advantage of testing at NPS was the ability to place a tri-axial accelerometer inside each CubeSat mass model and then compare this data to the re-designed Test POD.

Evaluation of the current testing methodology will be based upon comparison of the Test POD and P-POD inner CubeSat responses. The Test POD is expected to be the worst-case vibration environment.

3 NPS-SCAT SUBSYSTEM VIBRATION TESTING

Similarly to much larger spacecraft, payload development for NPS-SCAT required an extensive amount of time and resources. In a typical spacecraft development cycle, subsystems are often tested separately, but for picosatellite testing it is not uncommon to qualify the entire satellite (structure, subsystems and payload) at one time. Not only does this reduce the time and cost involved, it is also a logical step because CubeSats are actually the same size, or smaller, than the modules on a larger spacecraft that would be qualified individually.

In the case of NPS-SCAT however, the high cost and unconventional mounting of the Sinclair Sun Sensor on the SMS PCB caused the team to reevaluate the typical testing timeline. It was determined that the SMS board would undergo separate workmanship testing prior to satellite qualification. Therefore, a subsystem vibration testing method was developed.

3.1 TEST DEVELOPMENT

The goal of NPS-SCAT subsystem testing was to replicate the environment experienced by a PCB mounted inside of the NPS-SCAT CubeSat during qualification testing. Therefore, two considerations had to be addressed. First, a testing apparatus to hold an individual PCB was necessary. Second, test levels appropriate for workmanship testing were determined.

3.1.1 SUBSYSTEM TESTING INTERFACE PLATE

An interface plate is necessary to attach a test item to the vibration table. The first interface plate made for NPS-SCAT testing was designed for two purposes. One purpose was subsystem testing of individual PCBs and the other purpose was to attach the Cal Poly Test POD for integrated satellite testing. The Test POD only requires 6 holes and assumes the interface plate will transfer the input from the shake table to the Test POD. This was accomplished with a sufficiently thick, aluminum interface plate. For compatibility with the subsystem testing goals, further modifications to the plate were necessary.

Two subsystem configurations were considered based on the following factors:

1) Mimic the satellite configuration as close as possible. This option would include use of stand-offs to elevate the board above the plate as well as the attachment of two 52-pin headers to imitate the satellite bus connection to the PCB.
2) Minimize the interface connections to transfer the shaker input directly to the PCB. This option only included four connections to the board, using the corner holes on the PC-104 standard board.

Because option one did not guarantee the board would respond the same as in the satellite, the second option was chosen. Option two minimized the variables within the set-up. The resulting interface plate is shown in the vertical shake position in Figure 1313.

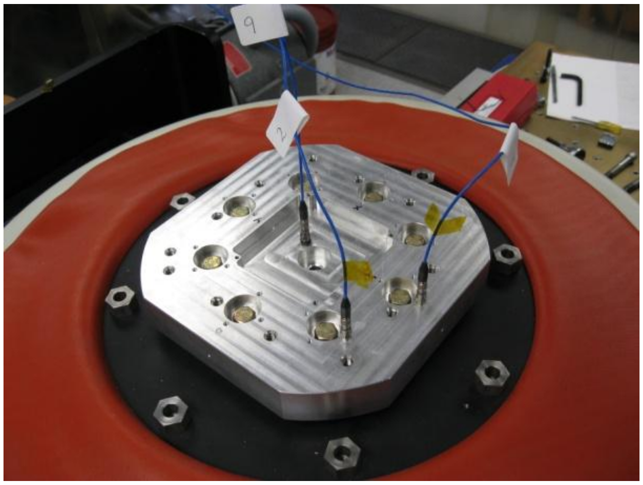


FIGURE 13: NPS-SCAT VIBRATION INTERFACE PLATE

The plate accommodates a PC-104 standard board as well as the Test POD in two separate axes. For subsystem testing, the interface plate must be removed to change axes, but the extra six holes that are compatible with the Test Pod allow it to be removed rather than the entire interface plate. For either test item, the interface plate must be removed and reattached for use in the vertical shake direction.

3.1.2 TEST CONFIGURATION AND LEVELS

Initial evaluation of the subsystem test set-up was completed with a blank PCB. The PCB was designed for use in NPS-SCAT and did have two 52-pin headers attached, however no other components were populated. The drawback to this configuration was the lack of an electrical functional test to confirm the PCB worked prior to and after vibration testing. Visual inspections were completed after each shake. The test configuration is shown in Figure 14.

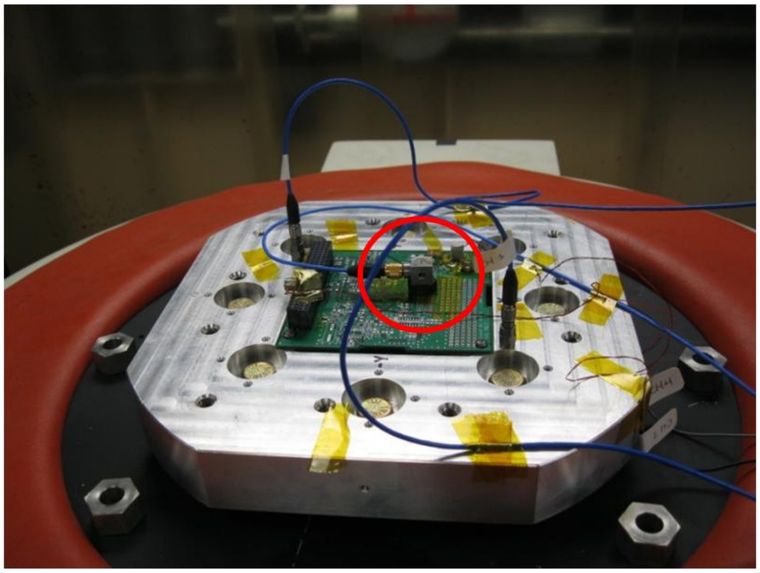


FIGURE 14: BLANK BOARD VIBRATION CONFIGURATION

Multiple accelerometers were placed on the board to record the response. A tri-axial accelerometer was placed in the middle of the PCB to record the response near the sun sensor attachment point on the SMS board . Two more uni-axial accelerometers were placed on the corner of the board (+Z) and on the 52-pin header (+X).

Even with the precaution of testing a blank board first, a mass model was substituted for the Sinclair Sun Sensor on the SMS Board to ensure the payload sensor was not damaged prior to EDU qualification. The SMS board is shown in the horizontal and vertical testing axes in Figure 15 and Figure 16 below. A tri-axial accelerometer was placed on top of the sun sensor mass model to record the response. It is important to note that all accelerometers were attached with glue rather than wax to ensure accurate response recording.

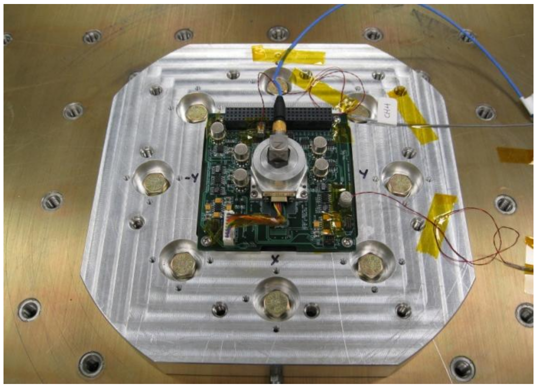


FIGURE 15: SMS CONFIGURATION, X AND Y AXES

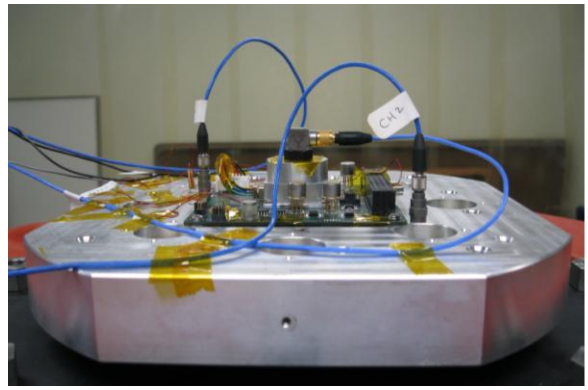


FIGURE 16: SMS CONFIGURATION, X AND Y AXES

Testing levels were determined based on NASA testing standards and considerations specific to NPS-SCAT. First, it was assumed that the damping present within the integrated satellite would cause the subsystem boards to experience a lower vibration level than the NASA GEVS Qualification levels the EDU would be tested at. Therefore, the options were to tailor a vibration test profile based upon an assumed level inside the Test POD, or utilize a test profile set forth by NASA. Without prior knowledge of the vibration environment within the Test POD, it was not possible to predict the levels and tailor a test. Therefore, NASA GEVS Component Workmanship levels were chosen.

The NASA Technical Standard 7001, Payload Vibroacoustic Test Criteria (NASA-STD-7001), was also utilized. The workmanship test levels in NASA-STD-7001 are the same as the component workmanship test levels in NASA-GEVS. This standard outlines component minimum workmanship random vibration test levels for an item that is less than 23kg (50 lb) and stipulates that test levels for larger items must encompass the minimum workmanship levels regardless of the maximum expected environment (MEE).[18] Therefore, the subsystem testing criteria met NASA standards because the component workmanship profile encompasses the published Falcon 1 levels. The workmanship levels and the relevant profiles are shown in Table 5 and Figure 7.

TABLE 5: NASA GEVS COMPONENT MINIMUM WORKMANSHIP RANDOM VIBRATION TEST LEVELS (UNITS WITH MASS LESS THAN 50KG)

Frequency (Hz)	ASD (g^2/Hz)
20	.01
20-80	+3dB/oct
80-500	.04
500-2000	-3dB/oct
2000	.01
Overall	6.8 grms

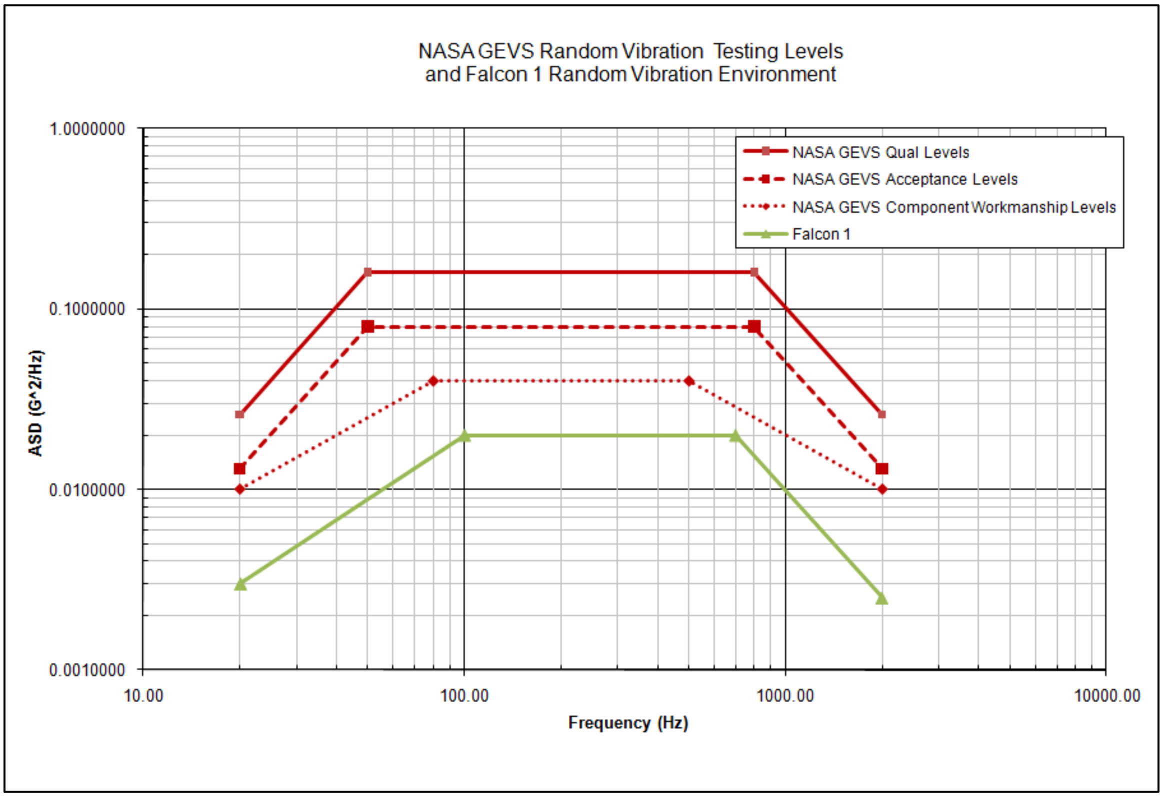


FIGURE 17: NASA GEVS RANDOM VIBRATION LEVELS AND FALCON 1 VIBRATION ENVIRONEMENT

The testing sequence for the subsystem testing consisted of a pre-testing .25g sine sweep, the random vibration testing at NASA GEVS Component Workmanship Level, and a post-testing .25g sine sweep. The testing started with the axes that were expected to show a lower response and finished with the Z-Axis.

3.2 SUBSYSTEM TEST RESULTS

The test data for the blank PCB and the NPS-SCAT Solar Measurement System board are presented below followed by an evaluation of the results.

3.2.1 BLANK PCB RESPONSE

Only a short summary of the blank board data is presented because the purpose of testing the board was simply to evaluate the interface plate. An example plot of the raw data is shown below, in Figure 18, of the Z-axis. The response is from the tri-axial accelerometer located on the top, middle of the PCB.

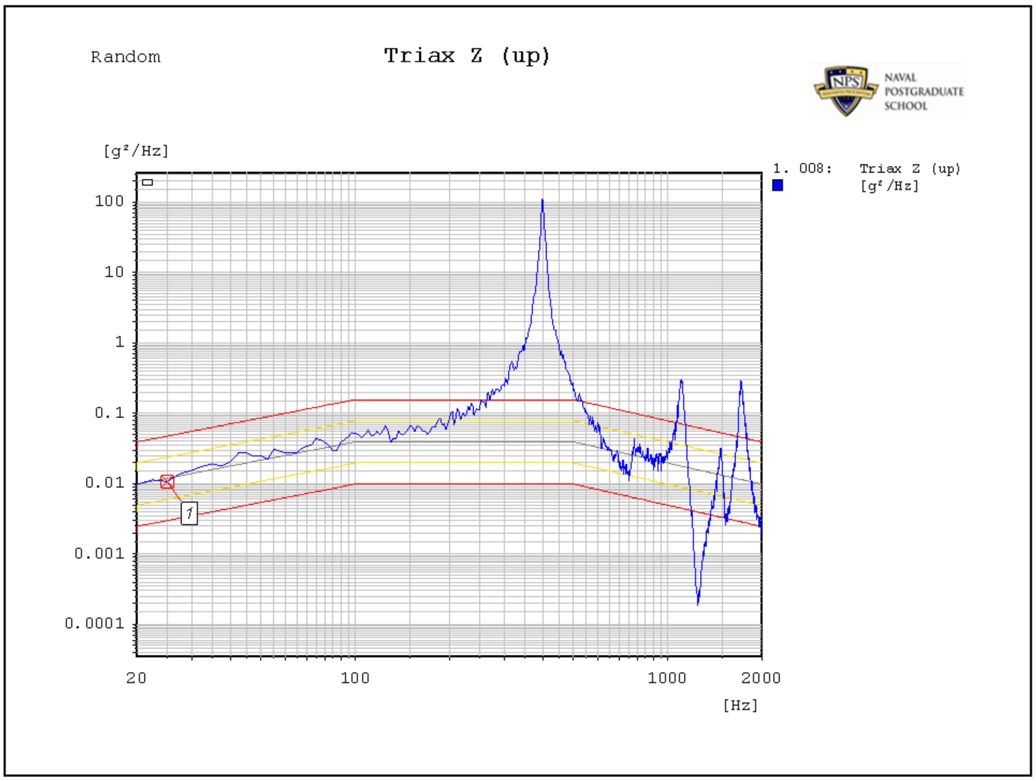


FIGURE 18: BLANK BOARD Z-AXIS RESPONSE PLOT, NASA GEVS WORKMANSHIP

The modes for each axis are identified in 6 as determined from the z-axis response in each shake axis.

TABLE 6: BLANK BOARD Z-AXIS RESPONSE FOR EACH SHAKE AXIS

	X-Axis	Y-Axis	Z-Axis
Frequency (Hz)	657.5	777.5	397.5
Response (g^2/Hz)	.039	.034	116.043

3.2.2 SMS Board Response

The SMS board testing required a more rigorous procedure and evaluation than the blank board testing. Functional testing was necessary in addition to the sine sweep comparisons.

As expected based upon the blank board results, the SMS z-axis again showed the largest response in each shake axis. An example of the sine sweep comparison is shown for the z-axis. Figure 19 is the pre-test sine sweep and figure 20 is the post-test sine sweep. The similarity confirms there were no significant structural changes in the board.

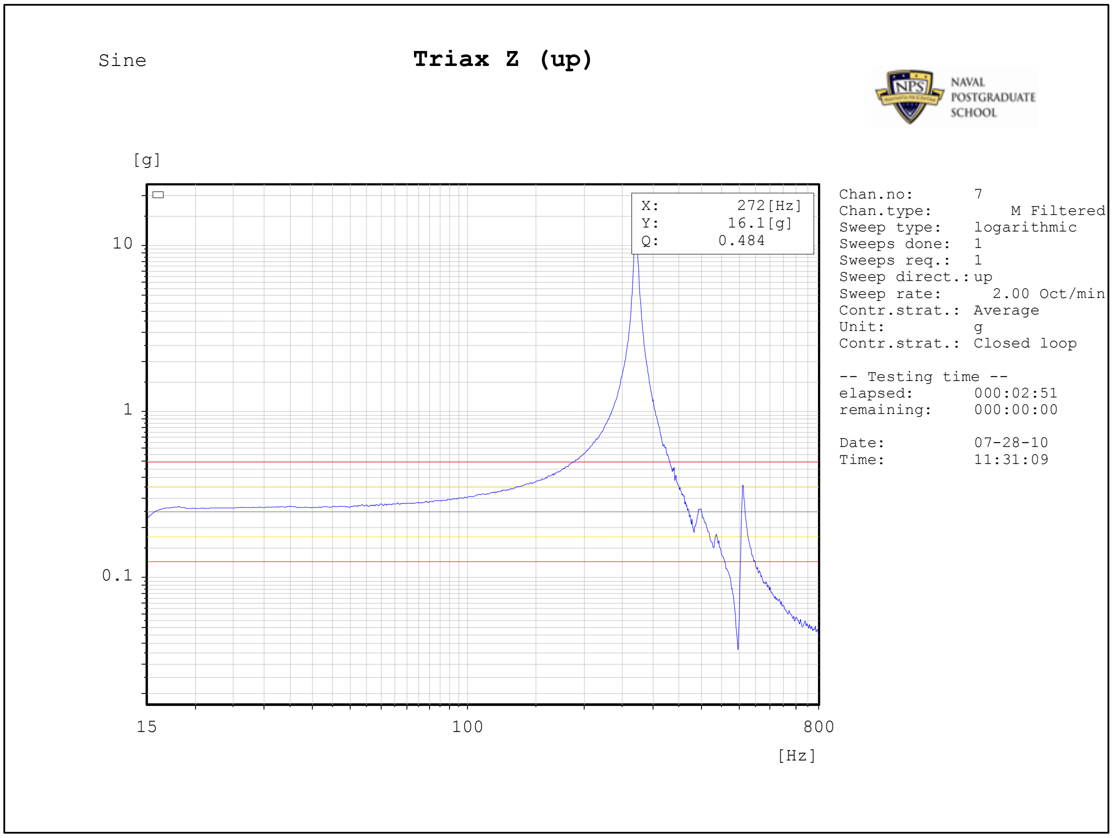


FIGURE 19: SMS Z-AXIS PRE-TEST SINE SWEEP RESPONSE

For the pre-test .25g sine sweep the board mode was at 272 Hz and a 16.1 g response. The post-test .25g sine sweep showed the mode did not move significantly, with a resonance at 270 Hz and a response of 11.9g.

