SPACE QUALIFICATION TESTING OF A SHAPE MEMORY ALLOY DEPLOYABLE CUBESAT ANTENNA

THESIS

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THESIS

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Abstract

Increasingly capable CubeSat missions require antennas with improved Radio Frequency (RF) performance over the traditional CubeSat antennas. Deployable quadrifilar helical antennas (QHA) enable an acceptable stowing volume and deploy to provide increased gain and bandwidth over traditional patch and dipole antennas. Extensive ground testing is required to ensure the antenna is space qualified and to characterize the antenna deployment in the space environment. AFIT requires a QHA to perform a future CubeSat geolocation mission and contracted Helical Communication Technologies (HCT) to design and manufacture a Shape Memory Alloy (SMA) L-band deployable QHA. In this research, a testing approach is developed to conduct random vibration, thermal vacuum, laser vibrometer, and Voltage Standing Wave Ratio (VSWR) experiments on the HCT antenna to verify the hardware is space qualified and to characterize the SMA deployment in the space environment.

The HCT QHA successfully passed all required NASA General Environmental Verification Standards space qualification testing. Several anomalies experienced by HCT's QHA design encourage a redesign of the hold down loops. The deployed antenna length varied from 250-290 mm and future RF testing and analysis is required to determine if the antenna geometry variations will impact the geolocation accuracy.

This research documents the testing sequence and results for a SMA QHA deployable CubeSat antenna testing and aids the development of deployment and attitude control concepts of operations for future CubeSat mission utilizing the HCT QHAs.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Richard Cobb, for his guidance and support throughout the course of this thesis effort. The insight and experience was certainly appreciated. I would, also, like to thank Dr. Eric Swenson for his invaluable input and feedback. I would like to thank Greg O'Neill and David Cross from Helical Communications Technologies for both the support and latitude provided to me in this endeavor. The testing, and therefore this research, would not have been successful without the assistance of Chris Sheffield and Jorge Urena. I would like to thank my wife for her continuous love and support.

Carl R. Kobza

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I. Introduction

1.1 Motivation

Small satellites are being increasingly called upon to perform various missions on orbit traditionally done by large, expensive and complex space platforms. The initial goal of creating small satellites was to provide an inexpensive and effective experimental platform in space. Small satellites, such as CubeSats, have evolved into a proven capability and have driven the development of a space asset industry independent of large, traditional satellites capable of accomplishing similar missions. [1] CubeSats are cheaper to build and cheaper to launch than traditional satellites and allow many more organizations to participate in the venture of using Earth orbits to achieve scientific and technological advancements that are otherwise impossible. [2]

Almost every satellite mission depends on radio frequency (RF) communications to receive and transmit data. CubeSat missions, such as providing communication and imagery collection, generate large amounts of data. In order to accommodate this data, the CubeSat must provide sufficient RF attributes, such as gain, beamwidth and bandwidth. These RF attributes can be achieved through various parts of the satellite's communications subsystem. However, the power and processing power available on a CubeSat is limited. A potential component of the satellite communications (SATCOM) architecture that could provide additional capability, without placing demands on power and computer processing, is the antenna.

A limiting factor of CubeSat antennas is the small internal volume and surface available on a CubeSat face to accommodate a larger antenna. A typical CubeSat unit is a 10x10x10cm^3 cube resulting in a maximum 100cm^2 area per unit on a single face of a CubeSat. [3] This small surface area restricts the size of a parabolic or patch antenna that can be mounted on a CubeSat face. Deployable antenna structures must be considered when a larger antenna surface is desired. Deployable space structures are challenging to design and test that result in high confidence that the component will deploy correctly in space. If an anomaly occurs in space, there are limited options to correct the condition.

This thesis will investigate current research and development into deployable CubeSat antennas and will devise and evaluate the steps required to verify and characterize the space readiness of a proposed deployable QHA CubeSat antenna.

1.2 Problem Statement

The Air Force Institute of Technology (AFIT) has conceived a CubeSat mission that will be able to detect and geolocate a ground-based L-band signals of interest (SOI). This type of mission cannot be achieved through use of typical CubeSat antennas, such as monopole and patch antennas, due to the gain, beamwidth, polarization, and signal delay measurement requirements in order to implement an angle of arrival (AoA) geolocation algorithm. AFIT desires a CubeSat antenna that is capable of meeting gain and beamwidth requirements for the specified geolocation mission. One candidate is the Helical Communications Technology (HCT) shape memory alloy (SMA) deployable L-band quadrifilar helical antenna (QHA) designed and manufactured by HCT, see Figure 1. The QHA is planned for a future AFIT CubeSat and will perform a geolocation mission utilizing four of the HCT QHAs. The HCT QHA has not been proven in space, nor has it been tested in a simulated space environment. The purpose of this thesis research is to develop a test plan for deployable CubeSat antennas for space qualification and deployment characterization in simulated space environments and then assess if the current HCT QHA design is suitable for a future AFIT mission. This test plan will be performed on the

HCT QHA to assess if the antenna as currently designed is a reliable and acceptable antenna for the planned AFIT mission.

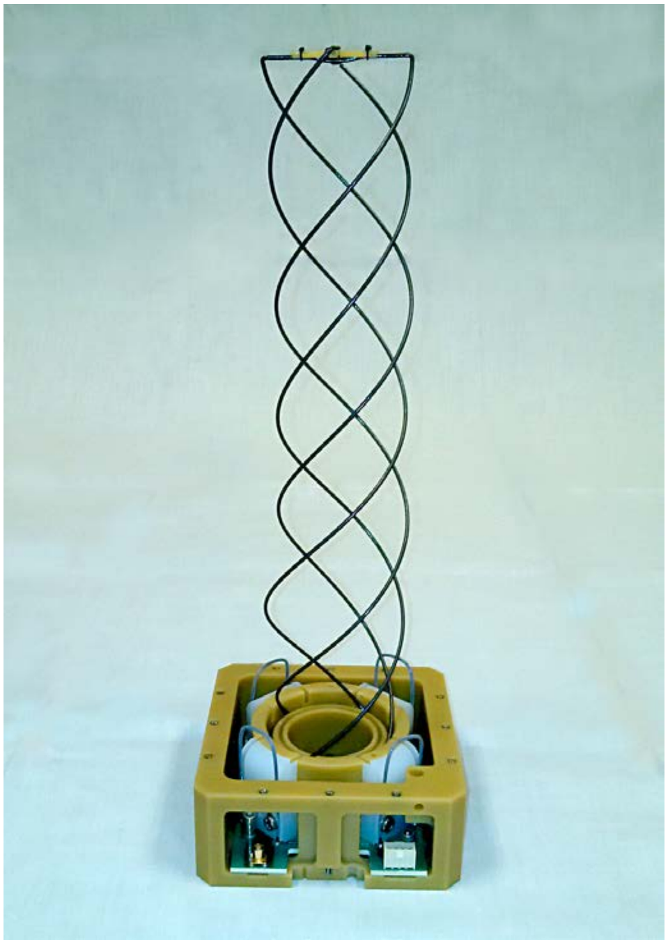

Figure 1. HCT QHA [4]

1.3 Scope

This research is limited to the environmental acceptance testing and the deployment characterization of the as-designed HCT QHA. The ground testing conducted for this thesis will form the basis from which predictions and verifications will be made as to how the antennas will deploy and perform on orbit from a mechanical perspective. RF testing will be limited to VSWR[1] measurements of the deployed antenna and simulated antenna beam patterns provided

[1] VSWR stands for Voltage Standing Wave Ratio and is an impedance measurement of the antenna elements taken at a particular frequency.

by HCT. By developing and conducting environmental and functional test plans for this thesis; the experimental approach of the HCT QHA flight units and future deployable CubeSat antennas can be typified. It is assumed that additional far field RF testing on the deployed HCT QHA will be conducted if the antenna is successfully space qualified.

The mission objectives of AFIT's or any future CubeSat mission utilizing the HCT QHAs will require that ground environmental testing and analysis be completed to verify the satellite, and therefore its components, satisfy the space launch and space environments. Certifying each component by individual testing ensures that the component will not need to be altered or removed from the design after integration with the entire system. Conducting component level testing of the HCT QHA will identify what testing needs to be done and how to accomplish that testing for future system level testing with the HCT QHA and the complete AFIT CubeSat. For all environmental testing, NASA GEVS[2] will be used as the testing requirement document.

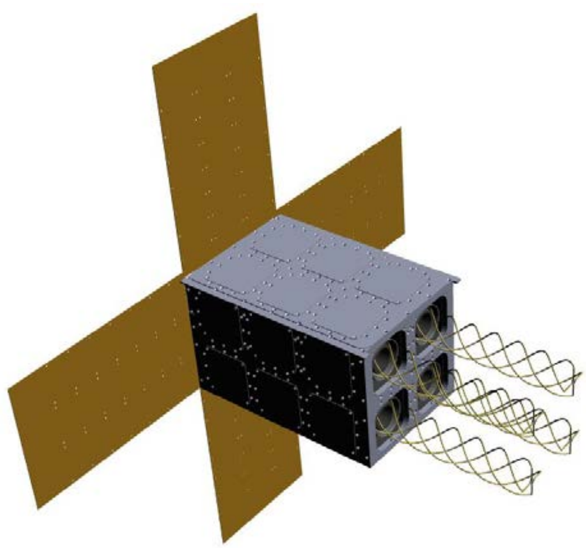

Figure 2. AFIT 12U CubeSat CAD model with four HCT QHAs

[2] NASA General Environmental Verification Standard (GEVS) provides environmental test requirements for space flight hardware.

Environmental experiments will include vibration and thermal vacuum (TVAC) testing. These tests simulate the space environment and are required for space-bound components that have not been previously space qualified. The HCT QHA will undergo vibration acceptance testing to verify launch survivability and workmanship. The antenna will also be subjected to TVAC temperature cycle to verify that it is able to survive and operate within the temperature limits that the satellite will experience in low Earth orbit (LEO). Since the HCT QHA has not undergone any vibration or TVAC testing, there is uncertainty regarding its design and workmanship as well as its deployment performance at different temperatures. The success criteria for each test will be discussed in Chapter 3.

In addition to the acceptance testing each antenna will undergo deployment testing and analysis in various simulated space environments to predict and characterize the antenna's deployment performance in space. Antenna units will be deployed in both hot and cold TVAC temperature cycles and orientated towards a solar simulator while in the TVAC chamber to verify that the SMA antenna elements will not attain a high enough temperature to change state and cause the antenna to deploy inadvertently. Various parameters such as the deployed length and power required to deploy will be recorded and compared over the various environmental deployment conditions.

Ambient lab deployment tests will be conducted before environmental testing begins to establish baseline deployment characterization. The vibration modal survey of the deployed antenna will be conducted first, followed by the TVAC tests, random and sine sweep vibration tests of the stowed antenna, and solar simulator tests. The testing will conclude with repeated ambient lab tests and deployed modal survey tests. The experiments will be conducted in this order to minimize the risk of a failure occurring during the higher risk vibration tests and hindering the other tests.

Additional experiments will be conducted to verify and characterize the HCT antenna. The natural frequencies and mode shapes of the deployed antenna will be predicted using Finite Element Analysis (FEA) models and the predicted results will be compared with laser vibrometer values.

In order to mitigate risk for the future AFIT mission ground testing and operational employment, the HCT antenna will be individually qualification tested as a component to be proven and certified for flight. The goal of this thesis is to space qualify the HCT QHA design by developing and conducting testing procedures that characterize the antenna's deployment performance and verify the antenna will meet or exceed the defined operability and survivability limits in NASA GEVS.

1.4 Research Objectives

Given the protoflight development state of the HCT antenna and the intended AFIT mission; the following primary and secondary objectives were developed for the environmental and deployment testing.

1.4.1 Primary Objectives

1. Create a testing approach and appropriate test plans for a deployable CubeSat antenna, based on requirements outlined in NASA GEVS.
2. Perform TVAC testing and analyses to evaluate the ability of the antenna to deploy on orbit, and operate in an orbit representative vacuum and temperature environment.
3. Perform vibration test and analyses according to NASA GEVS specifications for random and sine sweep vibration frequency tests on the stowed HCT antenna to verify survivability in the launch environment.

4. Characterize the HCT antenna deployment in various scenarios by measuring deployed height, power required to deploy, and deployed axial geometry deformation.

1.4.2 Secondary Objectives:

1. Predict any impact on RF performance after the environmental testing has concluded by measuring the VSWR of the deployed antenna using the worst case deployment geometry obtained through the deployment tests in various space-simulated environments.
2. Evaluate FEA model predictions with experimentally measure the measured natural frequencies of the antenna.

1.5 Background

An antenna that delivers high gain and wideband capabilities are often sized much larger than what is suitable for a CubeSat. Traditional communications satellites use antennas that are much bigger than an entire CubeSat. The small size of a CubeSat is its primary advantage; however, this places restrictions on the size of its subsystems. CubeSats predominately rely on patch, monopole, and dipole antennas; these antennas provide sufficient gain and bandwidth for many CubeSat missions. [5] These antennas are inexpensive and easy to integrate with a CubeSat but for missions that require greater RF performance, a different antenna solution is required.

A solution for a larger antenna that is compatible with CubeSat size and mass requirements is an antenna that deploys and expands to act as a larger conductive surface to receive incoming communication signals. A typical 1U cube unit on a CubeSat antenna has a volume of 1000 cm^3, therefore the mechanical design of a deployable antenna must interface with the surface area a single unit (100 cm^2). The antenna must be able to stow to a volume inside bus structure that satisfies the CubeSat's volume requirements. The benefits of a deployable antenna are the increased gain and beamwidth; however, the complexity and cost of the antenna will increase. This increased complexity motivates additional research and testing to characterize deployment performance to assure mission success.

The HCT L-band antenna deploys into a quadrifilar helix, see Figure 1, and provides an Iso-flux beam pattern, see Figure 3. Quadrifilar indicates four windings, or four elements, phased 90 degrees apart. The Iso-flux beam pattern is driven by the length of the antenna. An isotropic antenna radiates equally in all directions, an Iso-flux pattern antenna provides 360 degree azimuth coverage but is designed to suppress radiation along the zenith and radiate only at specific elevation angles. [6] This design enables a satellite to remain nadir pointing while still being able to receive low elevation signals. These characteristics make it an ideal antenna for CubeSat AoA geolocation mission.

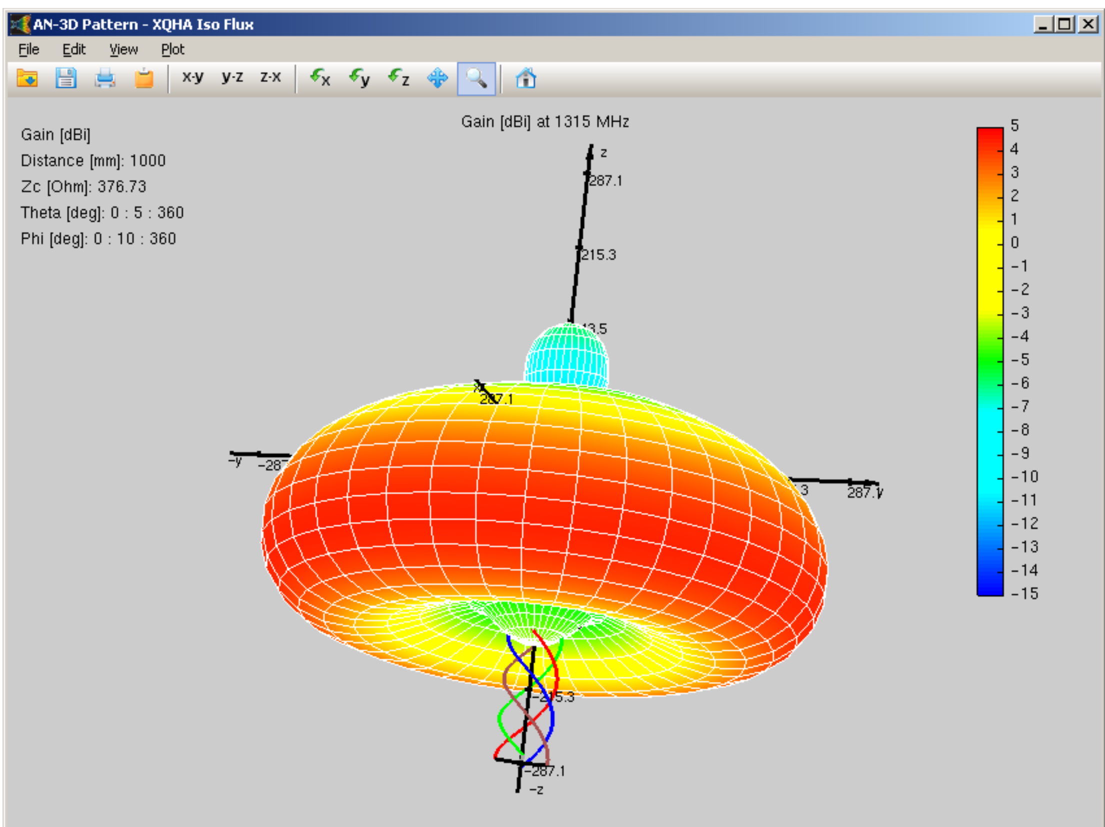

Figure 3. HCT QHA Iso-flux simulated beam pattern plot [4]

In order to be accepted as a payload on a launch vehicle, any satellite must meet criteria that are achieved through various testing to predict if the test subject is able to survive the harsh launch environment. The launch environment is only the first stage in a satellite's journey as it leaves Earth. The LEO space environment is also extreme; ground testing is performed to ensure the satellite will be able to operate when it is detached from the launch vehicle after it has reached the desired orbit. NASA's GEVS is the accepted environmental testing criterion for CubeSats when the launch provider is unknown. [7] Random vibration tests simulate the expected launch environment. TVAC testing demonstrates that the satellite can operate and survive in the thermal extremes as it orbits the Earth.

It is vital to characterize the antenna deployment in simulated space environments to verify successful deployment and to ascertain deployed length, shape and orientation. If the antenna fails to deploy then the satellite will lose the communication capabilities relying on that antenna. If the antenna deploys partially or incorrectly the directivity and gain of the antenna could also degrade the communication capability relying on the antenna. In order to understand the geometry criteria necessary for the four HCT QHAs to complete their mission on AFIT's CubeSat, the beam pattern must be measured for all geometry configurations experienced by the antenna during the environmental testing. Voltage Standing Wave Ratio (VSWR) measurements will be made to assess whether the geometry has a significant effect on the transmitted waveform and if additional RF testing is required.

1.6 Implications

The experiments conducted for this research will guide future testing of the HCT QHA and other deployable CubeSat antennas. Understanding which tests are necessary to verify and characterize deployment and knowing how to analyze and interpret the data will enable more thorough and efficient space qualification testing at AFIT and other institutions.

1.7 Preview

Considering the challenges a satellite must overcome to operate successfully in orbit, this thesis will explore the efforts of an AFIT sponsored, HCT designed and built CubeSat antenna to verify it is space qualified and assess if it is ready to be incorporated on a future AFIT CubeSat mission.

In Chapter 2 a background on the HCT antenna and other proposed and available deployable CubeSat antennas will be introduced. The environmental and deployment test methodology for the HCT antenna are presented in Chapter 3. Chapter 4 presents the laser vibrometer, TVAC, vibration and solar simulator test results. A summary and recommendations for future research are provided in Chapter 5.

2. Literature Review

2.1 Chapter Overview

This chapter provides an overview of deployable satellite antennas, including the motivation, history, and current research/applications.

2.2 Antenna Overview

The purpose of an antenna is to focus incoming or outgoing radio frequency (RF) waves and convert them to electrical signals. RF waves have magnitude and direction, so how the antenna accounts for the directivity of the incoming waves affects the performance of the antenna. The primary antenna performance attribute is quantified as “gain” and is determined by the efficiency of this conversion and is measured in decibels (dB). Decibels isotropic (dBi) refers to gain with respect to a theoretical isotropic radiator, which radiates equally in all directions. [8]

Gain is not the only antenna characteristic that must be considered when designing the RF system. Bandwidth is the range of frequencies over which the antenna can operate. A larger bandwidth means more energy or data can be sent and received over the frequency range. [9]

Beamwidth is the direction of maximum radiation and typically applies to directional antennas, such as parabolic dishes. The gain over this direction is usually characterized by the half power beamwidth (HPBW), as shown in Figure 4, which is the angular region in which the magnitude of the radiation decreases by 50%. [10]

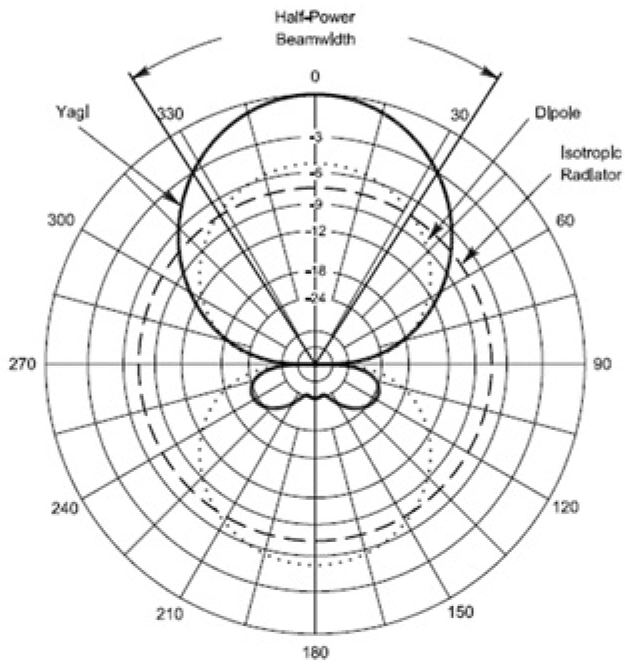

Figure 4. Parabolic antenna beam pattern [11]

There are various antenna shapes and designs that can collect incoming waves. Directional antennas are normally pointed towards the incoming signal so that the main lobe of the antenna pattern is aligned with the transmit source. Omnidirectional antennas have a 360 degree horizontal radiation pattern. This pattern provides less gain but provides coverage in all directions and reduces the requirement to point the antenna or satellite towards the intended target. Omnidirectional dipole antennas are commonly used on CubeSats due to their low cost and complexity and ability to provide continuous coverage. [12]

Many satellites require antennas with large gain and a focused beam, especially those in geostationary orbit. Typically directional antennas are utilized in order to achieve the required gain. In order to satisfy launch vehicle restrictions, many satellite antennas must be stowed during launch and then deployed on orbit. Traditional satellites typically use large reflector antennas that can be mechanically deployable or inflated to achieve the desired shape and surface area. [13]

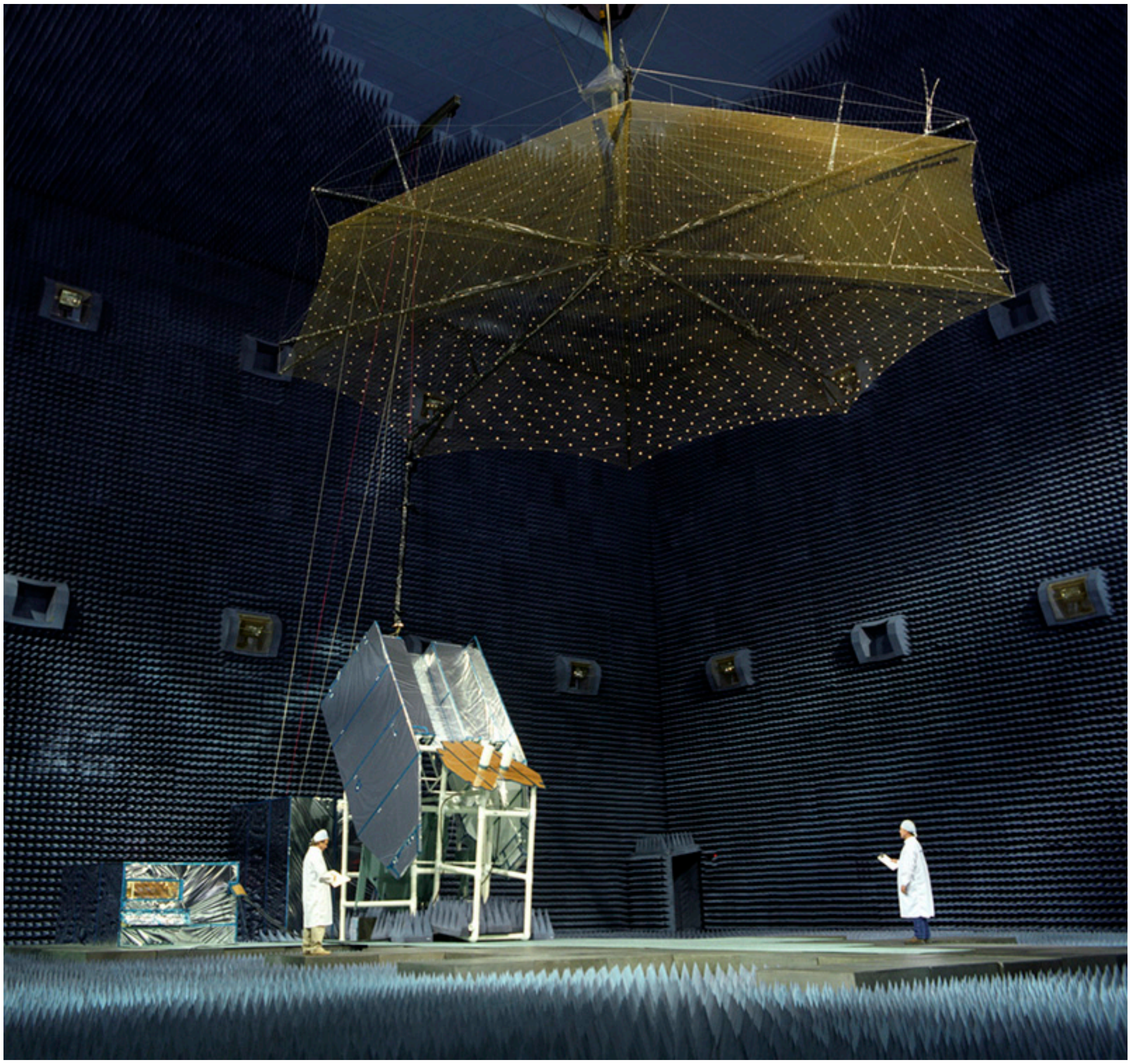

Figure 5. Harris Ka-band unfurlable mesh reflector [14]

The Galileo mission launched in 1989 experienced this issue when its primary antenna, a parabolic dish designed to fold similar to an umbrella, failed to deploy. Galileo's mission was to observe Jupiter and its moons, without the high gain antenna it was forced to rely on its low gain antenna to communicate with Earth. [15]

CubeSat missions that need to transmit large amounts of data must be able to achieve greater antenna gain and bandwidth in order to close the RF link. There are relatively few deployable CubeSat antenna designs, even fewer which have been proven through extensive ground testing or space demonstration. To better understand the motivation and issues surrounding deployable antennas the current research, development, and employment of deployable CubeSat antennas will be discussed in the following section. Deployable antenna developments for larger, traditional satellites will not be discussed as part of this research.

2.3 CubeSat Antenna Types

A satellite communication link is limited by the relation between gain and antenna dimensions. For a CubeSat, the small size restricts the surface area and volume of the antenna. The commonly used canesterized satellite dispenser (CSD), which encases the CubeSat during launch, restricts the use of antennas that protrude more than a few millimeters beyond the external faces of the satellite. Given these restrictions, CubeSats typically use patch and whip monopole or dipole antennas that have small mass and volume as well as their relatively low cost. These types of antennas are capable of transmitting and receiving from VHF to S-band (30 MHz – 4 GHz). Monopole and dipole antennas technically deploy in the sense that they are folded against the satellite while encased in the launch vehicle and then spring open using strain energy when released. In order to operate at higher frequencies and provide additional gain and beamwidth, other antenna types must be utilized. There are advancements being made to develop CubeSat antennas that stow within the small volume of the bus and then deploy to a larger area. There are no commercially offered deployable CubeSat antennas and only several examples of past research and testing, the deployable antennas will be discussed after the traditional patch and pole CubeSat antennas. [16] [17]

2.3.1 Monopole and Dipole Antennas

Most small satellites use simple monopole and dipole antennas for their telemetry, tracking, and control (TTC) uplink and downlink communications with the ground station. Deployable tape spring whip monopole and dipole antennas are offered by many companies for direct CubeSat application. [18], [19] Dipole antennas consist of a rod with two conductive elements, both of which receive half of the incoming signal. [20] [21]

A monopole antenna is essentially a dipole antenna but twice the length. A monopole antenna requires a ground plane element. Both dipole and monopole antennas exhibit omnidirectional radiation patterns and are linearly polarized. These antennas are often referred to as "deployable" due to the fact that they fold against the satellite bus during launch and then expand to their designed orientation using the strain energy stored in the antenna when the satellite is ejected. The antenna length is a function of the operating frequency; the antenna length is a function of the RF wavelength and is typically at 1/2 wavelengths long for a dipole antenna and 1/4 wavelength for a monopole antenna. [9] CubeSat monopole and dipole antennas frequently operate in VHF and UHF bands. The typical gain for a dipole antenna is 2.15 dBi and 5.19 dBi for a monopole antenna. [22]

Figure 6. CubeSat UHF monopole antennas [19]

Satellites that use monopole or dipole antennas rely on a ground station with a high-gain antenna or a tracking antenna that can steer to orient the ground antenna to point towards the satellite during its pass when in view of the ground station. This is due to the low gain and non-directivity of the pole antenna on the satellite.

2.3.2 Patch Antennas

Many companies offer patch antennas specifically for CubeSats that are often used for GPS or other communication signals in S-band. A microstrip patch antennas consist of a layered structure with a metal ground plane, substrate, and an etched conductive metal top layer. [23] Patch antennas are attractive for CubeSat applications due to their slim profile which can be mounted on the exterior of the satellite, therefore minimizing the internal and external volume required. Patch antennas are semi-directional and offer a wide beamwidth that provides adequate gain as long as the antenna is on the face of the satellite that is pointed towards the target, typically nadir. [24] S-band patch antennas offer gain on the order of 6-8 dBi and are circularly polarized. [25]

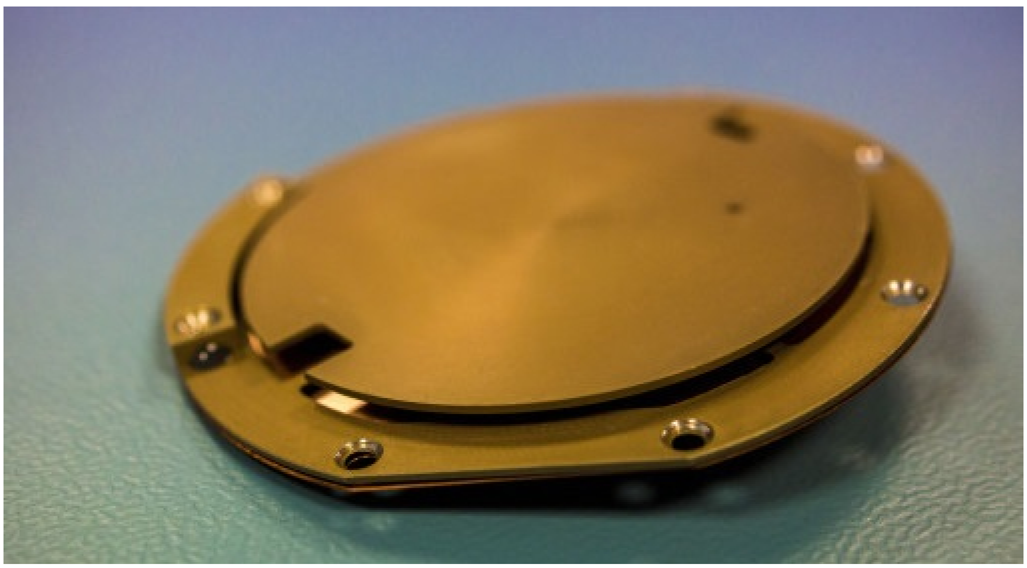

Figure 7. CubeSat S-band patch antenna [24]

Research has been conducted to create a larger microstrip antenna through the use of a deployable membrane array. Researchers at Physical Sciences, Inc. designed a tensioned membrane antenna that provides a larger effective aperture in an effort to increase gain. The prototype is a C-band 1.7 square meter surface that utilizes four folded booms that stows into a 2U volume. This antenna exhibited 30.5 dB gain as tested with a 3.4 degree beamwidth. Future work includes additional ground testing and design improvements that will lead to flight testing on a 6U CubeSat. [26]

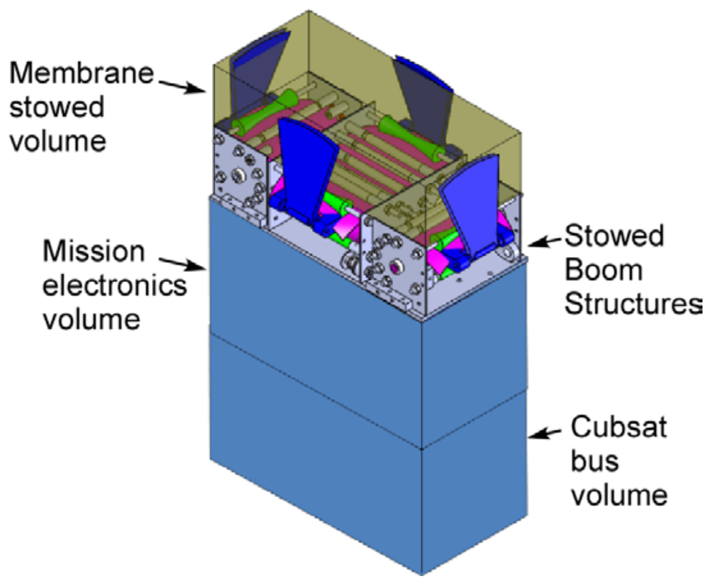

Figure 8. 6U CubeSat deployable S-band antenna, stowed [26]

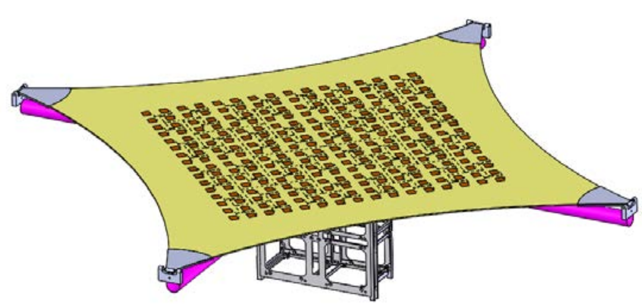

Figure 9. 6U CubeSat deployable S-band antenna, deployed [26]

The Physical Sciences tensioned membrane patch antenna is an example of research and development that is being conducted to expand the RF capabilities of CubeSats. Parabolic antennas use tensioned structures to focus the RF energy at a single point. Deployable CubeSat parabolic antenna examples will be discussed in the following section.