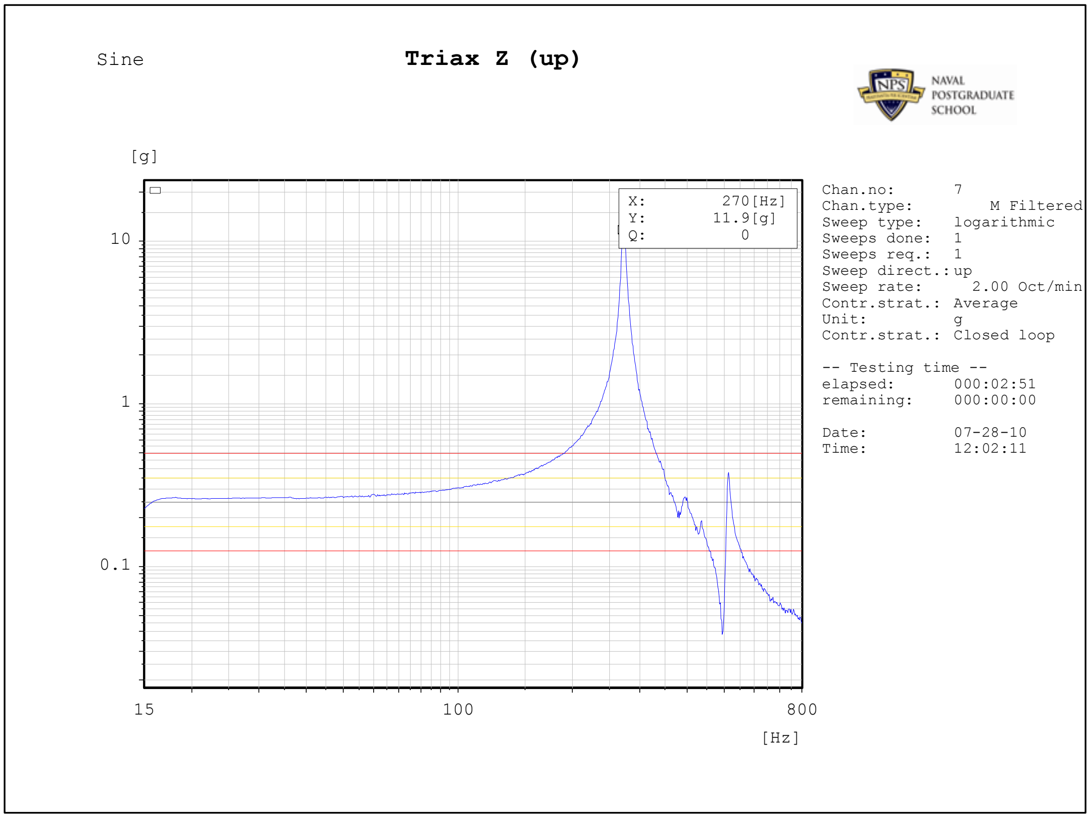


FIGURE 20: SMS Z-AXIS POST-SINE SWEEP RESPONSE

The random vibration responses from the z-axis of the tri-axial accelerometer are summarized in Table 7.

TABLE 7: SMS Z-AXIS RESPONSE FOR EACH SHAKE AXIS

Shake Axis	X-Axis	Y-Axis	Z-Axis
Frequency (Hz)	270	425	270
Response (g^2/Hz)	2.61	.034	44.26

The functional testing after each axis required attachment of the spacecraft bus to the SMS board. The configuration and testing harness is shown in Figure 21. The board successfully passed all three functional tests.

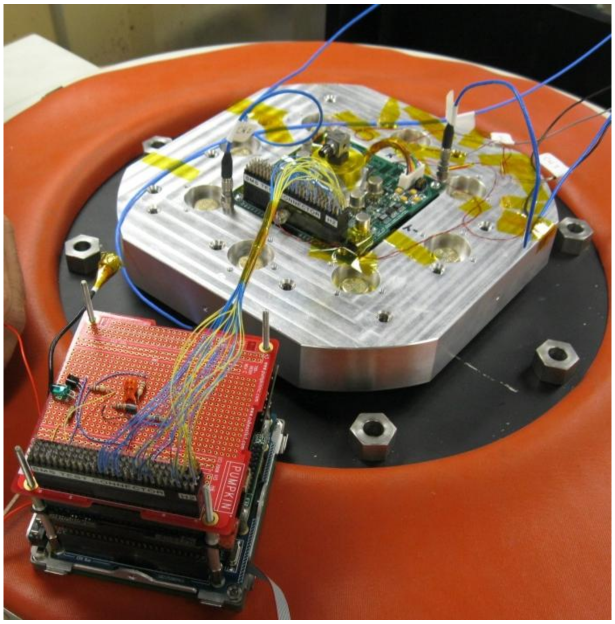


FIGURE 21: SMS BOARD, NPS-SCAT BUS, AND TEST HARNESS

One specific "lesson learned" to note is that the testing harness was checked prior to the SMS attachment to the interface plate, but not after the board was attached. Therefore, after the first shake axis the board appeared to fail the functional test and was removed from the interface plate. The board was fully functional after removal from the plate and further examination determined a pin was grounded. Application of Kapton tape solved the problem for the two remaining functional tests. Full review of the functional tests as well as the environmental tests in the actual configuration is necessary to ensure accurate results.

3.2.3 SUBSYSTEM TESTING EVALUATION

To compare the SMS board and blank board results, the amplification factor, Q, was calculated for each test item. The amplification factor "represents the system mechanical gain during forced vibration at the system natural frequency," as stated in the paper

"Acoustic and Random Vibration Test Tailoring for Low-Cost Missions."[19] To calculate Q using the half power method, see Appendix B.[20]

The amplification factors shown in Table 8 are calculated from the Z-axis response during the Z-axis vibration test.

TABLE 8: SUBSYSTEM AMPLIFICATION FACTORS

	SMS Board Workmanship	Blank PCB Workmanship
Q Factor	29.3	45.4

The magnitude and amplification factors for both the blank PCB and the SMS PCB vibration tests were unexpectedly high. To verify that these results were actually higher than the environment a PCB would experience within the CubeSat, it was necessary to record the response of a subsystem board within NPS-SCAT.

3.3 Improved Subsystem Testing

The goal of developing an independent subsystem testing configuration was to ensure the subsystem could withstand vibration testing before integration into the CubeSat, to avoid the time-consuming task of CubeSat integration, and to minimize the exposure of other subsystems to the vibration environment and possible over-testing. With these goals in mind, a Mock Satellite (Mock Sat) testing configuration was developed. The Mock Sat consisted of older NPS-SCAT subsystems and boards which would not be part of the NPS-SCAT EDU, including a completely different structure and solar panels. With this slightly modified satellite, an older SMS board could be instrumented and tested with no risk to the actual spacecraft or board. Though integration could not be avoided, the Mock

Sat does avoid stressing any other subsystems and will accurately represent the environment within the EDU.

3.3.1 MOCK SATELLITE CONFIGURATION AND TEST LEVEL

For the Mock Sat testing, accelerometers were placed inside the satellite. Three were placed similarly to the subsystem testing. One was attached to the 52-pin connector, one was near the stand-off and the last one was placed directly below the sun sensor mass model (see Figure 22). The last placement was different than the subsystem testing because an accelerometer would not fit within the Test POD if it were located on top. Lastly, a tri-axial accelerometer was placed near the bottom of the satellite, on the FM430 board, for general observation. The satellite prior to solar panel attachment is shown in Figure 23.

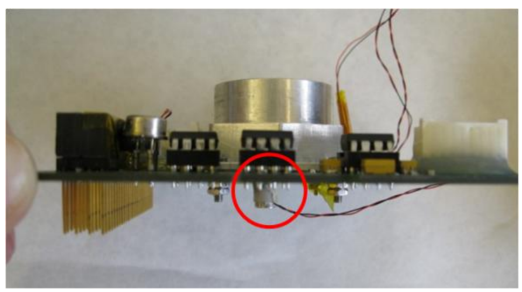


FIGURE 22: SIDE VIEW, NPS-SCAT SMS VERSION 1, MOCK SAT ACCELEROMETER PLACEMENT

FIGURE 23: MOCK SAT INTERNAL ACCELEROMETER PLACEMENT

For attachment to the shake table, the satellite was placed in the original Cal Poly Test POD, shown in Figure 24, which was bolted to the interface place. The Mock Sat was shaken in all three axes.

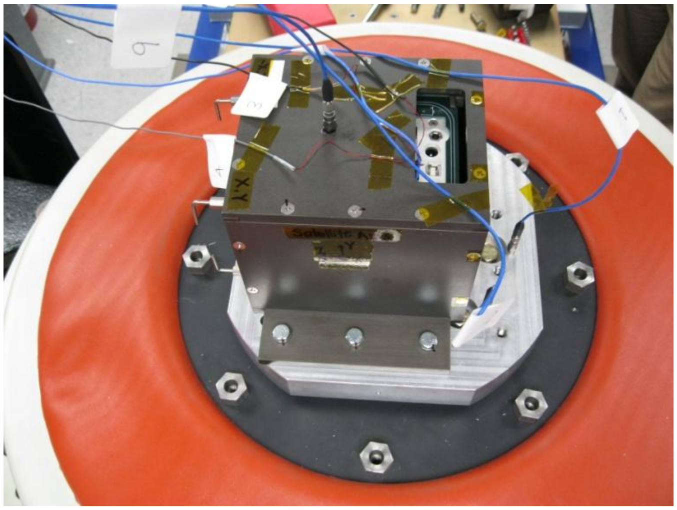


FIGURE 24: CAL POLY TEST POD ATTACHED TO NPS VIBRATION TABLE

For Mock Sat testing, two random vibration tests were completed because it was important to record the response at GEVS Qualification levels and GEVS Workmanship levels. With both levels known, it was possible to compare to the previous subsystem testing and then use the qualification levels to identify the ideal subsystem testing level.

3.3.2 MOCK SAT RESULTS

The Mock Sat results (NASA GEVS Workmanship and Qualification) are presented with the SMS subsystem results for direct comparison. Results shown for the Mock Satellite represent the output from the z-axis accelerometer placed beneath the sun sensor, on the bottom of the SMS board. Results shown for the SMS board represent the output from the z-axis accelerometer placed on top of the sun sensor when the board was attached individually to the interface plate. It is recognized that the difference in accelerometer placement will not produce a definitive comparison between these two configurations; however for this purpose the results are adequate to facilitate the evaluation of the original testing configuration.

The Z-Axis, or worst-case results, are shown first in Figure 9 and the peaks are identified in Table 25.

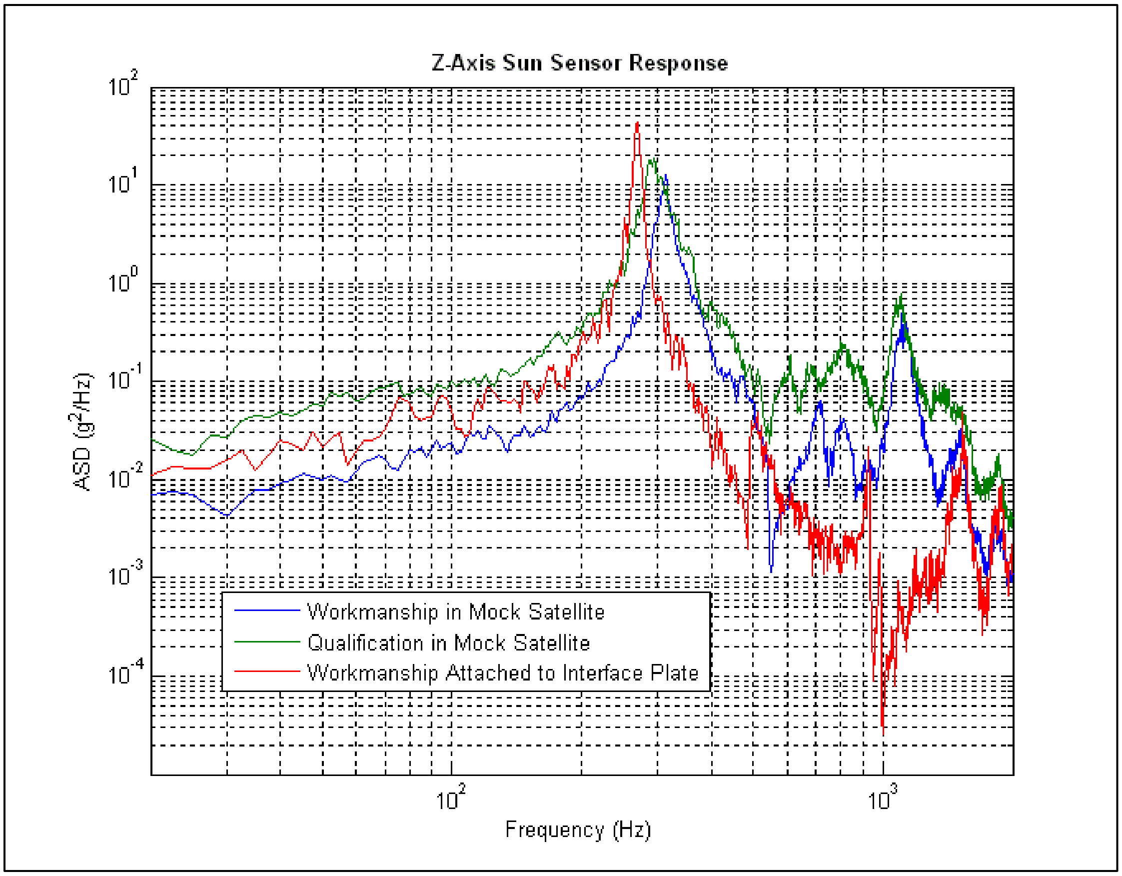


FIGURE 25: MOCK SAT Z-AXIS SUN SENSOR RESPONSE

TABLE 9: SUMMARY OF Z-AXIS SUN SENSOR RESPONSES

Z-Axis Vibration Test Sun Sensor Response			
Test Item	SMS Board (Red)	Mock Sat (Green)	Mock Sat (Blue)
Test Level	GEVS Workmanship	GEVS Qualification	GEVS Workmanship
Frequency (Hz)	270	295	312.5
Response (g^2/Hz)	44.27	18.9	12.43

These results show that over-testing occurs in the Z-axis when the board is directly attached to the interface plate.

The z-axis responses during Y-axis random vibration testing are shown in Figure 26, with the peaks identified in Table 10.

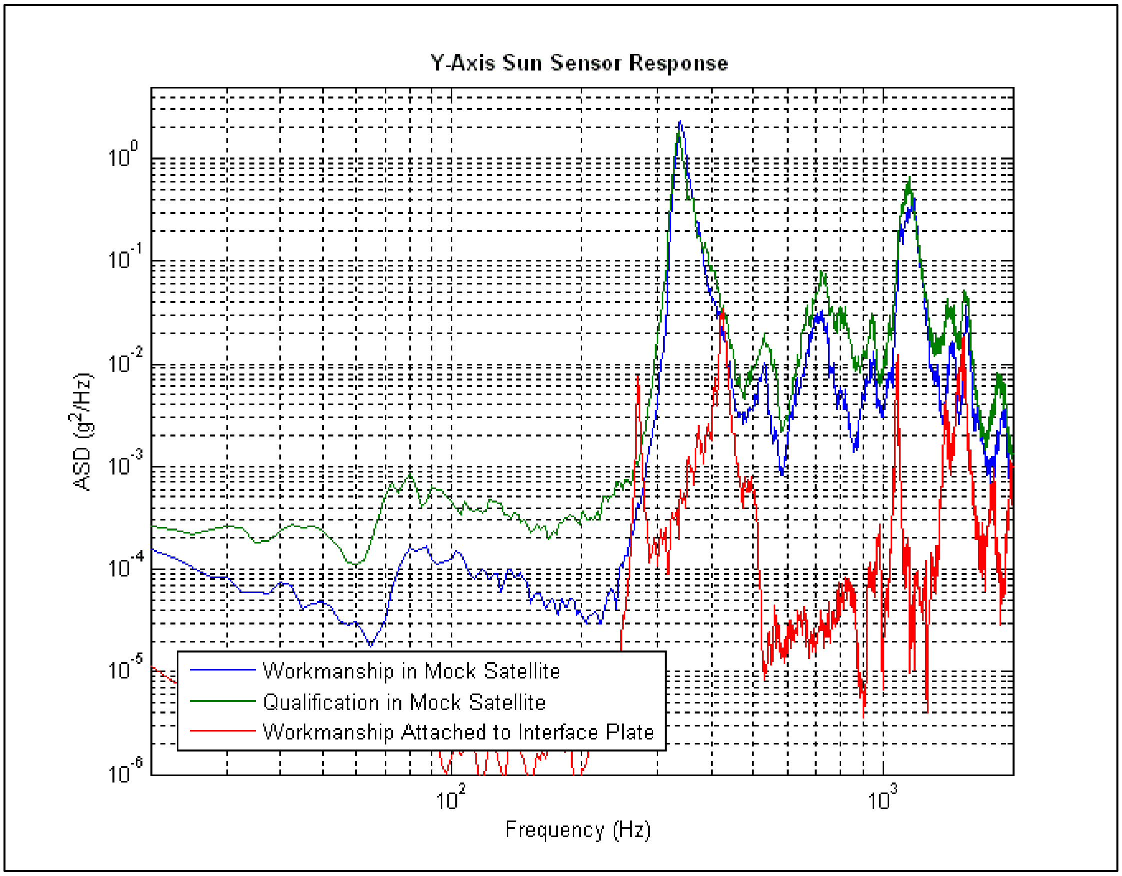


FIGURE 26: Y-AXIS VIBRATION TEST SUN SENSOR RESPONSE

TABLE 10: SUMMARY OF Y-AXIS VIBRATION TEST SUN SENSOR RESPONSES

Y-Axis Vibration Test Sun Sensor Response – 1st Peak			
Test Item	SMS Board (Red)	Mock Sat (Green)	Mock Sat (Blue)
Test Level	GEVS Workmanship	GEVS Qualification	GEVS Workmanship
Frequency (Hz)	425	340	335
Response (g^2/Hz)	.034	2.346	1.897
2nd Peak			
Test Item	SMS Board (Red)	Mock Sat (Green)	Mock Sat (Blue)
Test Level	GEVS Workmanship	GEVS Qualification	GEVS Workmanship
Frequency (Hz)	1080	1155	1168
Response (g^2/Hz)	.01242	.6585	.4514

The X-Axis vibration testing responses are shown below in Figure 27 and Table 11.

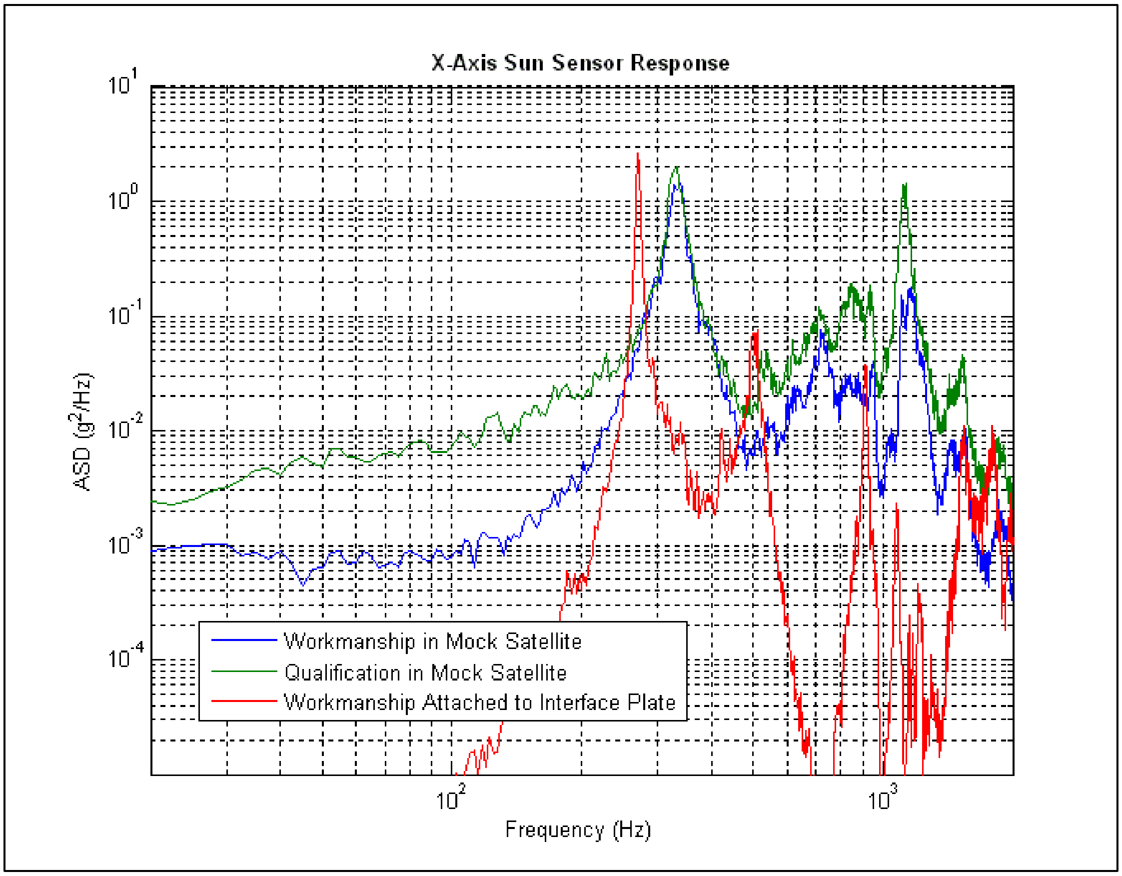


FIGURE 27: X-AXIS VIBRATION TEST SUN SENSOR RESPONSE

TABLE 11: SUMMARY OF X-AXIS VIBRATION TEST SUN SENSOR RESPONSES

X-Axis Sun Sensor Response			
Test Item	SMS Board (Red)	Mock Sat (Green)	Mock Sat (Blue)
Test Level	GEVS Workmanship	GEVS Qualification	GEVS Workmanship
Frequency (Hz)	270	332.5	340
Response (g^2/Hz)	2.615	2.022	1.432

The X and Y-axis plots show the worst-case vibration levels occur when the board is in the satellite. Based upon these results, it is assumed the interface plate over constrained the motion of the board in these axes.

The amplification factors calculated for the Z-Axis shake test are shown below. The SMS Board and Blank PCB are shown for comparison.

TABLE 12: Z-AXIS AMPLIFICATION FACTOR SUMMARY

	SMS Board Workmanship	Blank PCB Workmanship	Mock Sat Qualification	Mock Sat Workmanship
Q Factor	29.3	45.4	10.5	18.4

The amplification factors immediately show the testing on the interface plate does not accurately represent the environment within the CubeSat. This could be due to either the stand-offs placed between boards, the 52-pin header connections, or simply the damping due to the outer CubeSat structure.

In addition to the measurements taken during the vibration testing, other test parameters were evaluated, including the integration procedures. After testing, two loose nuts were found despite the use of staking compound. To mitigate this issue, the integration procedures now refer to the applicable NASA Technical Standard, NASA-STD-8739.1.

A capacitor also broke off of the substitute beacon board. Fortunately, the broken component is not used on the EDU beacon board. It did however place an emphasis on stacking components interfaces to ensure their safety at high vibration levels. Using surface mount components is also a solution which was already utilized throughout the satellite. Both test anomalies are shown in Figure 28 and Figure 29.

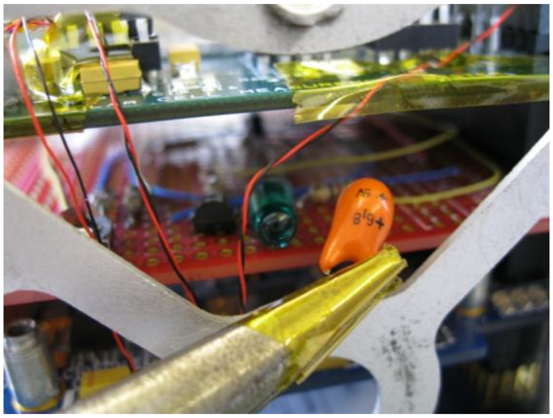


FIGURE 28: POST TESTING BROKEN CAPACITOR

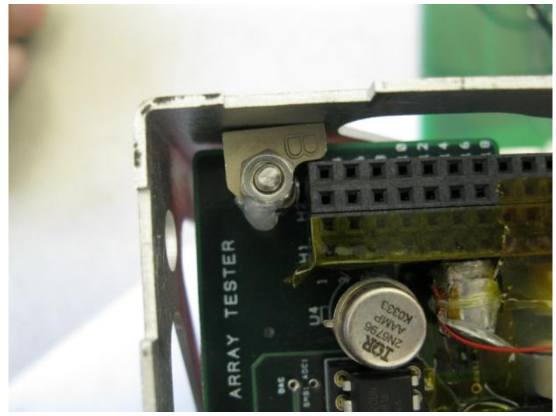


FIGURE 29: LOOSE NUT AND STAKING COMPOUND

The connection between integration and test was demonstrated multiple times throughout the NPS-SCAT testing process and ultimately shows that on-orbit success is highly dependent on thorough and accurate testing.

3.3.2 EVALUATION OF SUBSYSTEM TESTING

Based upon the extremely high magnitude of the PCBs' responses on the testing interface plate and comparison with the Mock Sat test results, it was determined the subsystem testing was too harsh. This was also confirmed by the amplification factor comparison. Finding a testing profile and configuration for use with the subsystem testing apparatus was an ideal solution because it would eliminate the task of integrating a Mock Sat, which not only required a large amount of set-up for a single board's test, it also required the team to have spare subsystem parts and boards that can be exposed to satellite qualification test levels. Therefore, to avoid over-testing, modifications to the subsystem test profile and subsystem test configuration were suggested.

The testing completed on the SMS board demonstrated the PCB would withstand EDU testing because the worst-case, z-axis, was dramatically higher than Mock Sat response levels. Therefore, the board did not require any modified testing before integration into the EDU. To meet the testing timeline of NPS-SCAT, and because no other subsystems required individual qualification, integration of the satellite was started to prepare for EDU Qualification.

3.3.3 Modified Subsystem Testing

The goal of the modified vibration profile and configuration was to produce a response similar to the Mock Sat GEVS Random Vibration Qualification testing. For NPS-SCAT that input represents a worst-case environment for a subsystem PCB.

3.3.3.1 Test Profiles

Two modified profiles were chosen to facilitate comparison of data from both the initial subsystem testing, which used the GEVS Workmanship levels, and the MockSat testing, which used both the GEVS Workmanship and GEVS Qualification levels. For simplicity, a linear scale was first used to compare the responses, then the input profiles were lowered by 3 decibels (dB) for every factor of two above the optimal response (seen in the satellite configuration).

The first profile is based upon the satellite response to GEVS Random Vibration Qualification testing. The profile is 12 dB below GEVS Qualification. See Table 13 for testing inputs.

TABLE 13: 12 DB BELOW GEVS QUALIFICATION

GEVS Qualification -12 dB	
20	.001625
20-50	+6dB/oct
50-800	.01
800-2000	-6dB/oct
2000	.001625
Overall	3.53

The second profile is based upon the SMS response when the Mock Sat experienced GEVS Workmanship Levels. The profile is 6 dB below GEVS Workmanship and can be seen in Table 14.

TABLE 14: 6 DB BELOW GEVS WORKMANSHIP

GEVS Workmanship -6 dB	
20	.0025
20-80	+3 dB/oct
80-50	.01
500-2000	+3 dB/oct
2000	.0025
Overall	3.39 Grms

The difference between these test inputs is very minimal, however it is necessary to use both because the initial subsystem testing used the GEVS Workmanship profile, which has lower levels at the high and low end of the test frequency range.

3.3.3.2 TEST CONFIGURATIONS

The configuration modifications were based upon the damping that was evident during the Mock Sat testing. The subsystem testing apparatus was originally designed to transfer the input directly to the PCB because the damping in the actual CubeSat was unknown. Analysis of the Mock Sat results did however show that damping was significant within the NPS-SCAT CubeSat. To mimic the damping within the CubeSat, two new configurations were tested in addition to the original configuration (shown in Figure 30).

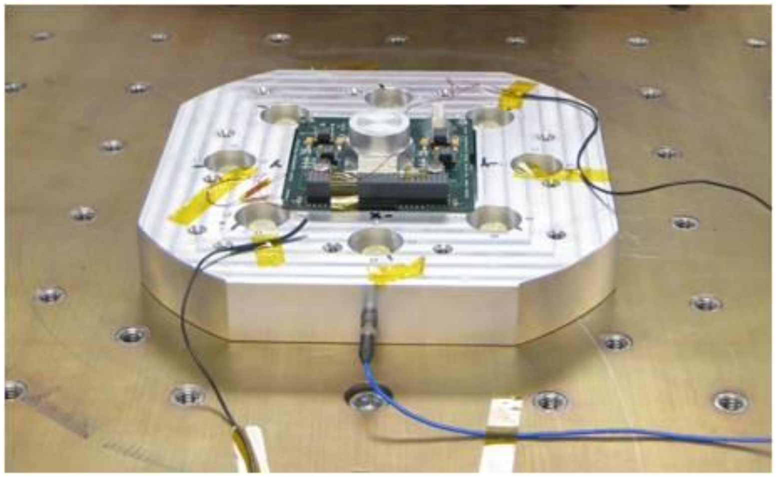


FIGURE 30: RE-TEST OF ORIGINAL SUBSYSTEM CONFIGURATION

In the NPS-SCAT CubeSat, subsystem PCBs are separated by short metal stand-offs and attached on one end by two 52-pin connectors. It is assumed the 52-pin connectors significantly contribute to the damping. The first modified configuration was a PCB elevated above the subsystem testing interface plate by a set of stand-offs.

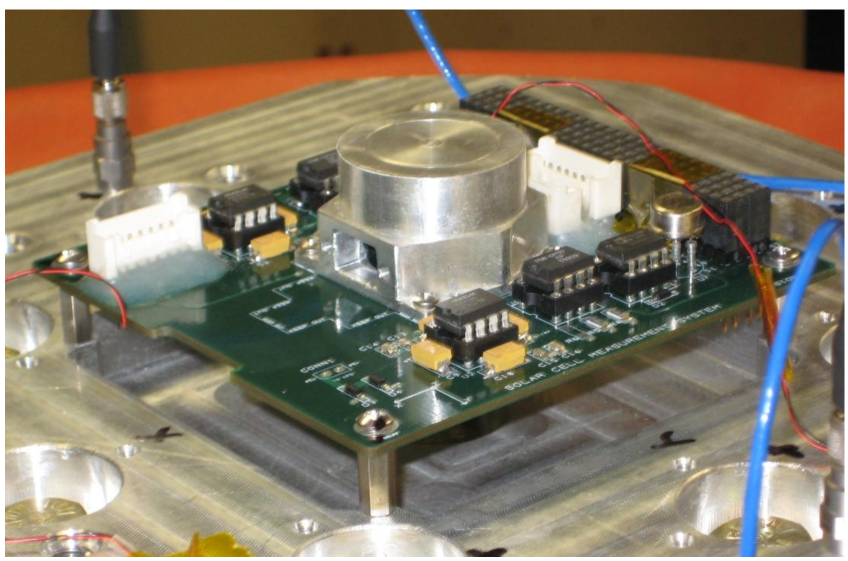


FIGURE 31: SUBSYSTEM BOARD ON STANDOFFS

The second modified configuration was a stack of two PCBs, separated by stand-offs and elevated above the subsystem testing apparatus by a set of stand-offs, the same as the first modified configuration.

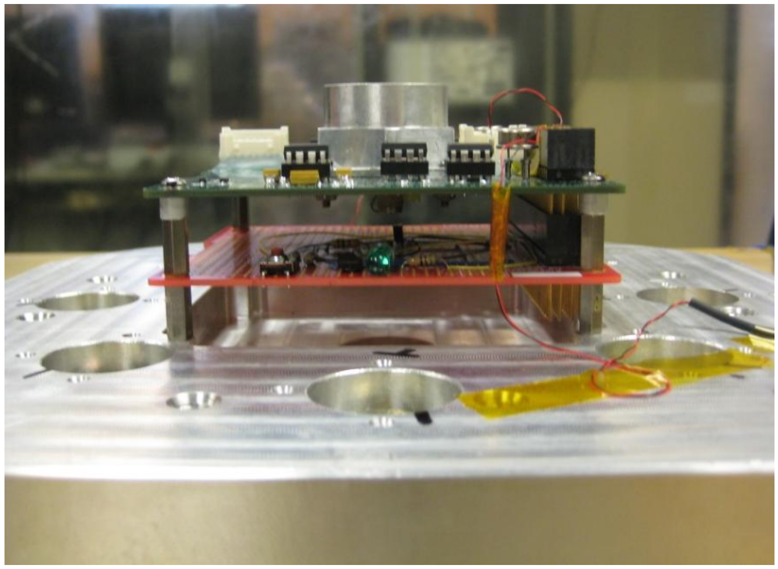


FIGURE 32: SUBSYSTEM CONFIGURATION, TWO BOARD STACK ON STANDOFFS

3.3.3.3 TEST RESULTS

The following paired graphs show the responses for the lowered GEVS Qualification level testing and the lowered GEVS Workmanship level testing, respectively. All of the results presented are the Z-Axis response because these results were the largest factor in recommending a future subsystem testing configuration.

The first pair of graphs show the results for the original subsystem testing configuration (Figure 33), which consisted of a single board directly attached to the interface plate.

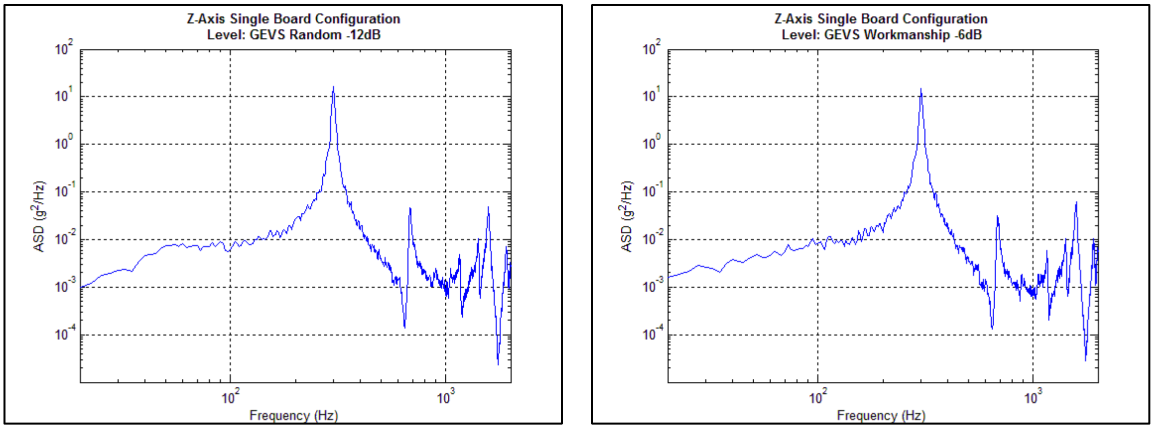


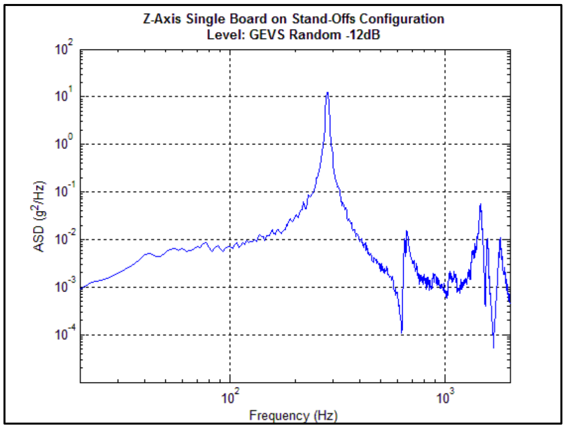
FIGURE 33: ORIGINAL SUBSYSTEM CONFIGURATION, Z-AXIS RESPONSES

For comparison, the following table shows the response for each test level as well as the original SMS board response at GEVS Workmanship and the Mock Sat GEVS Qualification response. The initial SMS testing was included because it was tested in the same configuration.

TABLE 15: ORIGINAL CONFIGURATION; AMPLIFICATION FACTORS, FREQUENCIES AND RESPONSES

Configuration	Initial SMS Board GEVS Workmanship	Mock Sat GEVS Qualification	12 dB below GEVS Qualification	6 dB below GEVS Workmanship
Q	45.4	10.5	33.71	35.55
Frequency (Hz)	270	295	300	302.5
Response (g^2/Hz)	44.27	18.9	16.45	14.71

The results for the second configuration, consisting of a single board elevated by the stand-offs, are shown in Figure 34.



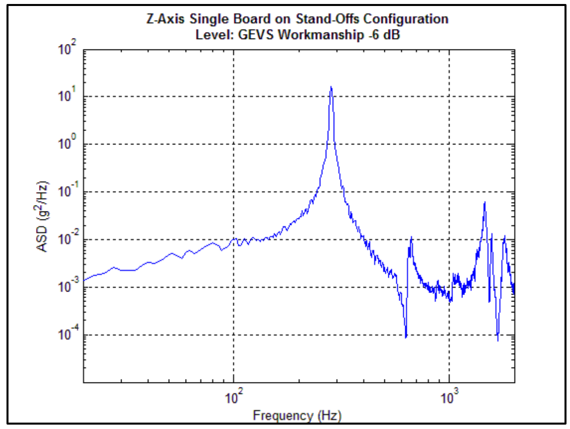


FIGURE 34: SINGLE BOARD WITH STANDOFFS, Z-AXIS RESPONSES

A slight decrease in amplification was noted for this configuration over the original configuration, as seen in Table 16.

TABLE 16: SINGLE BOARD WITH STANDOFFS; AMPLIFICATION FACTORS, FREQUENCIES AND RESPONSES

Configuration	Mock Sat GEVS Qualification	12 dB below GEVS Qualification	6 dB below GEVS Workmanship
Q	10.5	30.05	33.75
Frequency (Hz)	295	282.5	282.5
Response (g^2/Hz)	18.9	12.31	16.7

The responses from the final configuration, which consisted of two boards stacked (SMS on top), are shown in Figure 35. This configuration was expected to offer damping based on the added stiffness from the 52-pin connectors which attach between the boards.

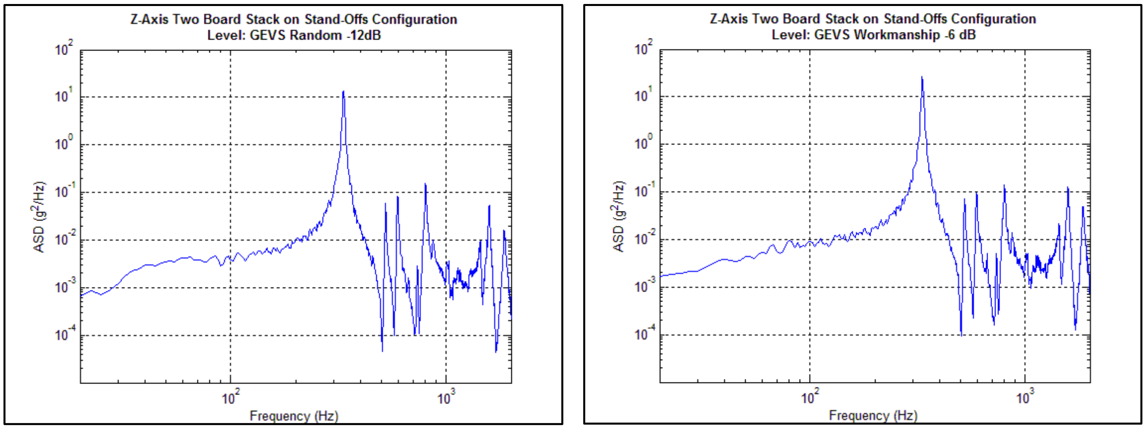


FIGURE 35: TWO BOARD STACK ON STANDOFFS CONFIGURATION, Z-AXIS RESPONSES

The results were opposite of what was expected. For the testing at 12 dB below GEVS Qualification, the maximum board response was not unexpected, but the amplification factor was. The board response and amplification factor were extremely high for the second profile as well. All values are shown in Table 17.

TABLE 17: TWO BOARD STACK ON STANDOFFS, AMPLIFICATION FACTORS, FREQUENCIES AND RESPONSES

Configuration	Mock Sat GEVS Qualification	12 dB below GEVS Qualification	6 dB below GEVS Workmanship
Q	10.5	47.86	50.3
Frequency (Hz)	295	335	332.5
Response (g^2/Hz)	18.9	13.66	27

Overall, both the first and second configurations showed an improvement in damping, represented by the lower amplification factors, as compared to the original SMS testing. Both test configurations demonstrated response amplitudes close to the Mock Sat excitation frequency at NASA GEVS random vibration levels.

3.3.4 SUBSYSTEM TESTING RECOMMENDATIONS

Based upon the above results, the following recommendations are for future NPS subsystem testing.

The most accurate test configuration, to mimic the environment experienced within the CubeSat, is still the original set-up of a single PCB attached to the plate without stand-offs. Although the amplification factor was still higher than the MockSat testing response, the magnitude of the response was similar. The similarity in resonance frequency is also an added benefit; 300 Hz and 295 Hz for the recommended configuration and Mock Sat, respectively. Since the amplitude was lower than the MockSat response, it is still necessary to modify the testing profile to best mimic the actual satellite environment.

Although improvements to the configuration can still be made to offer a reduction in amplification, the board placed on the plate alone offers advantages over the other configurations. The test set-up has minimal variables because it only requires four interface connections compared to the addition of stand-offs or another PCB. Additionally, testing without stand-offs transfers the vibration input more directly to the PCB.

The recommended testing level is 9 dB below the NASA GEVS Qualification profile. Adding an additional margin of 3 dB will ensure future tests with a different subsystem (and different mass characteristics) will not be under tested. This results in the test levels shown in Table 18.

TABLE 18: 9 DB BELOW NASA GEVS QUALIFICATION

NASA GEVS Qualification -9 dB	
20	.001625
20-50	+6dB/oct
50-800	.02
800-2000	-6dB/oct
2000	.00325
Overall	5 Grms

Ideally, future testing will also include use of two 52-pin headers attached to the test apparatus and subsystem board. The minimal difference in the results for the one or two board stack (with standoffs) demonstrated that the 52-pin headers anchored to the satellite contribute significantly to the stiffness of the satellite configuration and dramatically increase the damping (shown above by the decrease in amplification factor for the Mock Sat configuration).