2.3.3 Parabolic Deployable Antennas

Parabolic deployable antennas (PDAs) incorporate some stowing method and then deploy to the shape of a parabolic dish. A flexible material such as a mesh is typically attached to rib structural elements. There are multiple ways to fold, or pack, the mesh and ribs. The packed height and diameter is a function of the rib length, the number of ribs, and the number of folds. Folding rib architecture is an attractive stowing method for deployable parabolic antennas due to its effective stowing efficiency. [27]

USC Space Engineering Research Center (SERC) in collaboration with NASA Jet Propulsion Laboratory (JPL) developed a PDA for their experimental satellite Aeneas. The satellite was launched in September 2012 and demonstrated the first high gain CubeSat antenna. The parabolic deployable antenna demonstrated a receive gain of 18 dBi at 2.4 GHz. The dish has a deployed diameter of 0.5m and stows in a volume of 1.6U. The antenna consists of 30 ribs with two joints each that collapse and lower into a canister in the payload section of the CubeSat. [28]

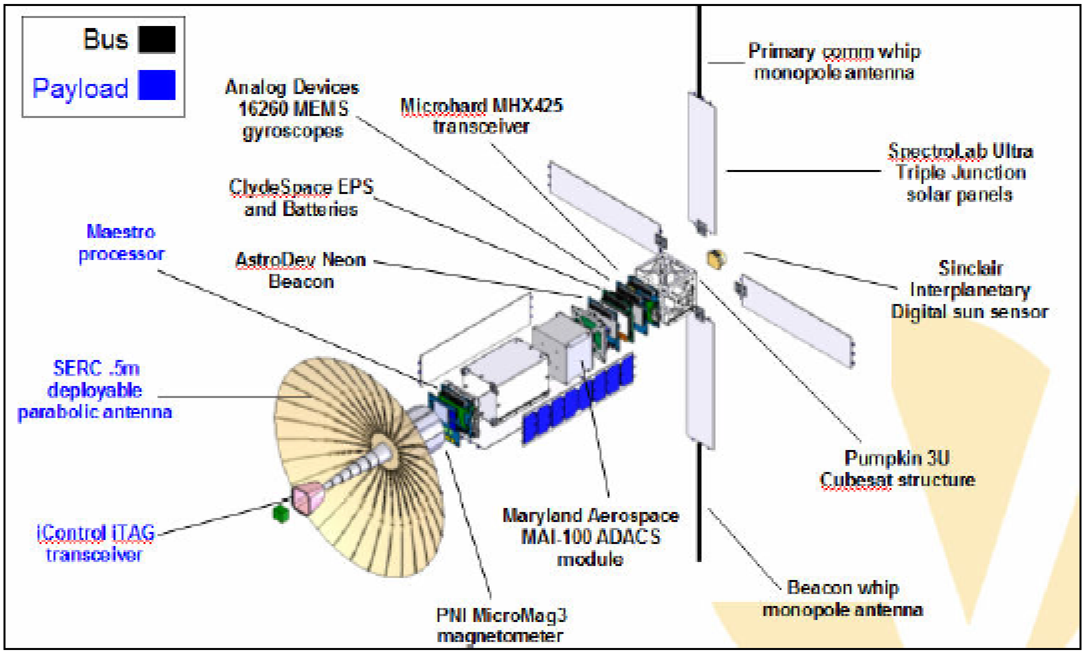

Figure 10. SERC and NASA/JPL parabolic deployable antenna design [28]

Figure 11. SERC and NASA/JPL parabolic antenna prototype [28]

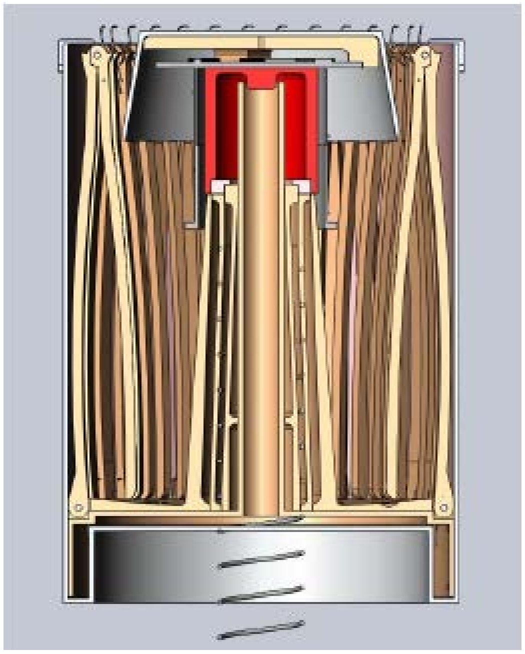

Figure 12. SERC and NASA/JPL parabolic antenna stowed configuration [28]

JPL is building off of the folding CubeSat antenna design flown on Aeneas and is develop X- and Ka-band versions of the PDA. A redesign of the Aeneas antenna is required due to the surface characterization required for Ka-band operation. The KaPDA design goal is to provide 42 dBi at a 34 GHz downlink. The design requirement to stow in a 1.5U remains. [29]

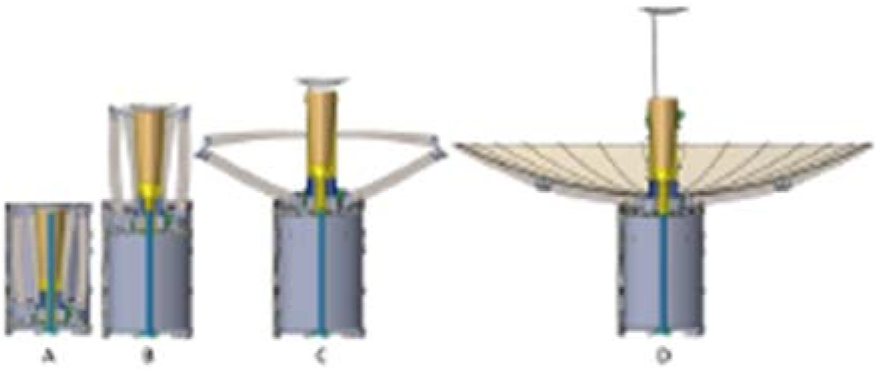

Figure 13. JPL KaPDA antenna [29]

A design team at California Polytechnic State University conducted a research project sponsored by NASA JPL created a design for a “Compact Deployable Antenna for CubeSat Units.” Their design utilized a telescoping mast and scissor trusses to create a mesh parabolic dish Ka-band antenna. The antenna had requirements of a deployed diameter of 50cm, a mass of less than 1kg, and a stowed volume of less than 1.5U. The team’s design satisfied all requirements except for the deployed diameter; this was due to a non-perfect truss expansion. The team also conducted structural, thermal, and vibe testing on their design unit. The team did not create the desired Ka-band mesh antenna and feedhorn. The design team did not develop a complete prototype and did not perform any RF analysis on the antenna. [8]

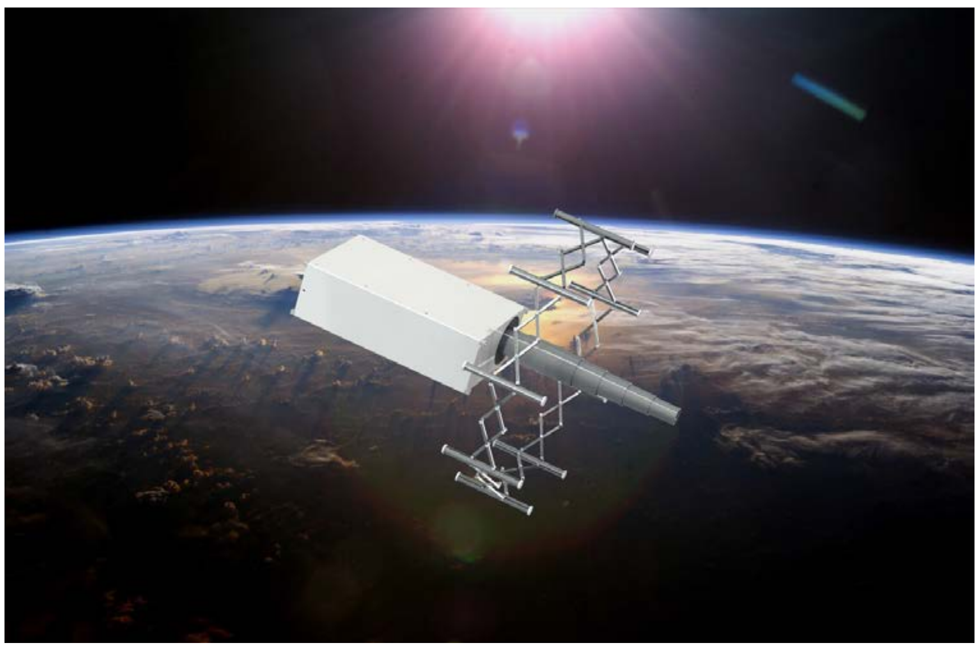

Figure 14. CAD render of Cal Poly design team deployable antenna structure [8]

Boeing Phantom Works presented a design for a miniature deployable high gain antenna for CubeSats. The antenna would operate in S-band and provide 18 dBi of gain through a 50cm dish weighing less than 1kg and stowing in 0.5U. Boeing successfully tested the mechanical deployment of the dish to prove the design concept was fundamentally sound. Future work is to construct a final design prototype and conduct a flight demonstration. [30]

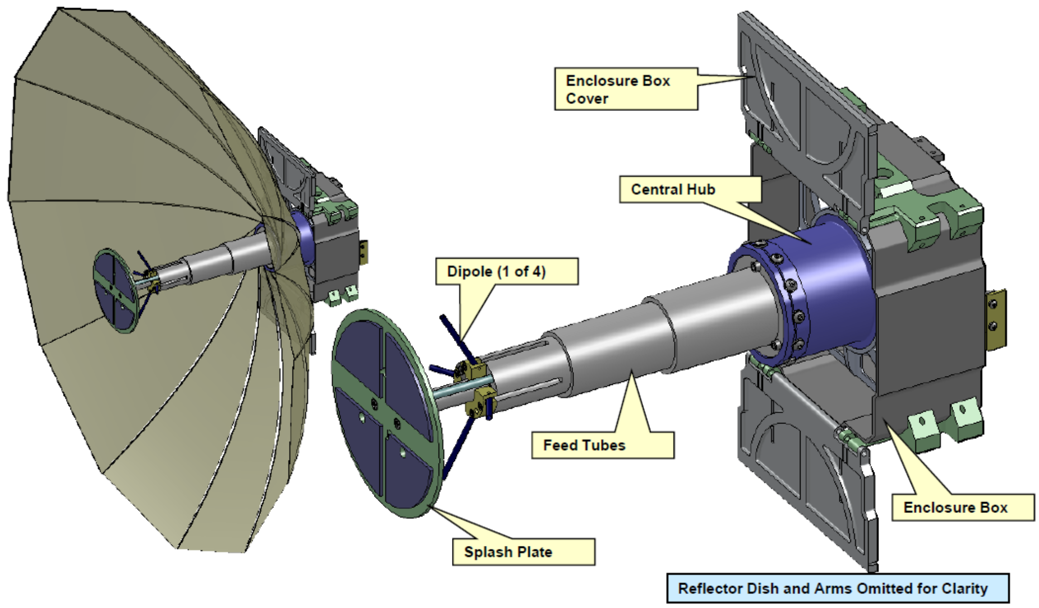

Figure 15. Boeing Phantom Works deployable CubeSat antenna design [30]

Figure 16. Boeing Phantom Works deployable CubeSat mesh antenna prototype [30]

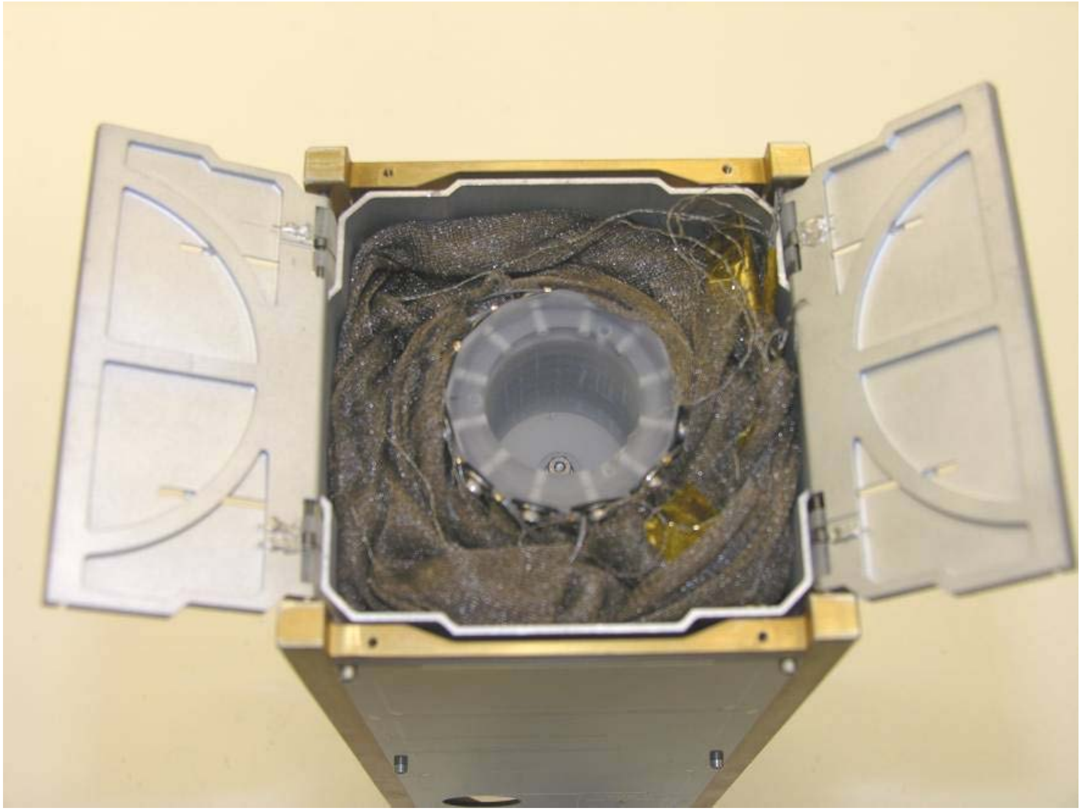

Figure 17. Boeing Phantom Works deployable CubeSat stowed mesh antenna [30]

Another example of a PDA that doesn't utilize a folding rib structure was demonstrated by students at Massachusetts Institute of Technology (MIT) who researched the feasibility of using inflatable parabolic reflector on a CubeSat. Their objective was to achieve at least 20 dB of gain using a 1m effective diameter inflatable parabolic reflector antenna that operates in X-band. The inflatable structure is constructed of two materials, one is a transparent canopy that allows the signal to pass through and the other is a reflective membrane that focuses the signal on a receive feed that is suspended within the balloon. [31]

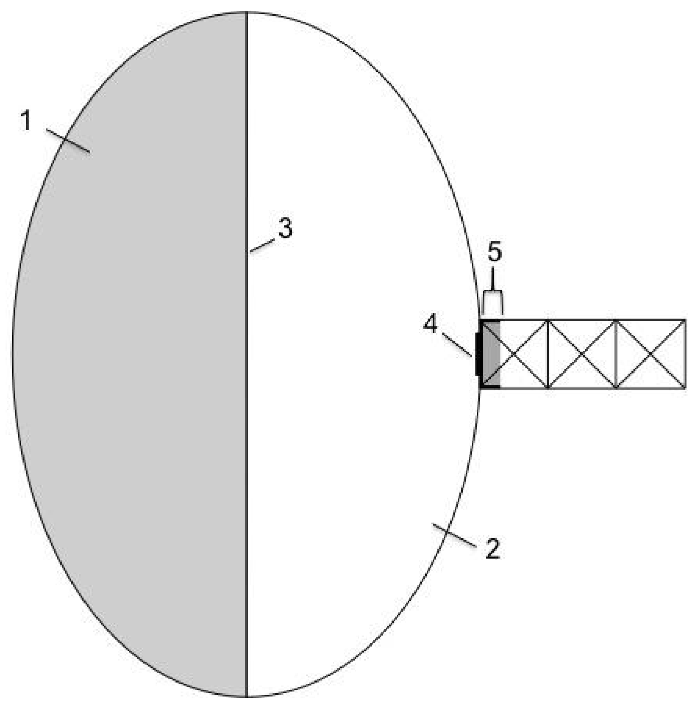

Figure 18. MIT inflatable parabolic CubeSat antenna design [31]

2.3.4 Helical Antennas

Another antenna type available to CubeSats that provides increased bandwidth and gain over patch and monopole or dipole are helical antennas. Helical antennas provide natural circular polarization and exhibit a 360° azimuth beam pattern. The elevation of the beam pattern can be modified by employing an Iso-flux radiation pattern by altering the antenna height as a function of wavelength. The Iso-flux antenna beam pattern exhibits a higher gain at designated elevation angles. This radiation pattern makes helical antennas an attractive option for satellite missions that are attempting to receive low power incoming signals that are sent at low elevation angles which are common for terrestrial emitters. Achieving higher gain at low elevation (grazing) angles allows the satellite to remain nadir pointing while still receiving RF energy from terrestrial emitters.

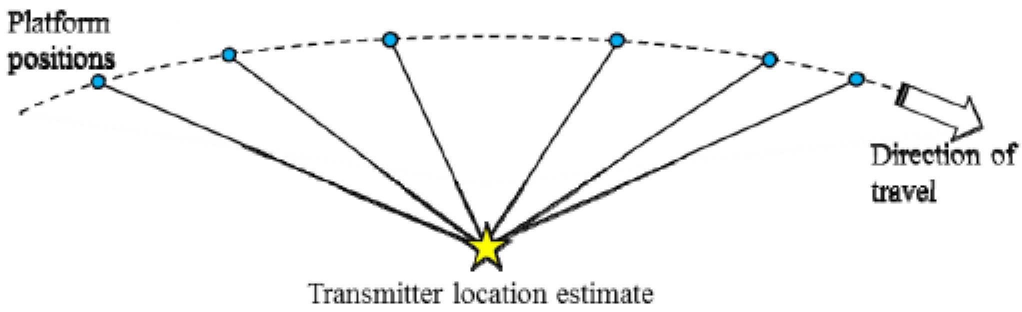

Figure 19. Geolocation lines of bearing [32]

A helical antenna, as shown in Figure 20, consists of a wound wire tread that forms a helix with parameters being the circumference, coil spacing, and coil circumference. The overall length of the helical antenna is determined by the wavelength and the coil parameters. [33]

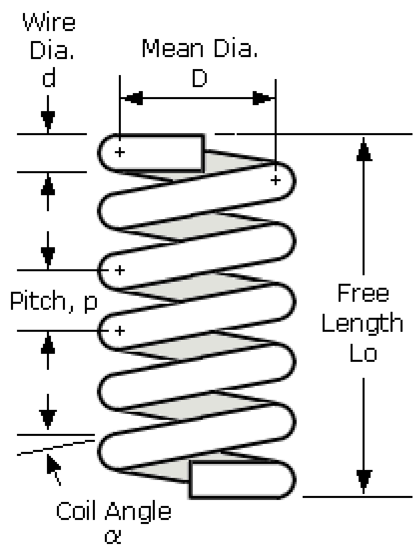

Figure 20. Helix parameters [33]

The helix parameters of coil circumference (C), wavelength (λ), pitch spacing (p), pitch angle (α), Half Power Beamwidth (HPBW), the number of turns (N), and impedance (R) are calculated using the following equations: [17]

$$\frac{3}{4}\lambda \leq C \leq \frac{4}{3}\lambda \quad or \quad \frac{3}{4\pi}\lambda \leq C \leq \frac{4}{3\pi}\lambda \tag{1}$$

$$Pitch\ Spacing, p = \frac{\lambda}{4} \tag{2}$$

$$Pitch\ Angle, \alpha = \tan^{-1}\frac{p}{C} \tag{3}$$

$$HPBW = \frac{K_B\lambda^{\frac{3}{2}}}{C\sqrt{NS}} \tag{4}$$

$$Impedence, R = \frac{140C}{\lambda} \tag{5}$$

When considering the axial mode of a helical antenna, the gain is dependent on the number of turns, the circumference, the pitch spacing, and the wavelength of the operating RF frequency. [34]

$$Gain = 15N\left(\frac{C}{\lambda}\right)^2\left(\frac{p}{\lambda}\right)^2 \tag{6}$$

There are different mechanical design options for creating a helix that has structural integrity and satisfies the electromagnetic requirements of an antenna. Most helical antennas are cylindrical (constant diameter), however then can also utilize a conical shape. A conical tapering of the helix changes the active region and beam pattern of the antenna and must be accounted for.

A helical antenna can be comprised of multiple helical elements. Increasing the number of elements increases the beamwidth. [35] The HCT antenna uses four elements configured into a quadrifilar design with four winding elements phased 90 degrees apart.

There are different methods for creating helical antennas that can be stowed into a condensed volume and then be deployed to its operational shape. Typically the helix is flattened to eliminate the pitch spacing during stowage and then extended to revive the designed pitch spacing; a constant diameter is maintained for both the stowed and deployed configurations if a cylindrical design is used. In applications where gravity is present, a deployable helical antenna must have the structural rigidity to maintain the helix in the deployed position and must be flexible to enable a stowed configuration. In space, the deployed antenna structure will not be affected by gravity, but this must be accounted for in the antenna mechanical design to ensure the helix geometry does not rely on gravity to maintain its shape.

Different helical element materials and cross sections and can give the desired stiffness when deployed but still allow for storage. This requires the material selected to have sufficient strain energy to maintain its shape or the helix structure must utilize additional support elements. Beryllium copper, composites, fiberglass, and shape memory alloys are some example materials. The HCT antenna, tested herein, uses a shape memory alloy (SMA) in order to achieve the structural integrity and stowing requirements. [36]

One of the few space proven deployable helical CubeSat antennas was on GOMX-1. Launched in 2013 the GOMX-1 is a 2U CubeSat developed by GomSpace, DSE Airport Solutions, and Aslborg University. The helical antenna uses a monofilar helix that provides around 10 dB of gain and operates in UHF band. The antenna deploys to 40cm in length and stows to a depth of 2cm. The end of GOMX-1's life was purportedly caused by magnetization of the helix antenna that caused a dipole moment that eventually could not be compensated by the ADCS. [37] [38] The HCT QHA tested for this research is made of Nickle and Titanium, both of which are non-ferrous metals and will not be affected by Earth's magnetic field. [39]

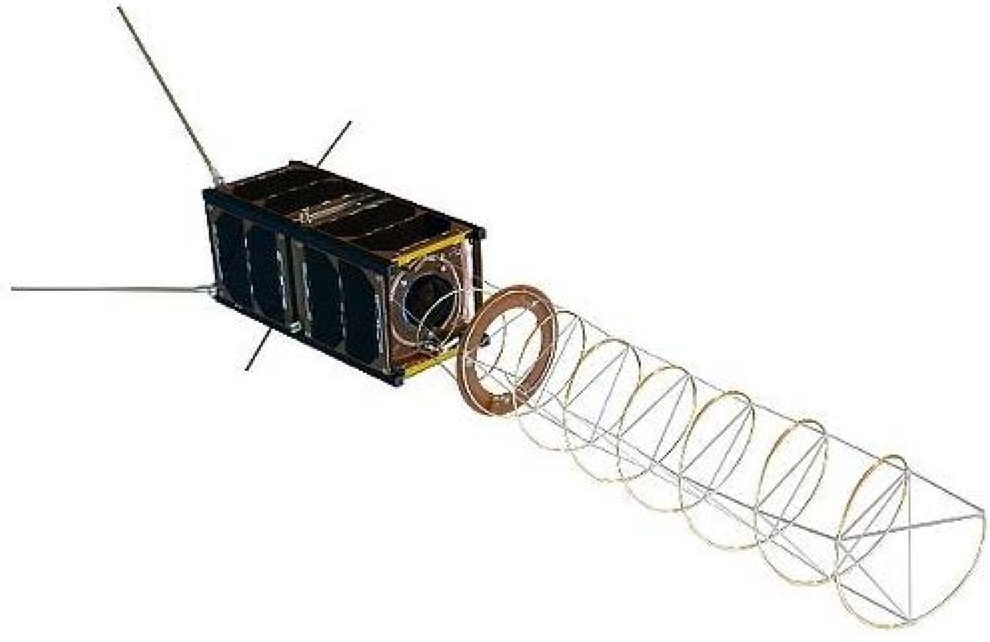

Figure 21. Illustration of deployed GOMX-1 [37]

Tethers Unlimited, Inc. is developing a UHF CubeSat quadrifilar helical antenna. The antenna exhibits an Iso-flux radiation pattern that allows the antenna to cover the entire field of regard while remaining nadir pointing. The antenna requirements include a stowed volume of less than 0.5 U and a deployed length of 1.5m and a diameter of 7cm. The antenna design will provide circular polarization with up to 4 dBi of gain. [40]

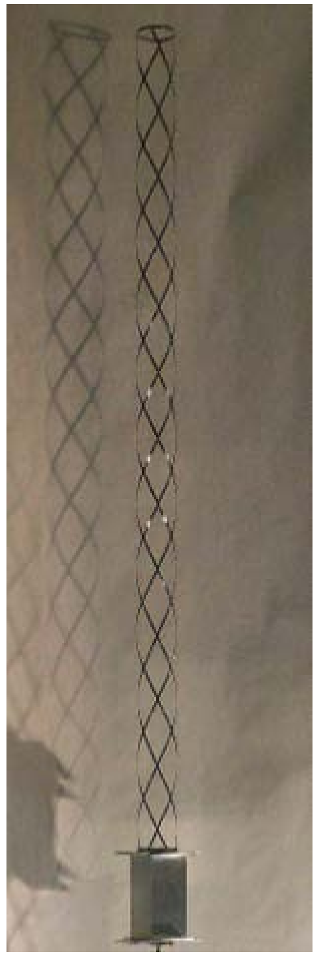

Figure 22. TUI quadrifilar helical antenna [40]

A student at the University of New Mexico designed a deployable bottom fed conical log-spiral CubeSat antenna, see Figure 23. This antenna design addresses the need for the antenna to be deployable and the author alludes to a direct compression of the antenna for storage but the author does not address the deployment process or mechanisms. This antenna does represent the research and incentive for helical CubeSat antennas. The antenna is log-periodic and can be treated as frequency independent. This means that the antenna geometry and angles are scaled as a periodic structure and accommodates a large range of frequencies. The bottom fed design changes how the backfire radiation is produced and requires a ground plane. The bottom feed location reduces the amount of structure required for the antenna thus simplifying the deployment scheme. Simulated results for S-band yielded a gain of 7 dBi. [17] [41]

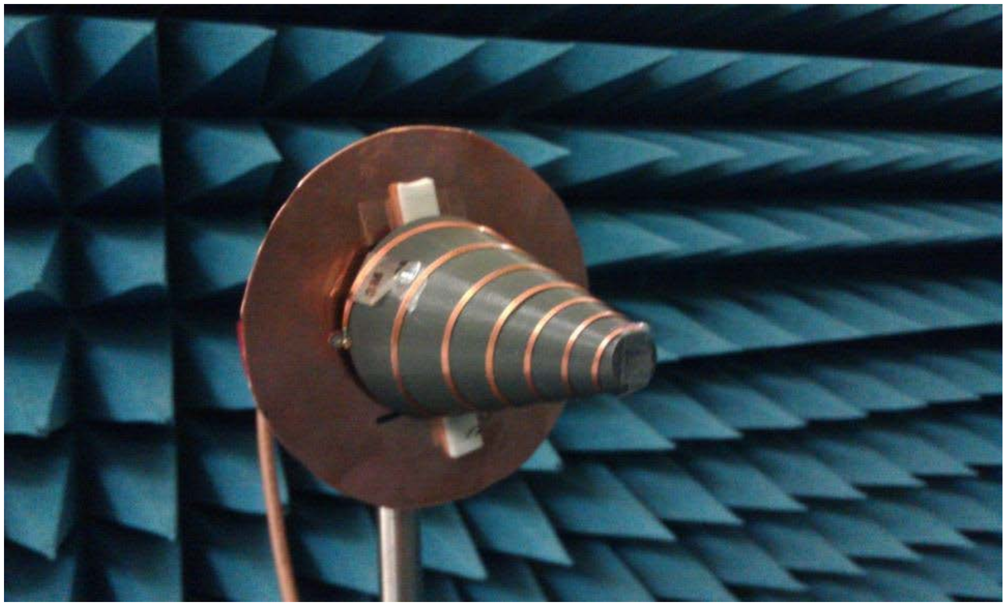

Figure 23. University of New Mexico conical log-spiral CubeSat antenna [17]

Researchers from Northrop Grumman Aerospace Systems created a design for a deployable helical UHF antenna. Their design stows in 0.5U and deploys to 137cm in length with a diameter of 35.5cm. The Northrop Grumman design utilizes a framework of two opposing fiberglass/thermoplastic helical elements that uses its own stored strain energy to deploy into a column. The antenna exhibited a maximum gain of approximately 13 dBi at 400 MHz. [42]

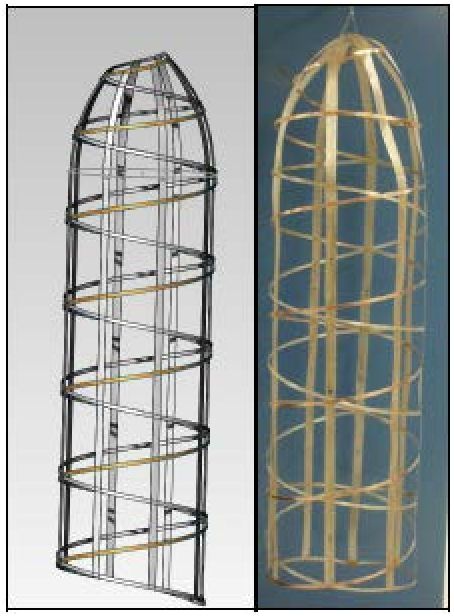

Figure 24. Northrop Grumman deployable helical UHF antenna [42]

Researchers from Air Force Research Laboratory, California Institute of Technology and California State University developed a self-deploying helical pantograph antenna for CubeSats. Their antenna operates in UHF band and has a gain of 8 dBi. A helical pantograph consists of two identical opposed helical rods formed together at the joints. The deployed height of the helix depends on the pitch of the helix. The prototype measured just under 0.5m when fully deployed. The stowed height depends on the number of turns of the helix, the number of helices, and the height of the band. The prototype height was approximately 0.22 m when stowed. [36]

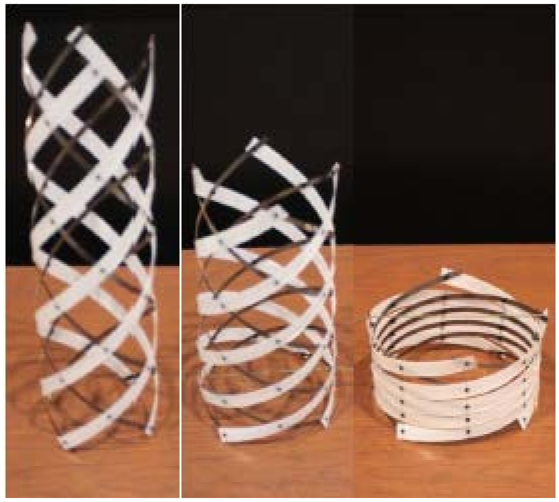

Figure 25. Self-deploying helical pantograph antenna for CubeSats [36]

A modified helix CubeSat UHF antenna [43] was designed to both deploy the helix as well as a 120cm x 120cm ground plane. The helix has a maximum diameter of 27cm and a height of 43.7 cm. This antenna consists of only a single turn helix and exhibits of a gain of at least 7 dB. The antenna and ground plane combination greatly reduces the back lobe radiation. [43]

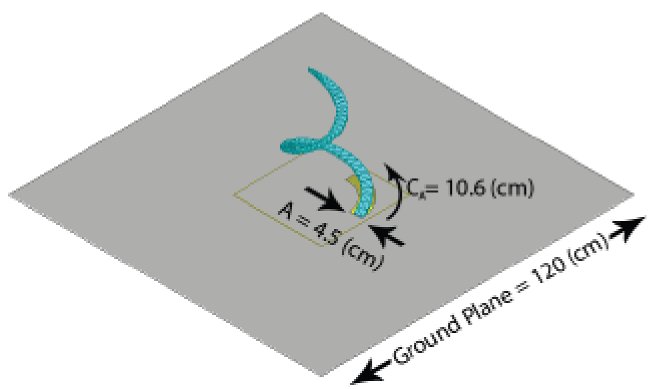

Figure 26. Single helix antenna with ground plane [43]

Another design of a deployable quadrifilar helix UHF CubeSat antenna is given in Reference 41. The design utilizes four orthogonal arms to define two separate helixes. This configuration provides a hemispherical radiation pattern and is circularly polarized. The antenna has a diameter of 17.3cm and the maximum gain this design can theoretically achieve is 5.4 dB. [44]

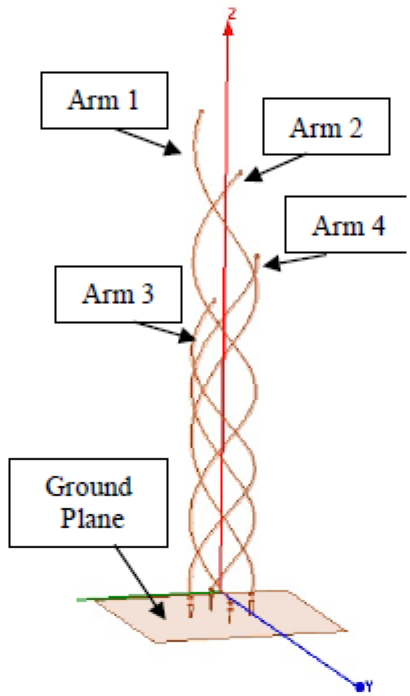

Figure 27. Deployable quadrifilar helix UHF CubeSat antenna [44]

The stowing and deployment complexity and their need to remain dimensionally true when deployed is a reason that helical CubeSat antennas are not more widely used. An axial helical antenna exhibits circular polarization, wide bandwidth, and an Iso-flux radiation pattern. This characteristic make them attractive for certain CubeSat missions, such as AFIT's geolocation mission and is what motivated AFIT to procure the design and manufacturing of a helical CubeSat antenna. An overview of the design of the HCT four element helical antenna is presented in the following section.

2.4 HCT Quadrifilar Helical Antenna

For the specific testing herein, AFIT procured the design and manufacturing of an antenna to be flown on a future CubeSat geolocation mission. Helical antennas provide slightly more gain than patch and dipole antennas, therefore making them a plausible candidate for a mission that requires detection of potentially low-power signals. The use of multiple quadrifilar helical antennas spaced less than ½ wavelengths apart also allows the use an angle of arrival (AoA) geolocation method by measuring the time phase difference of arrival of the signal of interest (SOI) at each individual antenna element. At the operational frequency of 1.315 Ghz the wavelength is 22.8 cm making the 10cm spacing on the CubeSat suitable for the ½ wavelength criteria.

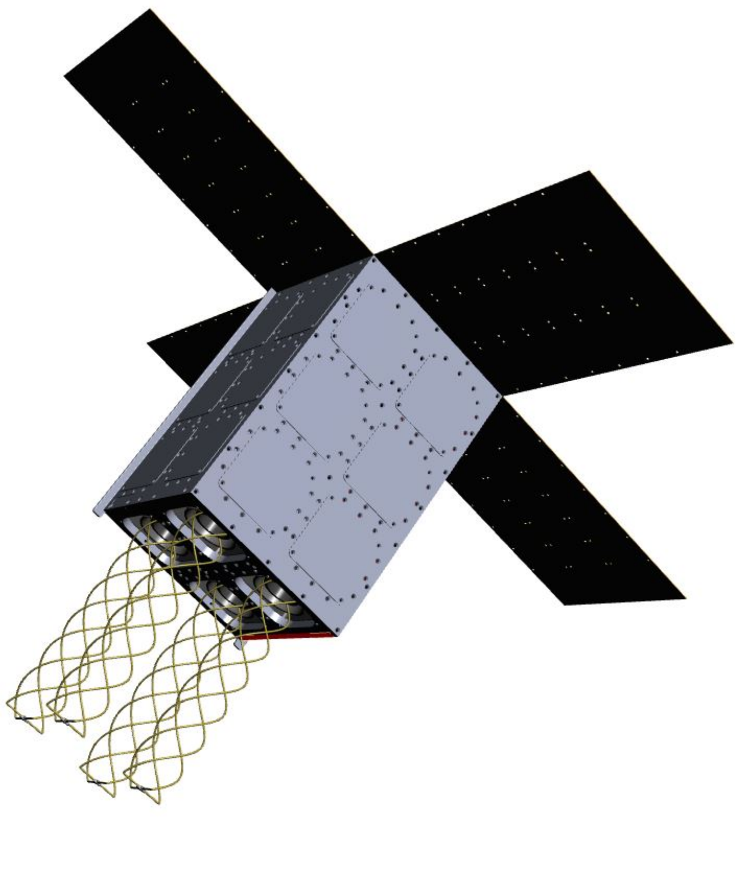

Figure 28. CAD model of AFIT CubeSat mission with four HCT antennas

2.4.1 Requirements

The AFIT generated requirements drove the design of the antenna. AFIT required that HCT deliver four deployable engineering development units (EDUs) and four flight-ready antenna units. The required antenna type was a quadrifilar helix circularly polarized antennas capable with a center frequency of 1.315 GHz. Additional requirements included a two year minimum on orbit lifetime, must be able to survive NASA GEVS thermal vacuum and vibration profiles through demonstrated testing, and the use of only NASA approved materials. Capabilities and features of the antenna were listed in the following original contract requirements:

1. Antenna deployed length: 0.35 to 0.45 meters
2. Antenna deployed diameter: 0.03 to 0.05 meters
3. Individual Antenna max weight: 50 grams
4. Antenna lowest natural frequency (deployed): 10 Hz
5. Stowed max dimensions (per antenna including all housing and release components): 100mm (base) x 100mm (base) x35 mm (height)
6. Total system weight (per antenna including all housing and release components): <400 grams
7. 3-dB Bandwidth: > 50 MHz
8. Gain pattern: Iso-flux beam pattern with maximum gain to receive a terrestrial signal emitting at 10-35 degree elevation from an orbit altitude of 500 km
9. RF Interface: SMA 3.5mm coaxial connector or smaller
10. Deployment electrical interface: Four wires, two per channel, redundant DC power
11. Release mechanism redundancy: Dual Modular Redundant

12. Release mechanisms: Shape Memory Alloy Non-Explosive Actuator

13. Deployment testing: Greater than ninety percent success rate

This research will directly test requirements 1, 4 and 13. Requirement 1 was adjusted by HCT to design the antenna to optimally operate at the 1.315 Mhz frequency. By deploying the antennas, requirements 9, 10, 11 and 12 were indirectly tested by this research.