Another difference between the test set-up and the CubeSat configuration is the use of mid-plane stand-offs. These small metal attachments connect the stacked subsystem boards to the top of the CubeSat frame. The high amplification of the two-board testing configuration demonstrated these attachments to the structure significantly contribute to the constraint of the subsystem stack within the satellite. Therefore, if further modifications were made, a clamped configuration should be considered.

4 NPS-SCAT QUALIFICATION AND FLIGHT TESTING

The NPS-SCAT EDU completed qualification level vibration testing and thermal-vacuum testing during the summer of 2010. A summary of the EDU vibration testing is presented with additional recommendations for the Flight Unit testing that should follow. Detailed procedures and test plans can be referenced by NPS students on the SSAG server, in the CubeSat folder.

4.1 NPS-SCAT ENGINEERING DEVELOPMENT UNIT (EDU)

The NPS-SCAT EDU vibration qualification test represented the first vibration test for many of the NPS-SCAT subsystems. Although the Mock Sat did include many similar subsystems, they were not operational, therefore only their structural integrity was verified during the previous testing. Unlike the previous SMS testing, the EDU testing included a fully functional payload with the Sinclair Sun Sensor.

4.1.1 QUALIFICATION TESTING

Preparation for qualification testing of NPS-SCAT included modification of the satellite integration procedures to include torque values and staking compound placement. After these additions, the entire process was extended to 3-days due to the drying time for the staking compound on the fasteners and connectors.

After integration, the satellite completed a Comprehensive Functional Test (CFT) to ensure all subsystems worked individually and as an integrated system. The CFT included both indoor and outdoor testing of the satellite.

The original Cal Poly Test POD was used for the qualification test because no requirements had been set forth by the integrating contractor regarding the testing apparatus. In Figure 36, NPS-SCAT is shown in the Test POD before the top plate was attached according to the Test POD Users Guide.[21]

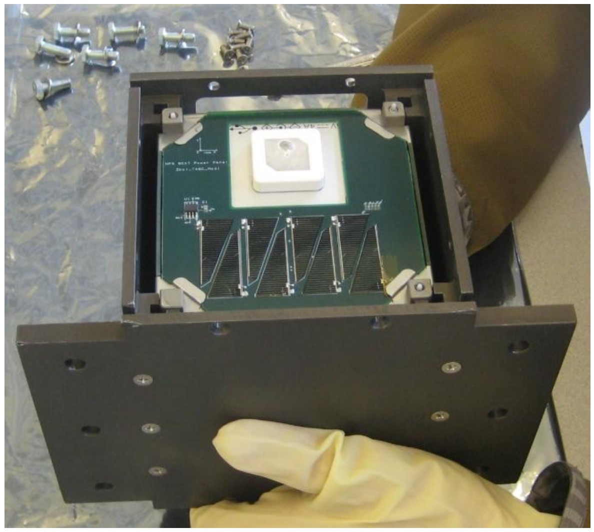


FIGURE 36: NPS-SCAT EDU IN TEST POD

The test set-up for the EDU was different than prior testing because there was no way to instrument the inside of the CubeSat. An inner accelerometer is preferred in order to monitor the pre and post-test sine sweeps for changes which might indicate a broken test item. A compromise was found by placing an accelerometer on the outside of the CubeSat, after integration into the Test POD. The accelerometer can be seen in Figure 37, it is the tri-axial accelerometer that is slightly recessed into the access port on the top of the Test POD. This accelerometer was only monitored for change rather than the magnitude of the response.

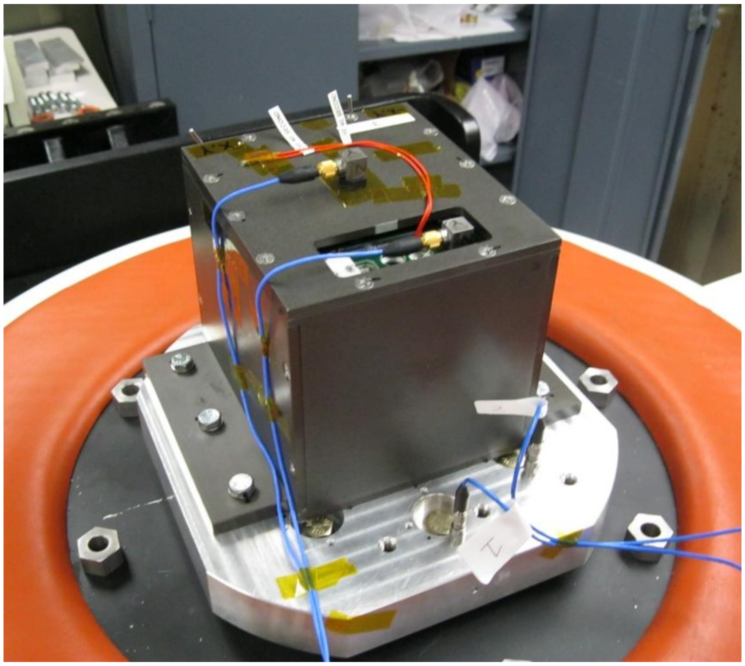


FIGURE 37: NPS-SCAT EDU ON SHAKE TABLE

The testing profile for the EDU vibration test was the NASA GEVS Qualification level. The EDU was tested in all three axes and each random vibration qualification test was encompassed by a pre and post-test .25g sine sweep. The results from the outer accelerometer, placed on the Test POD are shown in Figures 38, 39 and 40.

The Test POD User's Guide does not identify a fundamental frequency for the Y-Axis and the NPS EDU testing also showed this to be true.

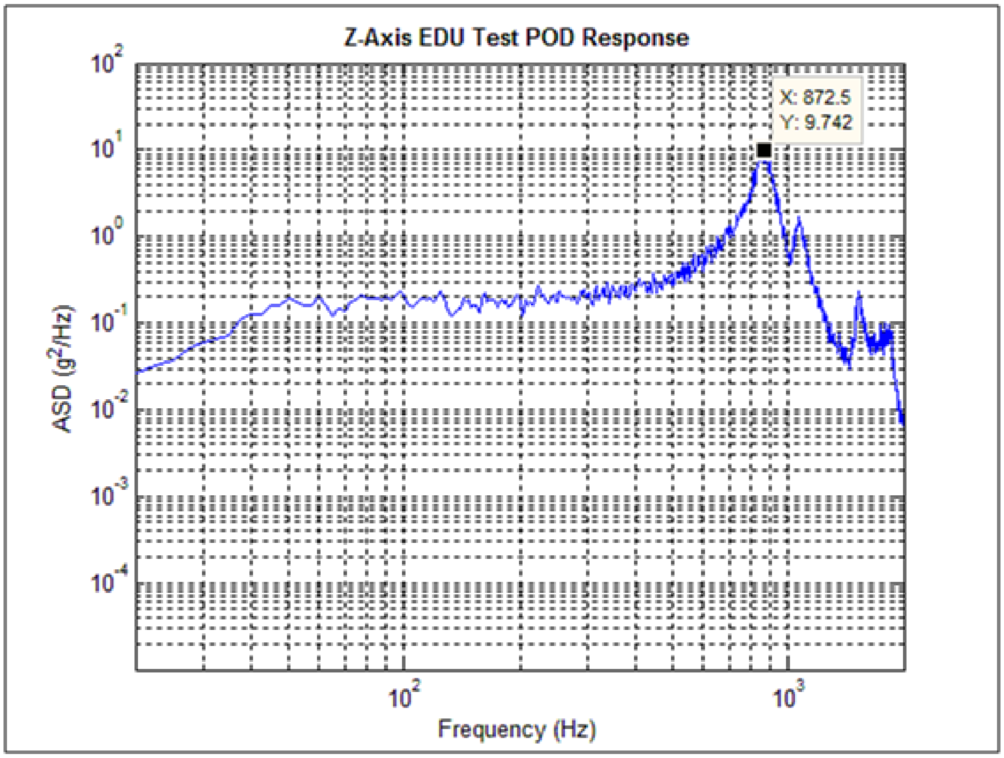


FIGURE 38: Z-AXIS TEST POD RESPONSE DURING EDU TESTING

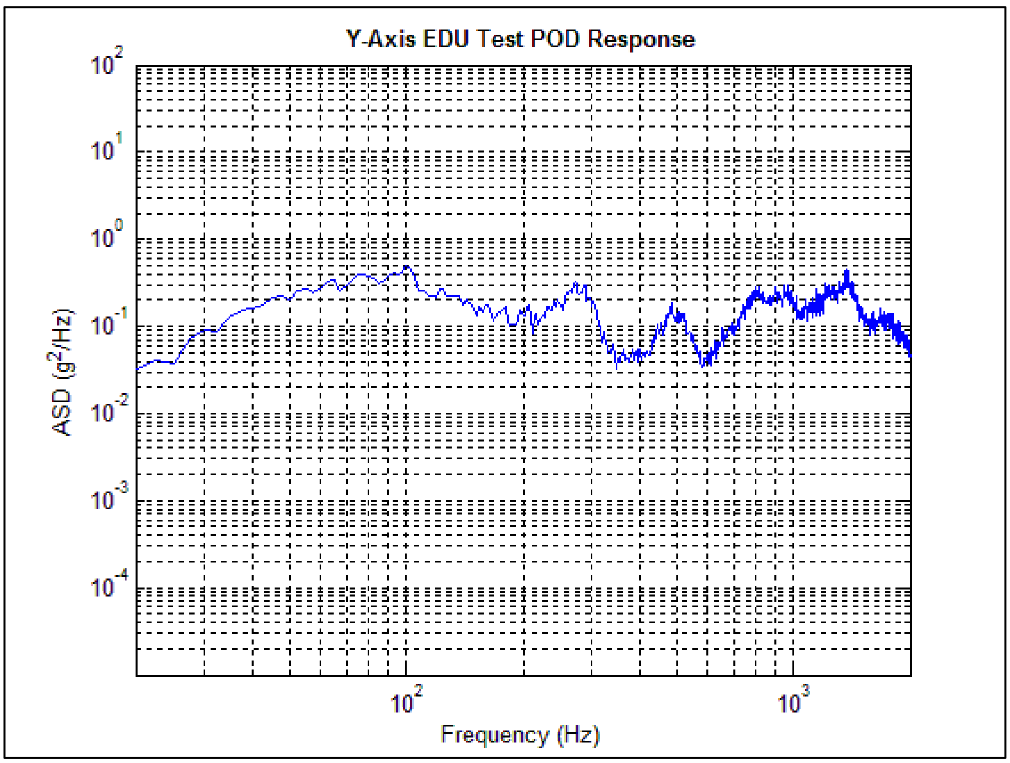


FIGURE 39: Y-AXIS TEST POD RESPONSE DURING EDU TESTING

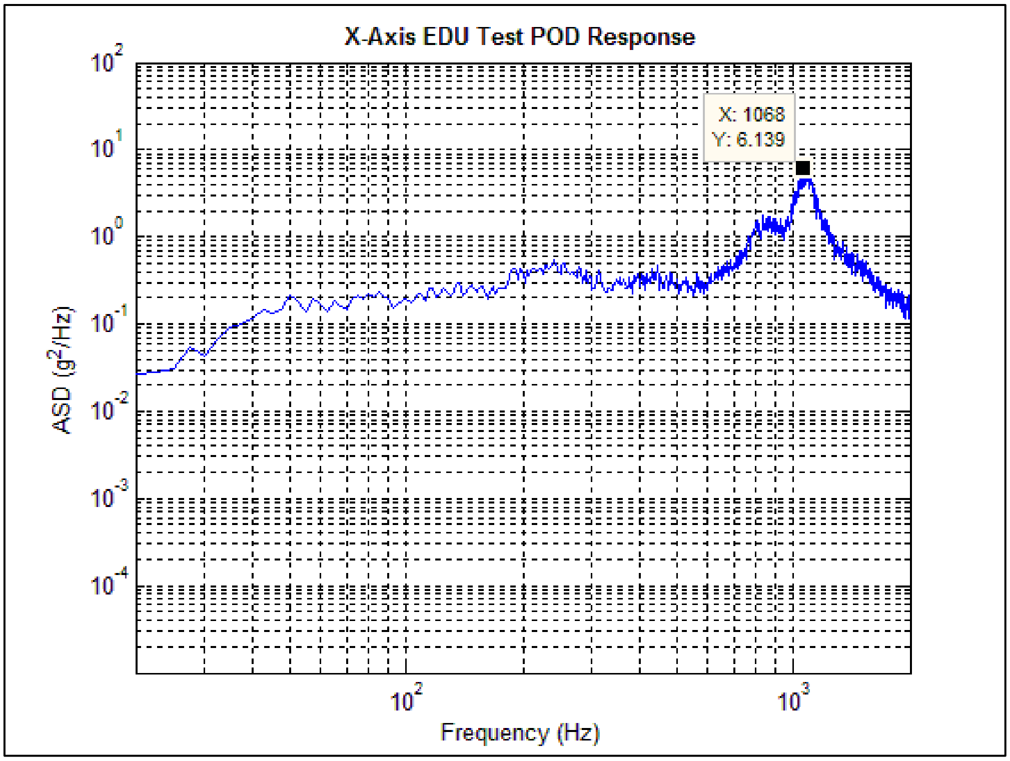


FIGURE 40: X-AXIS TEST POD RESPONSE DURING EDU TESTING

Initially, the NPS-SCAT EDU successfully passed the post-test CFT, but during further functional testing an issue with the radio developed. Due to the uncertainty of the cause of the malfunction, the satellite was de-integrated and inspected. It was found that the cable to the patch antenna was actually damaged. The cable was staked to the bottom part of the CubeSat structure, with a thick layer of the dried staking compound covering the chord. Despite this protection, the slight motion of a sharp metal protrusion from the bottom of the FM430 sliced into the staking compound and slightly into the cable covering. For future use the protrusion was removed and the cable functioned properly without the metal protruding into it.

The value of an EDU was demonstrated with this one testing anomaly. On many other occasions it was also important to have the ability to remove and replace subsystems and components, which offered further proof that an EDU allows a much greater amount of flexibility in the CubeSat development process.

4.2 Flight Unit Testing

The launch delays thus far have allowed an increased development and test time. Unfortunately, each time there is a launch slip, the publication of the launch environment and CubeSat requirements are further delayed as well. For this reason, the NASA GEVS testing levels will be used for acceptance or proto-flight testing.

The choice between acceptance and proto-flight levels will not be determined until the flight unit is fully integrated. The shorter duration acceptance testing specification can be used in the case that the CubeSat has no major structural changes from the NPS-SCAT EDU. It is unlikely any major modifications will take place, however the Cal Poly beacon board was not available when the EDU was tested, therefore that subsystem has not been qualified.

One option is to qualify the beacon board individually, using the modified testing levels and configuration, and then use acceptance testing levels for the integrated CubeSat. This would provide assurance that the beacon board can withstand qualification levels and will not force the entire satellite to be tested at the proto-flight levels. Although there is a scheduling consideration with this option, it does mitigate risks by identifying any beacon board vibration issues prior to flight unit integration. Scheduling is a consideration because the beacon board subsystem testing will require a three-axis test with functional tests between axes.

The second option for flight unit testing is to substitute the beacon board in the satellite and use proto-flight levels. Proto-flight testing levels are normally used for a one-of-a-kind system when qualification is not an option, but in this case it would be used because the beacon board has never been vibration tested. Qualification of the EDU showed the structural integrity of the system and that does not change when the beacon board is substituted for the previously tested board. Therefore, this option could be utilized if there is limited time for testing due to late delivery of the new beacon board or a change in the launch schedule.

Although the launch date and beacon board delivery are drivers behind the flight unit build and test timeline, the other factor is the personnel turnover that is characteristic of a university team. NPS does have the advantage of requiring a thesis to graduate, which allows newer team members to reference the development of the satellite fairly easily, but these documents are no substitute for learning from another engineer. At this advanced stage in the satellite development it is to the team's advantage to have all subsystems acceptance tested and ready for integration before key project engineers graduate. The ideal situation involves the completion of system and environmental testing before the end of March regardless of the launch date.

4.3.1 RECOMMENDED SATELLITE CONFIGURATION AND TEST LEVELS

The flight unit configuration of NPS-SCAT will be identical to the EDU except for the substitution of the Cal Poly beacon board. The satellite will use the original Cal Poly Test POD because the Test POD Mk III will not yet be available.

The vibration testing for NPS-SCAT will only take place after thorough integrated testing. A Comprehensive Functional Test (CFT) is the minimum testing necessary to ensure the satellite is operating as set forth in the KPPs. The applicable NASA GEVS acceptance and proto-flight testing levels are defined earlier, in Figure 9.

5 CUBESAT VIBRATION RESPONSE TESTING

The underlying assumption of qualifying the NPS-SCAT CubeSat in the Cal Poly Test POD is that the test environment is the same or worse than the qualification environment within the P-POD Mk III.

Previous versions of the P-POD and Test POD had been tested[22], however the newly re-designed Test POD Mk III had not been qualified or compared to the P-POD Mk III during the time period in which NPS vibration testing was taking place. The chance to further evaluate the NPS-SCAT testing methodology while also providing test results to Cal Poly and the CubeSat community, allowed the Test POD Mk III and P-POD Mk III response testing to take place at NPS. The opportunity to use the advanced testing capabilities at NPS was an additional benefit because the CubeSat mass models were instrumented inside the P-POD and Test POD rather than only instrumenting the outer structure.

5.1 TEST POD MK. III CUBESAT RESPONSE TESTING

The objective of the Test POD Mk III testing is to record the response of the CubeSat mass model and compare the data to the response of CubeSats within the P-POD.

5.1.1 TEST CONFIGURATION AND LEVELS

The Test POD Mk III was previously introduced and can be seen in Figure 41.

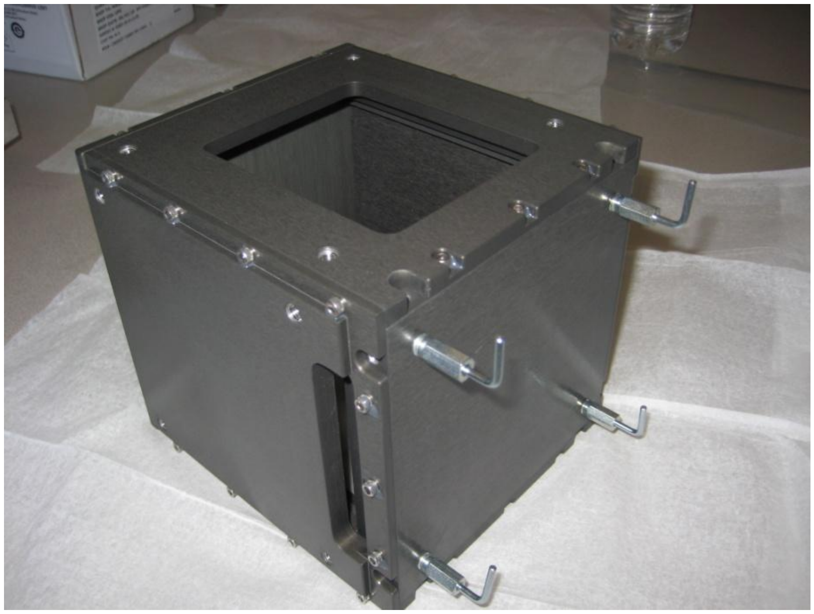


FIGURE 41: CAL POLY TEST POD MK III

A mass model was used to evaluate the Test POD, and two additional mass models were also necessary for P-POD testing. The accelerometer placement for the Test POD Mk III testing was in accordance with the following list:

- 2 Single axis control accelerometers
- 1 Tri-axial accelerometer on outer surface of 1U Mass Model
- 1 Tri-axial accelerometer on inner surface of 1U Mass Model
- 3 Single axis accelerometers on outer edges of Test POD

An example of the mass model and internal accelerometer placement is shown in Figure 42.