2.4.2 Design

An HCT antenna unit consists of a milled ULTEM casing, electronics board, shape memory alloy (SMA) antenna filars, and SMA hold-downs (see Figure 30). The hold downs are present to restrict the QHA from deploying prematurely. The SMA antenna filars will not achieve their set geometry until sufficient power (heat) is applied but they still possess enough strain energy to extend and protrude from the antenna casing.

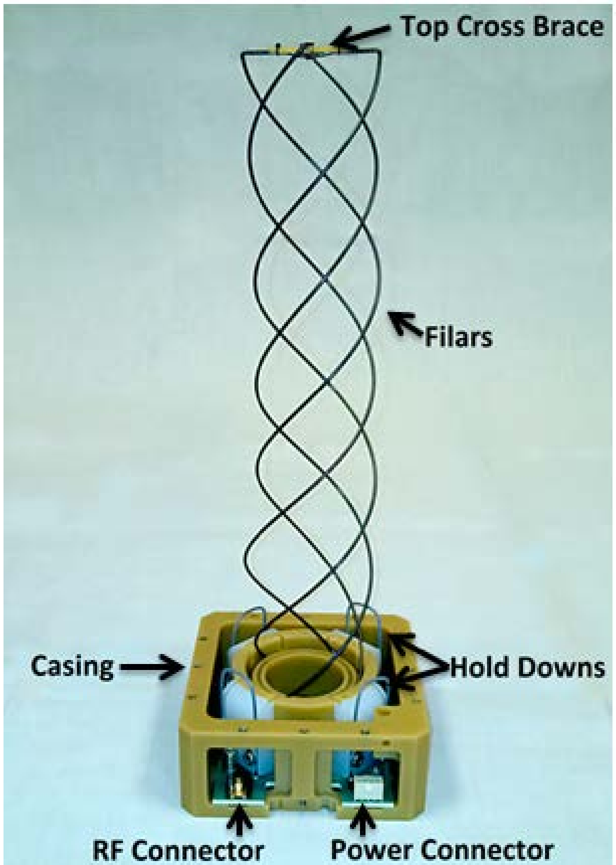

Figure 29. HCT QHA components [4]

2.4.2.1 Casing

The case is made of primarily of ULTEM 2300 with Nylon 6 used for the hold down loop channels. The case was milled and the dimensions and screw locations were designed to match up with the AFIT 12U CubeSat chassis. Non-locking Helicoil screws holes were utilized for the EDUs and locking helicoils are utilized in the flight-ready design.

2.4.2.2 Filars

The antenna elements consist of two bifilar loops that form a helix with a crossover bracket at the top of the helix, see Figure 29. The HCT QHA dimensions and parameters are listed in Table 1.

Table 1. HCT QHA parameters

Helix Parameter	Value
Filar Length	400mm
Filar Diameter	1.5mm
Pitch Angle	45^{o}
Axial Length	283mm
Diameter	50mm
Pitch Height	5.66mm

The filars are made of nitinol and coated with a high heat resistant paint that prevents the individual filars from coming into contact and causing an electrical short. Nitinol is an alloy of Nickel and Titanium and has excellent electrical and mechanical properties. [39] The impedance of each filar is matched to 50Ω using coils and capacitors. [4] Each filar has one degree of freedom (DOF) at the base that allows it to rotate as the antenna extends during deployment. As shown in the cross-sectional cutout view of Figure 30, each filar bends into the base and then rotates about its axis.

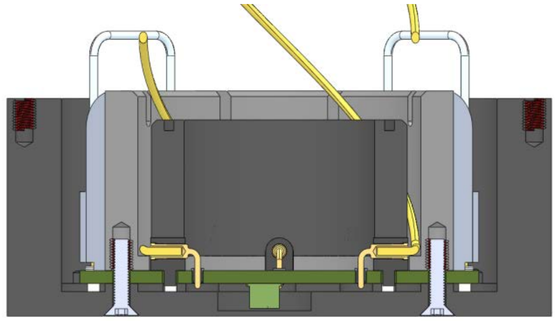

Figure 30. HCT QHA antenna CAD cross section

2.4.2.3 Antenna Handling and Stowing

Due to the SMA characteristics, excessive heating and unnecessary bending of the antenna should be avoided. The antennas do not need to be stored and handled exclusively in a clean room, however care should be taken to avoid bending the antenna elements outside of their designed helical configuration. HCT designed and fabricated a stowing tool to facilitate compressing the antenna filars in the appropriate configuration when stowing the antenna, shown in Figure 31.

Figure 31. HCT QHA stowing tool [45]

RF connectors and DC power cabling from the CubeSat bus or the test equipment should attach to the HCT antenna's printed circuit board (PCB) as shown in Figure 32.

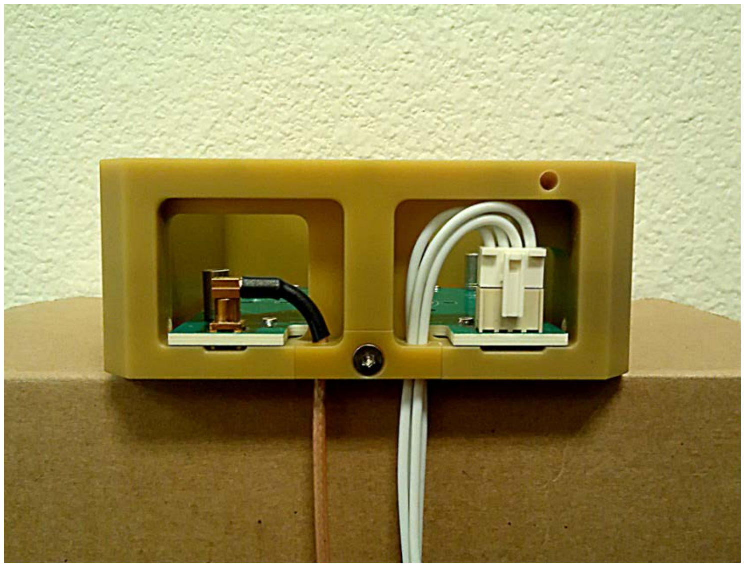

Figure 32. HCT QHA EDU RF and power cable routing [46]

2.4.2.4 Input Power

The antenna is designed to receive the input DC power from the satellite bus. Currently, the AFIT CubeSat's Electrical Power System (EPS) supplies 8.4 Volts, for the HCT antenna deployment this will be applied at a maximum 7 Amps until the antenna fully deploys, approximately 60 seconds in atmospheric pressure at room temperature.

2.4.2.5 Beam Pattern

The antenna design provides an Iso-flux radiation gain pattern. The antenna exhibits a 3dB solid angle beamwidth of 70° that is uniform over the 360° azimuth of the antenna beam pattern, as shown in Figure 33. A single antenna produces a maximum gain of 4.3dBi at 1315 MHz at an elevation angle of 135°.

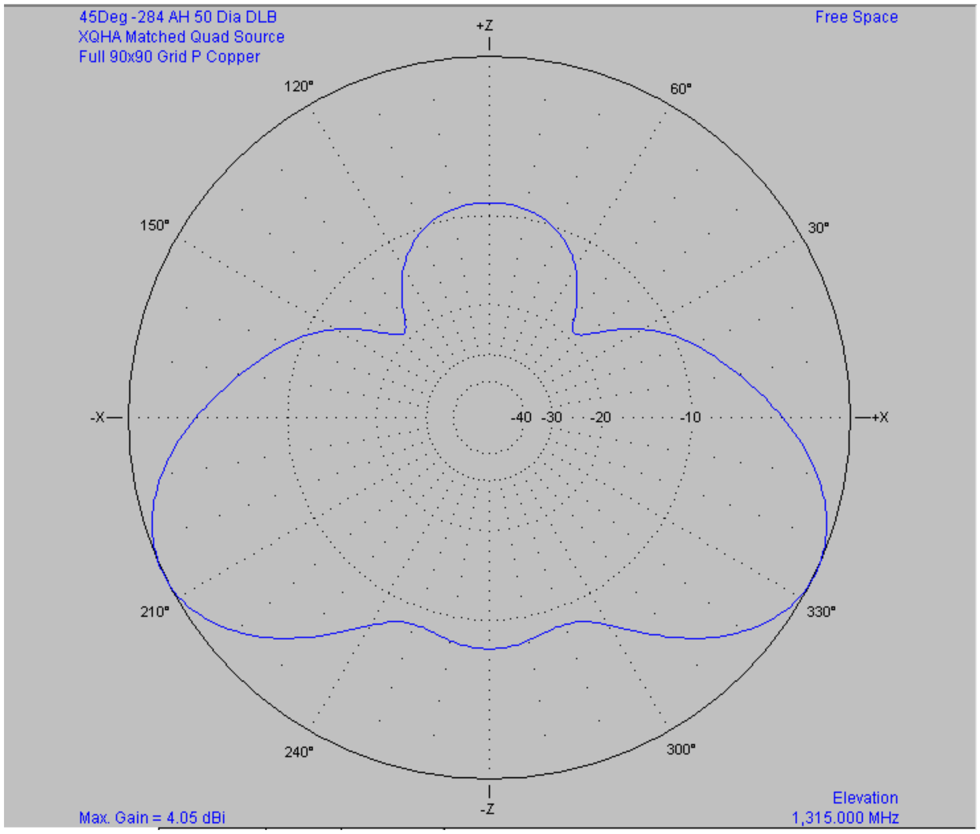

Figure 33. HCT QHA simulated 2D beam pattern of a single antenna [4]

This single antenna beam pattern exhibits more gain at low elevation angles, this is a function of the Iso-flux radiation pattern. This improves the gain at those elevation angles; this is an intentional design characteristic due to the mission parameters of the future geolocation CubeSat that the antennas will fly on.

The intent is to mount four HCT antennas on a single 4U (2x2) nadir face of a 12U CubeSat. This will place each antenna center approximately 10cm apart. Having four antennas in close proximity changes the beam pattern of the individual antennas. To simulate the expected gain pattern of the antenna, one antenna is active and the other three antennas are loaded with 50Ω. Figure 34 shows the simulated antenna beam pattern. The colored antenna filars represent the operational antenna and the black filars are inactive. [4]

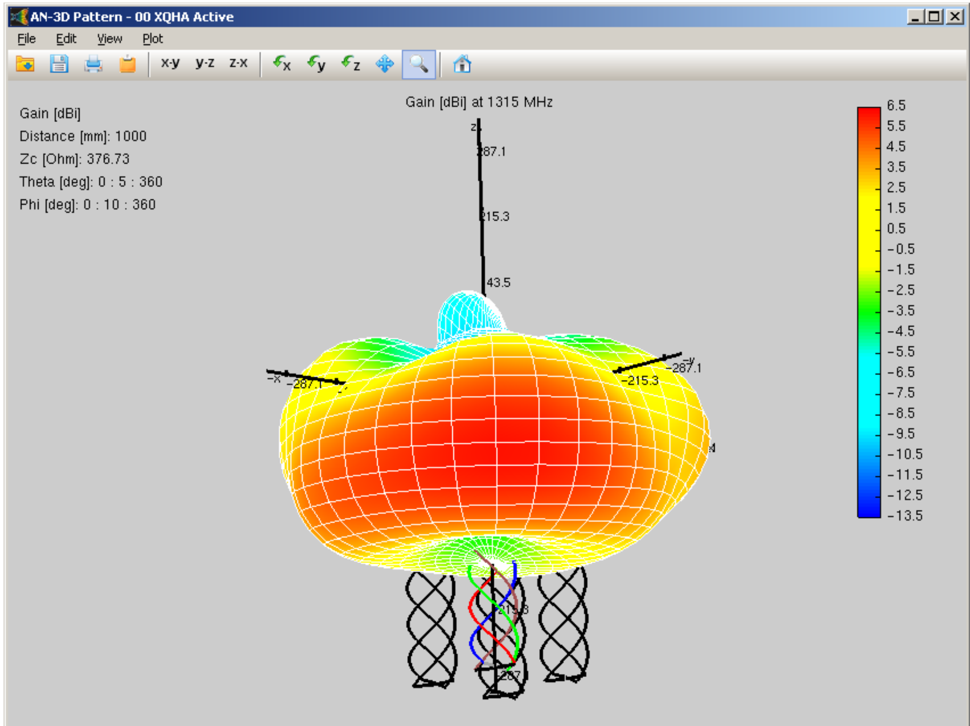

Figure 34. HCT QHA simulated 3D beam pattern, side view [4]

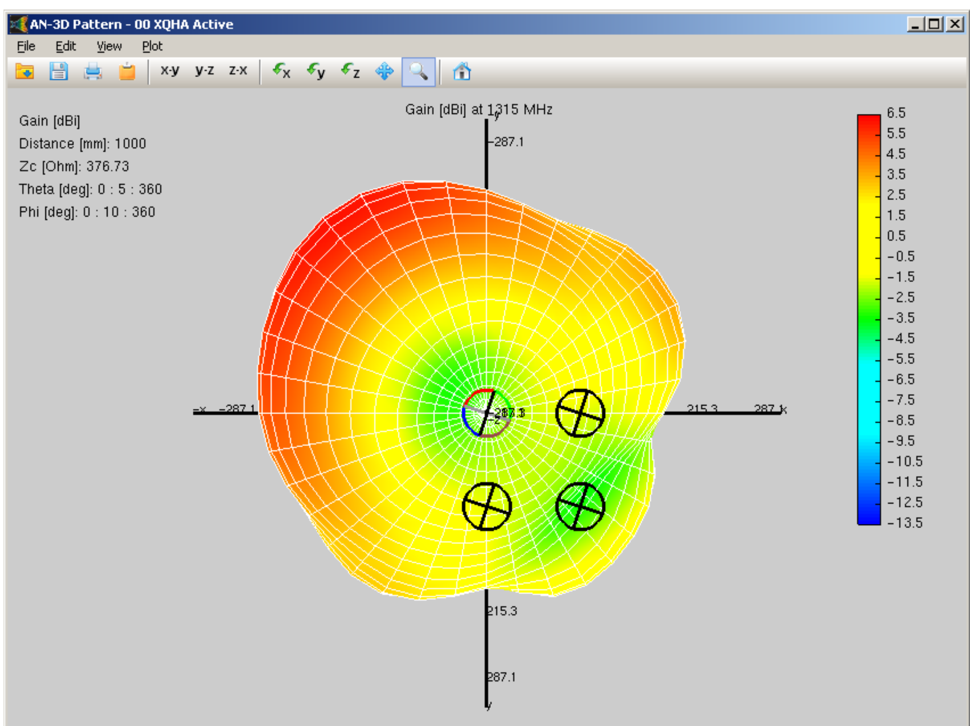

Figure 35. HCT QHA simulated 3D beam pattern, bottom view [4]

For a single antenna; the gain is highest on the corner nearest the active antenna. Varying which of the four antennas is active produces similar results. Combining the four antennas produces a max gain 6.2dBi. The proximity of the four antennas increases the maximum gain of an individual antenna but it deforms the azimuthal beam pattern.

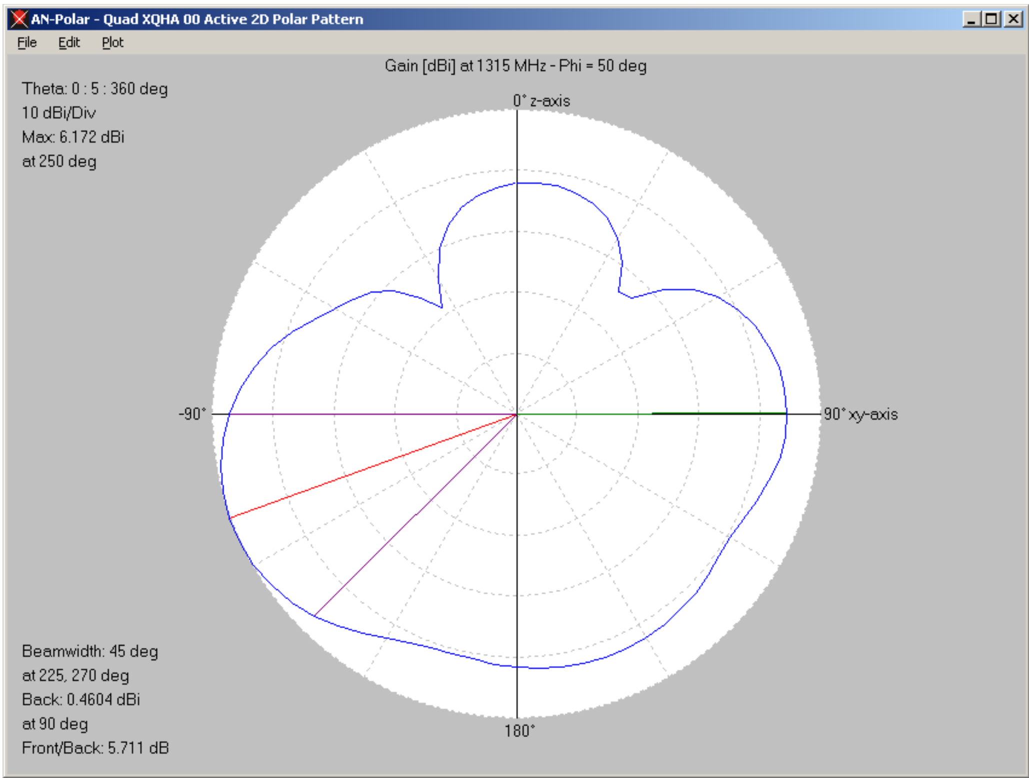

Figure 36. HCT QHA simulated 2D beam pattern of four antennas [4]

The 2D plot reveals the 3dB beamwidth is no longer uniform over the 360º of Azimuth. These perturbed results will affect the maximum gain of the antenna but will not reduce the minimum antenna gain of 4.3 dB.

2.4.3 Shape Memory Alloys

Both the helical filars and the hold-downs of the HCT antenna are SMAs. According to the American Society for Metals (ASM), SMAs are "metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure.” [39] The thermal procedure that activates the alloy is usually an electric current that heats the resistive material until it reaches its designated shape. The heating is achieved through the resistance in the SMA material as the current flows through the circuit. [47]

SMAs for use in space applications are commonplace. Nitinol is the widely used SMA for spacecraft mechanisms and actuators. These types of space applications are commercially available for direct and custom products. [48] HCT developed experience designing and manufacturing space qualified SMA components and utilized nitinol from a space component experienced supplier, Kellogg’s Research Labs, for the CubeSat deployable QHA.

For the HCT antenna, the ‘memorized’ state is the extended “deployed” helix. The antenna is designed so that at atmospheric pressure and room temperature a voltage of 8.4 Volts will generate enough heat in the filars to extend to the memorized state. Even after the applied voltage is removed, the antenna will remain in this position.

The HCT antenna is designed to deploy to its set shape when the wire temperature reaches 80°C. Heating the HCT antenna filar wire to or above 350°C for any period can adversely affect the performance of the wire. According to HCT, if the filar wires are bent more than 10% of their designed shape the antenna will take a new set. Care must be taken when handling and stowing the elements to ensure the wires are not contorted from their cylindrical helix shape. [45]

Hold downs are incorporated into the antenna design to deny the antenna from partially extending due to the stored strain energy. The hold downs fold over the compressed helix in four places, see Figure 37. These hold downs are also SMAs that are on the same serial circuit as the filars. When they are subjected to the applied voltage they will fold back and allow the antenna to extend.

Figure 37. HCT QHA hold downs

The SMA QHA structure will be affected by gravity during deployment on Earth. The antenna is designed to provide sufficient structural integrity in the microgravity space environment. The deployed antenna may experience geometry deformations such as drooping when deployed on Earth. Deploying the antenna upwards means it has to work against gravity. Deploying it downwards means it is receiving a gravity assist. Conducting a simulated microgravity deployment test requires a special test that mimics the effect of zero gravity. Since the HCT SMA QHA is capable of deploying against gravity, this research will not include microgravity deployment tests on the HCT QHA but will rely on the averaged results of gravity hindered and assisted tests to assess the deployment performance.

2.5 Summary

A short antenna theory background and history of CubeSat deployable antennas was presented in this chapter. An overview of the HCT antenna and its components and parameters was presented. The HCT design presents a unique approach to deploying a QHA by using SMA antenna elements as opposed to a kinematic mechanical structure.

Most of the helical CubeSat antenna designs presented in this chapter have not flown in space or been space qualified through environmental testing. This testing is critical to verify the antenna will correctly deploy in the space environment. The next chapter provides an overview of the qualification and deployment characterization testing required for the HCT antenna and outlines the methodology and test setup of the experiments.

3. Methodology

3.1 Chapter Overview

The intent of this thesis is to create and execute a test plan for deployable CubeSat antennas to space qualify the HCT QHA. This research will determine if the current HCT antenna design is ready to be flown on a future AFIT CubeSat mission and will provide testing architecture for future deployable CubeSat antennas. The testing approach will also provide baseline data that can be used to verify on-orbit antenna deployments.

This chapter first discusses the validation process required before a satellite or component is approved for launch. This chapter will then present an overview of additional testing required to verify and characterize the deployment aspect of the antenna. Finally, the chapter will present the test plan and procedures for the experiments conducted for this research.

3.2 Space Qualification Testing

3.2.1 Overview

Before a satellite or component is launched, it must meet specific requirements and guidelines that ensure it will be able to survive the launch and on-orbit environments. Verification tests cover the qualification and acceptance steps in the design process. Qualification tests are conducted on components and system designs which are considered flight-ready to ensure the mechanical and structural requirements are met. Acceptance tests are the formal test conducted on each flight unit to provide final approval for the unit.

Verification testing process typically incorporate the development of structural models and simulations, experimental tests to simulate the operational environment, and functional tests of the hardware and software to verify proper operation. The combination of these experiments and simulations predict how the system will perform and provide confidence in the design engineering.

The verification testing required for a space payload is determined by the launch provider. If the launch vehicle is not known, the NASA GSFC-STD-7000 [7] is typically used as the standard for acceptance testing. NASA's GEVS satisfies requirements for typical launch providers and vehicles and is commonly used for AFIT CubeSats and components. NASA GEVS creates a standard for physical testing, modeling and analyses that demonstrate satisfactory performance of space hardware. The standards are general guidelines for all spacecraft and contain a variety of different tests. NASA GEVS is intended for use when other more specific guidance is not provided, as is typically done for large spacecraft.

NASA GEVS defines a variety of tests and analyses for satellites to verify the structural, thermal, and electrical integrity of satellite hardware. The verification approach includes creating models representing hardware to simulate performance and assist experimental testing. The physical testing is conducted at a level of Maximum Expected Flight Level (MEFL) plus margin. The duration of the tests is also related to the expected duration of the specific loading type the satellite will experience during launch. There are a variety of tests to verify multiple characteristics of the spacecraft. Not all of these tests are required for CubeSats.

NASA-STD-7001A, the Payload Vibroacoustic Test Criteria, states that mechanical components weighing less than 50 kilograms are only required to subject to random vibration tests. Launch providers' main concern is that the CubeSat will survive launch and ejection into orbit. The 12U CubeSat that the HCT antenna is expected to fly on is limited to 24kg by the CSD. [49] Therefore, the only required vibroacoustic test for the HCT antenna is random vibration. In order to increase confidence in the antenna design and expose it to other aspects of the space environment other than launch, additional tests will be conducted. Thermal vacuum testing is typically conducted to demonstrate that the satellite and its components will survive and operate in the space environment.

The NASA approach endorses the full system verification approach where the satellite is tested at the highest system level possible. However, new components, both prototype and protoflight, require additional testing that can be done at the unit level. After a CubeSat passes pre-launch space qualification testing, it cannot be modified. Therefore, it is advantageous to complete space qualification testing at the component level so the entire CubeSat does not have to repeat space qualification testing due to a failed component. One of the primary research objectives of this thesis is to create and document the testing procedures for the HCT QHA to use for future testing of HCT QHA flight units and other future deployable CubeSat antennas.

NASA GEVS states that for a new space component, tests should be conducted at different stages in the component's design. These stages include: prototype qualification, protoflight qualification, and acceptance. Prototype qualification tests are performed on dedicated test hardware and demonstrate the design adequacy of the component for its intended mission use. [50] Prototype qualification tests strive to accurately simulate the loads that the component will experience in its flight environment. The test profiles used for these tests are determined by the chosen launch vehicle and intended orbit environments, but the component is not tested to failure. For this research, the HCT QHA will undergo various tests in order to assess its design and workmanship but the antenna will not be tested to intentionally cause failure.

Protoflight tests are performed on flight hardware when dedicated test hardware is not available. Protoflight testing seeks to verify that the final component design meets all requirements and specifications. This is done by designing tests that simulate the expected environments that the component will experience. The anticipated loads for a CubeSat are the vibration loads of the launch environment and the temperature and vacuum pressure loads of the space environment. There are mandatory tests designed to reduce the risk of failure during a space mission. [51]

The HCT QHAs tested in this research are considered protoflight hardware. The antenna manufacturer provided antenna units that are intended for both verification testing and flight. Protoflight tests serve the purpose of both prototype and flight acceptance test by using flight hardware components, not a prototype or engineering design unit. [50]

Space qualification testing should be performed after the critical design review (CDR) and design-development tests and will establish design adequacy, reliability and quality. [52] Since the HCT antenna is a protoflight component, without any prior space environmental testing, the design-development tests and the qualification tests will be conducted simultaneously for this thesis. Pending any failures of exposed design flaws, the testing will provide the flight certification and the antenna can be incorporated on AFIT's CubeSat mission.

The environmental testing is designed to identify failures; this is accomplished through functional tests. A functional test can be comprehensive to test the full performance of the test object or limited to demonstrate that functional capability has not been degraded by the tests. Both comprehensive and limited performance tests will be performed before, during and after, all environmental tests to verify and characterize the HCT antenna design, see Appendix C. [7]

The required NASA GEVS tests will be conducted on the HCT antenna to determine if it meets the environmental standards of launch and LEO. The results will be documented and provided to the future launch provider when the future AFIT CubeSat mission is launched. A proposed test plan that included the NASA GEVS required tests as well as the desired deployment characterization tests was generated and approved by the antenna manufacturer, HCT.

3.2.2 Vibration Testing

The HCT antenna will experience mechanical vibrations over a range of frequencies during launch. Random vibration tests on a shaker table simulate the vibration environment of the launch vehicle. Swept sine vibration tests expose structural weaknesses and changes by comparing the vibrational modes of pre and post sine sweeps. Vibration testing is typically conducted before TVAC testing to allow the LEO simulated thermal environment to exploit any cracks or other failures that may be a result of the random vibe tests. [53] However, for the HCT antenna test plan, vibe will be conducted after the ambient, cold and hot TVAC deployments to preserve the prototype components. A final TVAC test will be conducted after the vibration tests in combination with the solar simulator tests to uncover any failures or issues incurred during the vibe tests.

3.2.3 Thermal Vacuum Testing

TVAC testing verifies that the CubeSat or component can function in a vacuum and in the extreme temperature environment of space. Functional deployment tests will be performed when the vacuum chamber pressure is reduced to at least $2x10^{-4}$ Torr and when the satellite has reached equilibrium at various temperatures reflecting the conditions experienced on orbit. By characterizing the HCT QHA deployment at the hot and cold stages of the temperature cycle, as well as after multiple cycles, concept of operations (CONOPS) for the AFIT mission can be created to ensure the antennas are deployed at the optimum time and location in the CubeSat's orbit.

3.3 Space Hardware Deployment Testing

In addition to the previously discussed tests that validate that the antenna will survive the launch and space environments, there are other aspects that must be considered and extensively tested; the deployment rate and deployed state of the antenna. If the antenna fails to deploy when it reaches orbit or if it deploys prematurely while still enclosed in the launch vehicle, then the entire mission could result in a failure. This research will record and analyze the behavior and performance of both the antenna elements and the hold downs throughout the verification testing.

A component or subsystem that deploys into its operational state when on orbit increases the level of risk and therefore increases the amount and fidelity of modelling, analysis, and testing that the component must undergo before launch. In the case of a deployable antenna, the risk dramatically increases since the satellite relies on the antenna to transmit or receive mission data, whether payload data or tracking, telemetry and control (TT&C). For the AFIT mission, the HCT QHAs are used solely for the payload, and a separate antenna is used for TT&C communications but a loss of the HCT QHA antennas would result in an inability to conduct the geolocation mission.

The deployed antenna geometry can also affect the RF performance. If the antenna does not deploy within the defined axial tolerance, the gain beam pattern could affect angle of arrival (AoA) measurements. If an antenna only deploys partially and does not achieve its designed height within the specified tolerance, the beam pattern may be affected and the antenna may either be neglected for AoA or extensive calibration may be necessary. Additional RF testing of the HCT QHA in different geometric positions will provide better understand the impact of incorrect deployed geometry.

3.3.1 Modal Analysis Overview

Measuring the natural frequencies of the antenna is vital for model correlation and predicting the behavior of the antenna when subjected to dynamic loading. While on orbit, this is the extremely important for lightweight, flexible structures such as satellite antennas whose performance makes them more susceptible to unwanted vibrations. [54] NASA-STD-7000A requires that “all significant modes up to the required frequency must be determined both in terms of frequency and mode shape.” Modal predictions can be estimated using finite element analysis (FEA) and validated experimentally. FEA is a versatile analysis approach that enables the mechanical modelling of complex structure dynamics. The modelled and experimentally measured frequency response results should be compared to identify inaccuracies and improve the FEA model. [55]

FEA can be used to predict the antenna’s frequency response to inputs over the expected frequency range. FE starts from a mesh of points that reflects the geometry of the object, elements span between the nodes which represent mechanical and thermal material properties of the structure. [56]

The modal survey can also be conducted experimentally using a laser vibrometer to measure the frequency response of the test article that results from a specific input vibration. This excitation vibration can be applied acoustically through a speaker or physically by an impact hammer.

NASA-GEVS requires that the minimum fundamental frequency of the stowed launch payload must be less than 70 Hz. [7] This requirement ensures that the payload will not aggravate the fundamental frequencies of the launch vehicle and cause resonant vibrations that could result in failure. For most missions where the CubeSat is secondary payload the modal mass would be insignificant with respect to the primary payload and the launch vehicle.

The stowed HCT antenna represents the article whose natural frequencies must be considered when determining the minimum fundamental frequencies of the system to be launched. The stowed antenna is a compact, dense, object whose individual fundamental frequencies will not likely affect the fundamental frequencies of the assembled CubeSat or the launch vehicle. Because of this, Frequency Response Functions (FRFs) will be collected during sinusoidal and random vibration tests but a modal survey of the stowed HCT antenna will not be conducted as part of this research.

This thesis is focused on characterizing the antenna deployment, understanding the natural frequencies and mode shapes of the deployed antenna which will provide insight into how the deployed antenna elements will behave when deployed on a future CubeSat. Analyzing the first modes of the deployed antenna will provide insight into the lowest natural frequencies of the antenna. Understanding the natural frequencies and mode shapes of the deployed antennas can drive attitude determination and control system (ADCS) component selection to minimize or control spacecraft jitter that may excite the antennas. Understanding the natural frequencies of the antenna can also drive the allowed slew rate and acceleration of the CubeSat to perform various on-orbit scenarios defined in the CONOPS.

The CubeSat mission will employ four HCT antennas on the four corners of a CubeSat face, see Figure 2. The close proximity of the antennas, 10cm from center to center along the X and Y axes, introduces the risk of the antenna filars coming in contact with the filars of an adjacent antenna and causing the circuit to short. The filars could also become tangled during deployment.

Finite Element Models (FEM) were created in ANSYS using several different types of beam elements (Beam188 and Beam189) and varying the number of segments required to construct the helix. A mesh conversion study was conducted to optimize the FEM and a parametric approach was utilized to aid future analysis. HCT created their own FEM using a volume mesh to discretize the QHA CAD model. Predictions from the beam element and volume element FEMs will be compared with the experimentally measured natural frequencies and mode shapes to identify which EFA approach provides a better estimation of the QHA frequency response.

3.4 Test Methodology

Protoflight testing of the HCT QHA will provide the confidence and verification required to meet the objective. Characterizing the HCT antenna deployment throughout the environmental tests will provide confidence in the antenna design and will verify its on-orbit performance.

3.4.1 Functional Tests

Throughout the environmental testing, functional tests of the antenna will be conducted to determine if the antenna's performance was affected by any of the tests. By executing the functional tests before and after the environmental tests, failures can be identified and any differences in deployment can be characterized that may be a result of the environmental testing.

A mechanical functional test refers to the physical deployment of the antenna and is synonymous to a comprehensive performance test (CPT). In some cases, a complete mechanical deployment test is not necessary to determine if the antenna is still functional from an electrical perspective. In these cases, electrical functional tests will be used instead of a mechanical functional test. An electrical functional test can also be referred to as a limited performance test (LPT) and will measure the current through the antenna filar elements without applying enough power to heat the SMA elements and cause the antenna filars to change states and begin to deploy. Table 2 defines the two functional tests.

Table 2. Functional tests

Name	Objective	Criteria
CPT	Assess mechanical performance	Antenna physically deploys to at least 260mm (+/- 1 mm)
LPT	Assess electrical performance	Antenna current is at least 7 Amps (+/- 1 Amp)

The CPTs and LPTs will be conducted throughout the environmental testing, see Table 3.

Table 3. Functional test matrix

Environmental Test	LPT	CPT
TVAC	At ambient, at vacuum, at temperature	At temperature
Vibe	After each sine sweep	After test conclusion

3.4.1.1 Mechanical Functional Test

Mechanical functional tests will be conducted before the environmental testing commences to record baseline deployment characteristics. Mechanical functional tests will also be conducted during the TVAC tests, after vibe testing, and during solar simulator testing. The TVAC tests will incorporate the mechanical deployment as part of the test to characterize the antenna deployments at the hot and cold stages in the thermal cycle. The post-vibe deployment tests will identify any issues with the antenna circuit or filar elements that may have been occurred during random vibration testing. The goal of the on orbit simulated solar environment tests is to determine if pointing the antenna at the sun will cause it to deploy on its own.

HCT defines the antenna as fully deployed when it received the input voltage of 8.4V for duration of 60 seconds in atmospheric pressure and ambient temperature. The TVAC environment will likely alter this deployment timeline so the voltage input duration will be increased to ensure the antenna fully deploys. HCT confirmed that applying the power for longer than 60 seconds will not harm the antenna filar elements or the circuit, therefore a max duration criteria of 120 seconds was selected to ensure complete deployment in all environments. When the antenna reaches its set deployed position it will not continue to extend, regardless of the duration of input voltage. Since one of the goals of this test is to record the deployment time, we redefined fully deployed as when the antenna appears to be done extending, therefore each deployment test may have a unique duration. This can be confirmed visually by assessing the antenna’s length has ceased to increase and the quadrifilars have ceased to rotate about the axial axis. Visual measurements can be taken with +/- 1mm precision for all tests except for the

TVAC tests, this will be detailed in the TVAC test setup section later in this chapter. Analyzing the input current can also provide determination of complete deployment by observing when the current reaches a constant value.

The input voltage is held constant at 8.4V using a voltage controlled power supply. The resistance of the antenna elements increases as the filars heat up and extend. Measuring the input current to the antenna circuit will enable the power consumption to be monitored as the antenna deploys. When the antenna has reached its final deployed position, the resistance in the filars appears to remain constant and therefore the current converges on a constant value. Analyzing the recorded current data will provide the power and time required for the antenna to fully deploy. Knowledge of these values will be valuable for use in early orbit operations of the CubeSat.

Changing the fixed voltage from 8.4V will require the current limit to be adjusted and the approximate deployment time to be evaluated. HCT should be consulted to determine if the new voltage will adversely affect the antenna's components.

As designed, the nominal deployed length for the HCT antennas 283 mm from the top of the printed circuit board to the top of the antenna filars at the cross-brace, this measurement is illustrated in Figure 38.

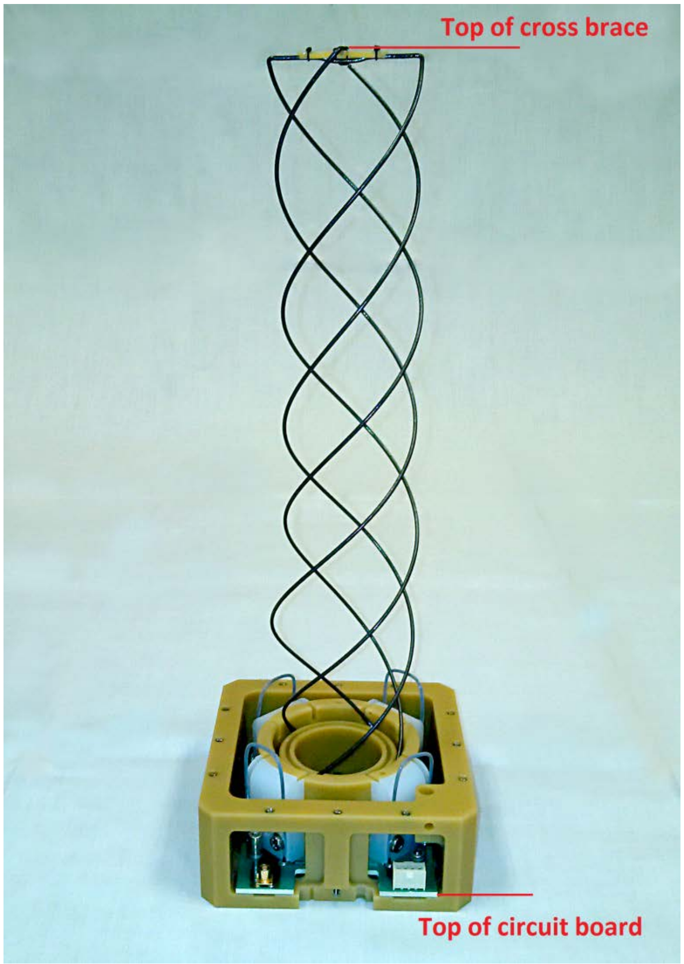

Figure 38. Deployed HCT antenna length measurements

3.4.1.1.3 Success Criteria

Complete success if the antenna deploys correctly to a length of at least 283 cm (+/- 1mm) within 90 seconds. Marginal success if the antenna deploys to at least 260 cm after 120 seconds. Failure if antenna does not deploy to at least 260 cm regardless of the deployment duration.

3.4.1.2 Electrical Functional Tests

A LPT can be conducted in place of the CPT to identify any electrical issues that may affect antenna deployment performance. Rather than measuring the antenna element resistance directly, it was simpler to measure the current to test for open or shorted conditions. By applying the input voltage for only several seconds and measuring the output current, we can determine if the antenna incurred any electrical anomalies, such as an increase in resistance or an open circuit, from the previous environmental test. By applying the voltage for only two seconds, the antenna will not receive enough heat to allow the SMA to begin to transition, but it will provide enough time to measure the current flowing through the antenna circuit.

LPTs will be conducted throughout the TVAC tests. Conducting the test before pumping the chamber to a vacuum and again when vacuum is reached before heating or cooling the chamber to the desired temperature will verify that the antenna has not incurred any electrical issues and will also verify that the wiring harness is connected correctly.

Electrical functional tests will be conducted between each sine and random vibration tests. A CPT will be conducted when vibration tests have concluded, but since the goal of the vibe tests is not to specifically characterize the deployed antenna, a LPT will suffice for determining if the antenna experienced an electrical short during a specific vibration profile of the vibe tests.

3.4.1.2.1 Success Criteria

Complete success is defined as the measured current is greater than 7 A (+/- 1 A). The antenna fails the test if the current is less than 7 A (+/- 1 A)

3.4.2 Deployed Length and Precision

The measurements we will be recording and comparing must be attributed a precision in order to confidently compare the results of each functional test and characterize the antenna performance. Deployment videos and pictures will be recorded for each deployment, see Figure 39 and Figure 40. A single 6U face (panel) of a 12U CubeSat was used to hold the four EDU QHAs. The geometry of the camera location in relation to the deployed end of the antenna precludes a precise length measurement using the videos or captured images, see Figure 40.

However, these media can be used to provide a rough measurement (± 2 mm) identify any changes in axial geometry deformation, such as leaning or changes in the antenna diameter, throughout the testing.

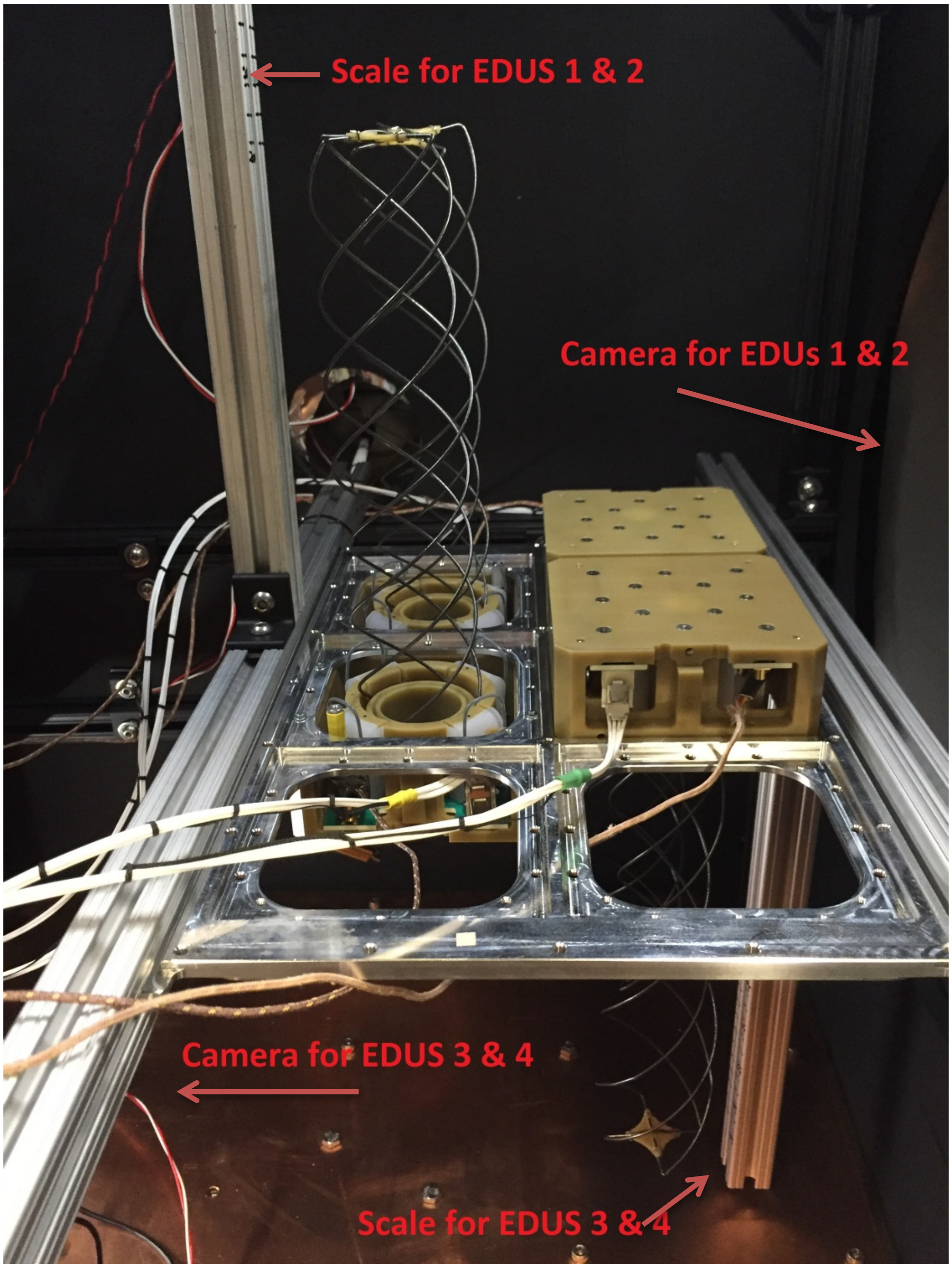

Figure 39. TVAC deployment tests recording setup

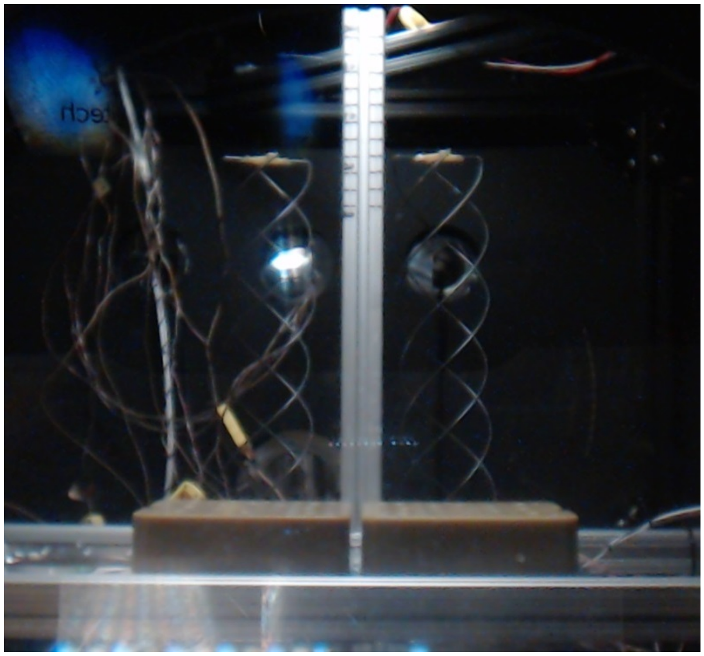

Figure 40. EDUs 1 & 2 TVAC deployment recorded by camera in chamber

The deployed antenna length will be measured by visual inspection with a ruler within +/- 1 millimeter. For the TVAC testing, these measurements will be taken immediately after deployment and then again after the antenna has been removed from the TVAC chamber as changes in length occurred while the chamber is venting back up to atmospheric pressure and ambient temperature.

The Hewlett Packard 6033A Power Supply will be utilized to supply the input voltage and measure the applied current. LabView software will be used to automate control of the power supply.

3.4.2 Test Plan Overview

The objective of the space verification tests are to use the EDU antenna units provided by HCT mounted in a flight-type configuration and subjected to qualification and acceptance tests that simulate the space environment with a sufficient level of margin to qualify the antenna design. The test matrix for the four HCT QHA EDUs is shown in Figure 41 in the order in which they will be conducted.

Test Article	Pre-Environmental Testing Lab Deployments (Up and Down)	Pre-Environmental Testing Laser Vibrometer Modal Survey	TVAC Deployments (Ambient, Cold, Hot) (Up)	TVAC Deployments (Ambient, Cold, Hot) (Down)	Vibe (Random and Sine Sweep)	Solar Simulator (Up)	Post-Environmental Testing Laser Vibrometer Modal Survey	Post-Environmental Testing Lab Deployments (Up and Down)	VSWR Measurments
EDU 1	X	X	X		X	X	X	X	X
EDU 2	X		X			X		X	
EDU 3	X	X		X	X	X	X	X	
EDU 4	X			X		X		X	

Figure 41. Test matrix for the HCT QHA EDUs

The following sections discuss each of the test types in detail. The requirement for why the test is conducted as well as an overview, success criteria, and detailed description will be presented.

3.4.2.2 Test Subjects

Four HCT QHA units tested are nearly identical to the flight ready units that will be flown on a future AFIT CubeSat. Four additional antennas are EDUs intended for environmental testing and are identical to the flight unit design aside from the use of locking helicoils in the flight design and non-locking helicoils in the EDUs. The AFIT requirements provided to HCT dictate that the four flight units must be subjected to ten deployments before launch. The deployment of the flight units will not be conducted as a part of this thesis.

Figure 42. HCT QHA EDU test subjects

It is time consuming to deploy and stow the antenna repeatedly for the various tests, especially in TVAC, when the chamber must reach the desired pressure and temperature. Therefore, the test sequence made full use of all four EDUs to cover as much of the test matrix as possible in a three week test campaign.

3.4.3 Ambient Deployment Test

Ambient functional tests are required to establish a baseline for the parameters that will be measured throughout the environmental tests to characterize the antenna performance CPT and LPT functional tests will be conducted in the lab environment to baseline deployment length and current measurements.

The testing will begin with deployment tests of all four EDUs conducted in the lab at ambient temperature and atmospheric pressure levels in order to characterize the antenna deployment performance and to familiarize the test operators with the antenna deployment and stowing procedures. The characterization includes measuring and recording deployment time, fully deployed height and axial inspection. The environmental tests will conclude with a repeat of the ambient tests of all four antennas to compare the results to the initial ambient tests.

Another goal of the ambient tests is to confirm the repeatability aspect of the antenna deployment. The HCT antennas will only be deployed once for their mission, but the antenna manufacturer is interested in how the SMA antenna elements and hold downs react to being stowed and deployed many times.

3.4.3.1 Test Setup

The following images depict the lab deployment setup for the vertical ambient deployments.

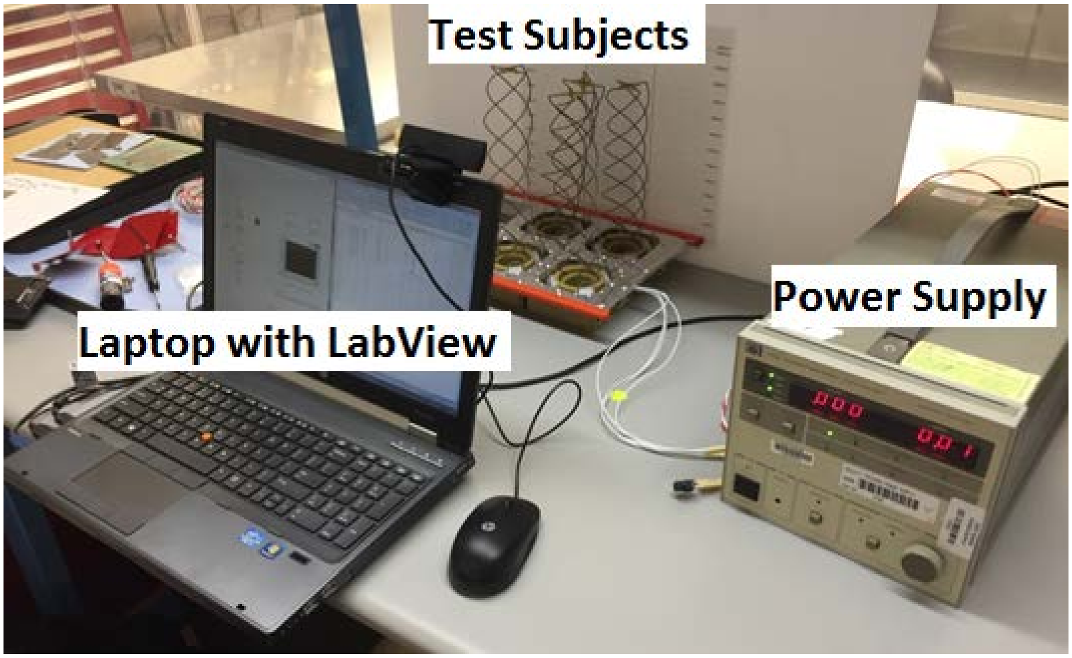

Figure 43. Lab deployment setup

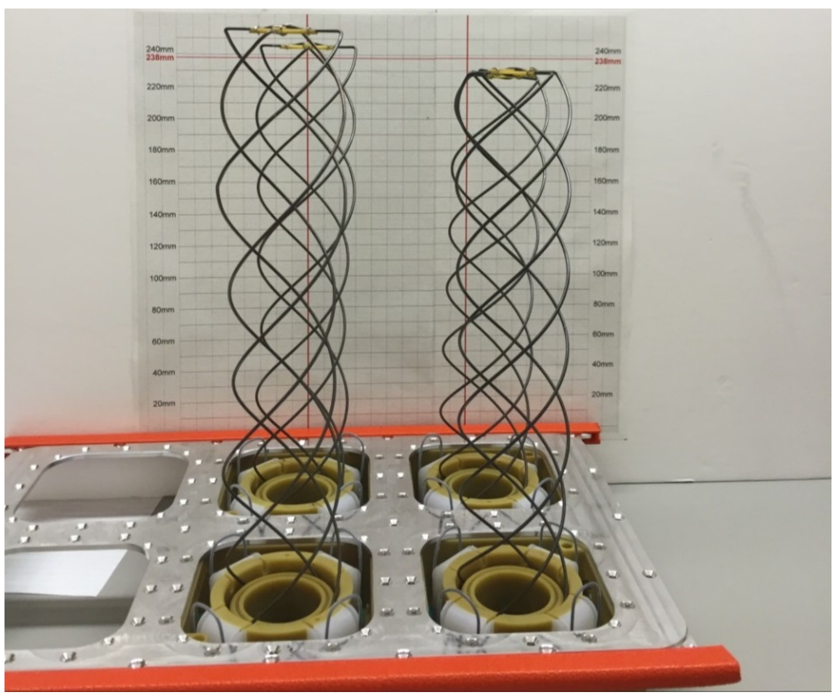

Figure 44. Lab ambient upward deployment

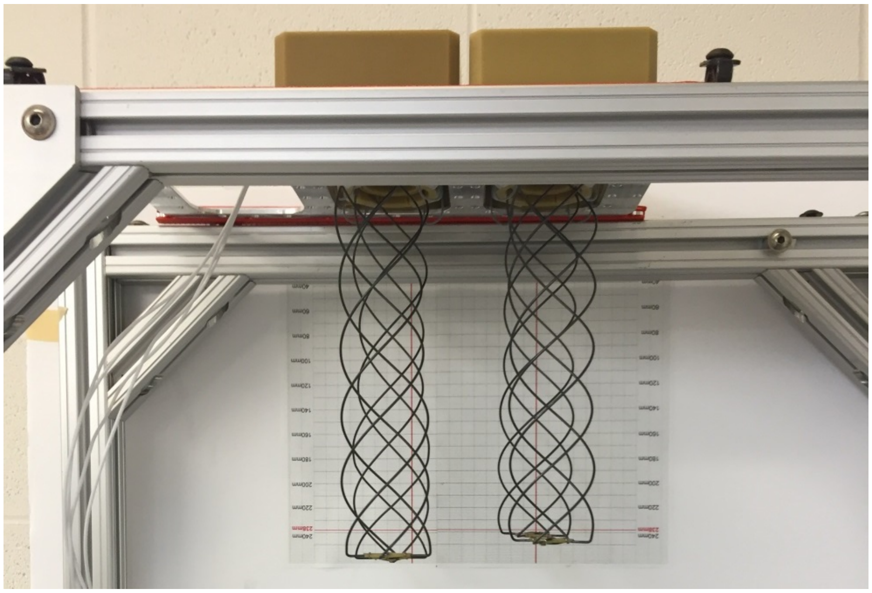

Figure 45. Lab ambient downward deployment setup

3.4.3.2 Data Collected

The data collected for the lab ambient vertical deployment tests will be standard for all CPTs to include deployment current and deployed length.

3.4.3.3 Deployment Length Success Criteria

The test will be completely successful if the antenna deploys to a length of at least 283mm. The test will be marginally successful if the antennas deploy to at least 260mm.[3] The test will be a failure if the antenna fails to fully deploy.

3.4.4 Modal Survey Test

The modal survey consists of Finite Element Models (FEM) and an laser vibrometer experiment to estimate and compare natural frequencies and mode shapes of the deployed HCT QHA. Two EDUs will be used for this test. The modal survey test will be conducted before and

[3] The 260 minimum deployed length was determined after the conclusion of the environmental testing using the results from the VSWR measurements.

after all environmental tests. The purpose of the repeated tests will be to determine if the environmental tests affected the natural frequencies of the deployed helix structure.

An input force from an impact hammer will be applied to the base of the deployed HCT antenna and a laser vibrometer will estimate the resulting fundamental frequencies by measuring the instantaneous velocity by computing a one dimensional frequency shift in the laser beam, see Figure 46. The laser vibrometer will survey and average measurements from eleven locations on the deployed antenna. The measurement positions were selected to provide distributed measurements across the deployed antenna structure to record any potential mode shapes that the antenna may exhibit in response to the impact hammer excitation. Having data points from locations across the width and height of the deployed antenna will enable the estimation of 3D mode shapes of the antenna filars.

These deployed antenna filars have a fixed-free boundary conditions due to the cantilever setup of the antenna with respect to the fixed base.

A modal survey tests uses a laser vibrometer to measure the natural frequencies and modes of vibration of an object by applying an input and measuring the response at numerous locations. The input must be clearly defined in order to correlate it with the response. For the testing herein, an impact hammer was used to apply a force at the antenna base and the response was measured at various locations on the filars in the form of velocity measurements facilitated by using a laser vibrometer. The laser virbometer measures velocities from the Doppler shift of the reflected laser beam. [57] For this research the Polytec Scanning Vibrometer (PSV) PSV-500 scanning head and PSV 9.1 acquisition software was used to capture the test results. [58]

The antenna will be fully deployed and reflective tape[4] will be attached to the filars at eleven locations, see Figure 46. The antenna base will be repeatedly struck in the same location and the velocities will be measured across the antenna and the natural frequencies below 50 Hz will be extracted from the time data and the mode shapes will be visualized through animation of the frequency responses of the eleven locations on the antenna filars.

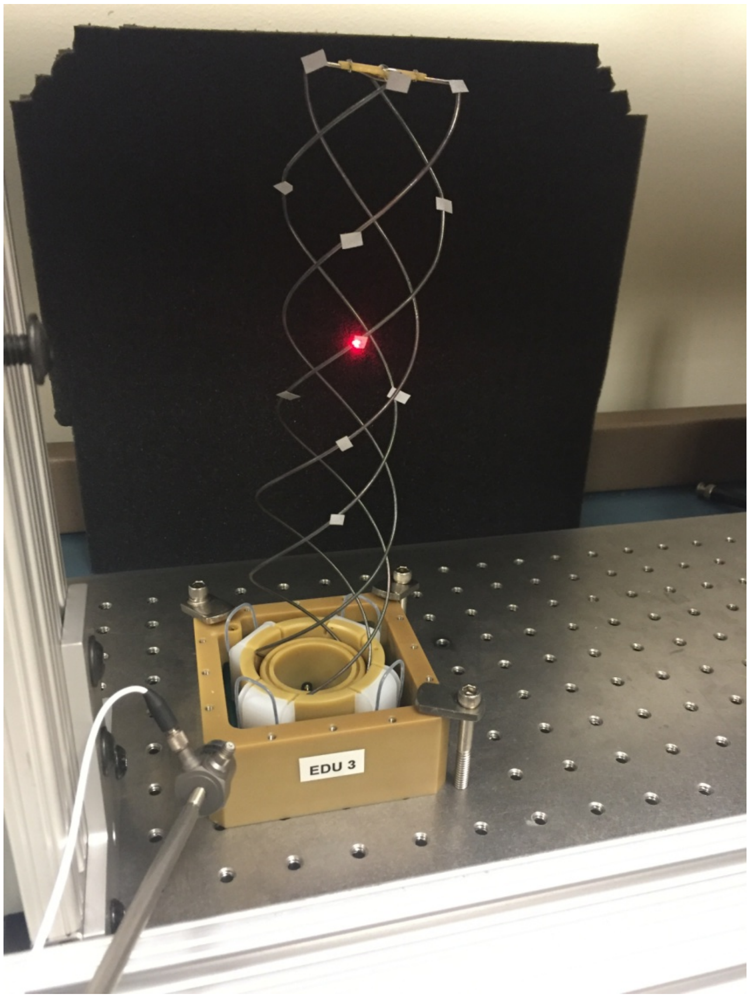

Figure 46. Laser vibrometer test subject

For this research a FEM was created using material properties, dimensions and boundary conditions provided by HCT. The Nitinol material properties are presented in Table 4 and the

[4] Reflective tape was used to ensure a good signal return of the filar, and not a reflection off the background. This also aided in providing an adequate size 'target' on each filar location

helix parameters were presented in 2.4.2.2 Filars of this report. The filars are attached to the base of the antenna through a hinge connection that allows them to rotate as the antenna deploys, see Figure 47.

Table 4. Nitinol material properties

Parameter	Value
Density (kg/m^3)	6450
Modulus of Elasticity (N/m^3)	75E9
Poisson's Ratio	0.3
Coefficient of Thermal Expansion (1/C)	0

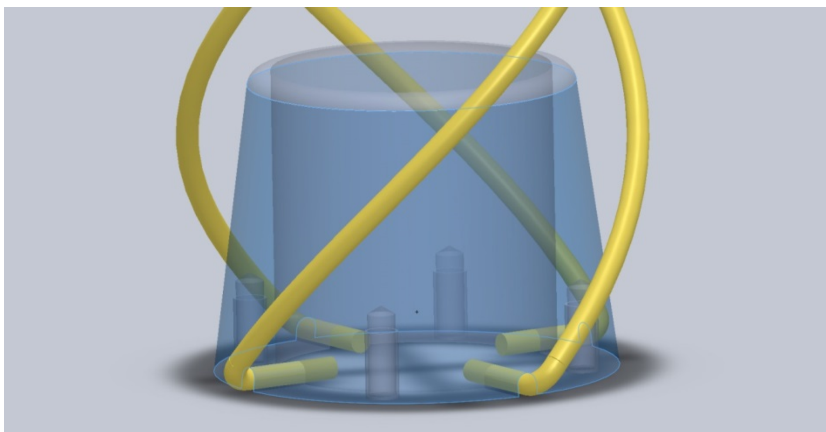

Figure 47. CAD model of HCT QHA base and filars

3.4.4.1 Test Setup

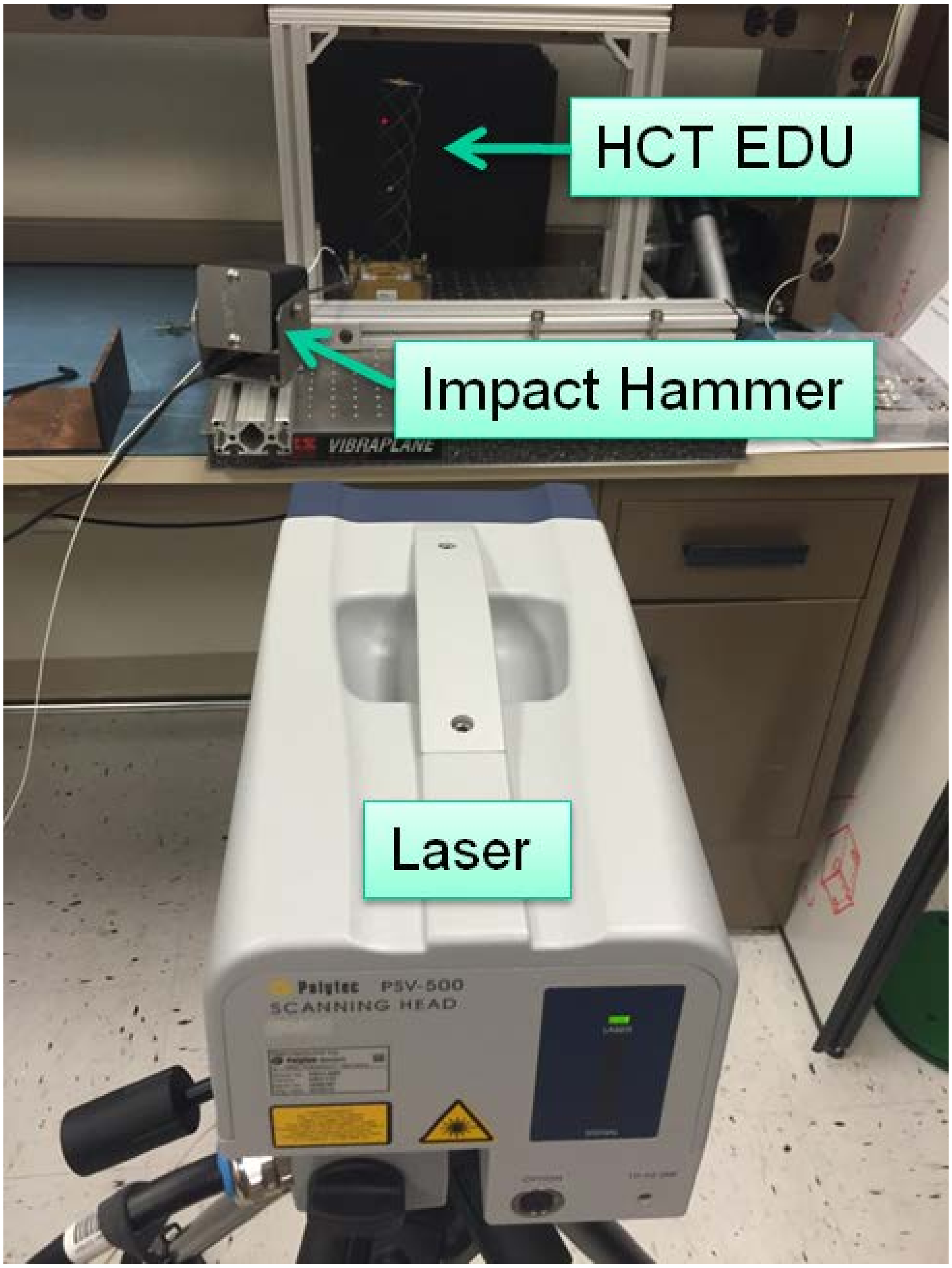

Figure 48. LASER vibrometer test setup

3.4.4.2 Data Collected

The PSV software computes and displays the magnitude and frequency response of the antenna. The system surveys all eleven defined locations and collects five measurements at each location. The velocity data for each location will be processed using a Fast Fourier Transform (FFT) to extract the mode shapes and the frequency response of the antenna.

3.4.4.3 Modal Survey Success Criteria

Complete success if modal survey natural frequencies and mode shapes under 50Hz are recorded and identified. Failure if the test is unable to measure the fundamental frequencies of the deployed antenna.

3.4.5 TVAC

A TVAC test is required to confirm the HCT antenna can operate in vacuum and extreme temperatures of a representative space environment. Deployment tests in the TVAC chamber are required to characterize the HCT antenna deployment performance in this environment, see Figure 39. The HCT antennas will be subjected to a temperature profile to simulate LEO. The antenna will be deployed at various points along the thermal profile to characterize the deployment by measuring deployment height, deployment current and axial geometry.

TVAC testing is intended to subject the antenna to the expected temperature range it will experience in LEO as well as the microgravity space environment. This temperature and pressure, or lack thereof, of this environment can cause components on the antenna to behave differently or to become non-operational and TVAC testing is necessary to expose issues in the antenna design.

The TVAC tests will follow the NASA GEVS profiles of the minimum, ambient, and maximum expected temperatures, with a CPT conducted at each position. These tests are designed to characterize the components functionality at each of the temperature levels of the profile. The temperature levels are defined by the operational and survivable levels of the antenna components. -20°C and +50°C are good estimates of the temperatures the interior of the

CubeSat will reach in LEO in the pre-deployed state. The complete temperature profile is given in the TVAC test plan in Appendix A.

For both the cold and hot portions of the thermal testing, the chamber will be left at the set temperature for twelve hours. LPTs will be conducted before and after the dwell. Leaving the chamber at the desired temperature will allow the HCT EDUs to soak and reach their equilibrium temperatures. The TVAC chamber reaches its temperatures through conduction and although it may reach -20°C, the antenna itself will retain heat in its casing and other components. The casing is made of a non-thermally conductive ULTEM material and therefore will take a long time for its temperature equilibrate in the TVAC chamber.

3.4.5.1 Test setup

The TVAC test setup is shown in Figure 49. The TVAC houses four HCT QHA EDUs, two oriented down and two oriented up, a 6U chassis face, two aluminum blocks with tick marks to measure deployment length, four thermocouples, one on each antenna, and two video cameras, one to capture the upwards deployments and another to capture the downward deployments, previously shown in Figure 39.

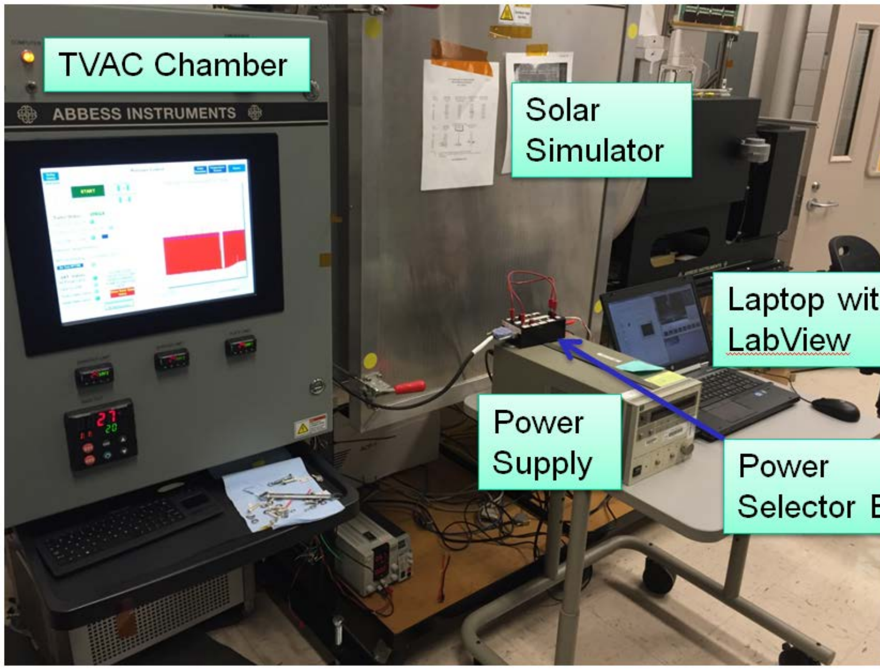

Figure 49. TVAC test setup

The solar simulator test was conducted in the TVAC with the addition of a mirror to reflect the incoming light, see Figure 50.