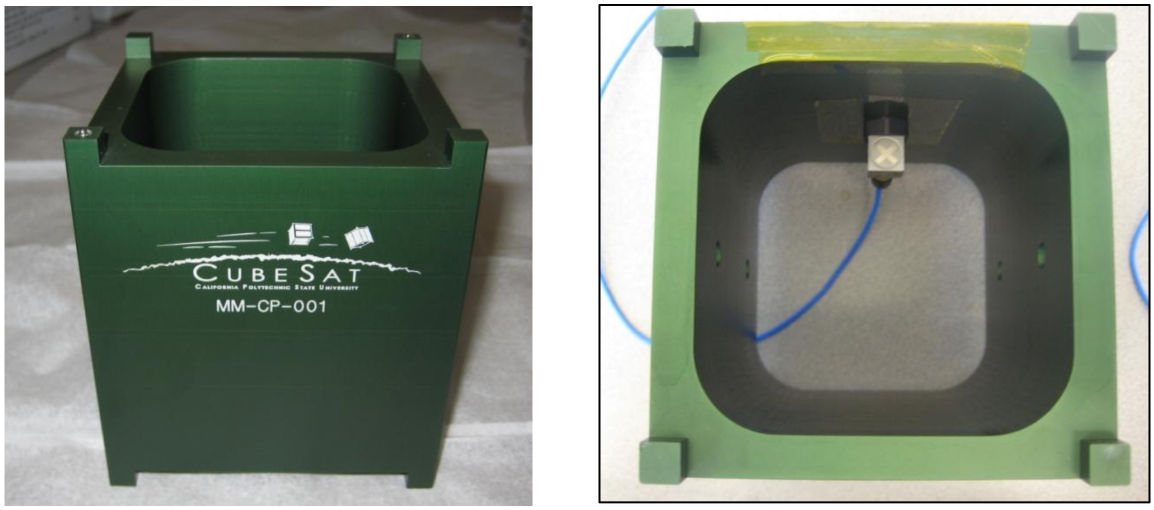


FIGURE 42: CUBESAT MASS MODEL AND EXAMPLE ACCELEROMETER PLACEMENT

The Test POD Mk III is integrated in accordance with the older Test POD User's Guide for the time being. Modifications to the procedure were made to accommodate the new set screws that must be inserted after the helicoils are adjusted.

The Test Pod and P-POD have similar hole patterns, which limit the way in which the items can be attached to the vibration table. The holes are located on the bottom of each item, therefore an oversized interface plate was used to accommodate both the Test POD and the P-POD on the vibration table. The vibration table mounting holes can be seen in the figure below, located on the flange created by the interface plate.

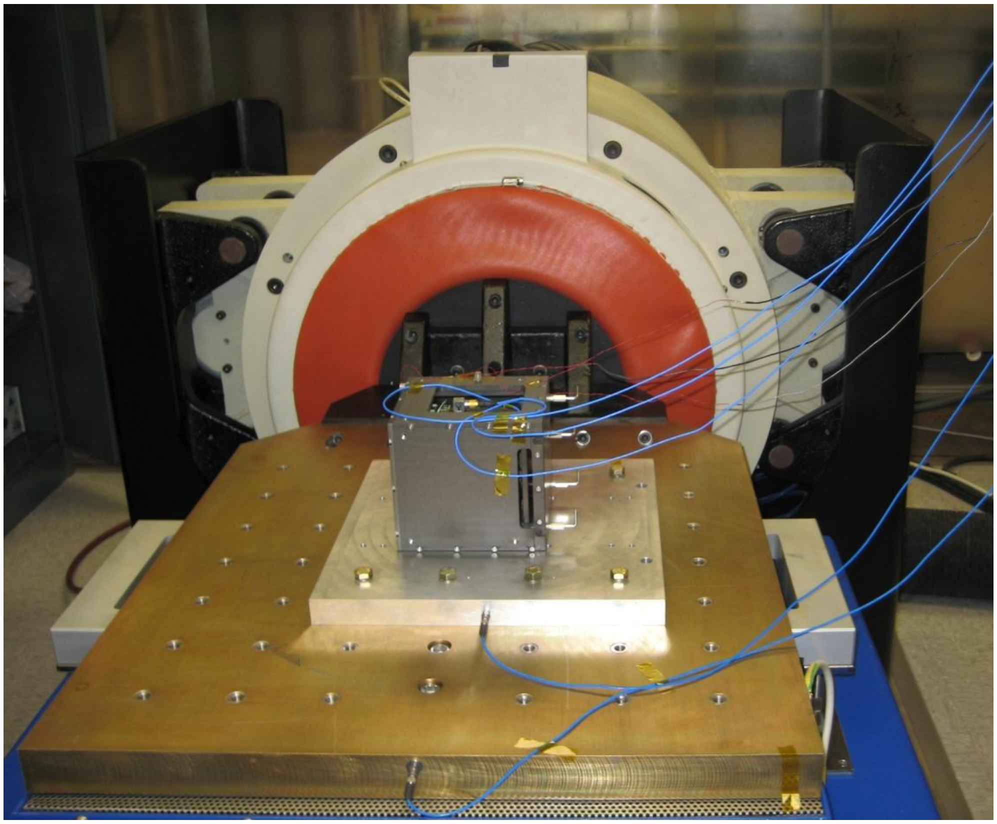


FIGURE 43: TEST POD MK III ON VIBRATION INTERFACE PLATE

For the horizontal testing axis the single interface plate is sufficient for attachment to the slip table. However, in the vertical testing axis, the NPS shake table only has a circular hole pattern. Therefore most test items require an additional interface plate to accommodate the circular pattern. Due to the high use of the NPS vibration table, a circular plate used by the Space Systems Academic Group (SSAG), was already available for testing purposes. Only small modifications were made to allow for attachment of the Test Pod interface plate.

NASA GEVS Qualification test levels were used, however the testing sequence was slightly different than previous tests. The modified sequence was because Cal Poly requested the Test POD Mk III undergo two random vibration tests to see if there was any change in the sine sweep, and therefore the satellite response, after the second random vibration test. A sine sweep was completed before and after testing, with an additional test in between the random vibration tests.

5.1.2 RESULTS

Due to the large amount of data from this testing sequence, only two graphs are shown for each shake axis. The random vibration response graphs shown represent the highest response, or worst case, of the two tests completed. The sine sweep data shown is the best representative of the three sweeps done. In this testing, a dissimilar first sine sweep was not uncommon due to the space available for the satellite to shift within the Test POD, however the second and third sine sweeps generally matched and indicated the satellite had "settled" into a position.

The Z-Axis results are presented first in Figure 44 and Figure 45. The random vibration GEVS Qualification test showed a peak response at 815 Hz and 15.22 g^2/Hz based on the Z-Axis output of the tri-axial accelerometer located within the mass model.

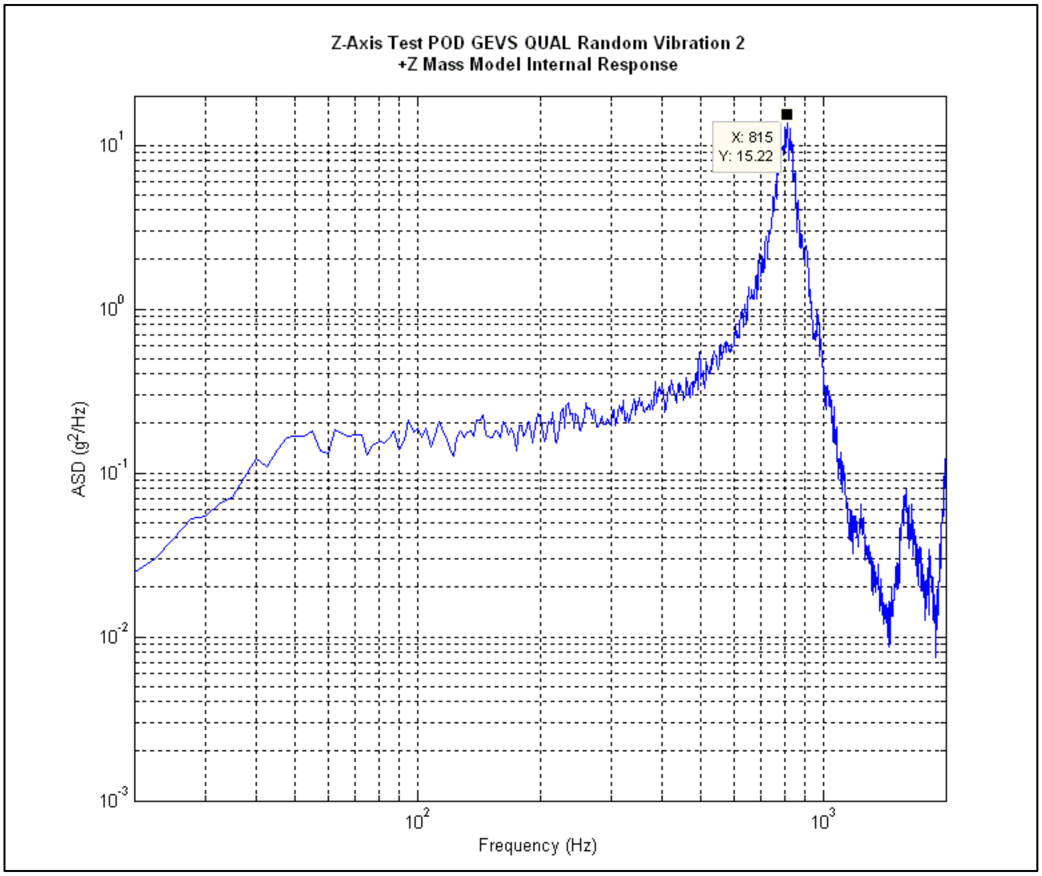


FIGURE 44: Z-AXIS TEST POD MK III GEVS QUALIFICATION MASS MODEL RESPONSE

The .25g sine sweep in the Z-Axis indicated a mode at 882 Hz and 4.296 g^2/Hz, as seen in Figure 45.

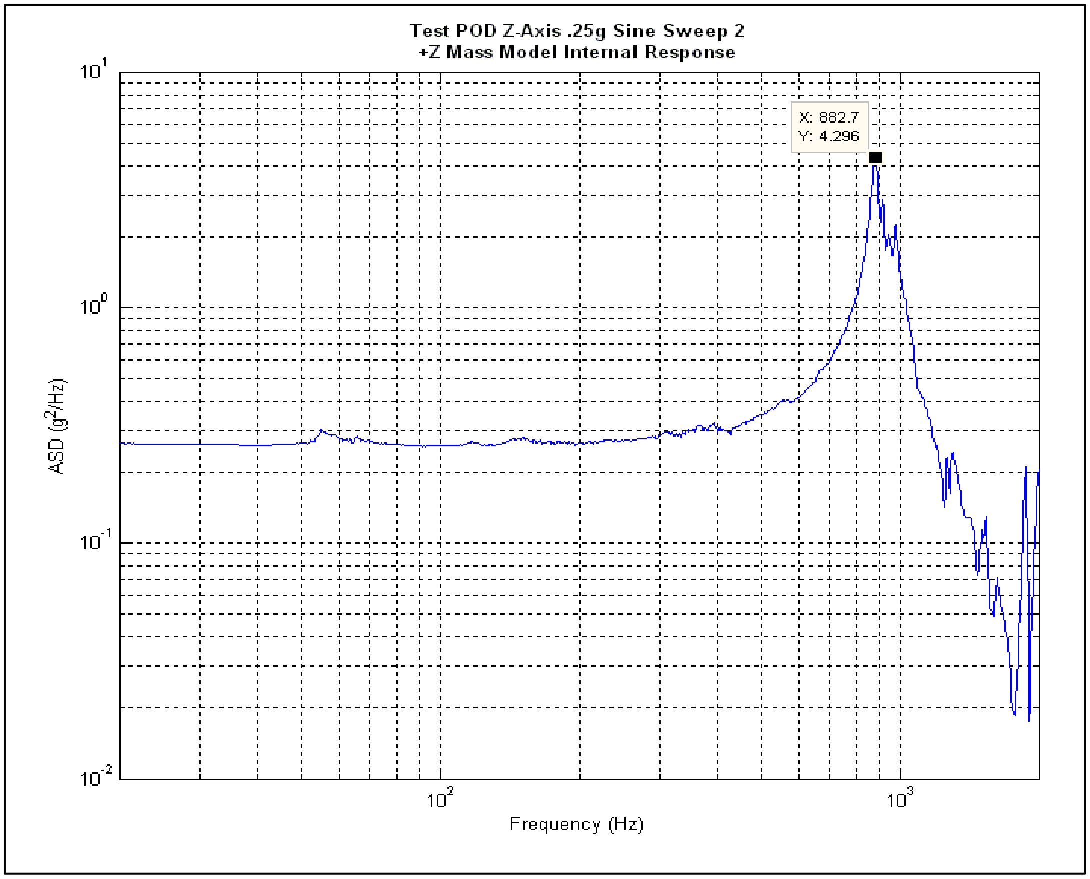


FIGURE 45: Z-AXIS TEST POD MK III SINE SWEEP MASS MODEL RESPONSE

A summary of all the Test POD Mk III results are shown in Table 19.

TABLE 19: Z-AXIS TEST POD MK III RESULTS

Test	Sine Sweep 1	GEVS Random Qual 1	Sine Sweep 2	GEVS Random Qual 2	Sine Sweep 3
Frequency	887	820	882.7	815	882.7
Response	4.23	12.04	4.29	15.22	4.221

The Y-Axis Test POD results show a much lower response than the Z-Axis data. For the random vibration test the mass model response peaked at 702.5 Hz and 2.656 g^2/Hz.

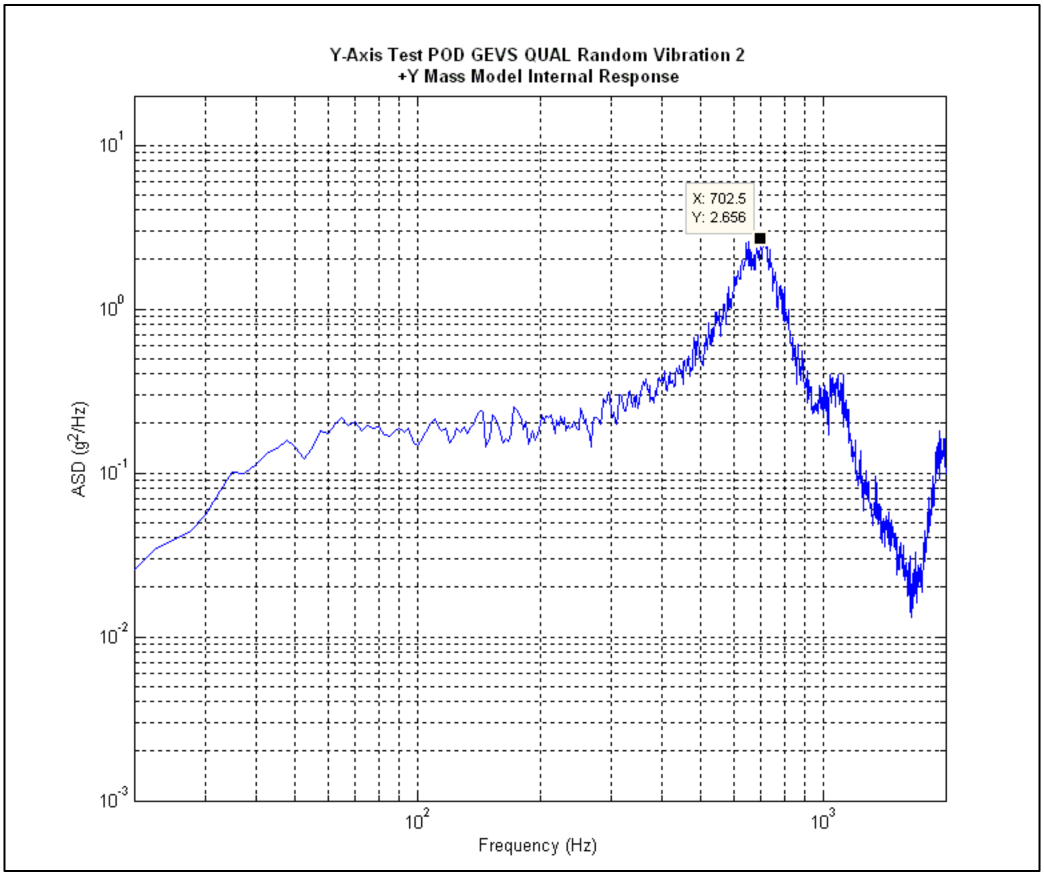


FIGURE 46: Y-AXIS TEST POD MK III GEVS QUALIFICATION MASS MODEL RESPONSE

The sine sweep for the Y-Axis of the Test POD Mk III indicated a mode at 798.4 Hz and a response of 7.23 g^2/Hz.

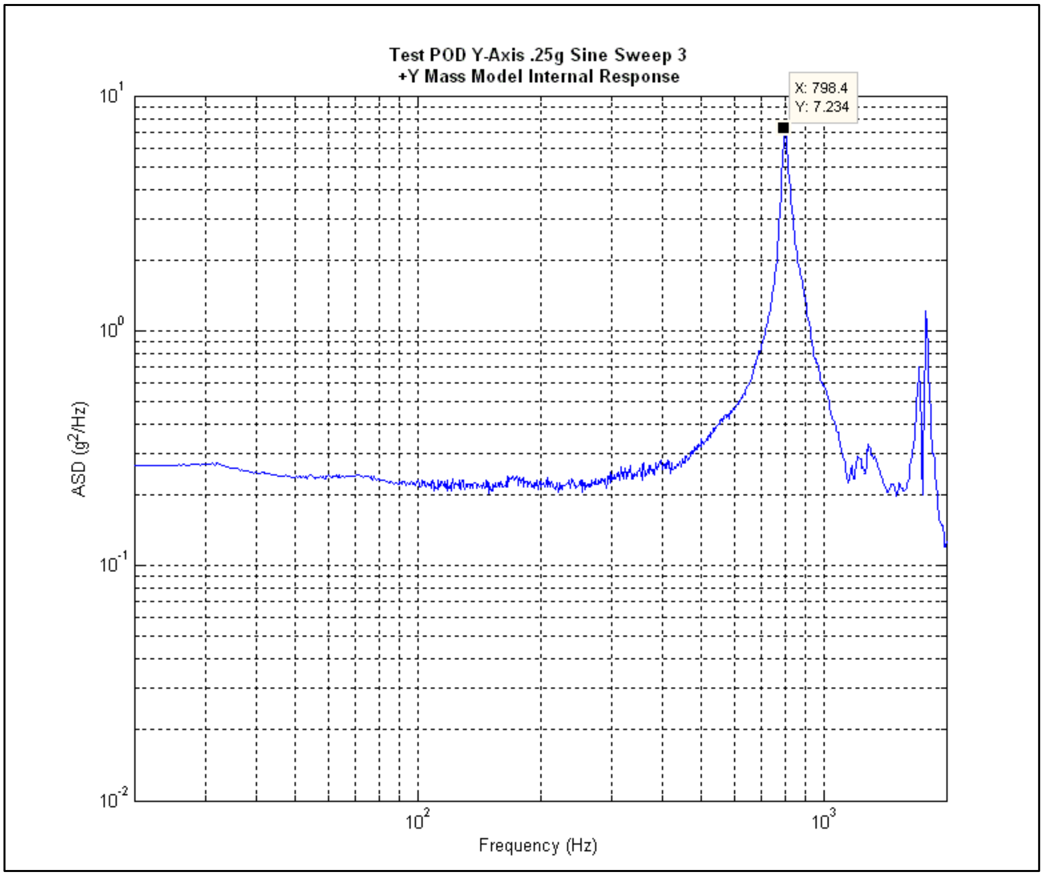


FIGURE 47: Y-AXIS TEST POD MK III SINE SWEEP MASS MODEL RESPONSE

All of the results for the Y-Axis can be compared in Table 20.

TABLE 20: Y-AXIS TEST POD MK III RESULTS

Test	Sine Sweep 1		GEVS Random Qual 1	Sine Sweep 2	GEVS Random Qual 2	Sine Sweep 3
	Peak 1	Peak 2				
Frequency	599.2	917.2	695	817	702.5	798.4
Amplitude	2.18	3.808	2.63	5.61	2.66	7.23

Finally, the X-Axis data is shown below for the random vibration testing. The X-Axis response was at a much higher frequency, 1150 Hz, and indicated a response of 4.44 g^2/Hz.