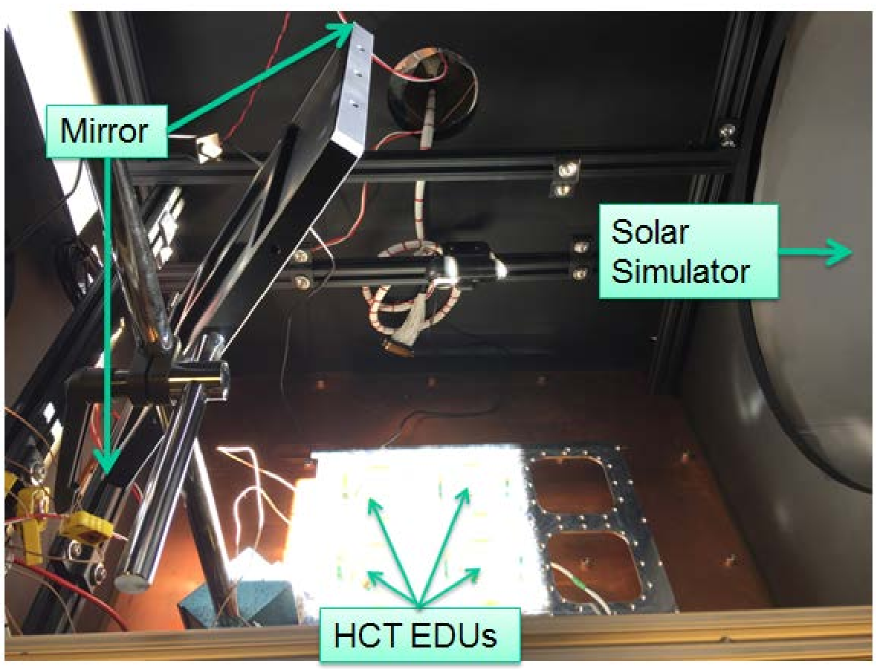

Figure 50. Solar simulator test setup

A high vacuum rated DB-25 connector was used to pass the antenna deployment power wires and thermocouples through the chamber wall. The VISIO diagram in Figure 51 provides a block diagram of the test layout and the VISIO diagram in Figure 52 depicts the pinouts.

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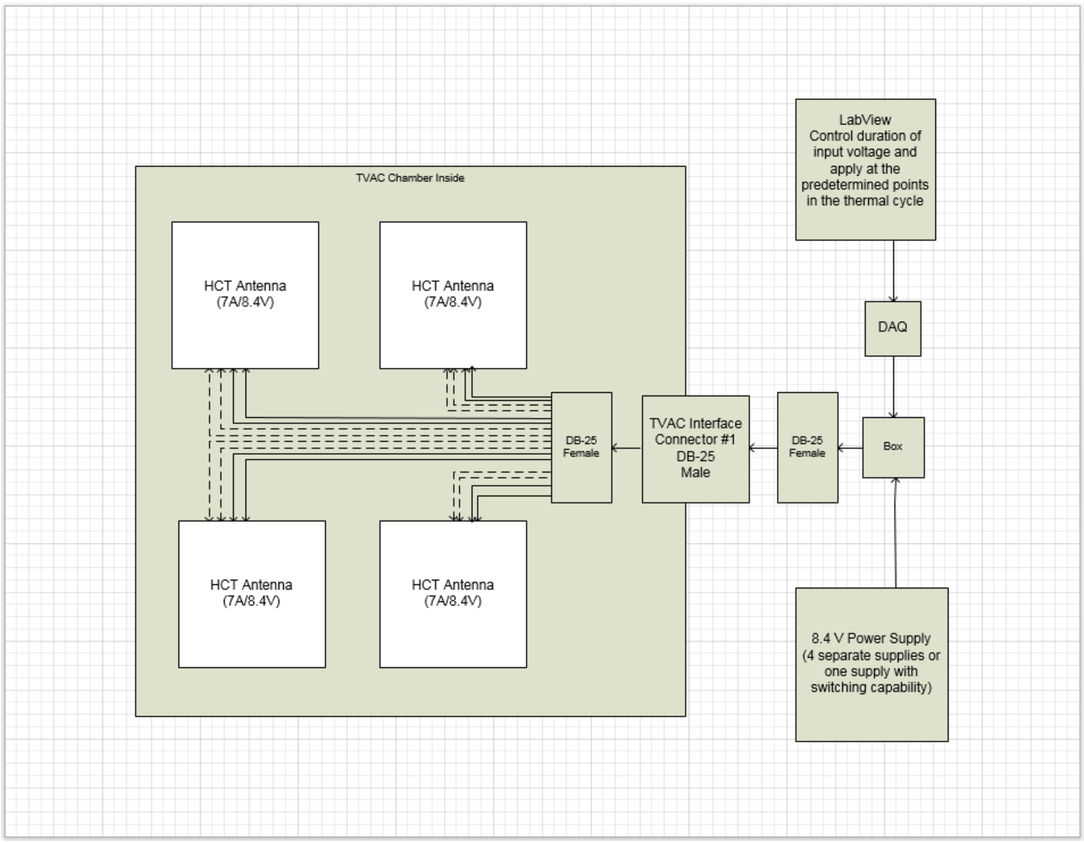

Figure 51. TVAC test layout VISO diagram

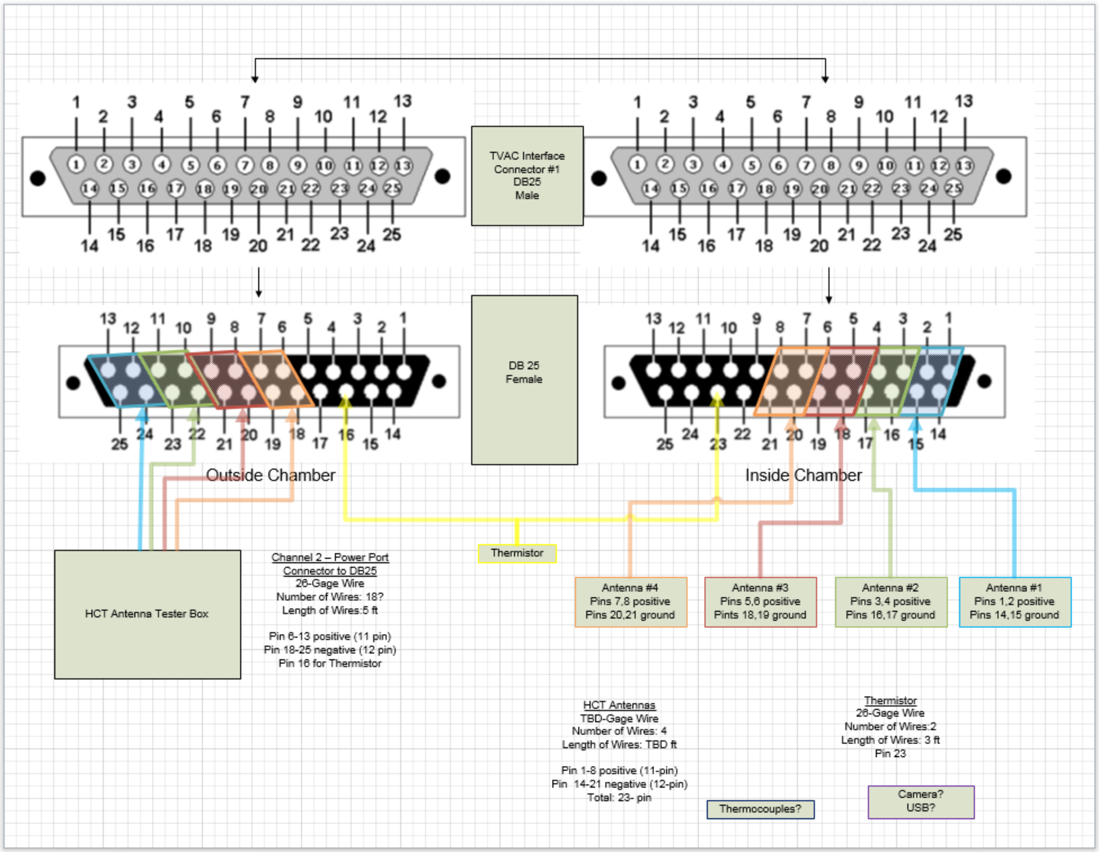

Figure 52. TVAC test VISIO diagram

K-type thermocouples will be placed on the HCT EDUs to measure the temperature of the antenna as the chamber reaches and holds at the desired temperature. The thermocouples will also record the temperature of the EDU as it deploys the antenna when the input voltage is applied. For a single ambient temperature TVAC test, thermocouples will be placed on the antenna filars (see Figure 53), for all other tests thermocouples will be placed on the screw hole intended for the remove before flight (RBF) cover (see Figure 54). This screw location will provide a good estimate of the temperature the EDU will reach.

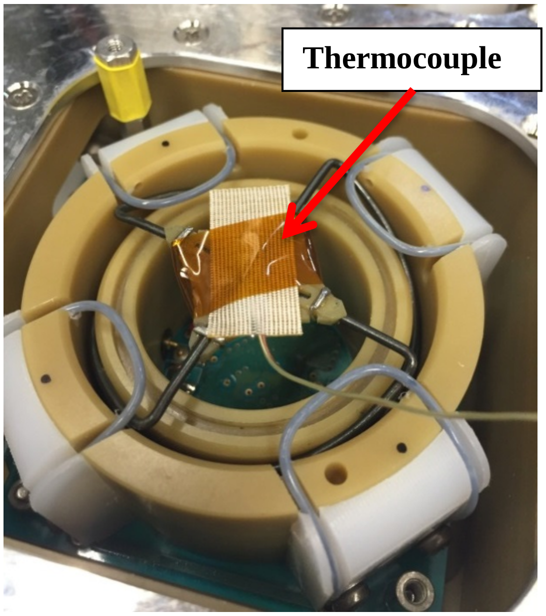

Figure 53. Thermocouple placed on antenna filar

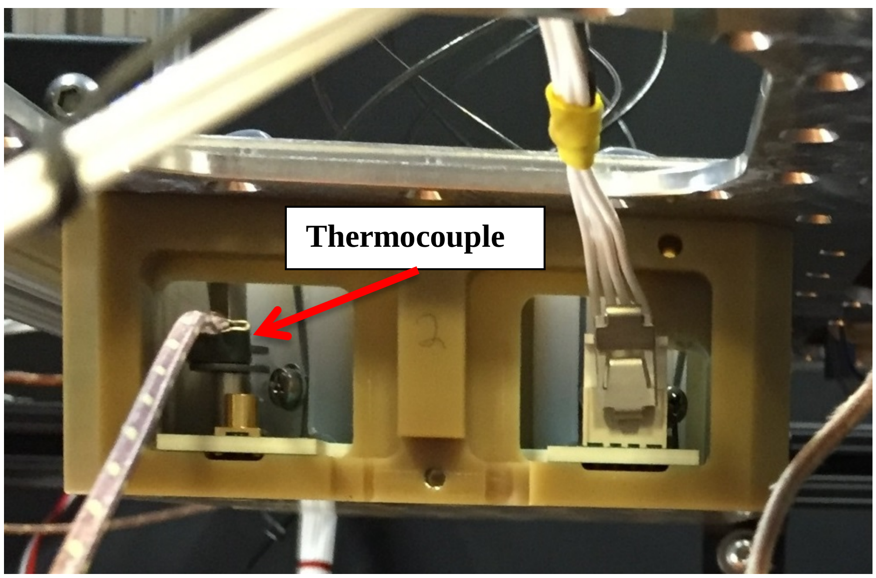

Figure 54. Thermocouple placed on hold down screw hole

3.4.5.2 Data Collected

Deployment height will be measured in the chamber immediately after deployment and again outside the chamber after the TVAC test has concluded. The power supply will record the deployment current. The video cameras will provide a rough estimate of deployment length and will enable the identification of any deployment issues or deformed deployed geometry.

3.4.5.3 TVAC Success Criteria

Complete success, is defined as the antenna successfully completes a mechanical functional test at all points along the thermal profile. Marginal success if at least one antenna along the thermal profile successfully completes a mechanical functional test. Failure if none of the antennas complete a mechanical functional test.

3.4.6 Random Vibe Test

Vibe tests are required by NASA GEVS to verify the HCT QHA will survive the launch environment in the stowed configuration by subjecting it to a random vibration profile with a maximum acceleration of 14.1Grms. [7] Two HCT antennas mounted on a 12U CubeSat chassis will undergo sine sweep and NASA GEVS random vibration profiles with functional tests conducted throughout to identify any mechanical or electrical failures.

The random vibration tests include multiple frequency and decibel level profiles intended to expose any design flaws and induce any failures that a component or satellite might experience during launch, see Figure 55. The tests are completed in all three axes for each test article. The first and final tests will be sinusoidal sweeps that provide calibration data and comparison results for the random vibration test that is conducted between the two sine sweeps. The sine sweep will identify changes in resonate frequencies of the test structure indicating structural failures.

Random vibration is recognized as the most accurate method of simulating dynamic environments that the test subject will experience in real life operations. In the case of our CubeSat components this is the launch vehicle. “A random vibration is one whose absolute value is not predictable at any point in time.” This means the instantaneous amplitude cannot be calculated as a function of time. However, the root mean square of the is controlled. A sinusoidal vibration is periodic and the amplitude can be mathematically expressed as a function of time. Random vibrations excite multiple frequencies at the same time, this can expose the test subject to resonances of multiple structural components. A sinusoidal vibration can only excite one frequency at a time, subjecting the test to a singular resonance. [59]

The random vibration profile delivered by the shaker table is input from an acceleration spectral density (ASD) function that defines the amplitude versus frequency. The ASD function defines the amplitude as the root mean square of (RMS) of the average acceleration with respect to Earth’s gravity and is referred to as Grms. [60] The HCT QHAs will be tested to a random vibration acceleration spectral density (ASD) level of 14.1Grms to satisfy NASA GEVS qualification testing requirements, Figure 55. The vibration test plan is detailed in Appendix B: Vibe Test Plan.

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

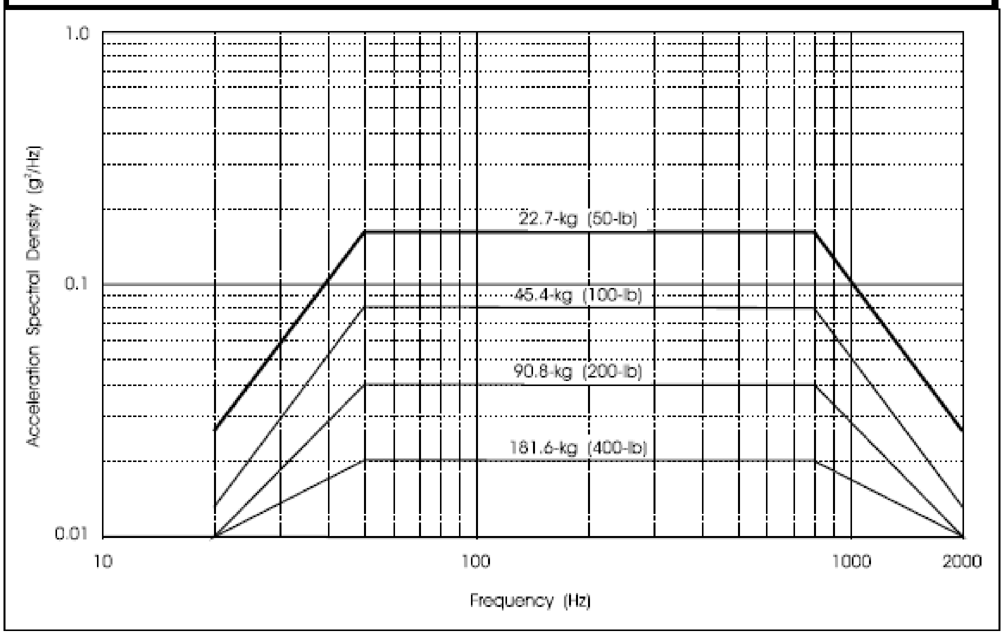

Figure 55. NASA GEVS 7000A Generalized Random Vibration Test Levels [7]

The amplitude for verification tests are determined by the maximum expected flight level (MEFL). For most verification tests an additional margin is added to the MEFL to demonstrate the value of workmanship of the hardware and to ensure it is ready for flight. [50]

Table 5. NASA GEVS MEFLs [7]

Maximum Expected Flight Level (MEFL)	**95%/50% Probability Level**
Test levels	
Qualification/protoflight	MEFL +3 dB
Flight acceptance	MEFL
Minimum component vibration workmanship test	6.8 g_{rms}
Minimum acoustic workmanship test	138 dB
Test durations	
Qualification, single mission	2 minutes
Qualification, multiple (N) reflights	2 + 0.5N minutes
Protoflight	1 minute
Flight acceptance	1 minute
Payload classification applicability	Classes A, B, and C

The sinusoidal sweep from 20 to 2000 Hz has an amplitude of 0.5g. The frequency range of the sine sweep is identical to the range that is implemented for the random vibration profile and is used to acquire frequency response data over the full frequency range. [50] The sine sweep will be repeated after each of the following random vibration profiles at incremental amplitudes of +3 dB increments starting at -12 dB. The intent of the repeated sine sweep vibe test is to compare the frequency plots and to see if there are any changes in the modal response of the test object which is indicative of a structurally failed component.

The second vibration profile is the random vibration profile. According to NASA-STD-7001, random vibration requirements for qualification tests mandate that the test be conducted at MEFL plus 3 dB. [50] Since these test articles are considered protoflight, they are exposed to twice the level of expected flight. Each of the vibration profiles will be run for duration of one minute. The random vibration profile will be repeated at 3dB increments of the required 14g level in order to slowly expose the test subjects to the vibration environment and identify failures that occur before maximum acceleration. The test will begin at -12 dB which is 1/16 of the GEVS profile. The -12 dB test will be immediately repeated to settle any loose components in the test subjects. The random vibration test will be repeated at -6 dB (1/4 of full power), -3 dB (1/2 full power) and 0 dB (full power). The power increments allow identification of failure points before the full power of the test is achieved minimizing collateral damage if failure occurs. [61] The test sequence is illustrated in Figure 56.

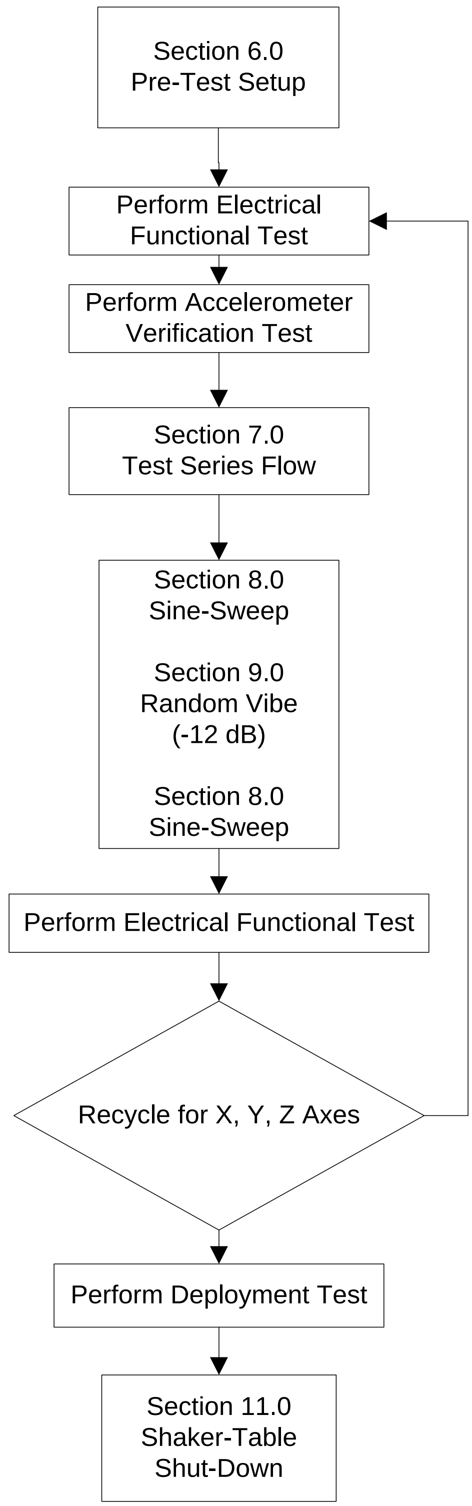

Figure 56. Vibe test flow diagram

As shown in Figure 56, LPT will be completed after each test type to see if an electrical short was incurred during the previous test. The results of each of these tests will be recorded. A CPT will be completed after the final sine sweep to measure the deployment length and current. If either of the antennas fails an LPT the vibe test will be stopped. The type and cause of failure will be identified and the test will be repeated on another EDU antenna unit.

3.4.6.1 Test setup

The vibe tests will be conducted on HCT antenna EDU units without remove before flight (RBF) covers attached. The antennas will be mounted on the 12U AFIT CubeSat chassis that has passed vibration tests. [62] The vibe test must be performed on all three axes of the test article; however the HCT antenna is symmetrical about its deploying axis. Therefore two antennas will be mounted into the 6U chassis oriented along all both the X and Y axes of the CubeSat chassis. In the flight configuration all antennas will be mounted on the same face facing the +Z direction (nadir).

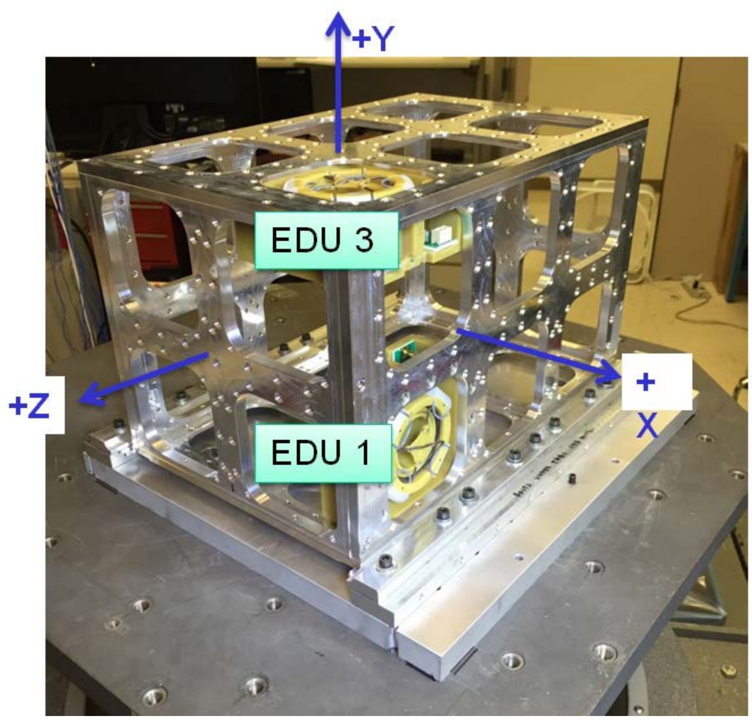

Figure 57. 12 Chassis and two HCT EDU vibe test configuration

Utilizing the empty 12U CubeSat chassis will subject the antenna units to a greater vibrational loading than if they were mounted directly to the shaker table, thus exceeding the levels of required testing. EDU 3 was placed on the +Y face of the 12U chassis to expose it to the worst case vibration environment. The frequency response of the 12U chassis will be imparted to the HCT EDUs. Testing the HCT antennas with the 12U CubeSat chassis will not invalidate the results of the individual antennas as they will still experience the random vibration but their frequency response will be coupled with that of the chassis. While an empty 12U chassis will not reflect the same vibratory response as a fully loaded 12U CubeSat, it represents how the antennas will interface with the CubeSat faces and also how the chassis will interface with the CSD. This satisfies the NASA GEVS requirement of a mechanical testing interface that simulates the launch configuration and when coupled with the 12U chassis will experience a greater loading than if it was mounted directly to the shaker table.

Accelerometers are placed on the article and are used to measure the frequency response to the vibrations. Eight accelerometer channels are available, one will be placed as a control on the vibe table and another will be placed directly on the 12U chassis. The other six accelerometers will be placed on the HCT EDUs at various locations to measure all three axes, see Table 6 and Figure 58.

Table 6. Vibe test accelerometer placement

Channel #	Location
1	Vibe table
2	Chassis +Y face
3	Top of Cylinder (+Y) EDU 3
4	Bottom (-Y) EDU 3
5	Side of Cylinder (+Y) EDU 1
6	+Y Side EDU 1
7	+X Side EDU 3
8	+Z Side EDU 3

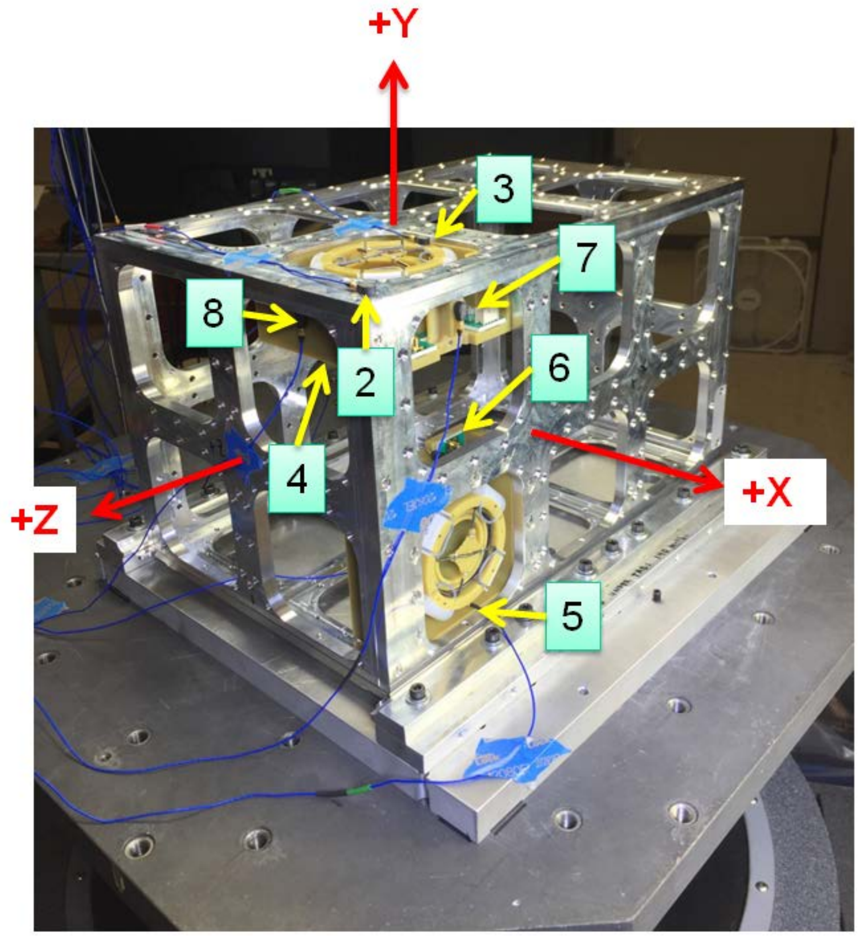

Figure 58. Vibe test accelerometer numbering

3.4.6.2 Data collected

The accelerometers will measure the acceleration response of the 12U chassis and two HCT EDUs in response to the vibe table excitation.

High-speed video will also be recorded throughout the vibe tests. Without high speed video it is impossible to see the motion of the test article during the vibration test due to the high frequency and low amplitude, most of which is faster than what the human eye can see.

Visual inspection will identify any obvious failures as well as the comparison between initial and post sine sweeps. If there are any broken components then there will be differences in the frequency response function of the sine sweep data recorded.

The antenna filar elements and hold downs will be visual inspected after the conclusion of the vibe tests to assess if the tech spray coating on the SMA was chaffed by rubbing on a surface. If the coating is degraded a short could occur. It is expected that a short will not keep the antenna from deploying, but it will likely cause the deployment to take longer since the current will not flow through the entire antenna filar until the antenna extends far enough to eliminate the short.

3.4.6.3 Random Vibe Success Criteria

Complete success if both antennas pass electrical functional tests after each sine sweep and pass a CPT after the final vibe test. Marginal success if one or more antennas CPT and LPT after each sine sweep. Unsuccessful test if none of the antenna units pass mechanical and electrical functional tests after each test.

3.4.7 RF Characterization Tests

After the conclusion of all environmental and deployment testing, 3D beam patterns will be simulated and experimentally measured for all four EDUs using the deployed geometry exhibited by the antennas. In order to completely understand how the geometry of the deployed antenna affects the RF beam pattern, RF beam pattern testing must be done in an anechoic chamber in various positions. The Iso-flux beam pattern impacts the geolocation performance so understanding how the beam pattern is affected by varying antenna deployment geometry is a necessary future test that will not be conducted as part of the research for this thesis. However, there is another method to investigate the impact of deployment geometry on the antenna's electrical performance, called a Voltage Standing Wave Ratio (VSWR) measurement.

3.4.7.1 VSWR Measurement

A VSWR is a simple test that was conducted on a single EDU after the conclusion of the environmental testing. The VSWR will not characterize the change in beam pattern for different antenna geometries, but it can identify whether changing the antenna geometry will affect the power at a set frequency by measuring how closely the source and load impedance are matched. If the radiated power experiences significant changes due to changing antenna geometry, the RF performance of the antenna might also change. Unless either the beam pattern or gain are known it is impossible to perform this analysis. [63]

VSWR is a ratio of the peak amplitude of a standing wave along a transmission line to the minimum amplitude of a standing wave from some input voltage. An ideal antenna would have a VSWR of 1.0, which indicates that no power is reflected back into the transmission line from the antenna. [64]

VSWR measurements will be taken of EDU 1 configured to length, tilt, and twist values of geometry deformation observed throughout the environmental testing. Superposition of a combination of length, tilt and twist will not be measured. The VSWR test setup is shown in Figure 59. The center frequency was set at 1315 Mhz and the bandwidth was set to 100 Mhz.

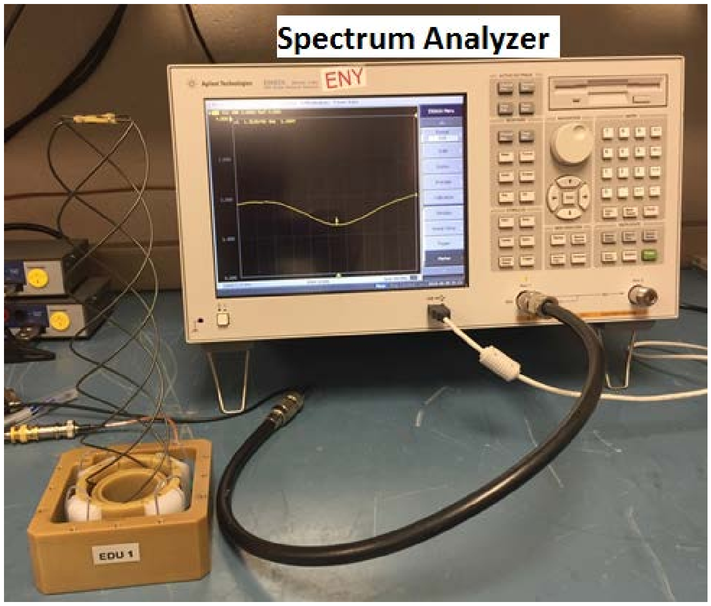

Figure 59. VSWR test setup

3.5 Summary

This chapter discussed the testing approach for the HCT QHA in order to verify the deployable CubeSat antenna will survive launch and to characterize the deployment and potential impacts on RF performance from poor deployment geometry. Chapter 4 will discuss the results from these experiments.

4. Analysis and Results

4.1 Chapter Overview

The results for the various environmental and deployment tests will be presented in the following sections. Overall, all QHAs successfully passed TVAC and vibe testing. The pre- and post-testing deployments and modal surveys provided insight into the effect the environmental testing had on the antenna's deployment performance. The data from the various deployment tests permit the prediction of on-orbit deployment performance as well as provide insight into the concept of operations (CONOPS) for deploying four antennas on a CubeSat mission.

Results for the modal survey, TVAC/solar simulator and vibe tests are presented followed by a deployment results section which presents the data from all deployment tests conducted before, during, and after all environmental testing.

4.2 Modal Survey Results

The experimentally measured modal survey will be used to validate the FEM in future work. The FEA estimated natural frequencies and mode shapes will be compared to those identified through the laser vibrometer experiment in the following sections.

4.2.1 FEA Results

The beam element FEM was used to estimate the modes for all natural frequencies under 50Hz. The mode shapes were determined through visual inspection of the ANSYS animations. The plots are a contour of the nodal displacement of the mode shapes. The mode shapes are defined by the eigenvectors that ANSYS defined to solve the system. The displacement values are scaled to provide a visual interpretation of the deformation of the mode shape and do not represent the actual displacement of the antenna when undergoing forced excitation. The first bending mode is shown in Figure 60, modes 2-9 are included in Appendix D: FEA Mode Shapes

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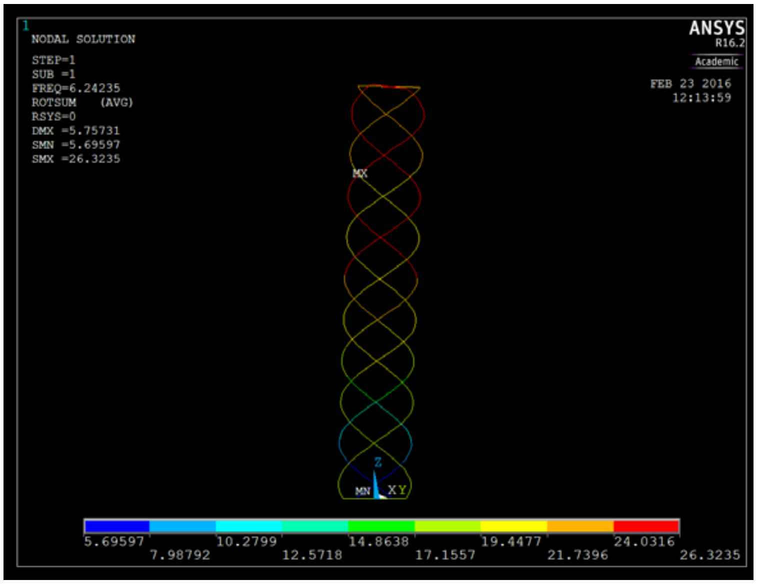


Figure 60. 1st bending mode identified by FEM

The comparison between FEA estimated first five natural frequencies provided by HCT and those calculated for this research are shown in Figure 61. The HCT FEM approach utilized a volume mesh and the FEM created for this research utilized beam elements with a line mesh.

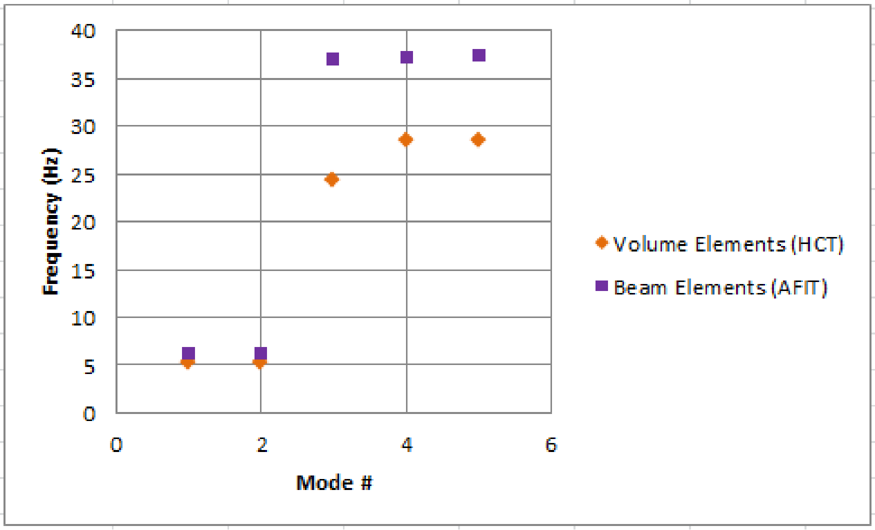


Figure 61. Comparison of volume mesh and beam element FEMs

4.2.2 Laser Vibrometer Experiment Results

A laser vibrometer test was conducted on two of the EDUs before any of the environmental and deployment testing. The experiments were repeated for the same EDUs after the conclusion of the environmental testing to identify any changes in the natural frequencies or mode shapes of the deployed antenna that may be a result of the previous environmental testing.

From the one dimension test, the laser vibrometer experiment identified multiple natural frequencies under 50 Hz for both EDUs tested. The comparison of the pre- and post-testing natural frequency results for EDUs 1 and 3 are shown in Figure 62 and Figure 63. The frequency versus magnitude plots recorded by the laser vibrometer for each test is included in Appendix E: Laser Vibrometer Measured Frequencies.

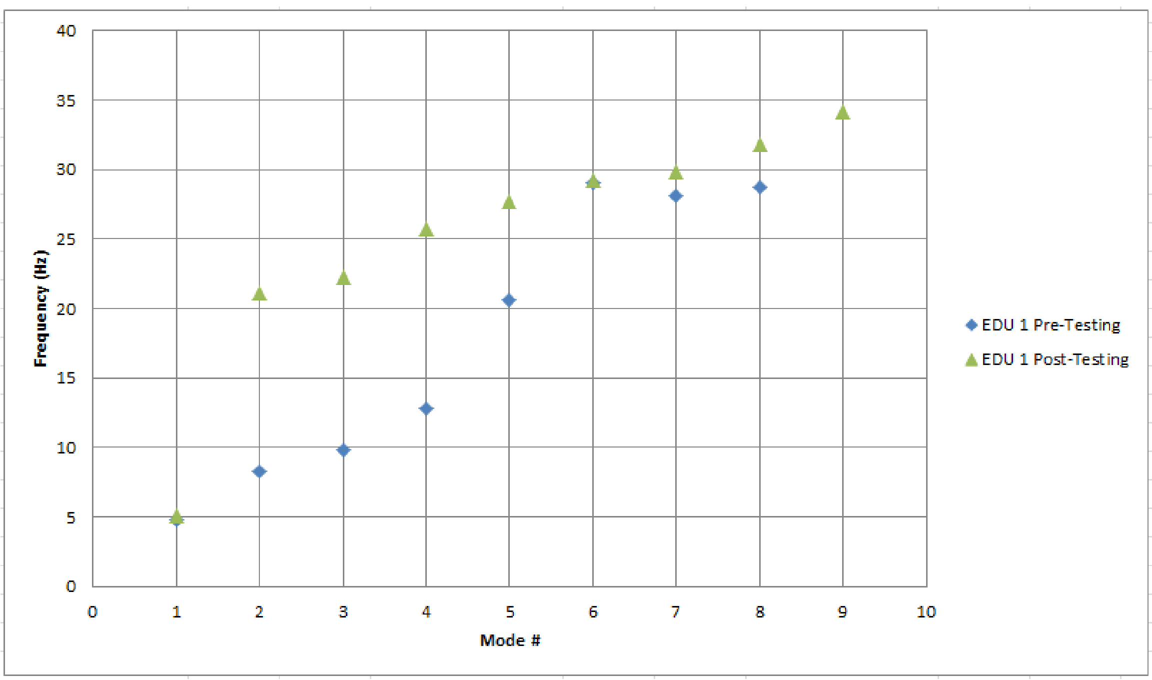


Figure 62. EDU 1 Laser vibrometer measured results for pre- and post-environmental testing

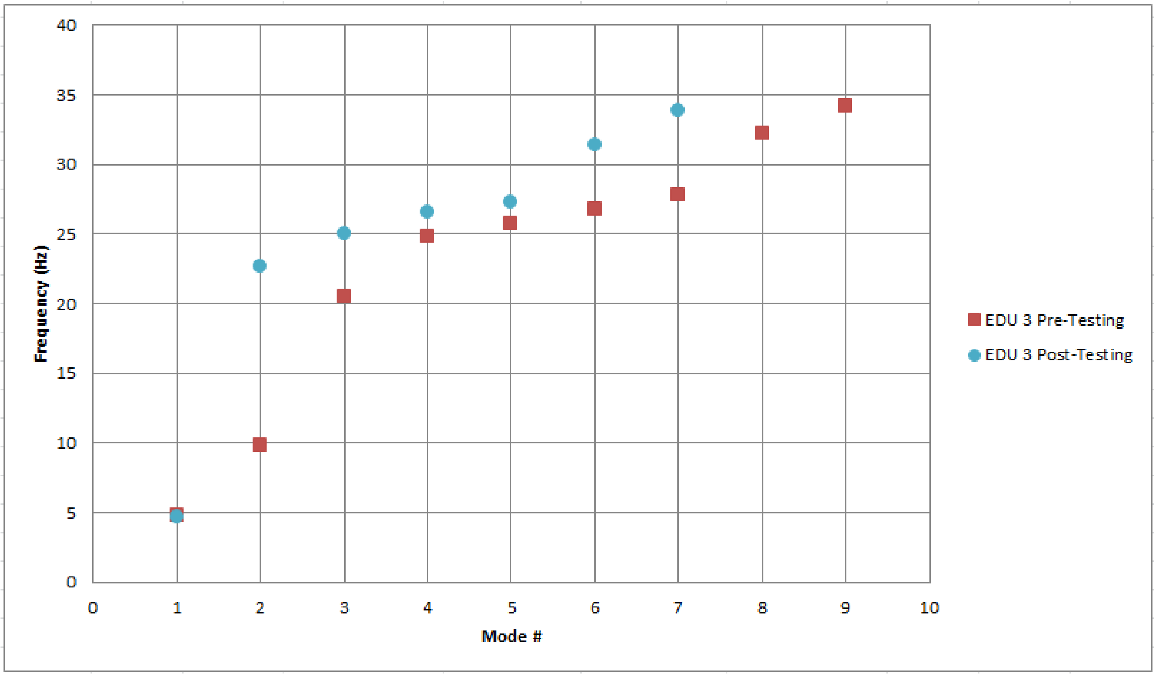


Figure 63. EDU 3 Laser vibrometer measured results for pre- and post-environmental testing

4.2.3 Natural Frequency Comparison

Comparing both the FEA results and the measured natural frequencies allows assessment of which method of FE modeling of the antenna approach works best. Figure 64 shows the identified modes and their respective frequencies for the pre- and post-environmental testing for EDUs 1 and 3 as well as the two FEA approaches.

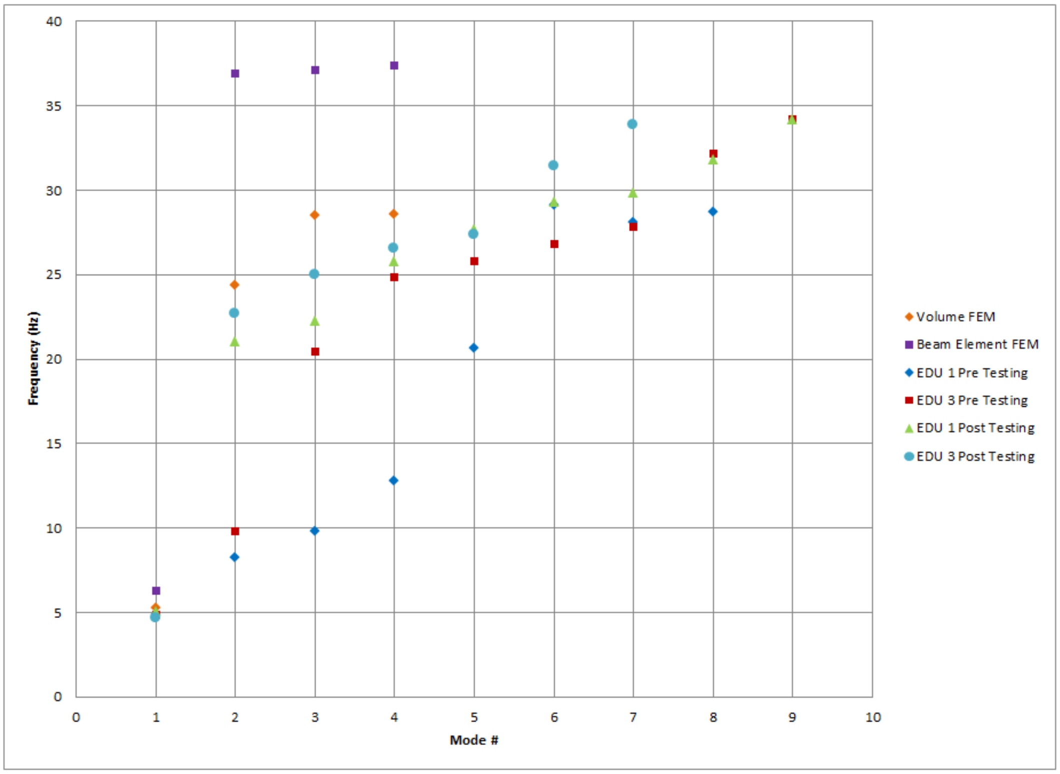


Figure 64. Natural frequency comparison

The volume mesh FEM provided by HCT provided a better approximation than the beam element FEM created for this thesis. Both FEMs overestimated the natural frequencies, especially after modes two and higher. The beam element approach for the AFIT FEM quickly deviated from the experimentally measured natural frequencies; this indicates that representing the helical structure using the Beam18 and Beam189 elements does not provide an accurate estimation of the antenna's frequency response. Tuning the FEM to match the experimentally measured natural frequencies is a recommendation for future work.

The FEA and the Polytec laser vibrometer software identified different natural frequencies; this makes it difficult to compare the mode shapes at each frequency. The flexible antenna exhibited primarily bending and torsion modes below 50 Hz. The FEA results identified several extension and breathing modes but these were not identified from the laser vibrometer experiments.

Additional research and testing is required to create a tuned FEM and to collect laser vibrometer data in more than one dimension to enable an accurate comparison of the natural frequencies and mode shapes. Higher fidelity results can identify whether the natural frequencies of the HCT QHA are affected by the extreme temperature, pressure and vibration environments the antennas were subjected to during environmental testing. Additionally, the damping rate of the deployed antenna should be measured to aide ADCS requirements and CONOPS.

4.3 TVAC Test Results

The temperature profiles of the thermocouples on the QHA recorded the equilibrium temperatures and temperature change during deployment. Length and current data from the deployment tests performed while the antennas were in the TVAC chamber will be presented later in this chapter.

4.3.1 Filar Deployment Temperatures

In order to record the temperature of the antenna filars during deployment, two EDUs were deployed in both atmospheric and vacuum pressures with thermocouples attached to the filar element at the top cross-brace and the RBF cover screw hole. The thermocouple data from these deployments are shown in Figure 65, Figure 66 and Figure 67.

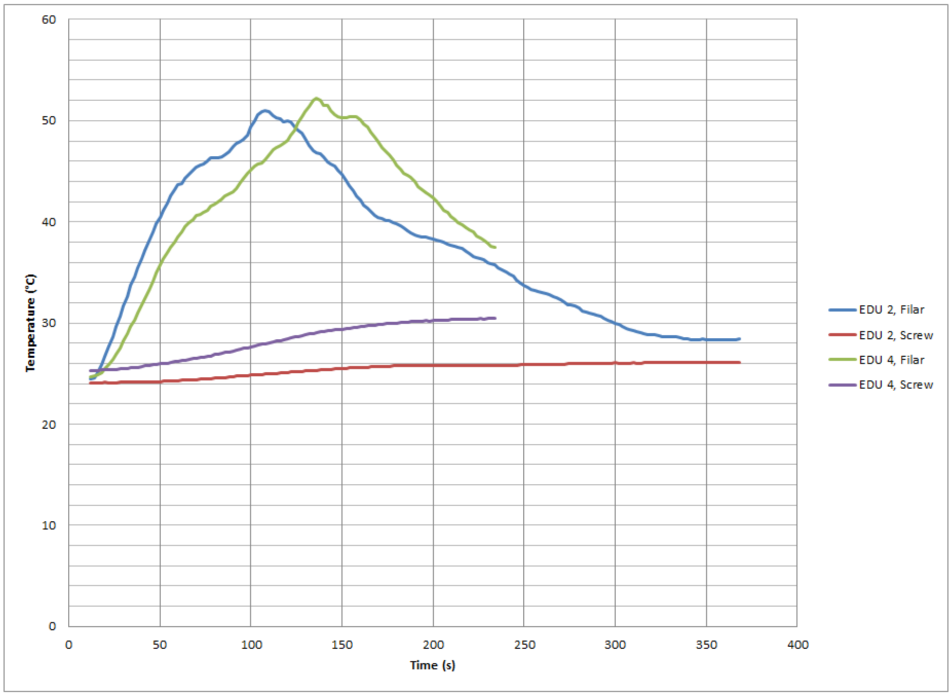


Figure 65. Deployment temperature profiles of thermocouples on the RBF screw hole and filars of EDUs 2 and 4 collected at ambient pressure

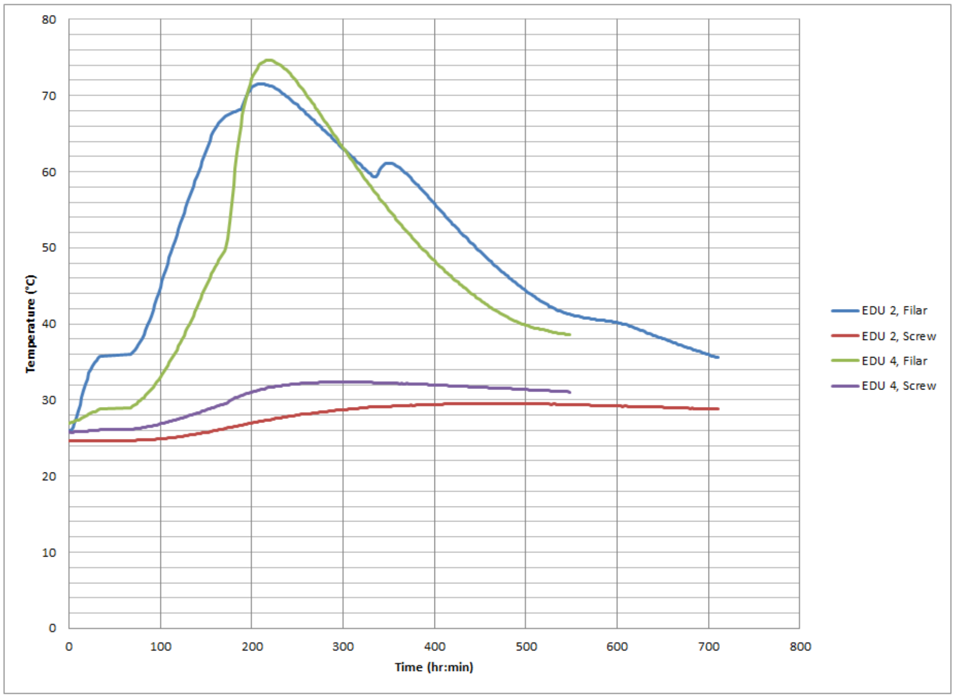


Figure 66. Deployment temperature profiles of thermocouples on the RBF screw hole and filars of EDUs 2 and 4 collected at vacuum

The maximum temperatures reached for each thermocouple and the average rate to reach this maximum are in Table 7. The difference in temperature for the screw hole thermocouples for each antenna is likely due to the single point calibration of the four thermocouples conducted at ambient temperature. At the extreme temperatures the variation is acceptable for this testing to assess the survivability of the HCT QHAs.

Table 7. Thermocouple deployment temperatures

EDU	Pressure	Maximum Filar Temp (°C)	Max Screw Hole Temp (°C)	Average Rate (°/S)
2	Ambient	51.0	26.1	0.27
4	Ambient	52.2	30.4	0.22
2	Vacuum	71.6	29.6	0.24
4	Vacuum	74.6	32.4	0.16

Comparing both the atmospheric and vacuum pressure environment deployments demonstrates the difference in temperature that the filars reach. Figure 67 depicts only the data from the thermocouples on the antenna filars for both the atmospheric and vacuum deployments.

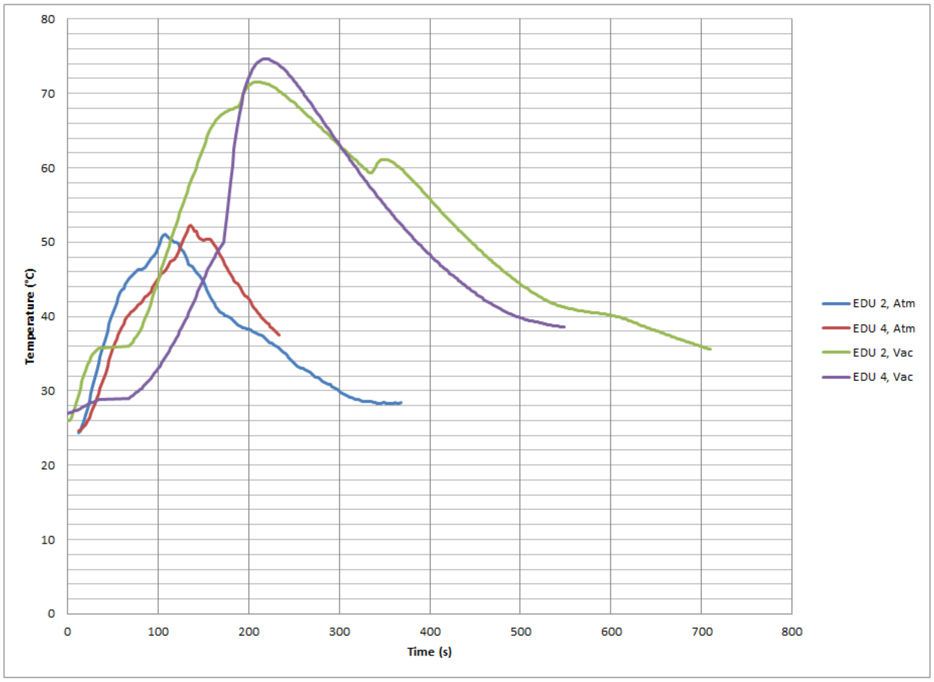


Figure 67. Comparison of ambient and vacuum deployment thermocouple data (thermocouples on fialrs)

4.3.2 Equilibrium Temperatures

The test plan included antenna deployments at ambient (25°C), cold (-20°C) and hot (50°C) temperatures at a near vacuum to simulate LEO orbit thermal conditions. The chambers were set for these temperatures and allowed to sit overnight (~16 hours) to measure the equilibrium temperature reached by the antennas. The temperature data in Figure 68 and Figure 69 are only from thermocouples attached to the RBF cover screw hole for each of the four EDUs. The differences in temperatures between the four EDUs are likely due to single point thermocouple calibration and proximity to the chamber shroud and plate.

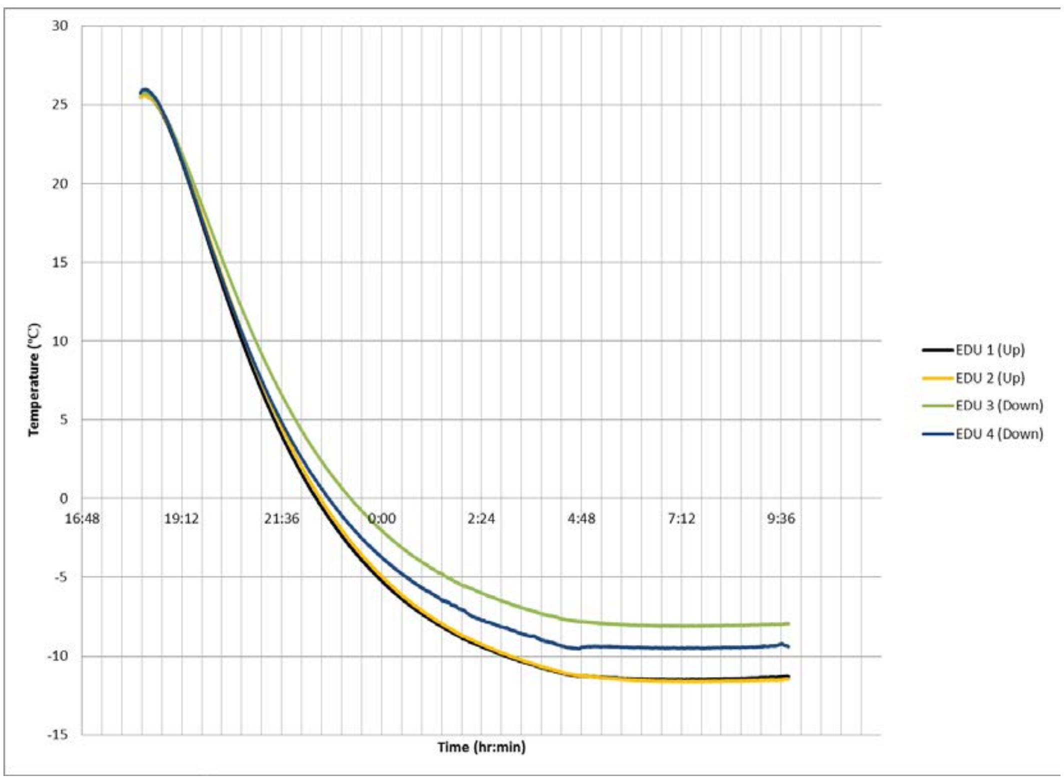


Figure 68. Cold (-20°C) TVAC profile thermocouple temperatures at RBF screw hole for all four EDUs

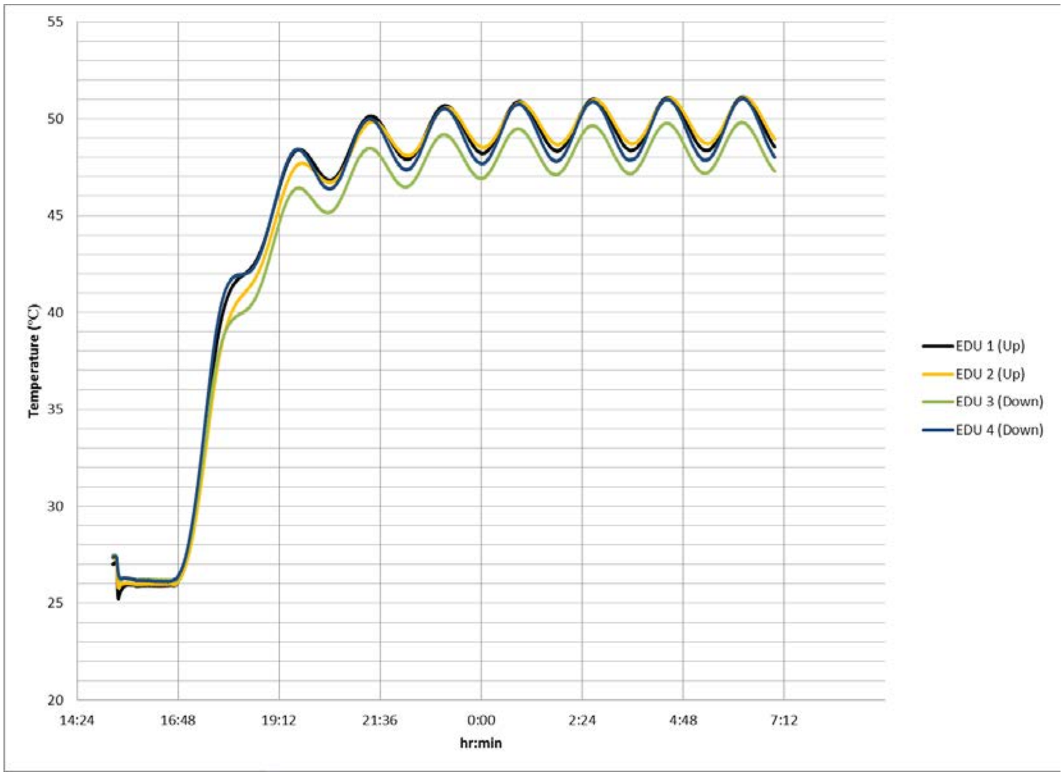


Figure 69. Hot TVAC profile thermocouple temperatures at RBF screw hole

Table 8 lists the minimum temperatures reached during the cold set and the maximum temperatures reached during the hot set. For the cold test, the variations in the equilibrium temperature reached by the EDUs were likely caused by the orientation and proximity to the chamber plate and shroud. The oscillating temperatures exhibited during the hot test are a result of the TVAC chamber itself oscillating to maintain the set temperature, see Figure 69.

Table 8. TVAC equilibrium temperatures recorded at RBF screw hole

EDU	Orientation	Min Temp Reached (°C)	Max Temp Reached (°C)
1	Up	-11.5	51.2
2	Up	-11.7	51.1
3	Down	-8.1	49.8
4	Down	-9.6	51.1

It took approximately 11 hours to reach the cold equilibrium temperature and approximately 5 hours to reach the hot equilibrium temperature. The rates for the near linear region each temperature profile was -.00386 degrees/second for the cold profile and .00701 degrees/second for the hot profile. The equilibrium temperature reached by the antennas will change when they are incased in a complete CubeSat with heat being generated by other components within the spacecraft.

4.3.4 TVAC Deployment Temperatures

Figure 70-Figure 72 depict the temperature reached by the thermocouple placed on the RBF cover screw hole during deployment at the various thermal profiles while at vacuum pressure (2^{-3} Torr).

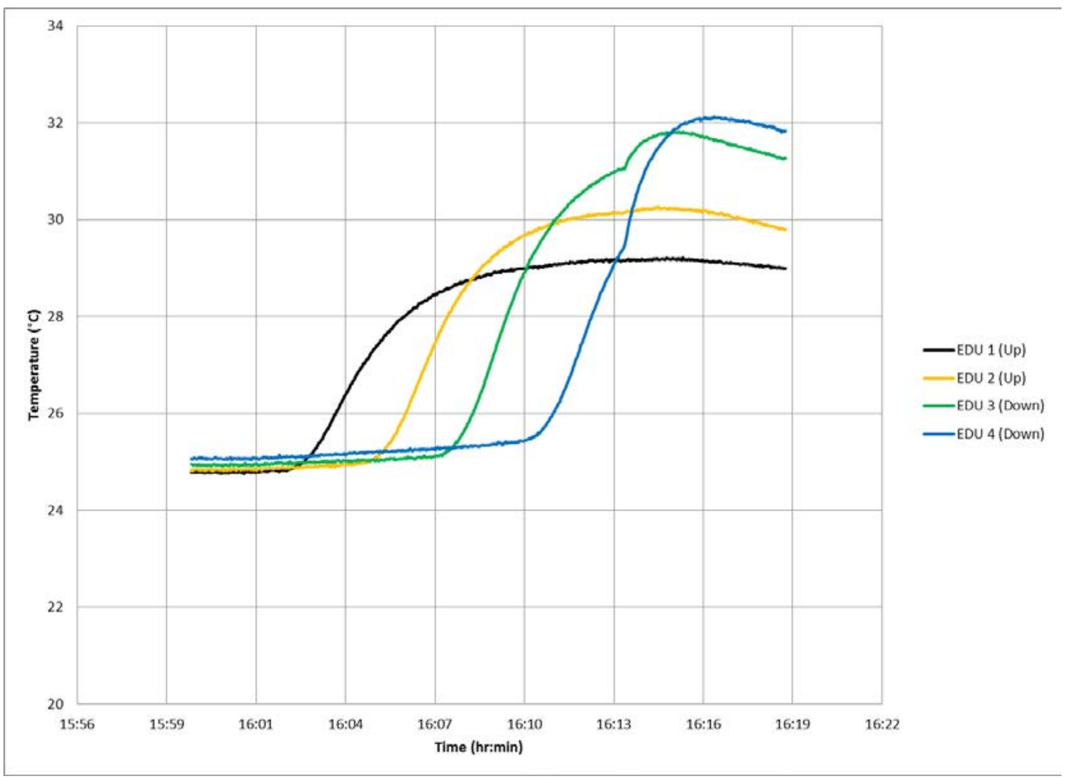


Figure 70. Ambient (25°C) temperature deployment temperatures recorded by thermocouples at RBF screw hole

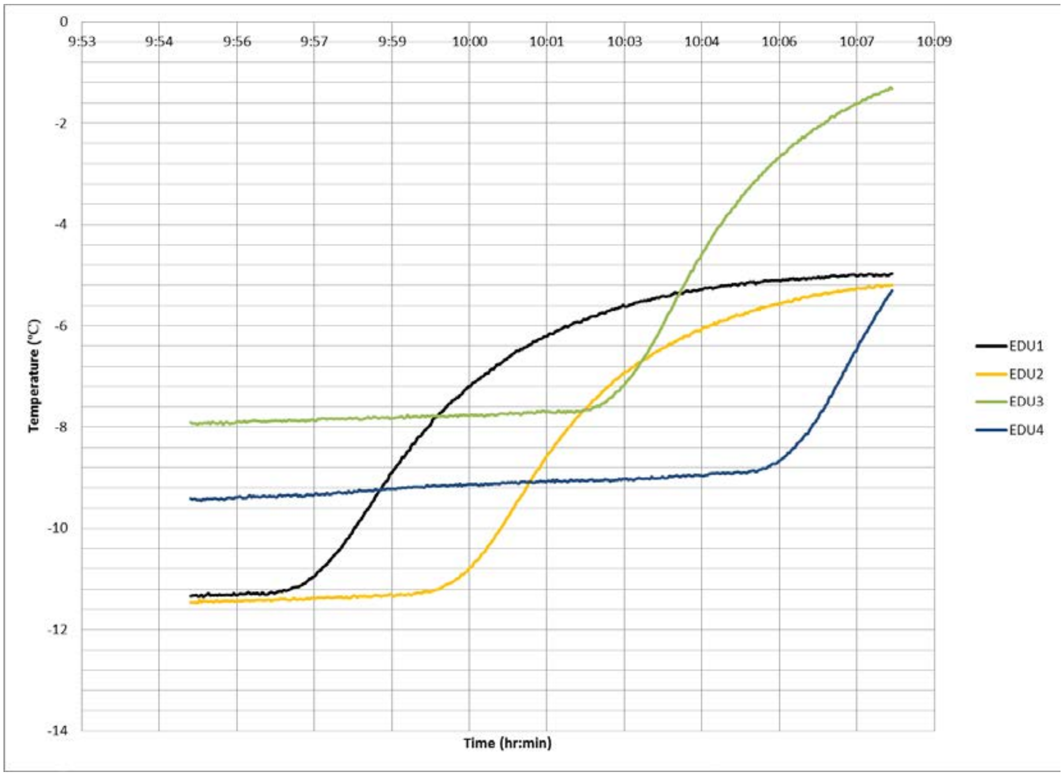


Figure 71. Cold (-20 °C) deployment temperatures recorded at RBF screw hole

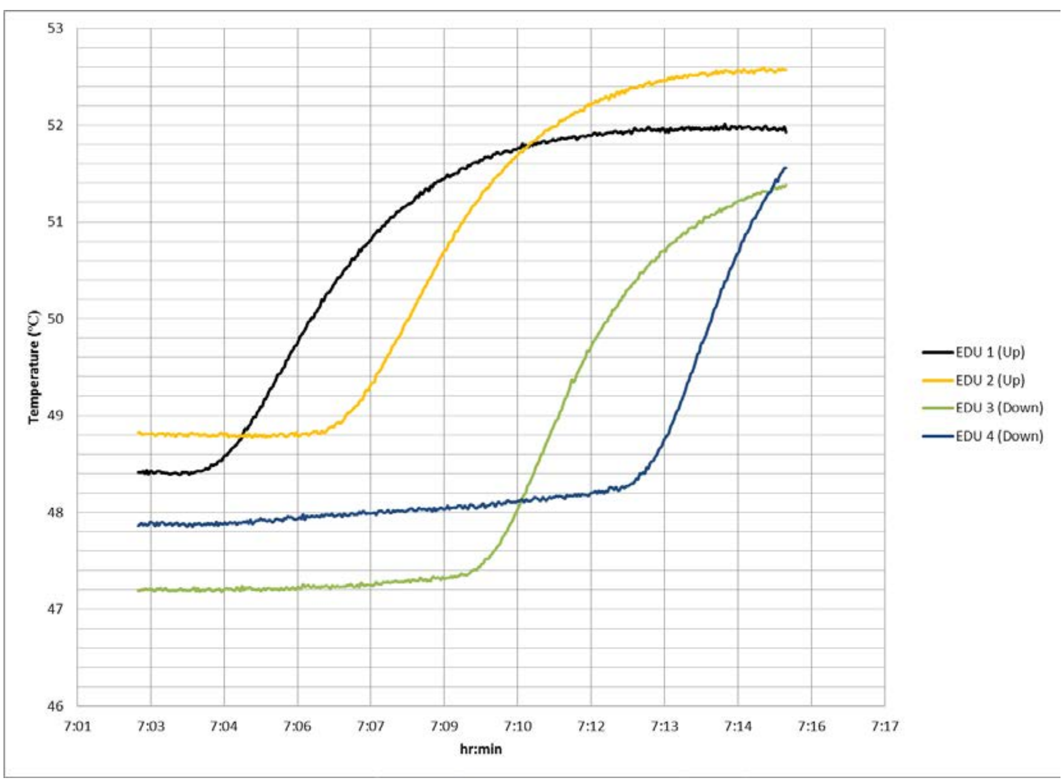


Figure 72. Hot (50 °C) deployment temperatures recorded at RBF screw hole

The increase in temperature measured by the thermocouples on the RBF screw holes due to the antenna deployments are listed in Table 9.

Table 9. TVAC deployment temperature increases recorded at RBF screw hole

EDU	Ambient Deployment Temp Increase (°C)	Cold Deployment Temp Increase (°C)	Hot Deployment Temp Increase (°C)
1	4.5	6.4	3.6
2	5.5	6.3	3.8
3	6.9	6.7	4.2
4	7.1	4.1	3.7

The temperature increase experienced by the filars is much greater than the temperature difference recorded at the RBF screw hole. The deployment temperature variations between the four EDUs was less significant for the thermocouples placed on the filar (≤4%) than for the thermocouples placed on the RBF screw hole (≤48%). The thermocouples placed at RBF screw hole provide a good estimation of the equilibrium temperature of the antenna unit as a whole but they do not provide a good estimation of the temperature the filars must reach to fully deploy. Attaching a thermocouple to the top of the antenna impedes deployment performance and is not a feasible solution for on orbit deployment thermal analysis. Additional research should be conducted to see if it is possible to disassemble the HCT QHA and place a thermocouple on the filar near at the base of the helix.

4.3.5 Solar Simulator

The solar simulator test was conducted in the TVAC chamber after the vibe test. The previous TVAC tests used the chamber plate and shroud to control the temperature. The solar simulator tests relied only on the heat from the solar simulator to affect the temperature of the TVAC chamber. The solar simulator emits light at a measured intensity of 1365 W/m^2. The chamber was pumped down to a vacuum of 2^{-3} Torr and the plate and shroud were set for 25°C.

The solar simulator was turned on and left on overnight. The thermocouples attached to the RBF cover screw hole measured the data shown in Figure 73.

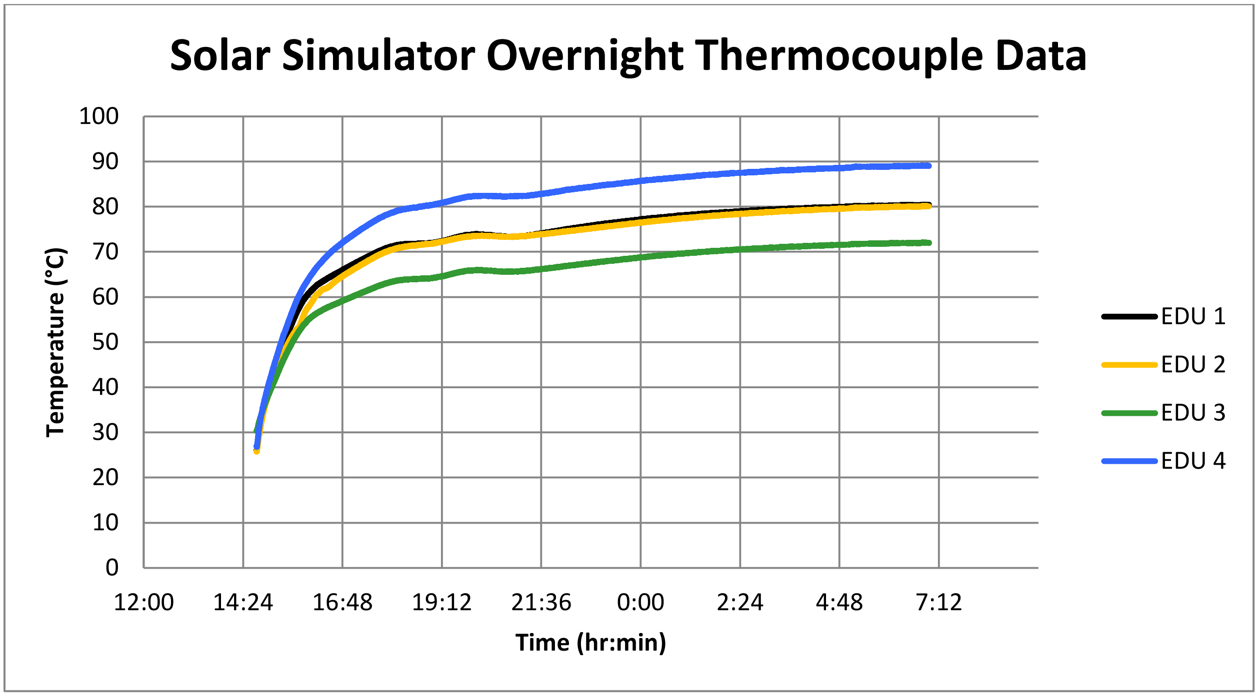


Figure 73. Solar simulator thermocouple temperatures at RBF screw holes

The EDUs reached an average equilibrium temperature after about 15 hours. EDUs 1 and 2 reached an equilibrium of 80°C, EDU 3 72°C, and EDU 4 90°C. The variation in temperature is likely due to the proximity to the mirror reflecting the solar illumination and due to the proximity to the chamber shroud.