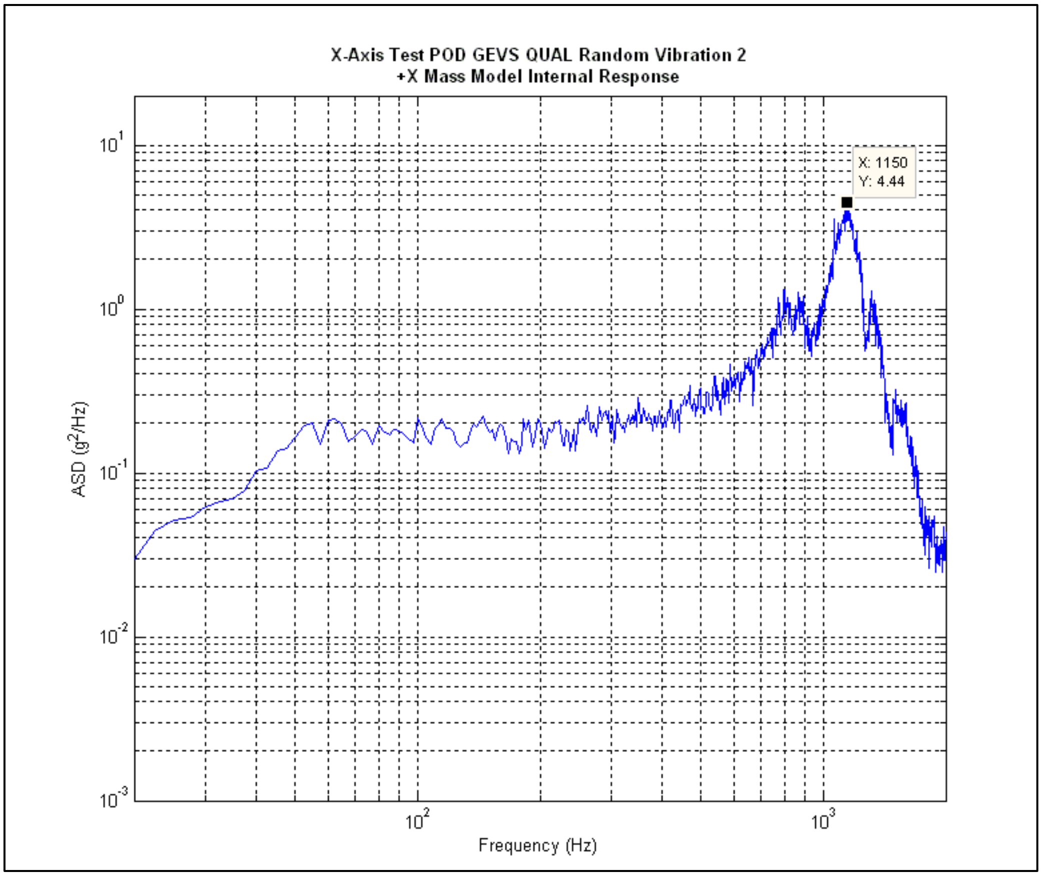


FIGURE 48: X-AXIS TEST POD MK III GEVS QUALIFICATION MASS MODEL RESPONSE

A maximum sine sweep response of 5.6 g at 1228 Hz was recorded for the X-Axis.

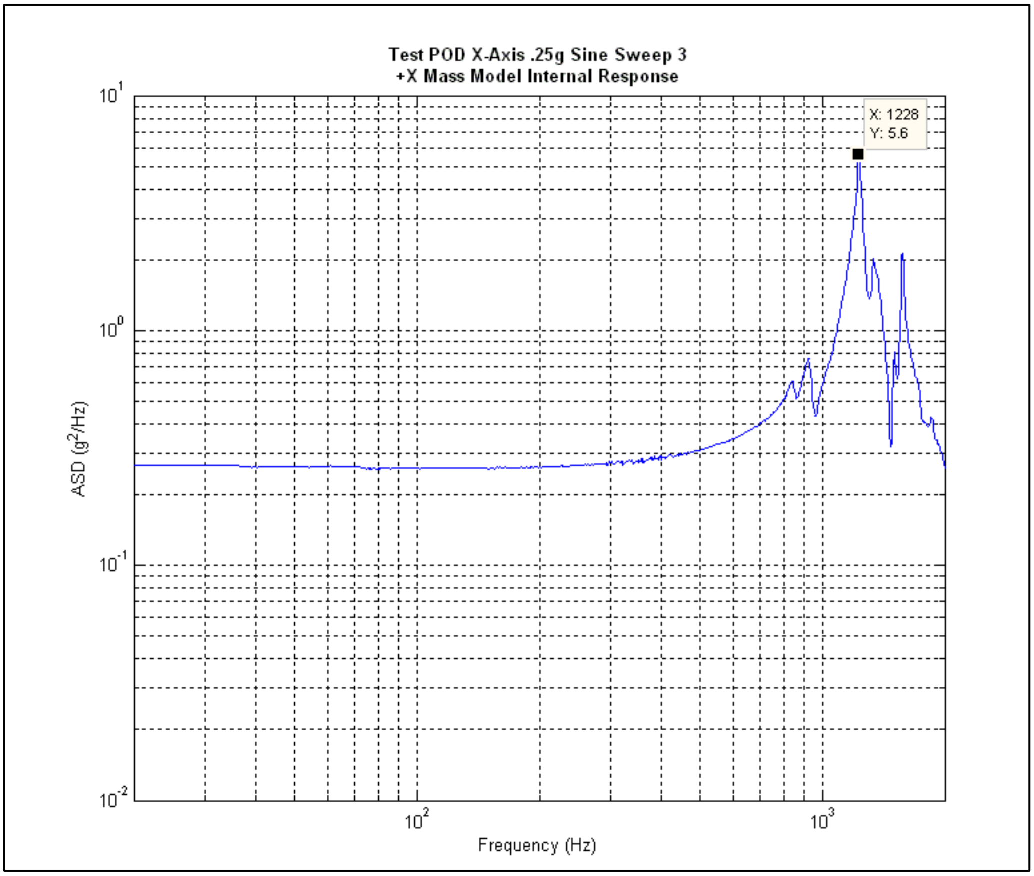


FIGURE 49: X-AXIS TEST POD MK III SINE SWEEP MASS MODEL RESPONSE

Table 21 shows a summary of the X-Axis testing results for the Test POD Mk III.

TABLE 21: X-AXIS TEST POD MK III RESULTS

Test	Sine Sweep 1	GEVS Random Qual 1	Sine Sweep 2	GEVS Random Qual 2	Sine Sweep 3
Frequency	1187	1140	1234	1150	1228 Hz
Amplitude	6.68	3.44	4.95	4.44	5.6 g

Another important factor in this testing, which was not represented by the accelerometer data, was the use of the newly-added set screws. There was no indication of the spring plungers loosening during testing, so they did act as intended during the vibration testing.

One drawback of using the set screws however, was the evidence that the spring plunger threads were slightly damaged after testing. This was not initially seen by the Cal Poly engineers when they threaded the set screws in and took them out for a fit- check, therefore it was a result of the loads on the spring plungers during vibration and the resulting interaction between the spring plungers and set screws. The Cal Poly CubeSat team will determine if further testing and/or modifications are necessary.

5.2 P-POD Mk III CubeSat Response Testing

Previous modeling and testing of the P-POD Mk III was completed by Wenschel Lan and documented in her Cal Poly thesis, "Redesign and Modal Analysis of the Poly Picosatellite Orbital Deployer."[17] At that time, the modes of the P-POD structure were identified and the new design of the P-POD Mk III was qualified. The additional data collected for this project was necessary for comparison of the P-POD Mk III and Test POD Mk III because there was no data regarding the response of the mass model(s) within the test items.

In addition, instrumentation was placed on all three individual mass models within the P-POD to record any differences in the CubeSat's responses based upon the satellite's placement in the deployer.

5.2.1 Test Configuration and Levels

To record the response of each mass model, a tri-axial accelerometer was placed on each one. The mass model that was used for Test POD Mk III testing and for P-POD testing utilized the same accelerometer for the entirety of the testing and was never removed or re-glued to ensure the measurements were comparable between the different test items. Figure 50 shows the P-POD and mass models during integration.

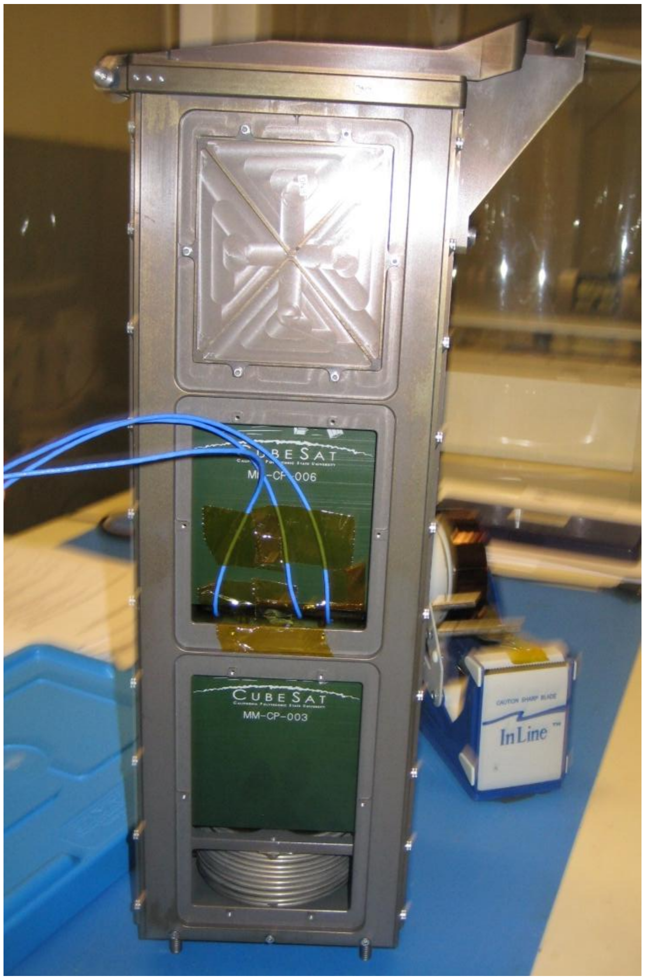


FIGURE 50: CAL POLY P-POD AND MASS MODELS DURING INTEGRATION

The following accelerometers were used for testing:

- 2 Control Accelerometers (single axis), on interface plate
- 1 Single Axis Accelerometer attached externally in the shake axis
- 1 Single Axis Accelerometer attached to P-POD Door
- 3 Tri-axial Accelerometers: One per 1U Mass Model

The P-POD was tested at GEVS Qualification levels and ramped up in 3 dB increments to record the response as the levels increased. The P-POD is shown attached to the shake table in Figure 51.

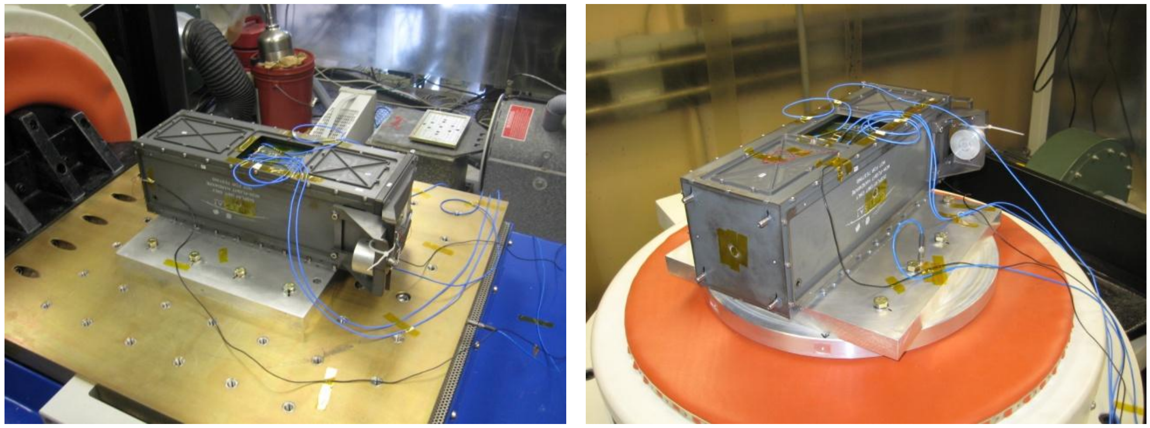


FIGURE 51: P-POD TESTING CONFIGURATION

5.2.2 RESULTS

The results shown for each P-POD testing axis represent the output from each mass model tri-axial accelerometer in the shake direction. The random vibration response, as well as a sine sweep for each axis, is shown.

The first figure below is the Z-Axis random vibration test, which showed the CubeSats did not have any significant difference in response based on their placement in the P-POD. The distinct peak was at 230 Hz with an amplitude of 9.8 g^2/Hz. This is an important result because it verifies the use of the spring plungers to minimize the motion in the Z-direction and adequately restrain the CubeSats.

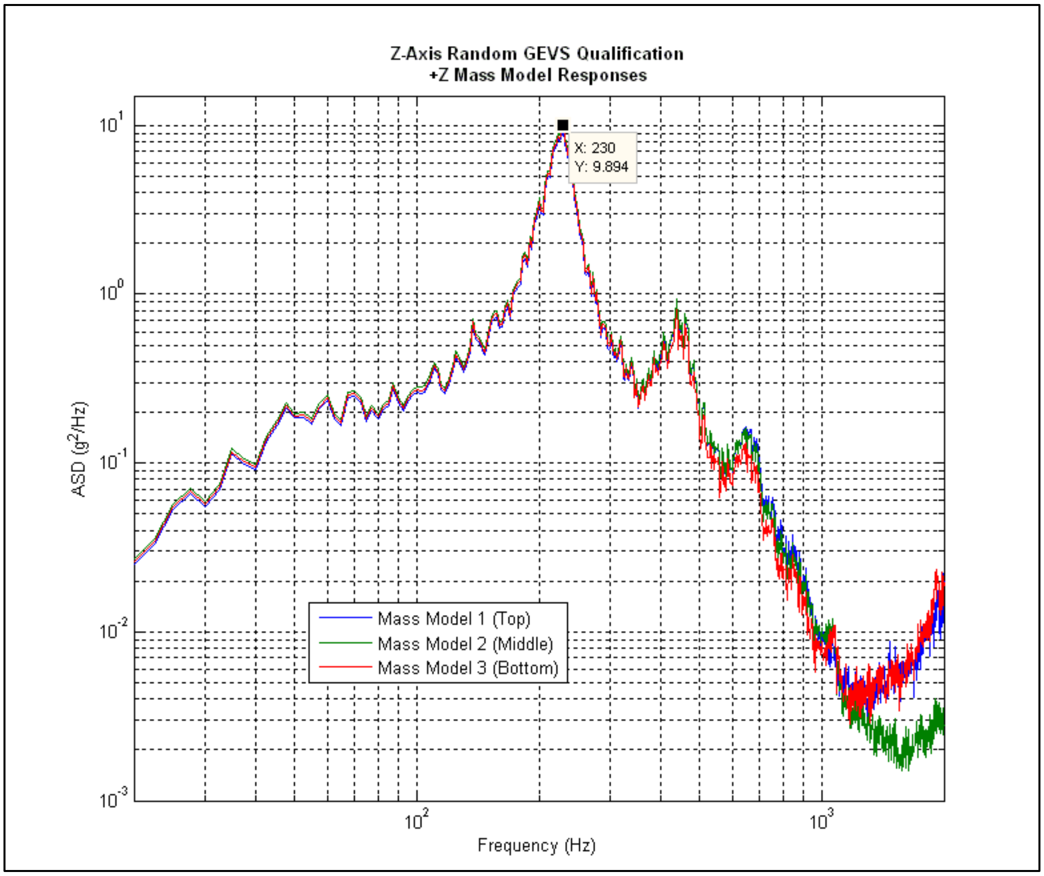


FIGURE 52: Z-AXIS P-POD MASS MODEL RESPONSE

Upon comparison of the pre-test and post-test sine sweep, the results demonstrated the CubeSats either shifted or settled into a position that was different than the original integrated position. A third sine sweep was performed to verify the change in response was not a testing anomaly, and it produced the same result, shown in Figure 53.

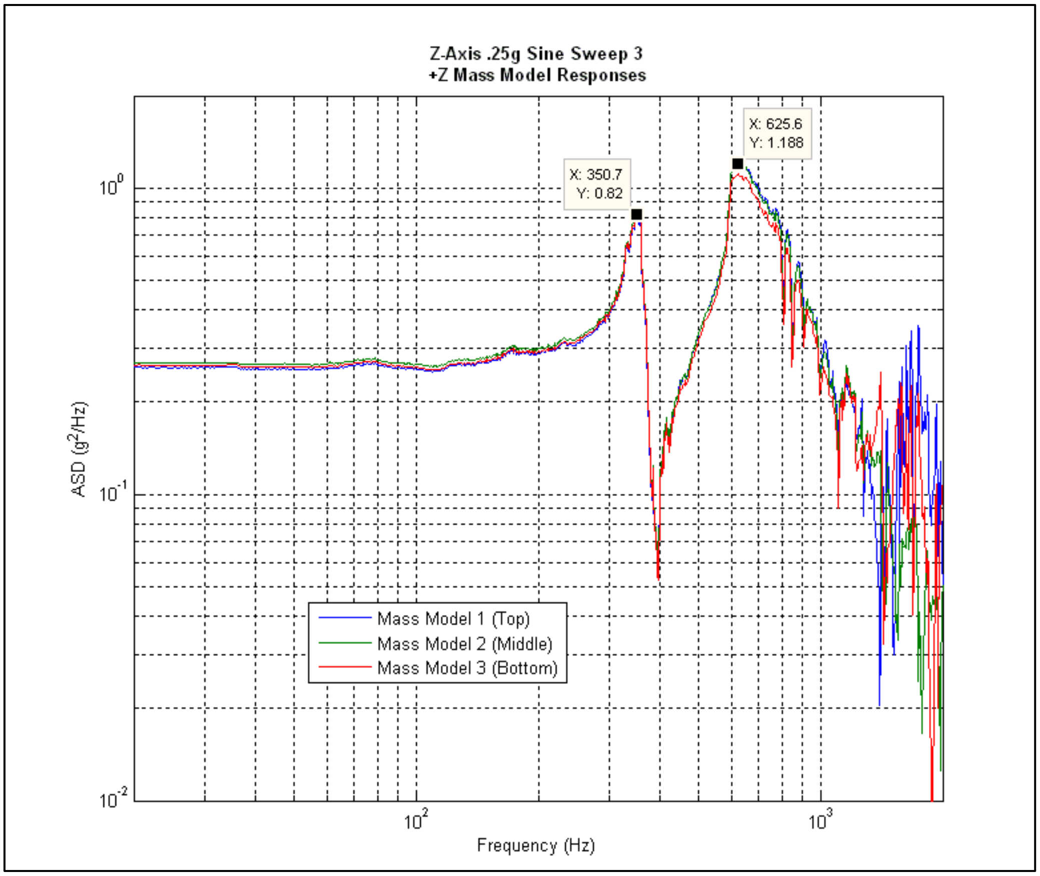


FIGURE 53: Z-AXIS POST-TEST SINE SWEEP

In a different testing scenario, the mismatch between pre and post-test sine sweeps might indicate something has broken, however the three CubeSats within the P-POD do have a small amount of space to shift in the X and Y axes, which could easily change the response.

In the Y-Axis random vibration test, the CubeSats did not demonstrate a definitive peak at a particular frequency, which is not necessarily surprising as it was previously mentioned, the satellites are less constrained in the Y and X axes than the Z-Axis.

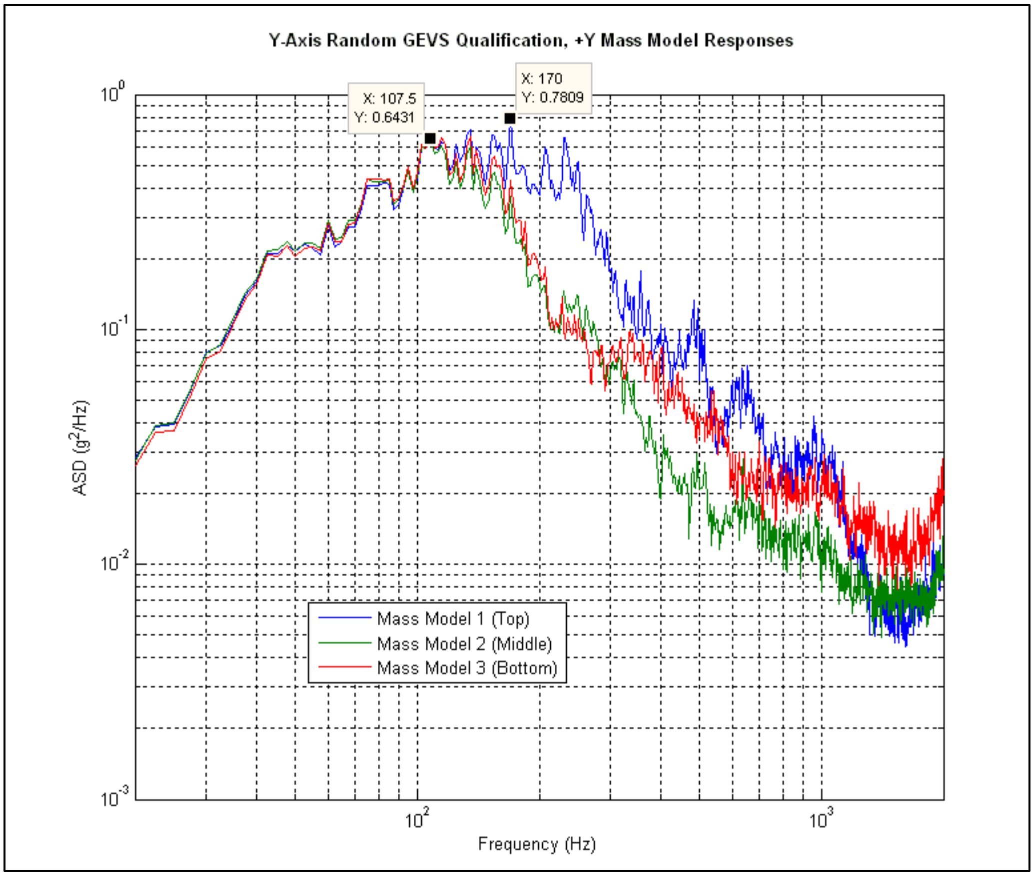


FIGURE 54: Y-AXIS P-POD MASS MODEL RESPONSES

The mass models did show a similar response until reaching 107.5 Hz (0.64 g^2/Hz), where the top mass model shows a slightly different and higher response than the other two mass models.