The high chamber temperature caused the SMA filars and hold downs to change state and deploy without any applied voltage. EDU 3 was deployed before the solar simulator turned on to observe any affects the solar simulator had on a deployed antenna. EDU 2 was the first to deploy without any input voltage see Figure 74. EDUs 1 and 4 followed suit shortly after, see Figure 75.

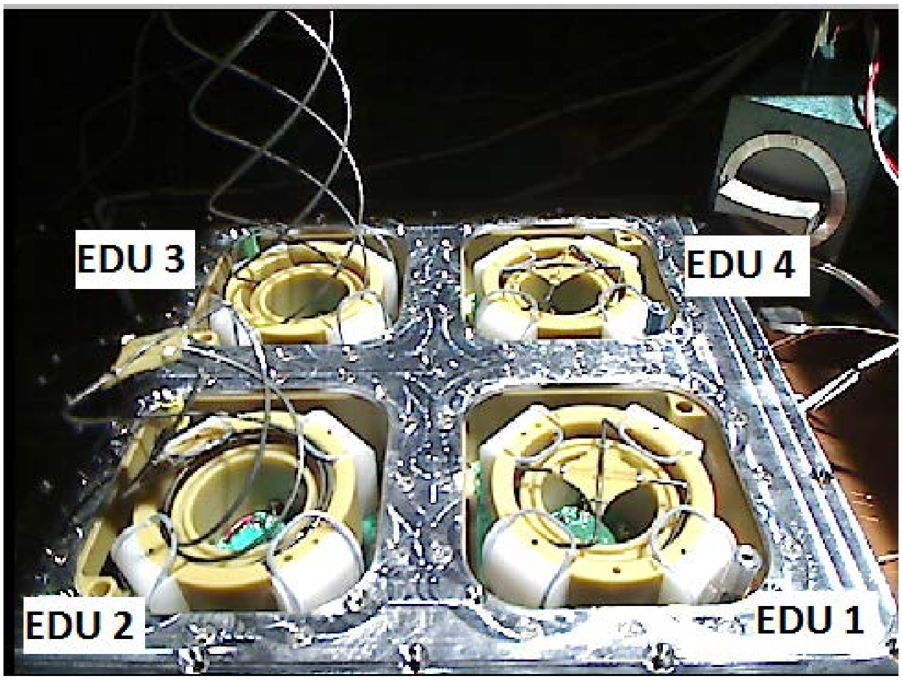


Figure 74. EDU 2 solar simulator premature deployment

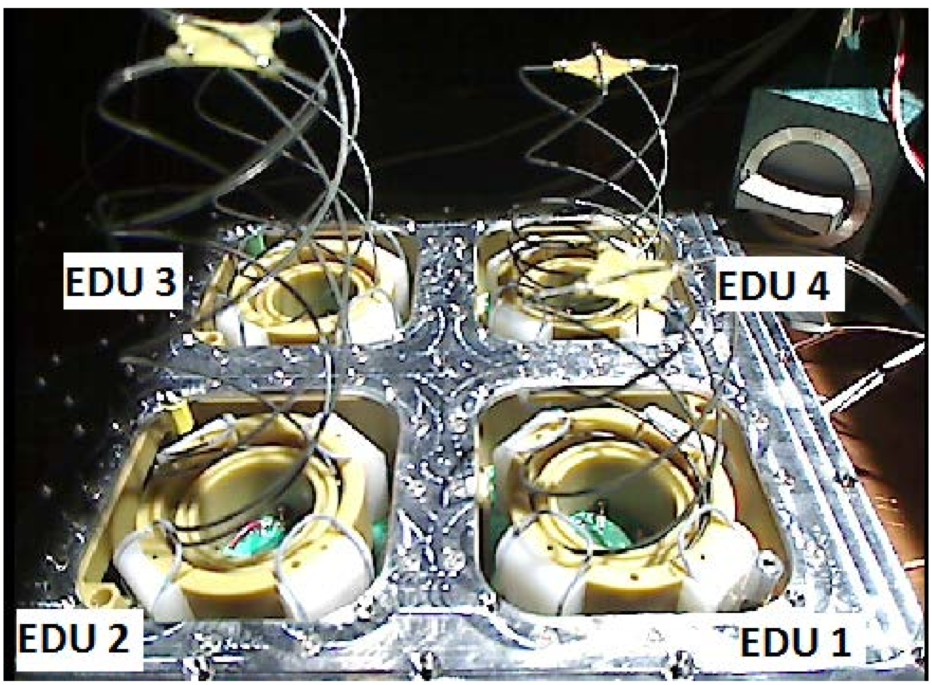


Figure 75. Solar simulator premature deployment, all EDUs

Table 10 shows when each EDU began to deploy (recorded from when the solar simulator was turned on) and when the antenna reached its fully deployed geometry (recorded from when the antenna began to deploy). The temperatures recorded by the thermocouples at the RBF cover screw hole were also recorded. The temperature of the filars and hold downs were much higher than the measured temperature by the thermocouples, as previously discussed in section 4.3.1. The nitinol filars and hold downs are expected to change state when the elements reach 80°C. The temperature of these components were not recorded and additional thermal testing and analysis is required to assess whether this temperature was reached or if the strain energy of the stowed helix caused the antennas to deploy before 80°C.

Table 10. Solar simulator premature deployment timeline

EDU	Time to start deployment (min)	Time from beginning of deployment to fully deployed (min)	EDU temp at beginning of deployment (°C)	EDU temp at end of deployment (°C)
1	50	45	52	63
2	20	60	38	58
4	48	42	54	66

The TVAC tests provided valuable temperature data that reveal the equilibrium and deployment temperatures of the antennas. Learning that the antennas will deploy without an input voltage is critical information will help define CONOPS for the orbit checkout phase and will identify the optimal orientation and location in orbit to deploy the four QHAs. The pressure and thermal effects on deployment will be presented later in this chapter.

4.4 Vibration Test Results

Two HCT QHA EDUs were subjected to sine and random vibrations according to the NASA GEVS profiles. The antennas exhibited only a slight difference in natural frequencies throughout the vibration testing and this is likely due to shifting of the loose stowed antenna elements. The natural frequencies of the combined 12U chassis and two EDUs will be presented in this section as well as any issues with the EDUs identified by the functional tests or by visual inspection.

4.4.1 Natural Frequencies

The first identified natural frequencies are shown in Table 11.

Table 11. Vibe test first natural frequency results

Test	HCT Vibe Test First Mode (Hz)
-12 dB (initial)	389
-12 dB (repeat)	389
-6 dB	387
-3 dB	387
0 dB	382.5

The first mode of the empty 12U chassis measured by Capt Miller [62] was a bending mode about the X-axis at 363.2 Hz at 0dB. The addition of the two HCT QHA EDUs shifted the first identified natural frequency to 382.5Hz. The added mass and stiffness of the two EDUs caused the first natural frequency of the 12U chassis to increase. The identified natural frequencies of the 12U chassis and two HCT antennas do not reflect the natural frequencies of a complete 12U CubeSat. The addition of other subsystems and components will change the frequency response of the satellite. Therefore, comparing the frequencies identified by these experiments to the frequencies allowed by the launch provider, or in this case NASA GEVS, is unnecessary since it does not reflect the final vibratory response of the CubeSat. However, identifying the lowest natural frequency during each sine sweep test and comparing them to the other tests can provide valuable information regarding the structural integrity of the test subjects by identifying any frequency shifts.

The results for channel three, EDU 3 +Y, accelerometer response for the sine sweep after each incremental random vibration profile is shown in Figure 76. The results for all of the other accelerometer channels are presented in Appendix F: Vibe Test Accelerometer Data.

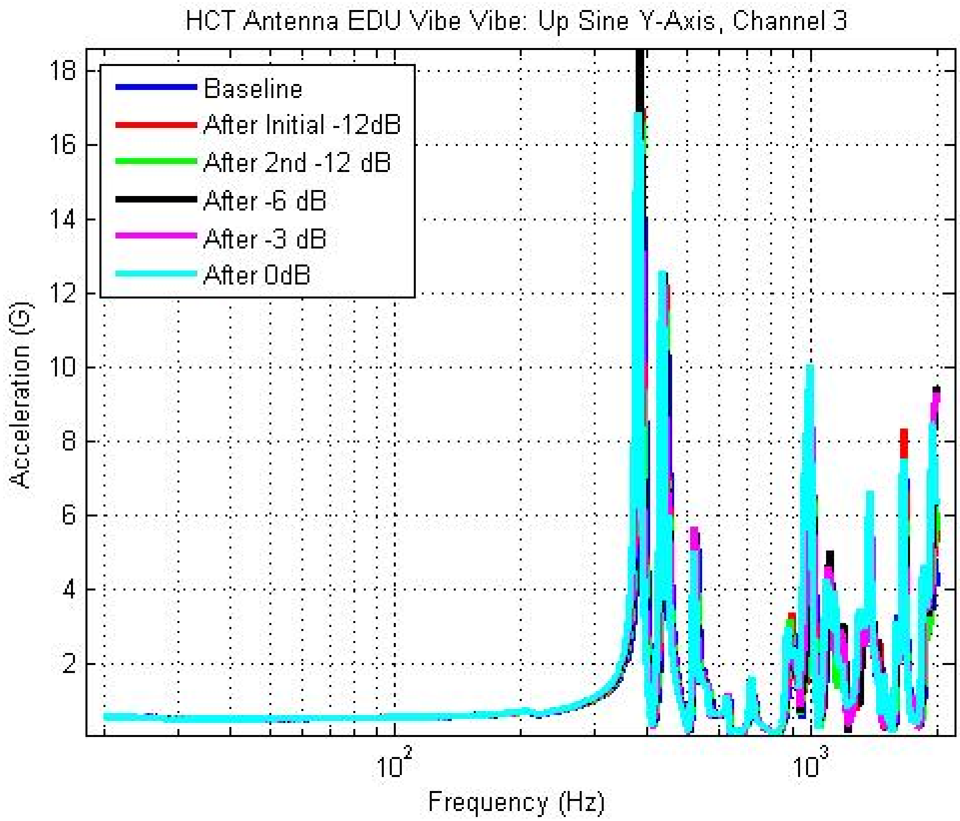


Figure 76. Channel 3 accelerometer data for all vibe tests

The natural frequencies identified during each sine sweep after the previous random vibration profile exhibited a 1.7% difference between the -12dB and 0dB acceleration increments. The small shifts in the first natural frequency indicates that the HCT EDUs did not experience any changes in the structural integrity of the antenna units. The small change in frequency may be a result of wiring harnesses repositioning or it may have been caused by small shifts in the antenna hold downs. The hold downs did not release during the testing but high speed video of the tests revealed that the hold downs did experience some oscillatory motion.

The movement of the hold downs may have changed the physical position of the stowed filars and thus the frequency response.

4.4.2 Structural Integrity Results

Both EDUs passed the electrical functional tests conducted throughout the vibe experiments and successfully deployed after the final 0dB test. The deployment results will be discussed in the following section.

The antennas did experience an issue with the Silicone coatings on the hold downs. The high speed video revealed that the hold downs oscillated and this motion caused the hold downs to rub on the filars and on the edge of the channel in composite casing designed for the hold downs to fold down into. This caused the coating on the hold downs to fray, on several of the hold downs the coating was completely rubbed through and the wire was visible. On some of the hold downs the coating was degraded but not worn all the way through to the wire. The red circles on Figure 77 through Figure 80 highlight several examples of the coating degradation and the blue circle indicates the channel in the composite casing on which the filars rubbed resulting in the coating being chaffed.

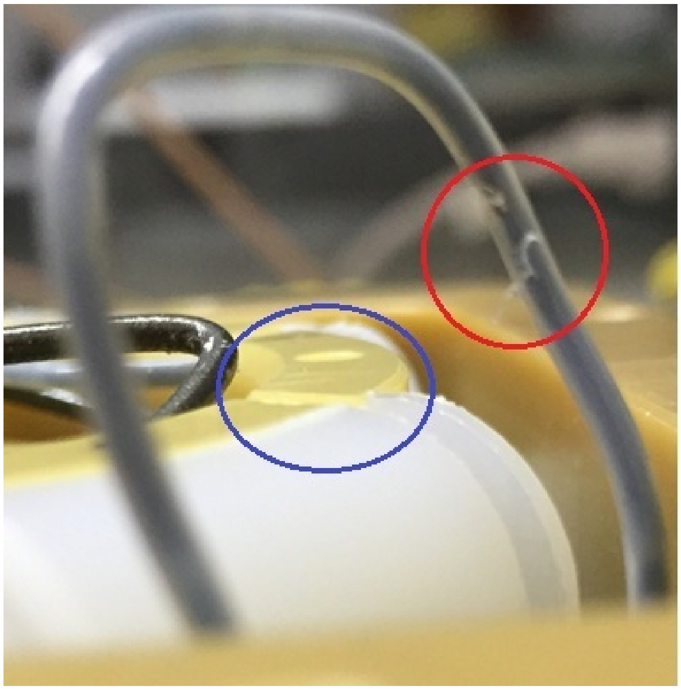


Figure 77. HCT antenna hold down wear

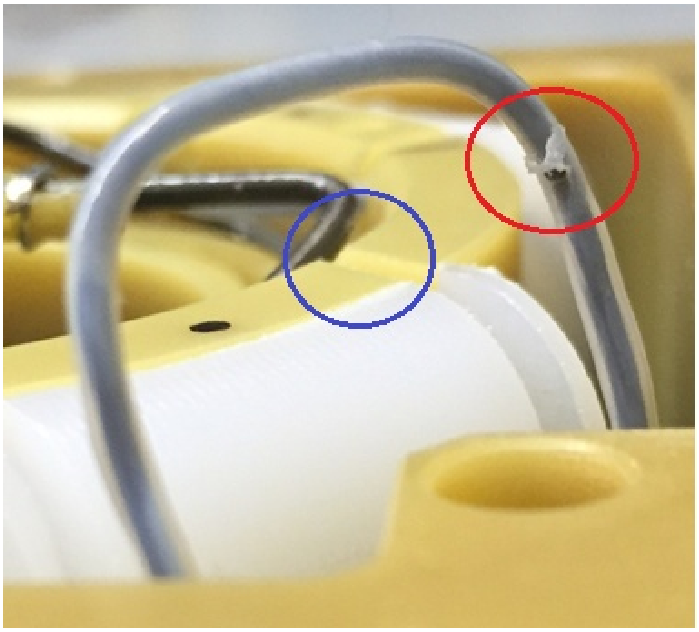


Figure 78. HCT antenna hold down degradation

Figure 79. HCT antenna hold down coating degradation

The hold downs also rubbed on the top of the stowed antenna helix. Some of the coatings on the antenna filar wires exhibited degradation. The green circle in Figure 80 identifies this issue.

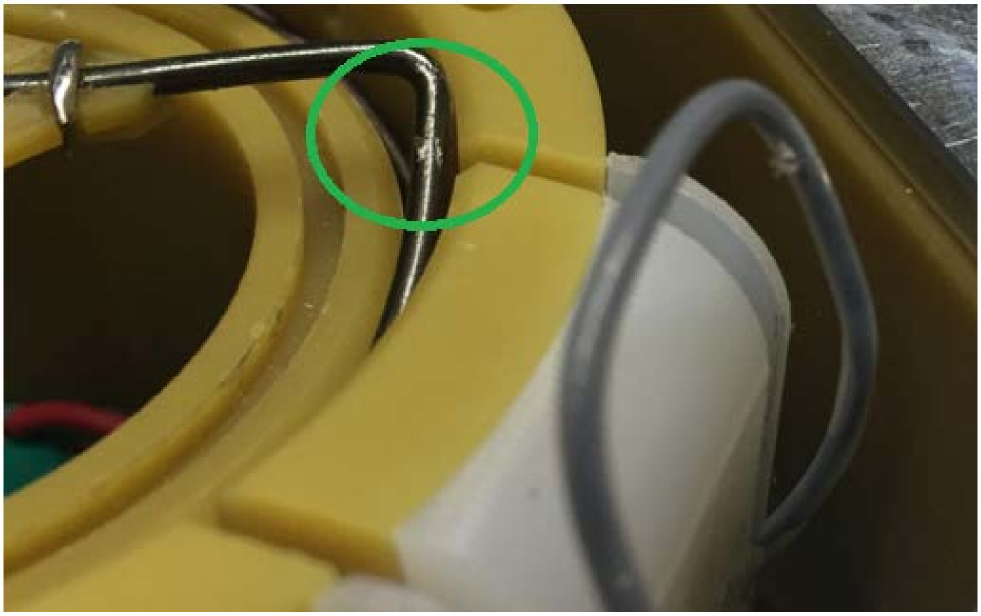


Figure 80. HCT antenna filar wear

The primary concern with the rubbing causing the hold down coating to degrade is the possibility of an electrical short occurring do to the exposed wiring contact. Degrading the filar coating will not affect RF performance but could induce a short during deployment. A short would not inhibit the antenna from deploying due to the single circuit design of the antenna but it may affect how the current flows through the circuit ultimately affecting the deployment rate or time required for the antenna to deploy.

4.5 Deployment Test Results

For each mechanical functional test two things were measured; the deployed length and the current supplied to the antenna circuit by the power supply.

4.5.1 Deployment Lengths

The deployment lengths for each HCT QHA EDU for the various tests are compared in Figure 81 and are presented in the sequence in which they occurred. The EDU vertical orientation for each test is documented, recall that for the TVAC tests EDUs 1 and 2 were oriented to deploy upwards and EDUS 3 and 4 deployed downwards.

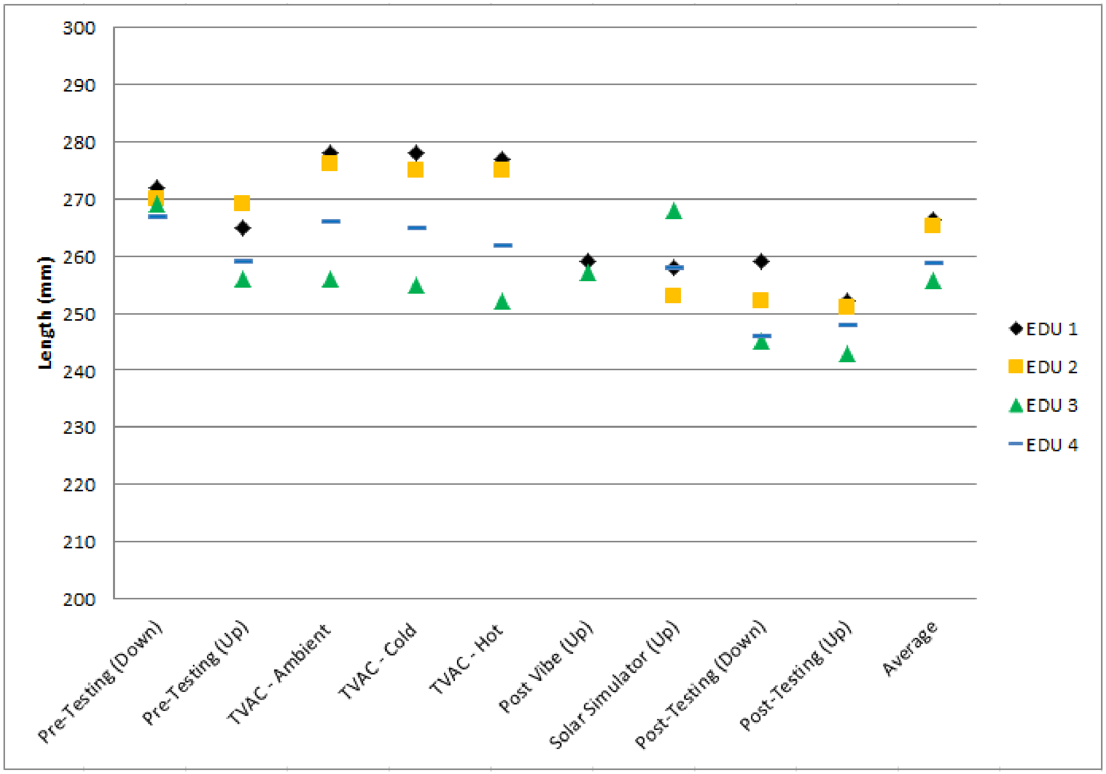


Figure 81. Deployment length results for all tests

The average deployed length for all EDUs was 261.5 mm +/- 30.6 mm (3σ). The variations in length are due the deployment environment and the time the length measurement was recorded. The pre- and post-environmental ambient lab tests indicate that the deployment length decreased after the environmental testing. This trend could be a result of the exposure to the temperature and thermal environments they were subjected to or it could be a result of repeated stowing and deploying. Length variation due to the deployment environment was expected and characterizing this behavior was one of the primary goals of this research.

For the TVAC tests the antenna length was measured in the chamber immediately after deployment and then again outside the chamber at ambient pressure and temperature. The antennas oriented upwards experienced a reduction in length after the chamber was pumped up from the vacuum and the antennas oriented downward experienced an increase in length. Table

12 lists the differences in length experienced by each EDU for the measurements taken inside the chamber at vacuum and temperature and those taken outside the chamber.

Table 12. Difference in antenna length for TVAC length measurements

Test	EDU 1 (mm)	EDU 2 (mm)	EDU 3 (mm)	EDU 4 (mm)
TVAC - Ambient	-21	-18	40	6
TVAC - Cold	-25	-41	41	22
TVAC - Hot	-22	-30	38	9

As the chamber was pumped back to atmospheric pressure and temperature, the geometry of the upwards oriented antennas changed, see Figure 82, taken immediately after EDU 2's deployment, and Figure 83, taken 50 minutes after deployment. In space, gravity will not cause the antenna length to vary after deployment so the TVAC antenna deployments do not accurately predict the deployed length in space but using the length data from all of the deployment tests provide a good estimation of the expected length.

Figure 82. EDUs 1 and 2 cold TVAC deployment, chamber at vacuum

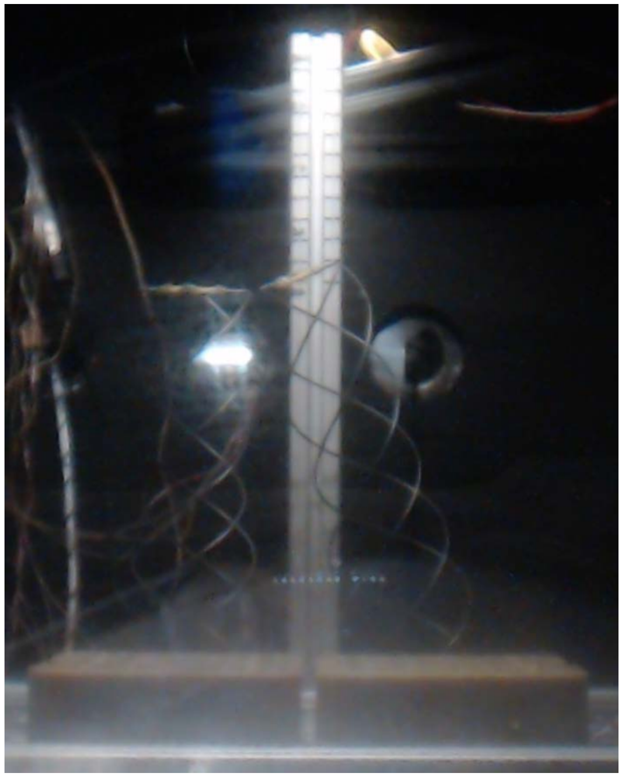


Figure 83. EDUs 1 and 2 cold TVAC deployment, chamber nearing atmospheric pressure

4.5.2 Deployment Current

Continuously measuring the current as the antenna deploys provides several key pieces of information on the antenna deployment. Since the voltage is held constant, it allows you to determine the amount of power required to deploy the antenna. Analyzing the rate at which the current changes indicates when the antenna has reached its final deployed position. When the change in current with time, or the slope, reaches zero then the resistance in the antenna elements is constant and the antenna elements are no longer changing state or shape.

The SMA filars have a resistance that changes as the Nitinol changes from the martensitic phase (32 micro-ohms*in) to the austenite phase (39 micro-ohms*in). [65] Therefore, the current through the QHA innately changes as the antenna deploys and under different test conditions.

For each deployment test the current was plotted against time and are shown in Figure 84-Figure 87. The overall duration of each individual test was not identical, as shown on the X-axis. The input power was turned off by the test operator when visual inspection assessed the antenna had reached its fully deployed length and orientation. Therefore, when analyzing the following graphs the magnitude and the slope of the current should be analyzed rather than the duration of the test. Additional graphs that separate the pre- and post-environmental lab deployments from the environmental deployment currents are included in Appendix G: Deployment Currents.

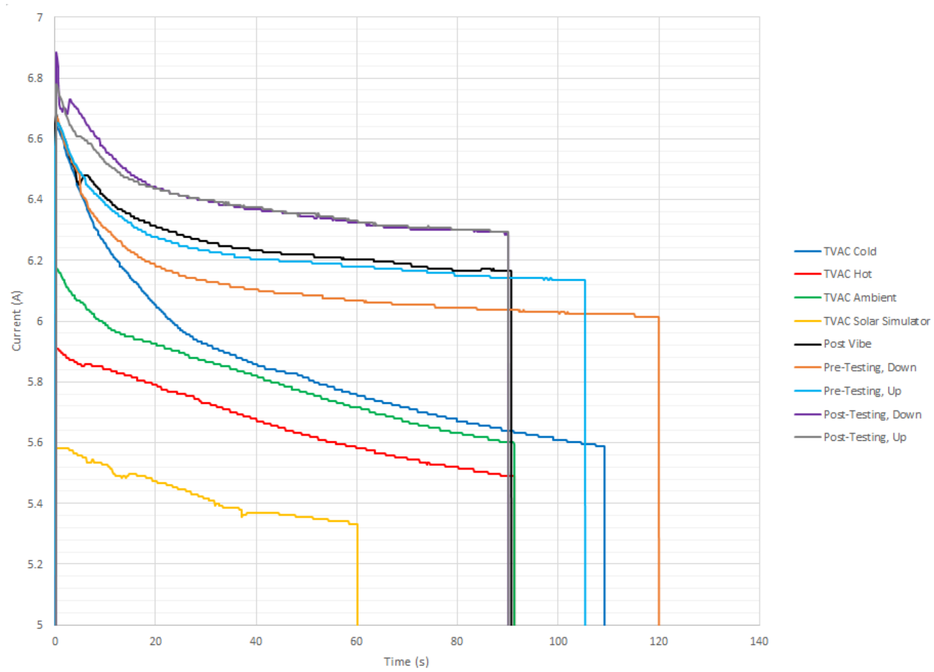


Figure 84. EDU 1 deployment currents for all tests

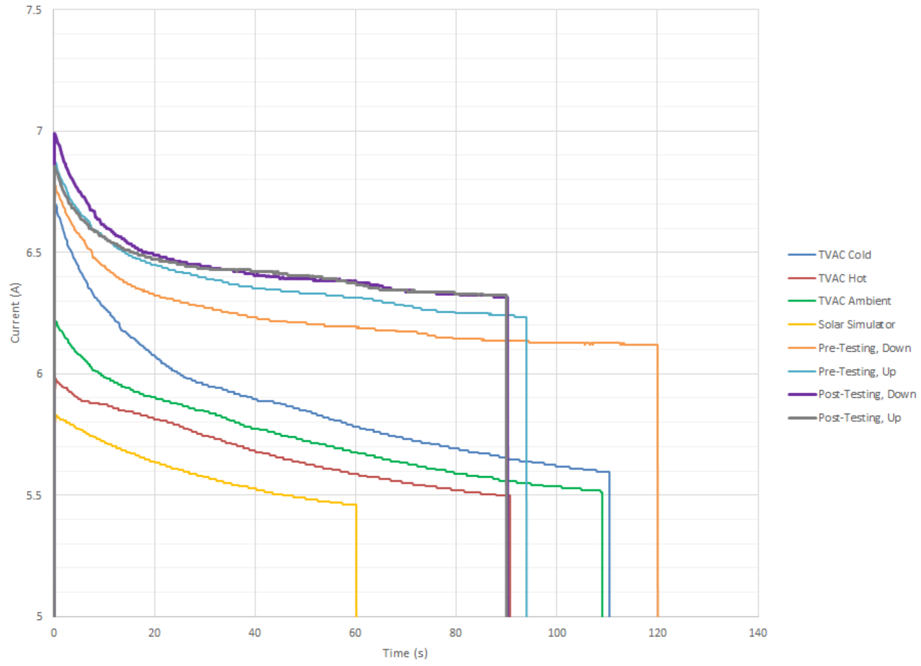


Figure 85. EDU 2 deployment currents for all tests

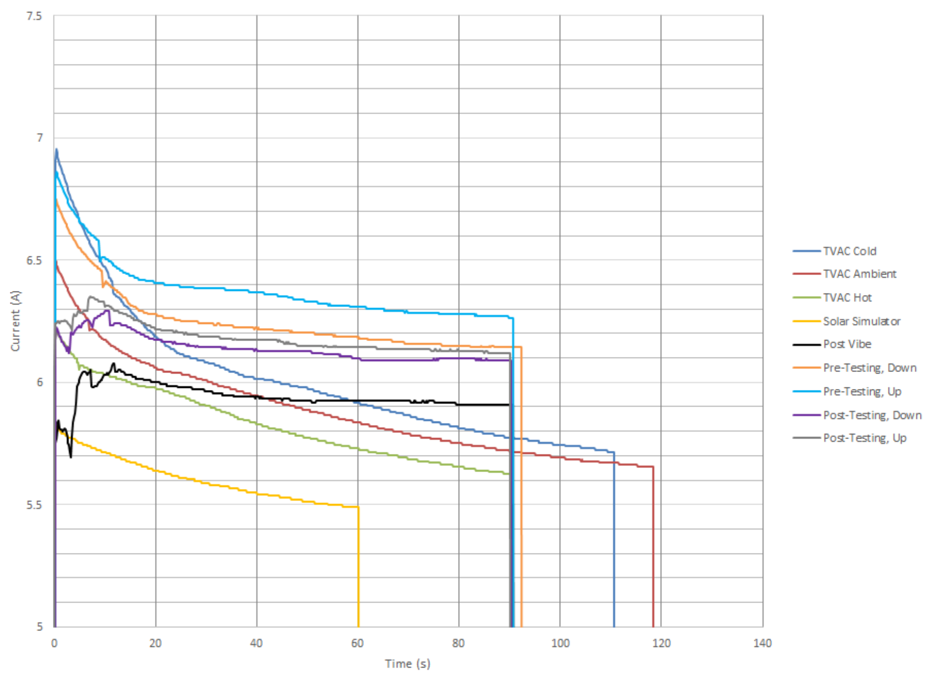


Figure 86. EDU 3 deployment currents for all tests

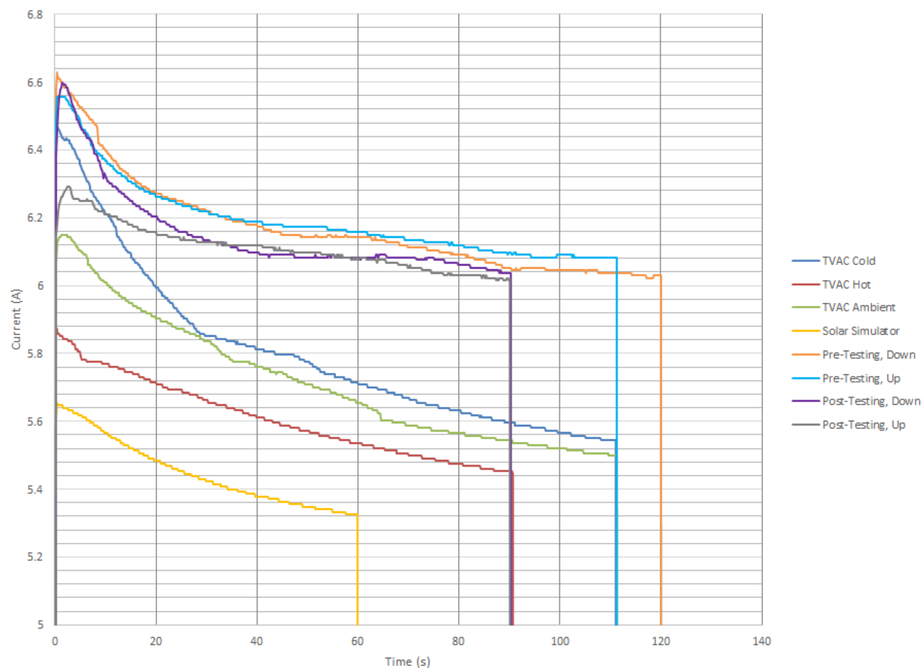


Figure 87. EDU 4 deployment currents for all tests

EDU 3 exhibited unique behavior for all three deployment tests conducted after the vibe test. EDU 1, the other unit to undergo vibe testing, did not exhibit this behavior. The sporadic current variations that occurred within the first 15 seconds indicate that an anomaly occurred somewhere on the antenna circuit to alter and increase the resistance. An electrical short is likely not the cause as it would cause the resistance to decrease, thus increasing the current. This may be a result of altered contact at the hinge connection between the filars and the base that was a result of the vibe tests. Additional analysis is recommended to identify the cause of the current anomalies exhibited by EDU 3.

A typical deployment current spiked up to a maximum value when the power was applied and then gradually decreased as the antenna extended. The magnitude of the initial spike varied by EDU and by test. The following tables present the current spike measured by the power supply for each EDU. EDUs 1 and 2 were oriented upwards during all TVAC tests and EDUs 3 and 4 deployed downwards for those tests.

Table 13. Maximum deployment max current for all EDUs

	Maximum Current (A)			
Test	**EDU 1**	**EDU 2**	**EDU 3**	**EDU 4**
TVAC Cold	6.65	6.7	6.95	6.47
TVAC Hot	5.91	5.98	6.22	5.87
TVAC Ambient	6.17	6.22	6.5	6.15
Post Vibe (Up)	6.68		6.08	
Solar Simulator (Up)	5.58	5.83	5.82	5.66
Pre-Testing (Down)	6.68	6.77	6.75	6.63
Pre-Testing (Up)	6.65	6.87	6.86	6.56
Post-Testing (Down)	6.89	6.99	6.29	6.6
Post-Testing (Up)	6.78	6.86	6.35	6.29
Average	6.44±1.4 (3σ)	6.53±1.4 (3σ)	6.42±1.1 (3σ)	6.28±1.1 (3σ)

Consistently, the atmospheric lab deployment tests experienced a larger current spike than the tests in the TVAC chamber. Of the three TVAC deployments, the cold test experienced the largest current spike. The downward deployments exhibited a greater current spike than the upward deployments.