The pre and post-test sine sweeps for the Y-Axis also did not match, but again the third sine sweep to confirm the change was almost an exact match (refer to Figure 55). The sweep indicated a system mode at 243.8 Hz with a response of 3.6 g^2/Hz.

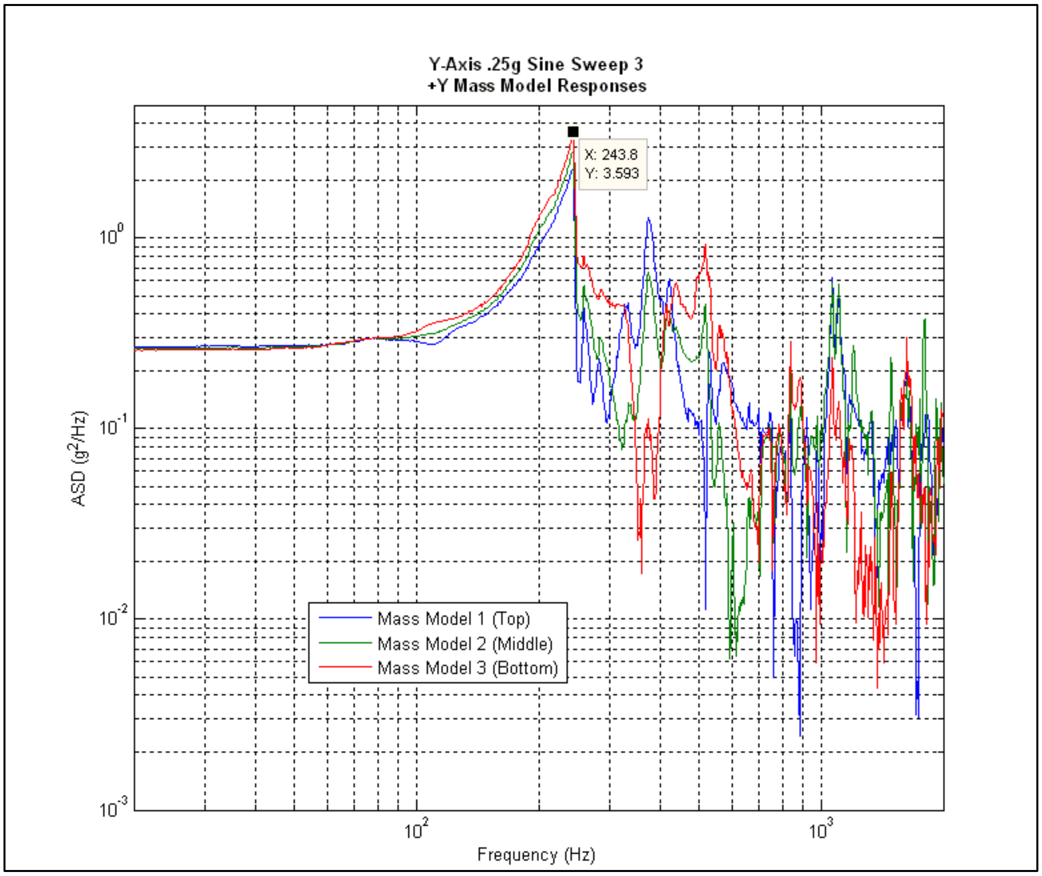


FIGURE 55: Y-AXIS POST-TEST SINE SWEEP

The X-Axis further showed that the individual CubeSats' responses to the vibration environment were similar to each other. The peak response for random vibration was at 297.5 Hz, with an amplitude of 2.3 g^2/Hz.

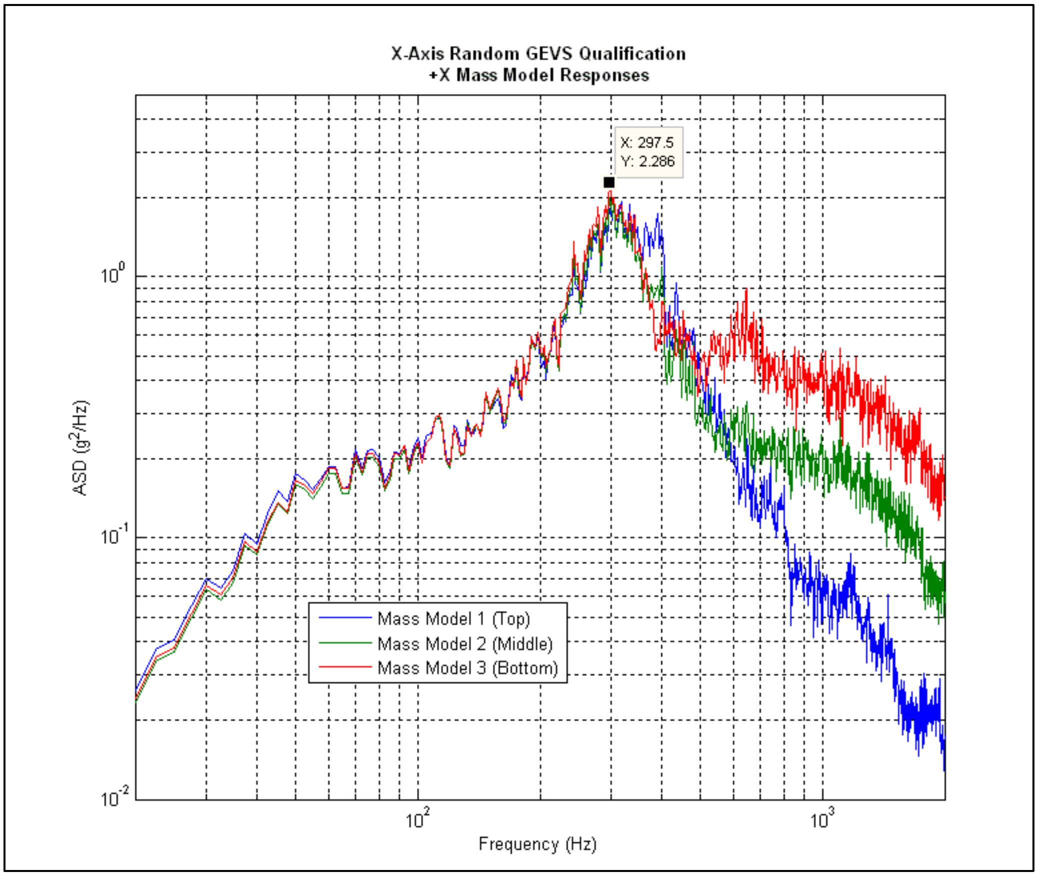


FIGURE 56: X-AXIS P-POD MASS MODEL RESPONSES

The X-axis sine sweep represented the highest resonance at 422.6 Hz with amplitude of 4.256 g^2/Hz.

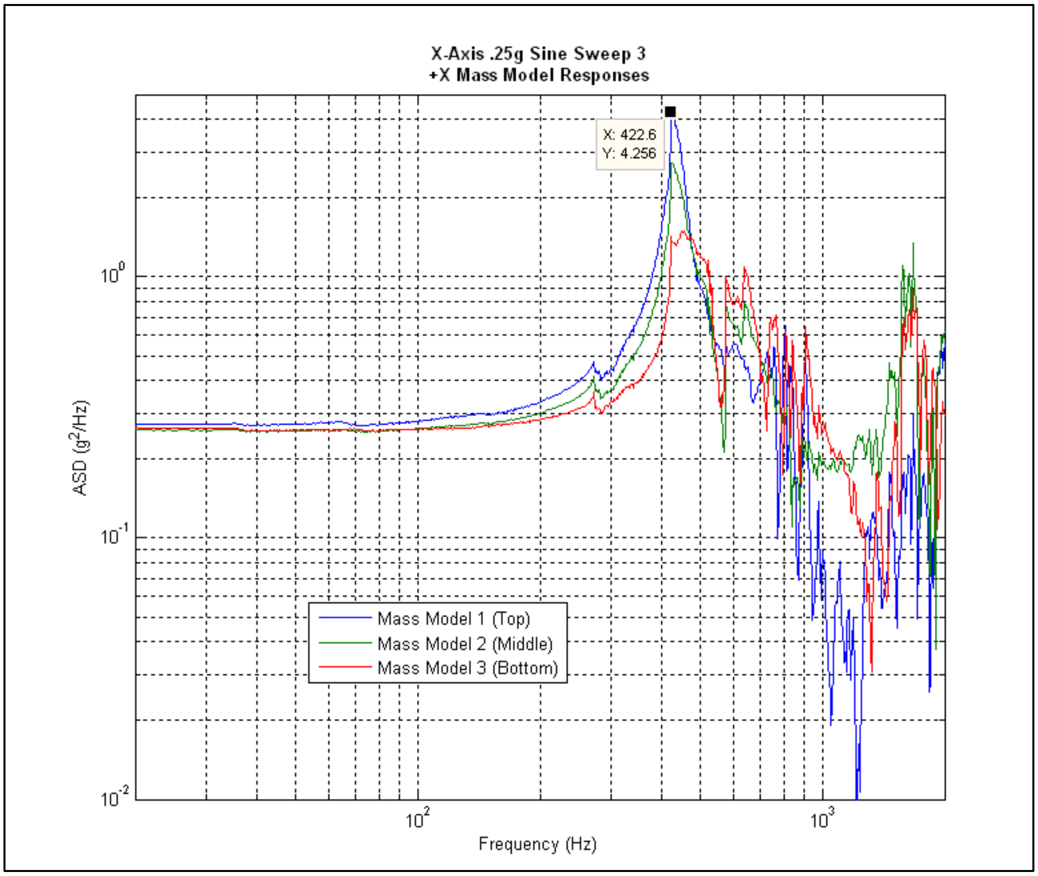


FIGURE 57: X-AXIS POST TEST SINE SWEEP

Overall, the results from the P-POD Mk III testing indicate that the position of a CubeSat within the P-POD does not change the average response. The data also demonstrates how the CubeSats settle after experiencing random vibration, but ultimately stay in the settled position.

4.2.4 Comparison with Previous P-POD Testing

The previous P-POD Mk III testing utilized a single 3 kg mass model and measured the response of the structure rather than the response of the CubeSat. It was indicated the 3U mass model was used for simplicity in order to minimize the nonlinearities caused by multiple mass models. The following P-POD modes were identified during the previous testing[17]:

- X-Axis First Natural Frequency, With Mass Model: 201 Hz
- Y-Axis First Natural Frequency, With Mass Model: 380 Hz
- Z-Axis First Natural Frequency, With Mass Model: 270 Hz

Comparison of these frequencies with the above CubeSat responses show the P-POD Mk III structural modes do not necessarily indicate the resonance of the satellites within the deployer, and further affirms that thorough testing of each individual CubeSat is a necessary step to ensure survival and mission success.

5.3 CubeSat Response Comparison

For comparison, the results from Mass Model 001 were utilized because the accelerometer remained attached to the mass model for both the P-POD and Test POD vibration tests. Due to the permanent placement of the accelerometer, the differences in the results can be fully attributed to the environment within the test item (Test POD or P-POD) rather than a test anomaly due to a change in the accelerometer orientation. The maximum responses during the random vibration testing were utilized and a summary of the data is presented in Table 22.

TABLE 22: CUBESAT RESPONSE COMPARISON, MASS MODEL #001

Test Item	Z- Axis		Y-Axis		X-Axis	
	Frequency	Response	Frequency	Response	Frequency	Response
Test POD Mk III	815	15.22	702.5	2.65	1150	4.44
P-POD Mk III	230	9.49	170	.78	305	1.94

The following plot, Figure 58, shows a large difference in resonance frequency between the Test POD and P-POD in the X-Axis vibration test.

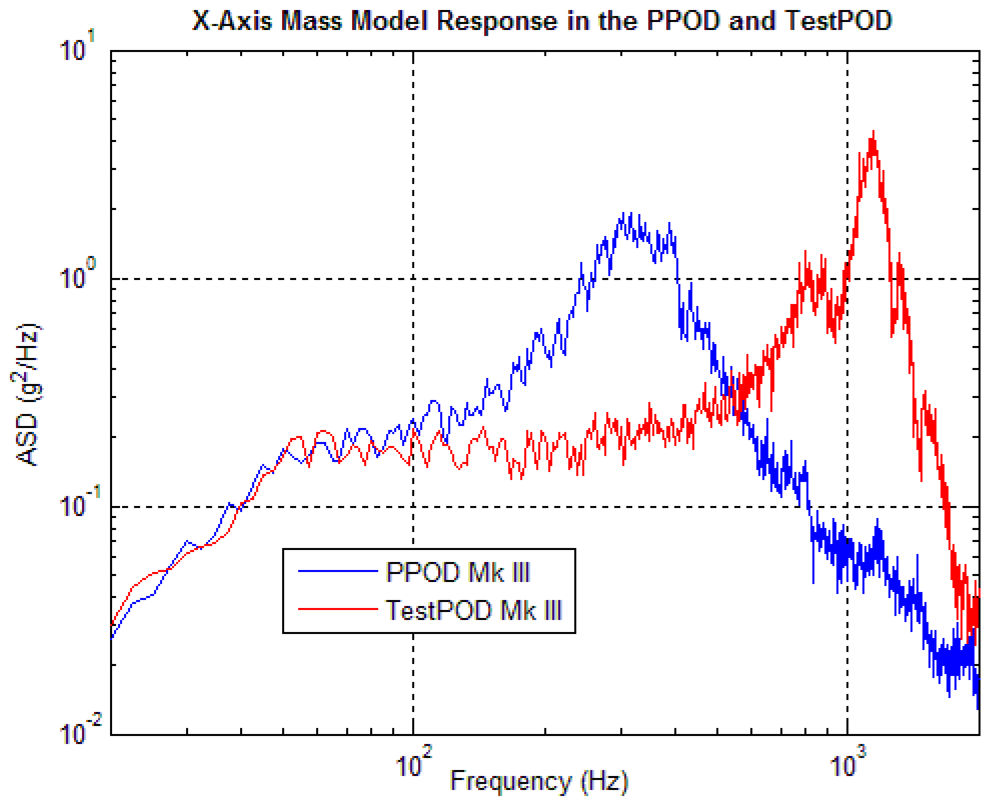


FIGURE 58: X-AXIS MASS MODEL RESPONSE COMPARISON

Due to the large discrepancy in resonance frequency, a transfer function was calculated to define the difference between the two responses. The transfer function shown is the response of the Test POD divided by the response of the P-POD. Although the large discrepancy was identified after testing was completed, the data will be utilized to tailor future Test POD vibration tests.

The X-Axis transfer function is shown in Figure 59. It will be necessary to increase the input to the Test POD in the vicinity of 300 Hz and lower the input in the vicinity of 1150 Hz.

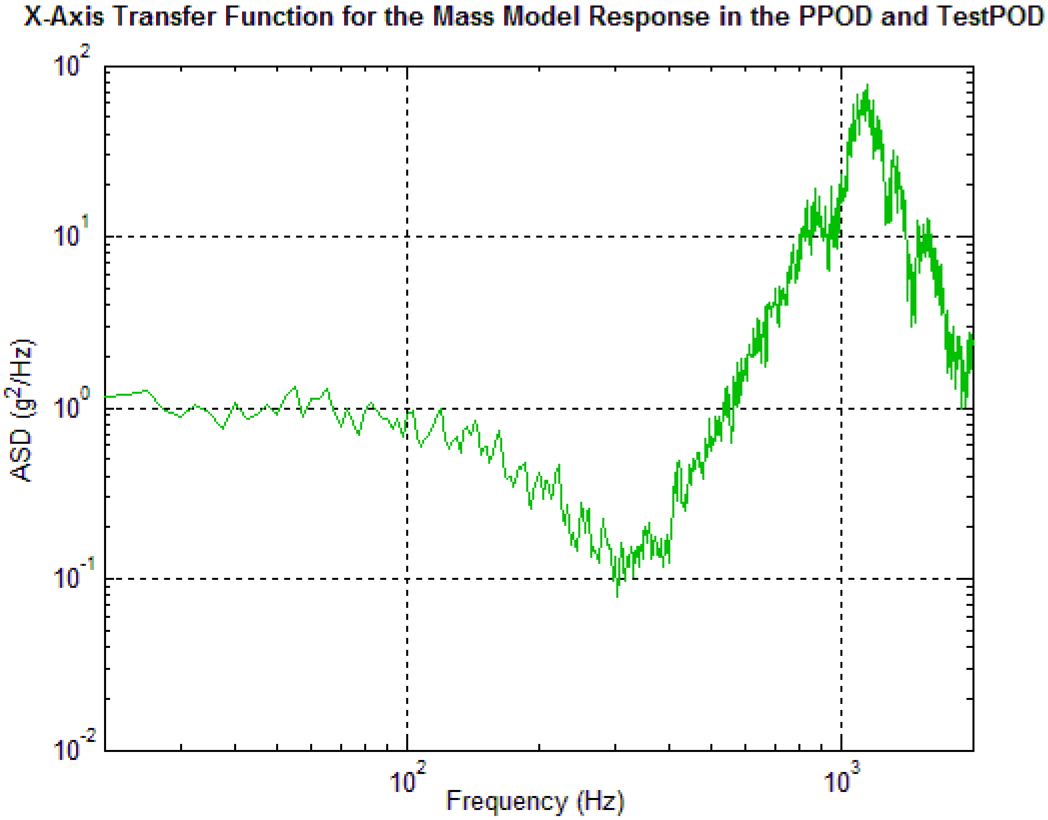


FIGURE 59: X-AXIS P-POD AND TEST POD TRANSFER FUNCTION

The Y-Axis response comparison is shown in Figure 60. In this axis, the Test POD results again diverged from the P-POD environment in the 300 to 1000 Hz range.

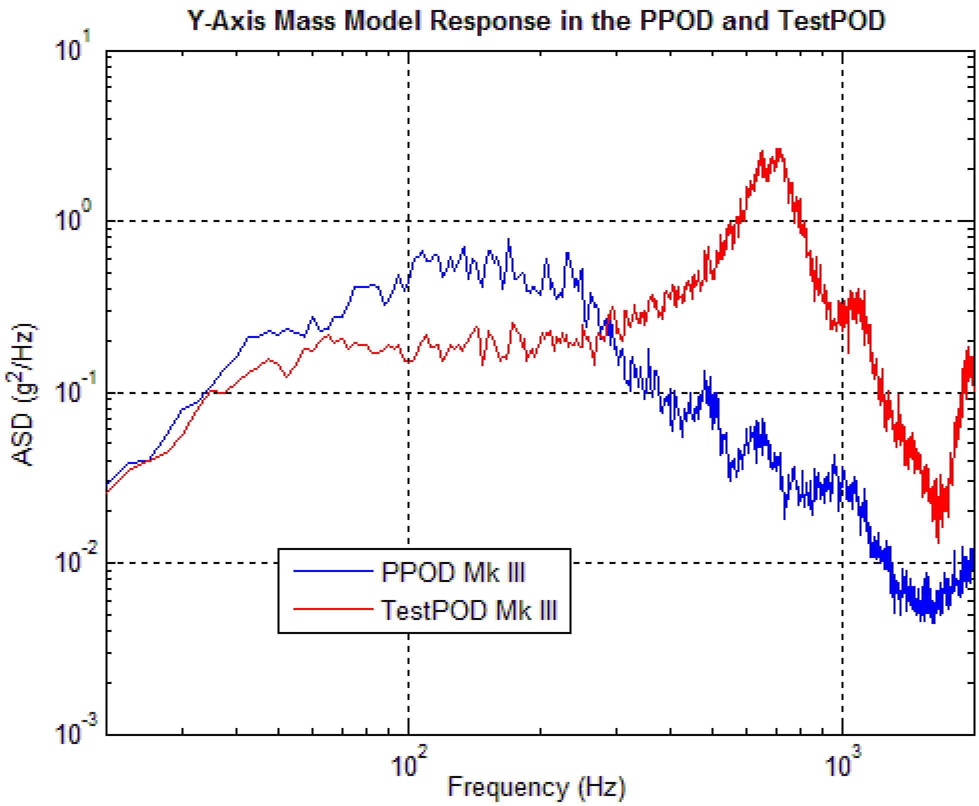


FIGURE 60: Y-AXIS MASS MODEL RESPONSE COMPARISON

Figure 61 illustrates the largest discrepancy is at approximately 700 Hz. For the Test POD to represent a qualification environment which is greater than the P-POD, the transfer function plots would all be above 1. At 1, the Test POD would be the same as the P-POD, therefore some above 1 shows Test POD as a worse environment.

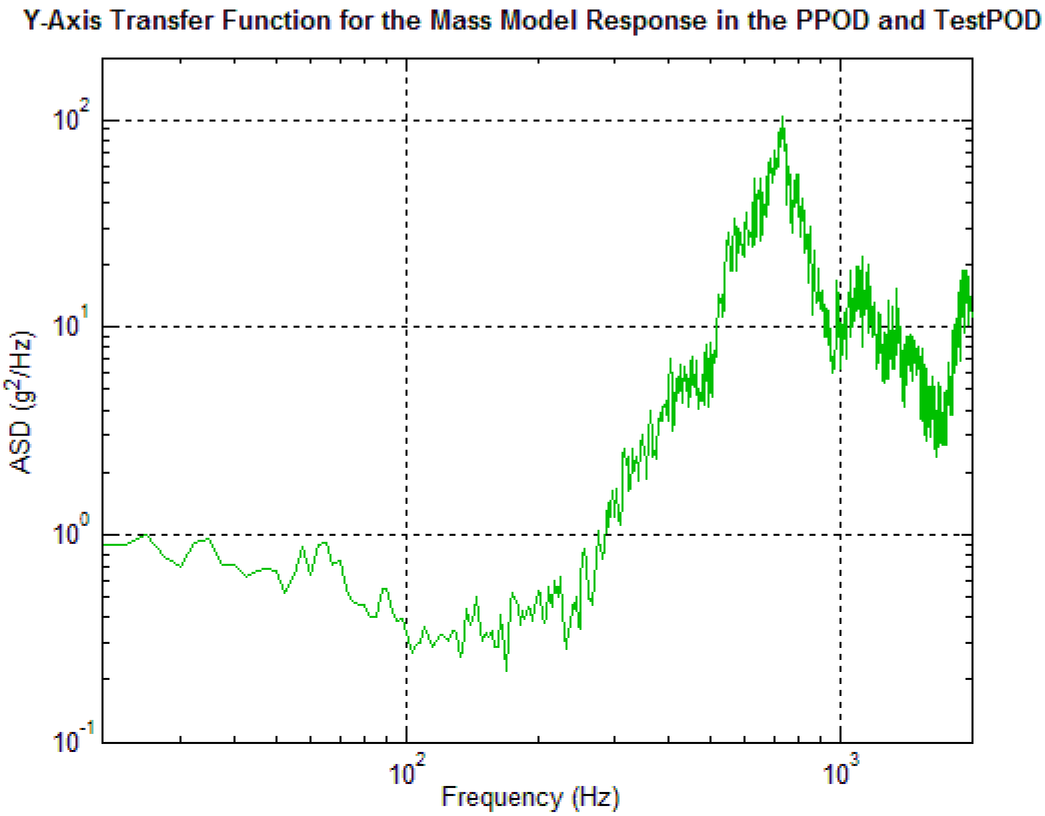


FIGURE 61: Y-AXIS P-POD AND TEST POD TRANSFER FUNCTION

In the Z-Axis a similar upward shift in the Test POD frequency as compared to the P-POD frequency was recorded. Figure 62 illustrates maxima at similar magnitude, but different frequencies of 815 Hz and 230 Hz respectively.

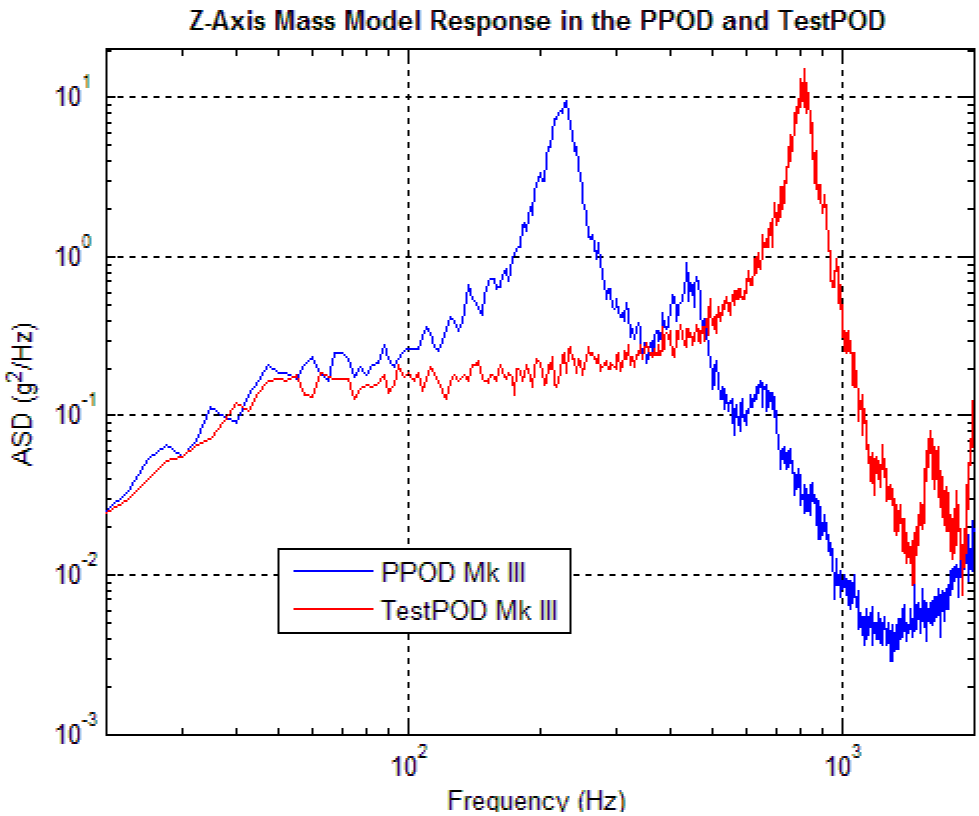


FIGURE 62: Z-AXIS MASS MODEL RESPONSE COMPARISON

The Z-Axis transfer function further illustrates the strong response of the Test POD at higher frequencies than the P-POD. The challenge in tailoring the Test POD profile is modifying the input to encompass the P-POD maxima. When the Test POD has a greater response, the input can be scaled down in that frequency range, but when the P-POD represents the higher response it is not as simple to mimic the response at the correct frequency.

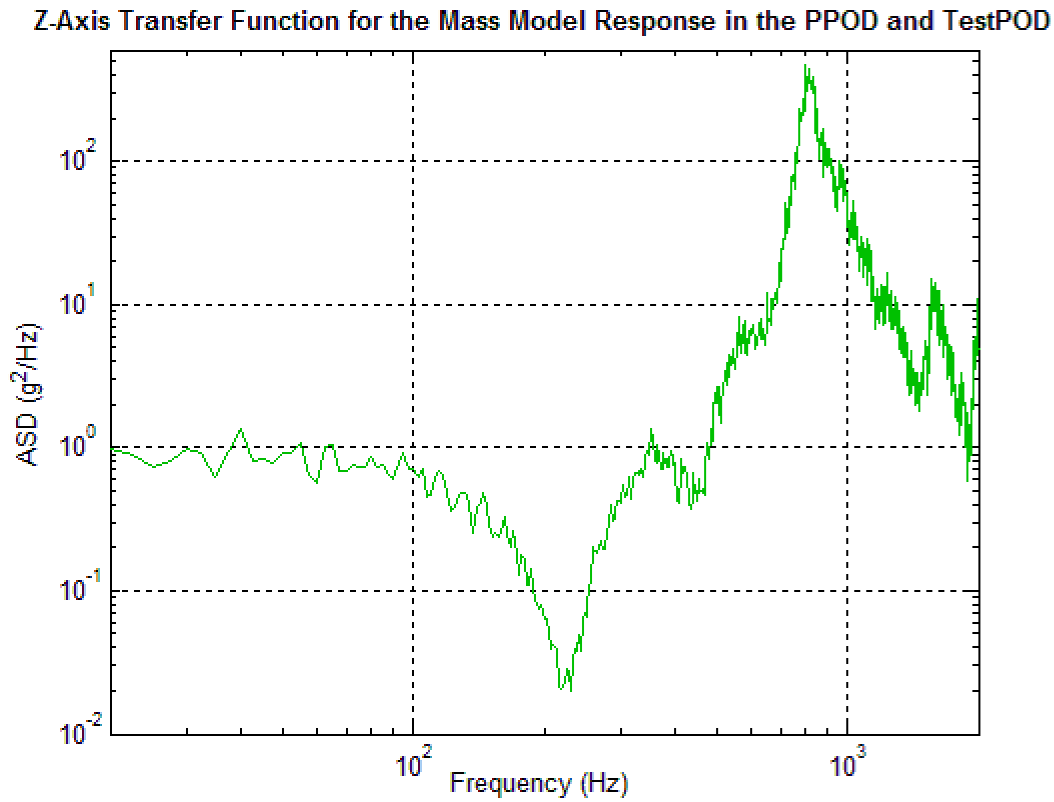


FIGURE 63: Z-AXIS P-POD AND TEST POD TRANSFER FUNCTION

Based on the comparison, the Test POD Mk III will need structural modifications and/or further testing based on a tailored profile.

With the data presented here, Cal Poly can evaluate each axis of the Test POD individually by running a profile and then immediately comparing the data to the P-POD results. If the transfer function does not present the desired results, the test profile can be modified and further testing can be completed in a time effective way. With better knowledge of the test items, this would have been the original testing format. Additionally, Cal Poly now has the ability to complete this evaluation in-house because the Test POD instrumentation only includes a single tri-axial accelerometer.

Though the Test POD was not able to be fully qualified based on this comparison, the environment recorded from within the P-POD can be used for future development and testing.

6 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

The two most significant contributions of this thesis are the long term benefits of developing in-house CubeSat testing capabilities at NPS and the evaluation of a new CubeSat Test POD Mk III for use throughout the CubeSat community.

6.1.1 SUBSYSTEM TESTING & SATELLITE QUALIFICATION

The vibration testing that was completed in order to qualify the NPS-SCAT CubeSat has laid the foundation for Flight Unit testing as well as future CubeSat testing. The plans and procedures developed for NPS-SCAT are all available to future NPS students and will allow new missions to spend time on payload development rather than test development.

Significant progress has also been made towards defining a subsystem testing configuration that more closely represents the environment inside of a CubeSat. Although a new payload board will have different characteristics than the NPS-SCAT SMS, tailoring of the suggested profile will at least minimize over-testing in the event that further analysis is not possible.

6.1.3 CUBESAT RESPONSE TESTING IN THE TEST POD MK III AND P-POD MK III

Through CubeSat response testing inside of the new Test POD Mk III and the P-POD Mk III, a comparison of the environments was completed. The data showed that the Test POD vibration profile must be modified or the Test POD itself must have structural modifications in order to accurately represent the P-POD at qualification levels. The P-POD results shared with Cal Poly will allow further testing to be completed.

The P-POD testing verified the similarity in the responses of the individual mass models, which confirms there is not preferential position within the P-POD.

6.2 Future Work

Multiple launch delays have extended the development and testing of NPS-SCAT, therefore the environmental testing of the flight unit is not complete at this time.

An additional project, to include an accelerometer on a CubeSat subsystem board, was also researched. Although one sensor was acquired, the compressed development timeline was found to be unrealistic based on the need for outside design and manufacturing.

6.2.1 NPS-SCAT Beacon Board and Flight Unit Testing

The most critical future work for students at NPS is to complete the qualification of the Cal Poly Beacon Board and the Flight Unit environmental testing – both vibration and thermal-vacuum. It is essential to continue the satellite integration and testing regardless of launch date because the personnel most familiar with the satellite are quickly graduating and unexpected issues are most likely to appear during testing.

Thorough documentation and test plans are available to new students, and SSAG staff are always willing to support, however there is no substitution for learning from the person who wrote the procedure or designed the subsystem.

Upon arrival at NPS, the Cal Poly Beacon Board will need to undergo vibration qualification testing according to the newly defined subsystem testing configuration and levels. It may also need to complete individual thermal-vacuum testing if required for radio testing. After integration the satellite will undergo vibration testing in the Test POD at either proto-flight or acceptance levels.

6.2.2 ACCELEROMETER BOARD DEVELOPMENT

NPS is also interested in the development of a CubeSat subsystem board that could act as a launch recorder, a transportation vibration recorder, or a vibration testing recorder.

A new Analog Devices accelerometer, the Digital Tri-Axial Vibration Sensor (ADIS16223) was acquired because of its high vibration sensing range of ±70 g. The original plan was to develop a stand-alone board that would not only fit in a NPS CubeSat, but could also be used autonomously. After the board was proposed it became more obvious the development and manufacture would not be complete in time for the testing endeavors addressed in this thesis. The accelerometer is currently at NPS and there are two obvious steps toward building the board mentioned above. First, basic characterization of the accelerometer is necessary. This would require an external power source and the necessary software to interface with the sensor. The second task is identifying the parts, including a microprocessor, memory, and batteries in order to lay out the circuitry for a stand-alone board.

6.2.3 TEST POD

For Test POD evaluation to be complete, another three axis test must be completed with a modified profile. Additionally, the use of set screws must be reevaluated based upon the spring plunger damage shown in the completed tests.

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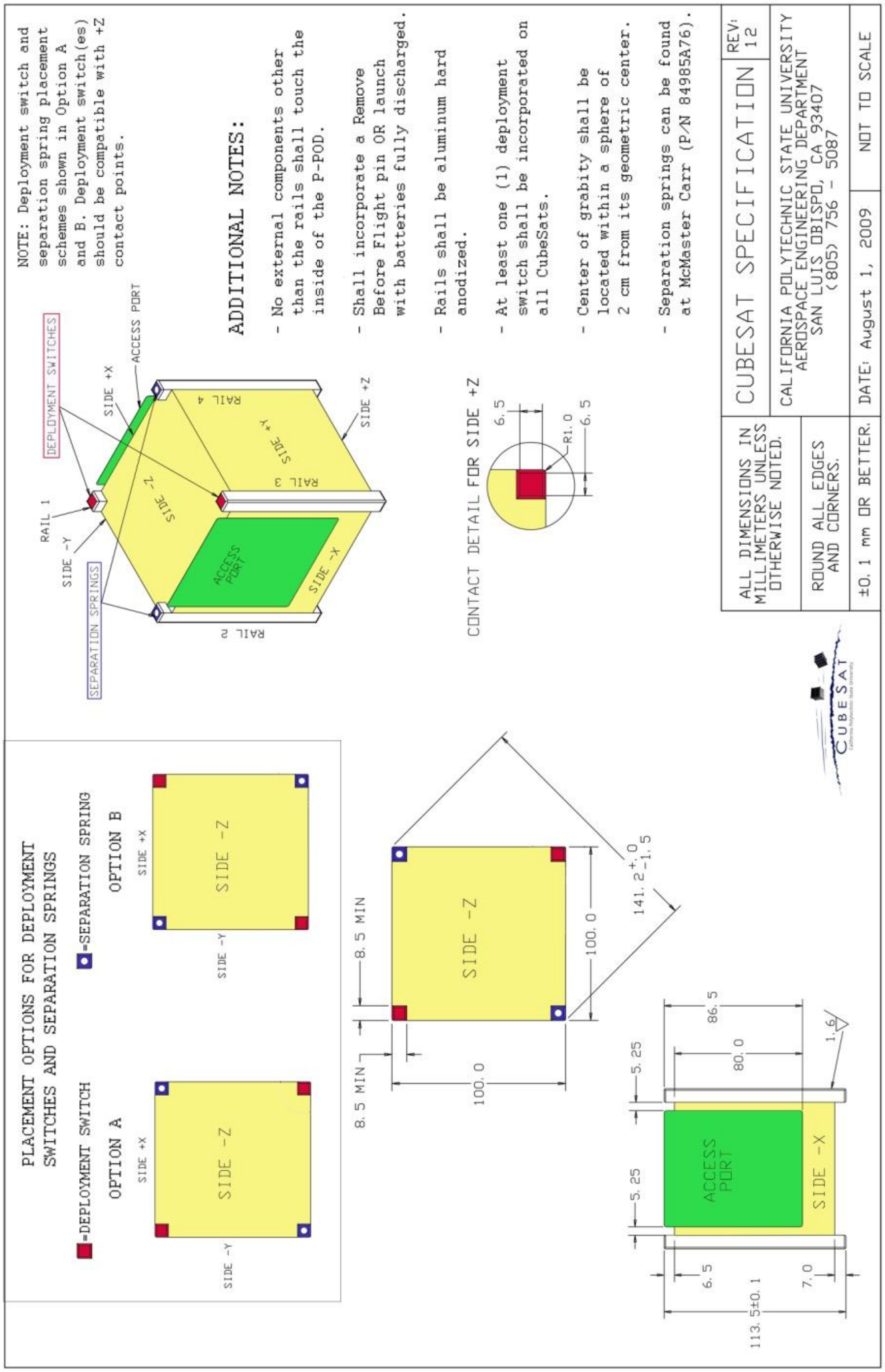
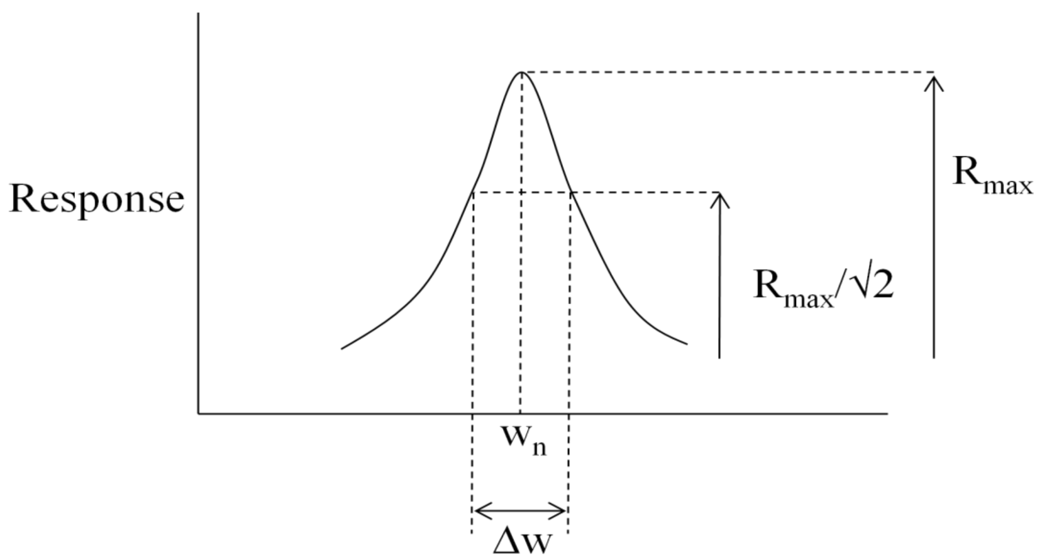
APPENDIX A: CUBESAT STANDARD



APPENDIX B: AMPLIFICATION FACTOR CALCULATION

From “Mechanical Vibrations in Spacecraft Design” by J. Jaap Wijker:

The half power method estimates the modal viscous damping, ξ, by measuring the frequency increment, $\Delta\omega$, at the half power point.



Modal viscous damping, ξ, is

$$\xi = \frac{\Delta\omega}{2\omega_n}$$

To find the amplification factor, it is known that

$$Q = \frac{1}{2\xi}$$

Therefore

$$Q = \frac{\omega_n}{\Delta\omega}$$

APPENDIX C: SUBSYSTEM TEST RESULTS

	Z No Standoffs Qual -12dB	Z No Standoffs Work -6dB
Input Spectrum (g^2/Hz)	0.01	0.01
Average Value of Peak(g^2/Hz)	16.45	14.71
3dB below Peak Value (g^2/Hz)	8.24	7.37
Bandwidth @ 3dB Below (Hz)	8.90	8.51
Grms	12.10	11.19
Static G's (g)	36.30	33.57
Resonant Frequency (Hz)	300.00	302.50
Q factor (Frequency Method)	33.71	35.55

	Z With Standoffs Qual -12dB	Z With Standoffs Work -6dB
Input Spectrum (g^2/Hz)	0.01	0.01
Average Value of Peak(g^2/Hz)	12.30	16.70
3dB below Peak Value (g^2/Hz)	6.16	8.37
Bandwidth @ 3dB Below (Hz)	9.40	8.37
Grms	10.75	11.82
Static G's (g)	32.26	35.47
Resonant Frequency (Hz)	282.50	282.50
Q factor (Frequency Method)	30.05	33.75

	Z With board and Standoffs Qual -12 dB	Z With Board and Standoffs Work -6dB
Input Spectrum (g^2/Hz)	0.01	0.01
Average Value of Peak(g^2/Hz)	13.66	27.00
3dB below Peak Value (g^2/Hz)	6.85	13.53
Bandwidth @ 3dB Below (Hz)	7.00	6.61
Grms	9.78	13.36
Static G's (g)	29.34	40.08
Resonant Frequency (Hz)	335.00	332.50
Q factor (Frequency Method)	47.86	50.30