After the initial spike and decay, the current leveled out as the slope approached zero, indicating the antenna was done extending. Another method to analyze the deployment current is to calculate the change in current, or rate, for each time step measurement**.** By examining the last ten current measurements recorded by the power supply before the test operator terminated the input voltage (after visually identifying the antenna as fully deployed), a running average can be calculated to determine the current rate that corresponds to a fully deployed antenna for each EDU in the various environments. This information, along with the time at which the voltage was terminated, is included in Table 14.

Table 14. Fully deployed current rates and time

	Current Rate at termination (Amps/Second)				Time of Termination (seconds)			
Test	EDU 1	EDU 2	EDU 3	EDU 4	EDU 1	EDU 2	EDU 3	EDU 4
Pre-testing, Up	0.025	0.025	0.025	0.024	105	94	90	111
Pre-testing, Down	0.024	0.024	0.025	0.024	120	118	90	120
TVAC, Ambient	0.022	0.022	0.023	0.022	91	109	118	111
TVAC, Cold	0.022	0.022	0.023	0.022	109	110	110	110
TVAC, Hot	0.022	0.022	0.022	0.022	91	90	90	90
Post Vibe	0.025		0.024		91		90	
Solar Simulator	0.021	0.022	0.022	0.021	60	60	60	60
Post-testing, Up	0.025	0.025	0.024	0.024	91	90	90	90
Post-testing, Down	0.025	0.025	0.024	0.024	90	90	90	90

The average current rate at termination 0.023 ± .004 (3σ) Amps/second. The deployment current rate data establishes a maximum current rate of .025 Amps/second that ground operators can use as a criteria to ensure the antenna is fully deployed when on orbit.

4.6 VSWR Results

The VSWR experiment recorded the VSWR for various changes in deployed antenna geometry. Figure 88 depicts an example VSWR measurement from the spectrum analyzer.

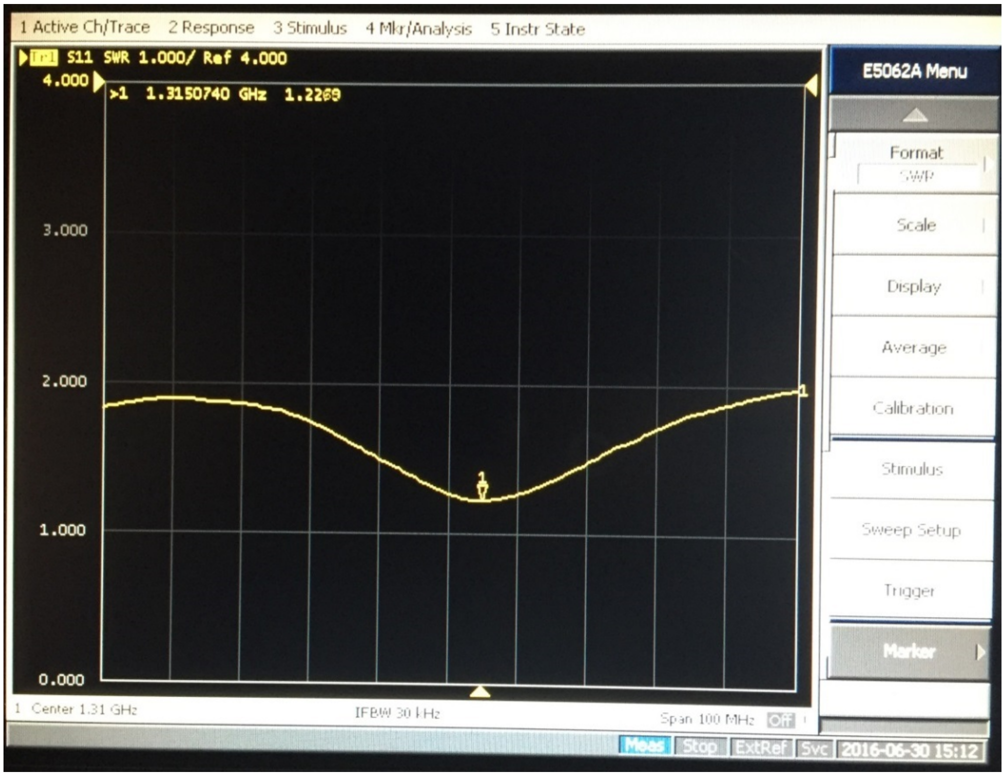


Figure 88. Example VSWR measurement

The results are presented in the following tables.

Table 15. VSWR variations with antenna length

Length (mm)	VSWR
250	1.37
260	1.54
270	1.48
280	1.51
283	1.52
290	1.34

Table 16. VSWR variations with antenna lean about X/Y-axis

Lean (degrees)	VSWR
0	1.39
5	1.40
10	1.42
20	1.53
30Depl	1.55

Table 17. VSWR variations with antenna twist about Z-axis

Twist (degrees)	VSWR
0	1.34
10	1.33
20	1.34
30	1.31
45	1.30
90	1.24

The VSWR test results indicated that if the deployed length was between 260mm and the designed 283mm length, the VSWR difference was within 4%. If the length was less than 260mm or greater than 283mm the VSWR decreased significantly.

Deviation from axial straightness was only exhibited in upwards deployment tests after time, this can be attributed to gravity and thus should not be an issue in space. The VSWR remained within 2.1% if the deviation was less than 10°.

The “twist” about the Z-axis was not recorded during the deployment tests. The VSWR measurements revealed that the ratio is not significantly affected by rotation of the deployed antenna about the Z-axis and remained within 3% under a ±45° rotation.

4.7 Summary

The current and length results from the various tests indicated that the HCT QHA EDUs deploy differently in different environments. The total average of all four EDUS was 261.3 mm. HCT designed the antenna to deploy to a specific length in ambient temperature, pressure and gravity, the tests conducted for this research indicated that the antenna will not deploy to this length in the space environment. A more detailed discussion of the implications of the testing results will be discussed in the following chapter.

5. Conclusions and Recommendations

5.1 Chapter Overview

The experiments conducted for this thesis research provided a testing approach for SMA deployable CubeSat antennas to verify that the antenna will survive launch and deploy and operate successfully on orbit. The research identified a testing sequence that incorporated the deployment testing into traditional environmental space qualification testing. The results from the testing can be used to assess and characterize on orbit antenna deployment. The testing sequence developed decreased the amount of time required to conduct all of the testing by using multiple test subjects simultaneously.

The testing approach was applied to four HCT QHAa which successfully passed all environmental and deployment experiments. The testing did reveal some design issues with the antenna, primarily the premature deployment during the solar simulator test and the degraded hold down wire coating during the vibe test. A premature deployment that occurs in orbit when the nadir face of the spacecraft is pointed towards the sun does not constitute a mission failure. However, if the hold downs failed to retain the stowed antennas during launch, mechanical issues could occur if the antenna deployed in the CSD that could affect the deployed antenna or prevent the CSD from ejecting the CubeSat correctly.

Redesigning the hold downs and their coating to provide a greater resistance when in a high temperature environment and using a different wire coating would deny the antenna from deploying prematurely and would reduce the possibility of an electrical short or other deployment anomalies when subjected to prolonged vibrations. This chapter will discuss the conclusions from each test and will discuss recommendations for future research.

5.2 Testing Conclusions

The testing conducted for this thesis provided deployment characterization data that can be used to plan CONOPS for the future AFIT CubeSat missions. Conclusions and assessments on the HCT QHA's performance for each of the environmental tests are presented in the following sections.

5.2.1 Modal Survey Conclusions

Performing laser vibrometer experiments to identify the natural frequencies and some of the mode shapes of the deployed antenna is critical in understanding the vibration behavior of the deployed antenna and also allowing one to tune a FEM. This was the only test that exclusively analyzed the deployed antenna and the data collected will help drive ADCS requirements/constraints and mission CONOPS related to slew rates.

The laser vibrometer modal surveys before and after the environmental testing showed the first fundamental frequency was not affected by the environmental testing. Both tests identified the first mode at 5 Hz. For all four tests, both EDUs exhibited a torsion mode at approximately 21 Hz. For EDU 1, the post-testing measurements exhibited a 2.2% increase over the pre-environmental testing modal survey. For EDU 3 a 10% increase was observed when comparing the post and pre-environmental testing modal surveys. The only other mode identified by both EDUs in all four tests was a bending mode at approximately 30 Hz. EDU 1 exhibited a 9% increase and EDU 3 a 6.8% increase when comparing the post-environmental modal survey results to the pre-environmental testing modal survey. The shift in natural frequencies identified by the post-environmental testing modal survey may be due to changes in the antenna element material properties dude to the environmental testing or it could just be a results of different behavior of the antenna elements due to inconsistent stowing conditions, such as time remained stowed or the arrangement of the stowed antenna filars. Additional laser vibrometer testing with varying configurations is recommended to increase coherence between identified modes.

The volume mesh FEM provided a more accurate estimate of the first five natural frequencies than the beam element FEM. This could be a result of not modeling the top cross brace in the FEM, or the use of (straight) beam elements to model helical geometry.

The QHA is a complex and flexible structure and a FEM with perfect symmetry and uniform material properties does not provide an accurate representation of the actual antenna behavior. The natural frequencies and mode shapes of the deployed antenna can be affected by the deployment geometry and rigidity of the SMA elements. The deployment tests demonstrated that the deployments are not consistent, and that the deployment lengths and deployment currents post-testing were not identical to the lab deployments pre-testing. The stowing method and duration of remaining stowed could impact the deployed antenna mechanical characteristics thus affecting the natural frequencies and mode shapes. Other difficulties in establishing boundary conditions and proper impact excitation limited the repeatability of the results. Both FEA approaches could be tuned to match the experimentally measured natural frequencies and mode shapes.

5.2.2 TVAC Conclusions

The TVAC temperature profiles and solar simulator provided confirmation that the antennas will deploy in a vacuum and in (-20°C to 50°C) thermal environments. The deployment videos and current data enabled characterization of the antenna deployments. All deployments completed within 120 seconds, with the majority of deployments concluding within 90 seconds. The average TVAC deployment length for the upward and downward oriented EDUs is 261.5 mm ± 10.2 mm (3σ). The deployment axial geometry for the various TVAC deployments did not exhibit any behavior that was different from the baseline deployments outside of the TVAC chamber.

Measuring the temperature of the antenna filars and antenna screw hole during deployment provided valuable thermal information that will assist design of the satellite's thermal subsystem. Analyzing the temperature of the antenna filars during deployment identified that there is a significant difference in temperature reached by the SMA antenna elements in a vacuum versus atmospheric pressure and also demonstrated that the temperature of the filars during deployment exceeds that of the RBF screw hole.

Allowing the antennas to soak at both the cold and hot temperatures revealed the equilibrium temperatures reached when subjected to representative space pressure and thermal environments. The equilibrium temperature of the antennas did not reach the -20°C of the chamber during the cold cycle but they did reach the 50°C during the hot cycle. During the solar simulator test the antennas did reach their hot equilibrium temperature at 72°C for EDU 3, 80°C for EDUs 1 and 2, and 90 degrees for EDU 4. The difference in temperatures reached is likely due to their proximity to the mirror and chamber shroud. This thermal analysis identifies the equilibrium temperature of the HCT QHAs and demonstrates that the unit's minimum temperature is ~15°C and their maximum equilibrium temperature reaches that of their environment.

All four EDUs consistently deployed with the least amount of power required during the hot TVAC cycle. During the solar simulator test the antennas reached the temperature that enabled them to deploy without any input power within an hour. The solar simulator was an excessive test as the nadir face of the satellite will not likely be pointing towards the sun for an extended period of time (for the current CubeSat design see Figure 2). Additional thermal testing and analysis is necessary to identify the temperatures the filars and hold downs must reach before they begin to change state and the antenna deploys.

This deployment thermal information will assist deployment CONOPS for future AFIT missions to identify the satellite's position and orientation that will minimize the risk to deploy the HCT antennas.

5.2.3 Random Vibe Test Conclusions

The random vibe tests verified that the stowed protoflight HCT antennas will survive launch. The consistent sine sweep frequency responses throughout the incremental vibration profiles and pre- and post-testing visual inspections indicated that the antennas internal components did not break or experience significant movement. The successful electrical and deployment functional tests demonstrated that the antenna maintained the ability to successfully deploy after being subjected to vibration (launch).

5.2.4 VSWR Conclusions

The VSWR measurements conducted on the deployed EDU 1 demonstrated that the antenna does experience up to 4% change in reflected voltage ratio if physically manipulated within the range of expected deployment geometries. The primary deployed geometry difference exhibited during the environmental deployments was a variation in length. Additional testing is required to qualify the change in VSWR and understand the impact on gain and beam pattern of the antenna. The <4% VSWR variation means the radiated or received power should also have a small variation. The antenna beam pattern however must also be considered as the geometry is deformed. VSWR cannot be directly related to beam pattern or gain without additional testing. Beam pattern testing of an antenna with deformed deployed geometry was not done as a part of this thesis but is recommended for future research.

5.2.5 HCT QHA Performance Conclusions

The HCT QHA is a robust design that successfully survived all environmental tests and deployed correctly every time the power was applied far exceeding the required 90 percent deployment success rate. HCT conducted RF characterization tests of all four EDUs and confirmed that they operated correctly and produced an expected beam pattern. This data is available from HCT. The lowest natural frequency of greater than 10Hz of the deployed antenna was not successfully achieved. The deployed length requirement was adjusted to 283mm by HCT, this objective was not met for the majority of the deployment tests.

The hold downs struggled to retain the antenna filars after repeated stowing and deployments. The antenna did deploy prematurely in the solar simulator, due to high ante4nna temperatures that exceeded those that retain the antenna filars and hold downs in their stowed state. A single bending axis for the hold downs did not provide enough strength to prevent the stowed filars from releasing. The hold downs had to be bent over and forcibly pushed back against themselves to create a stronger bend in the hold down wires. In addition to the structural integrity of the hold downs, the Silicone coating was degraded during the vibe test resulting several current anomalies in post-vibe deployments. In order to ensure the antenna does not deploy prematurely and to prevent electrical shorts the hold downs should be redesigned. Increasing the diameter of the hold down wires would increase the resistance and overall strength of the wires and would provide greater assurance that they will prevent the antenna filars from releasing until the input power is applied.

The deployed length varied in regards to the deployment tests. This varied between EDUs and by test. This research identified consistent trends in regards to deployment environment and orientation but did not identify any trends between the four EDUS. The VSWR measurements identified that changing the deployed length does affect the antenna waveform centered at 1.315

Ghz so additional research is suggested to study why the antennas deploy to varying lengths and analysis should be conducted to understand the relationship between the deployed geometry and the RF beam pattern.

5.3 Conclusions of Research

The testing approach adequately verified the space readiness of the antenna while characterizing the deployment. NASA GEVS requirements were satisfied by the TVAC and random vibe tests but traditional tests do not satisfy the deployment characterization requirements. Including deployment tests throughout provided information on the effect of each test environment on the HCT antenna's deployment performance.

The effect of gravity affects testing for deployable space structures. The HCT QHA SMA deployment approach did not require additional test equipment to conduct deployment tests. For the experiments conducted for this thesis, the average of upward and downward deployments was deemed sufficient to assess the deployment performance in the LEO microgravity environment. For more mechanical deployable structures, counter balance tests might be necessary to better simulate deployment performance in microgravity.

The current HCT QHA design passed all space qualification testing but two issues were exposed that encourage a redesign of the hold downs. The premature solar simulator deployment and the coating degradation caused by the vibe test could both potentially be fixed by increasing the strength of the hold down wires and improving the durability of the wire coating.

The variation of deployed length exhibited by all four EDUs through the various deployment tests should be used for future RF testing to understand the impact of inconsistent deployed antenna geometry on the beam pattern and ability to conduct AOA geolocation.

5.4 Significance of Research

Various testing results obtained through the testing for this research will aid development of subsystem requirements and CONOPS for a CubeSat utilizing the HCT QHA. Correlating the measured current deployment data and the visually measured deployment geometry will help to characterize antenna deployment while on orbit. Identifying the natural frequencies will help define ADCS slew rates and jitter requirements.

The test plan utilized for this is research only appropriate for SMA type deployable antennas. Other deployable CubeSat antenna types such as folding-rib parabolic dishes or segmented helix structures will require additional testing to verify their articulating deployment mechanisms. The gravity effect on the HCT QHAs was accounted for by deploying the antennas in multiple orientations. Other deployable antenna methods and mechanisms may require additional testing, such as counter-balance, to account for the effect of gravity on deployment performance.

5.5 Recommendations for Action

The test plans developed herein should be implemented for AFIT's flight versions of the HCT QHA to verify performance. A similar testing approach should also be implemented for future CubeSat deployable antennas to optimize the testing by combining the required space qualification testing with the deployment characterization testing.

The testing results divulged several recommendations for defining the CONOPS for antenna deployment and station keeping maneuvers. The nadir face of the satellite should not be oriented towards the sun until it is time for the antennas to deploy. The antennas should be deployed while pointed at the sun to provide the greatest likelihood of successful deployment. The constant 8.4 V should be applied for 120 seconds to ensure complete deployment. The

CubeSat should now slew at a frequency greater than 5 Hz to avoid exciting the natural frequencies of the antenna.

Measuring the current rate at termination provides the best indication of complete deployment. Using thermocouples to measuring the antenna filar temperature during deployment does not provide an accurate indicator of the SMA state change.

The HCT QHA hold downs should be redesigned to ensure the antennas do not deploy prematurely and to avoid electrical shorts. The antenna units with redesigned hold downs should undergo solar simulator and vibration testing to verify their performance.

5.6 Recommendations for Future Research

The variations in lengths, identified through the deployment experiments, should be utilized in experiments and simulations that analyze the effect on RF performance. The best and worst case scenarios identified by the experiments, or the shortest and longest deployments, should be utilized for this analysis.

Repeat the laser vibrometer modal survey multiple times and from varying angles, stowing and deploying the antenna between each time, to analyze whether the shift in natural frequencies identified during the post-environmental testing modal survey was caused by the environmental testing or by variations in the antenna frequency response dude due to inconsistent stowing conditions. The FEM should be tuned to correlate with the experimentally measured data, most likely done using a volume mesh similar to the FEM created by HCT.

Understanding the damping ratio of the deployed HCT antenna would aide ADCS requirements and CONOPS. This can be experimentally measured and would provide additional vibration analysis to supplement the natural frequencies and mode shapes identified by this research.

The issue with the hold down coating wearing through when exposed to extensive vibrations could be resolved by using a thicker or different coating on the hold downs or by rounding the edges of the channels. Additional research and testing is recommended to resolve this issue.

If the deployed axial length of the antennas in space is required research should be conducted to find a space-qualified accurate solution to measure the deployed antenna lengths. Possible methods include a witness camera to enable visual approximations or an RF or ultrasound measurement. If each antenna’s RF performance is characterized pre-flight to varying geometry then link analysis could correlate to the known RF performance of an antenna of a given length.

Since not all spacecraft operate an electrical power system at 8.4 V, additional research testing should be conducted to understand if the HCT QHA can operate at other voltage levels and to characterize the deployment duration at varying power levels.

5.7 Summary

Extensive testing is required to verify and characterize the deployment of a deployable CubeSat antenna. The results of these experiments should be compared to the acceptable deployment geometry and vibration parameters before incorporated on a CubeSat and launched to space.

Appendix A: TVAC Test Plan

TEST AREA B644 L125A
AFIT/ENY
HCT Antenna
WRIGHT-PATTERSON AFB, OH

PROCEDURE:	HCT_TVacTP_rev1
REVISION:	0
DATE REVISED:	22 March 2016
NUMBER OF PAGES:	33

AFIT / ENY
SPACE SIMULATOR VACUUM FACILITY
OPERATIONS

HCT Antenna
Thermal-Vacuum (TVAC) Testing

SYSTEM UNDERGOING TESTING ____________________

ASSOCIATED FUNCTIONAL TEST PLAN VERSION ____________________

TESTING TYPE:

[ ] TVAC Ambient, Cold, Hot, or Cycle Testing
[ ] TVAC/Functional Testing
[ ] TVAC/Solar Simulator Deployment Testing
[ ] Other ____________________

PREPARED BY:

Test Engineer____ DATE ____________
Test Conductor

REVIEWED / APPROVED BY:

AF Customer____ DATE ____________
Test Director

Revision	Notes	Prepared By
0	- Initial procedure modified from SOS	Mr. Kobza 4 Feb 2016
2	- Update document for testing HCT Antenna	Mr. Kobza 22 Mar 2016
	- Document cleanup	
	- Minor fixes and amendments	

TABLE OF CONTENTS

PERSONNEL

EXPERIMENTAL TVAC FACILITY DATE__________________________

The following personnel are designated as test team members, and are chartered to perform their assignment as follows:

Test Conductor (TC) – Responsible for the timely performance of the test as written. This includes coordinating and directing the activities of the Red Crew and other test support teams. TC is responsible for coordinating all pretest activities and outside support required, including (but not limited to) security, fire, medical, and safety. TC is responsible for initialing completion on each step of the master test procedure.
Name______________________________ Signature________________________________

Test Director (TD) – Responsible for overall facility and test safety. Responsible for ensuring all test goals are met and all critical data is acquired. Supervises test activities to ensure procedures are followed. Has authority to perform real-time redlines on test procedures as required to ensure test requirements and goals are met.
Name______________________________ Signature________________________________

Red Crew Leader (RCL) – Responsible for directing the activities of Red Crew members. Reports directly to the TC and ensures all Red Crew tasks are completed. Responsible for ensuring all RCM's have all required certifications and training. Responsible for ensuring all required equipment is available, accessible, and serviceable.
Name______________________________ Signature________________________________

Test Panel Operator (TPO) – Responsible for operating the facility control systems during test operations as directed by TC. TPO is responsible for notifying the TC of any anomalous conditions.
Name______________________________ Signature________________________________

Red Crew Member (RCM) – Reports to the RCL. RCM is responsible for performing test-related tasks as directed by RCL.
Name______________________________ Signature________________________________

Name______________________________ Signature________________________________

Functional Test Operator – Responsible for interactions with HCT antenna such as turning on/off, executing functional tests, verifying HCT antenna is operating correctly
Name______________________________ Signature________________________________

EXCEPTIONS – When filling all positions is not possible, the Test Conductor will assume the duties of any empty position until the completion of the test or a suitable replacement is designated.

ALL TEST TEAM MEMBERS – Responsible for the safe performance of the test. Have read and understood all portions of the test procedure. Any Test Team Member can declare an emergency or unsafe condition

1.0

1.0 ABBREVATIONS AND ACRYONMS

CM	Crew Member
DAQ	Data Acquisition
FCV	Fluid Control Valve
FV	Fluid Valve
HCT	Helical Communications Technologies
HPU	Hydraulic Power Unit
HV	Hand Valve
ICU	Instrument Computer Unit
MAGE	Mechanical Aerospace Ground Equipment
PI	Pressure Indicator
PPE	Personal Protective Equipment
QM	Qualification Model
STE	Special Test Equipment
TC	Test Conductor
TCS	Thermoelectric Cooling System
TD	Test Director
TP	Turbo Pump
TPO	Test Panel Operator
TVAC	Thermal Vacuum Chamber
TVTP	Thermal Vacuum Test Procedure
VP	Vacuum Pump

2.0

2.0 TEST DESCRIPTION AND OBJECTIVES

2.1

2.1 PURPOSE

This procedure provides the means to perform thermal-vacuum (TVAC) testing on the HCT antenna. A simulated space environment (vacuum and temperature gradients) will be utilized to characterize the HCT antenna protoflight component. The AFIT TVAC Facility will be configured with the proper special test equipment (STE) to direct, and measure "maximum predicted environments" associated with operating the HCT antenna in the space environment.

2.2

2.2 SCOPE

This procedure prepares the instrumentation and control system as well as verifies the proper mechanical configuration during the pre-test setup. Vacuum levels in excess of 1×10^{-3} Torr are expected to be reached with accompanying temperature profiles of -15 to +50 degrees Celsius. Test recycling will take place as necessary. The test facility will then be properly secured and reconfigured to a safe state for normal operations. Data will be reviewed and achieved. Any facility anomalies or lessons learned will be noted in a final test report.

2.3

2.3 OBJECTIVES

Complete Success
1. HCT antenna is subjected to all TVAC test requirements set forth in ICD
2. HCT antenna passes all functional tests before, during, and after TVAC testing

Unsuccessful
1. HCT antenna fails any functional tests during TVAC
2. Any HCT antenna component does not survive TVAC testing

3.0

3.0 DOCUMENTATION

The completion of each applicable event shall be verified by marking to the left of the item number. Deviations from these procedures will be coordinated with the Test Conductor (NOTE: TC has the local authority to approve red-line revisions to this procedure).

3.1

3.1 REFERENCE DOCUMENTS

WPAFB- Thermal Vacuum Solar Sim System Manual-081913.pdf

3.2

3.2 SPECIFICATIONS

General Environmental Verification Specification (GEVS)
HCT Antenna Functional Test Plan – April 2016
3.3 HCT Antenna Handling Instructions

3.3 DRAWINGS

0– Thermocouple Locations

4.0 | **4.0 TEST REQUIREMENTS AND RESTRICTIONS**

4.1 | 4.1 TRAINING

The following training is required for personnel using these procedures:

All personnel:
Job Site HAZCOM

4.2 | 4.2 MAXIMUM PERSONNEL:

Control Room: 4

Crew members will utilize the "buddy system" when performing appendices and setting up the Test Facility and will also work in shifts in order to complete the entire test.

4.3 | 4.3 LIST OF EQUIPMENT

HCT Antenna (4)
80/20 Aluminum Test Stand
Power Supply
HCT Antenna Power Selection Interface

Passthroughs:
DB25 Connector with 4 antenna wire harnesses
2 USB Cameras
4 Thermocouple Lines

Ensure all tools associated with this experiment/test/operation are accounted for prior to initiating system/item test. Assure all trash, debris, and FOD is picked up from around the test facility.

5.0 **5.0 SAFETY REQUIREMENTS**

5.1 5.1 PERSONNEL PROTECTIVE EQUIPMENT REQUIREMENTS

Standard PPE: Safety goggles or glasses (as required), hearing protection (when required), safety-toe boots (as required) – soles and heels made of semi-conductive rubber containing no nails.

Cryogenic PPE: Have the following available as required: cryogenic gloves with long cuffs, face shield or hood, and safety goggles.

All jewelry will be removed by Test Crew members while working on the test facility. No ties or other loose clothing permitted (at TC discretion).

5.2 5.2 ABBESS SAFETY INSTRUCTIONS

The equipment is to be operated with an ambient temperature of between 10 degrees C and 30 degrees C.

The equipment is to be operated with an ambient humidity of between 20 and 85 percent.

The use of samples containing ether based, fuel, munitions, or other extremely flammable or explosive materials, compounds, or residues should not be used in the equipment.

Use of acidic or base material may damage the product and are not recommended unless the product was ordered with the optional protective coating in Teflon or made of Stainless steel.

5.3 5.3 EMERGENCY PROCEDURES

In the event of an emergency that jeopardizes the safety of the operators or other personnel perform Section 11.0 – EMERGENCY RESPONSE at the end of this document.

5.4 5.4 SPECIAL INSTRUCTIONS

Test Crew Members shall notify the TC of any leaks from HPU, hydraulic system, or pneumatic system pipe or tubing connections.

5.5 EXPLOSIVE AND PERSONNEL LIMITS

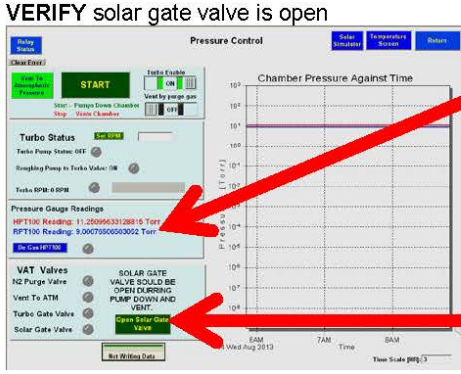
NONE

6.0		6.0 **PRE-TEST SETUP**
_____6.1	TC	**VERIFY** all pages in this procedure are intact and complete
_____6.2	TC	**READ** procedure and input any specific information required to perform operation.
_____6.3	TC	**VERIFY** with Facility Management that no open Work Orders / Issues are listed for the TVAC Test Facility, impeding operations.
_____6.4	TC	**PERFORM** Setup Brief with Test Crew Members and note any redline changes on Appendices.
_____6.5	TC	**VERIFY** Test Crew has donned standard PPE (and noted restrictions).
_____6.6	TC	**VERIFY** that Section 9.0 is complete.
		_____ Section 9.0
_____6.7	TC	**PERFORM** Pre-Operation Brief with Test Crew Members - Objective - Personnel and assigned roles/duties - Safety: materials, PPE, communication, etc. - Sequence of events - Emergency procedures
_____6.7.1.	TC	**RECORD** Pre-Test Brief Time ________
_____6.7.2.	TC	**VERIFY** all personnel involved with the operation have signed this procedure.

7.0		**7.0 VACUUM PUMP OPERATION**
_____**7.1**	TPO	**VERIFY** data recording started for: _____ Vacuum Chamber Logfile _____ Thermocouple & Electrical Power Recording Station
_____**7.2**	TPO	**RECORD** RPT-100 (Digital Pressure Gauge – Top Left of Chamber: ________________ Torr (TVAC Vac Level)

RPT-100 Digital Vacuum Gauge

_____**7.3**	TC	**VERIFY** GO/NO-GO status with test team to begin vacuum pump ops: _____ TD _____ TC _____ FTO _____ TPO
_____**7.4**	TPO	**VERIFY** solar gate valve is open



This is where the RPT pressure is read.

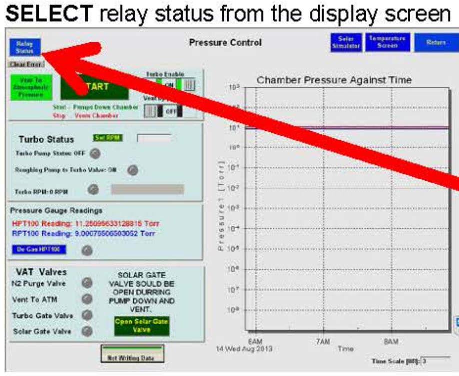
Click this button to open solar Gate Valve

_____**7.5** TPO **VERIFY** that nitrogen tank (in the back center of room) has a reading labeled PI-152 which is greater than 50psi.

_____**7.6** TPO **OPEN** yellow Nitrogen valve located at the back left on top of the chamber.

Nitrogen valve on top of chamber

SELECT relay status from the display screen



Click this button to enter the relay status screen

_____**7.7** TPO **START** Vent the chamber with nitrogen gas by switching relay 4 (N2 purge) into the on position.

Relay Number 4 Status Indicator

_____**7.8** TPO **STOP** Vent the chamber by switching relay 4 (N2 purge) into the off position when pressure is greater than 760 Torr

_____7.9	TPO	**CLOSE** Nitrogen valve
_____7.10	TPO	**START** Pump down the chamber by pressing the large green START button in the center top portion of the screen.
_____7.11	TPO	**RECORD** RPT-100 once every 5 minutes (or at TC discretion) during pump down:

Time (hhmm)	Vacuum Level (Torr)

NOTE: Roughing takes approximately 30 minutes to achieve desired condition

NOTE: When chamber vacuum reaches $2x10^{-3}$ Torr, record the time: ____________________

_____7.12	TPO	**VERIFY** data recording operating nominally, or as expected for: _____ Chamber Data log file Record name of file: ____________________ _____ Thermocouple & Electrical Power Recording Station
_____7.13	TPO	**RECORD** vacuum level: ____________ Torr
_____7.14	TC	**PROCEED** to Section 8.0 for Thermal Cycling

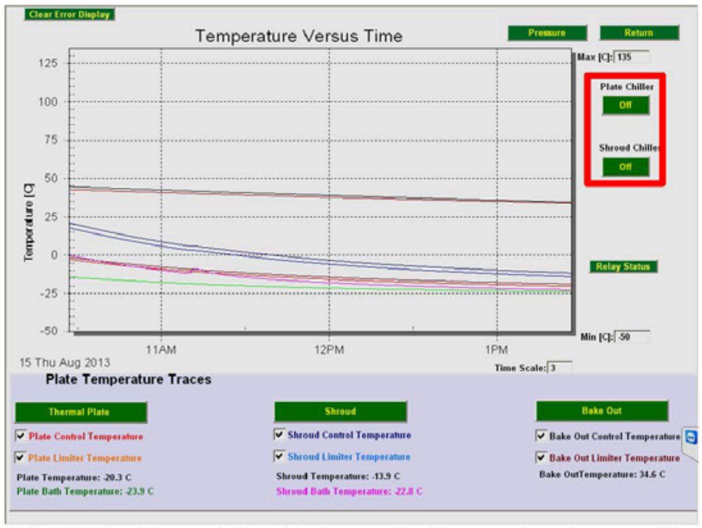
8.0		8.0 **THERMAL PROFILES**
_____8.1	FTO	**SET** thermocouple measurement period to desired time step.
_____8.2	FTO	**BEGIN** data recording (motion controlled video if desired)
_____8.3	FTO	**EXECUTE** functional test according to designated Functional Test Plan, per cover sheet. This will serve as a baseline functional check. All future functional tests will also be executed according to this Functional Test Plan. **NOTE**: All functional checks titles are referenced to those in the document "HCT TVAC Functional Checks".
_____8.4	FTO	**Execute** appropriate temperature profile or cycle according to the desired Appendix. Appendix _____ **NOTE**: Thermal cycling profile is found in Appendix 3, Hot profile Appendix 4, Hot profile in Appendix 5, Ambient profile in Appendix 6.
_____8.5	TC	**VERIFY** GO/NO-GO status with test team to begin thermal cycling: _____ TD _____ TC _____ FTO _____ TPO **NOTE:** Thermal cycling will commence with the completion of the next step. This is achieved by the use of a pair of Peltier plates (TCS) as opposed to the TVAC chamber cooling system.
_____8.6	TC	**RAMP** to desired temperature __°C
_____8.7	FTO	**EXECUTE** Electrical Functional Test according to functional test plan when control thermocouple reaches the desired temperature.
_____8.8	TPO	**BEGIN** dwell
_____8.9	TC	**RECORD** dwell start time: _____________
_____8.10	TC	**Record** dwell end time: _____________
_____8.11	FTO	**EXECUTE** Deployment test according to functional test plan
_____8.12	TC	**RECORD** test end time time: __________________
_____8.13	TPO	**EXECUTE** Section 10 "TVAC Shut Down"

9.0 | | 9.0 **TVAC CHAMBER TEMPERATURE OPERATION**

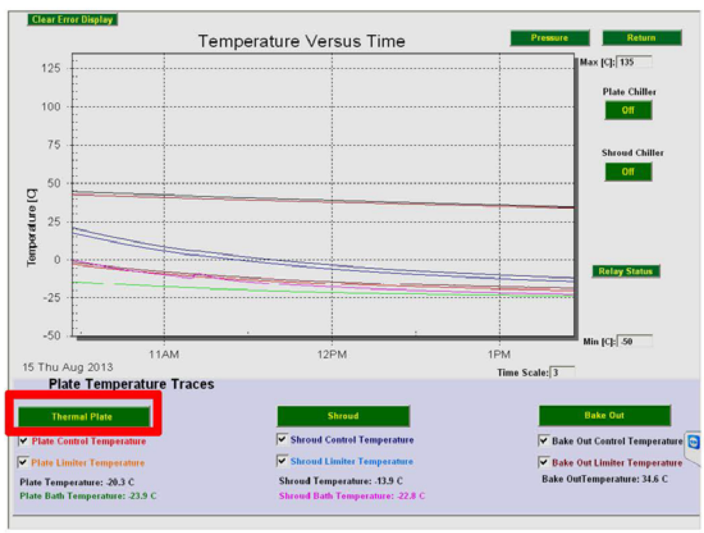
_____**9.1** | TPO | **VERIFY** the chamber is in vacuum greater than $2x10^{-3}$ Torr.

_____**9.2** | TPO | **VERIFY** all HCT systems are powered off.

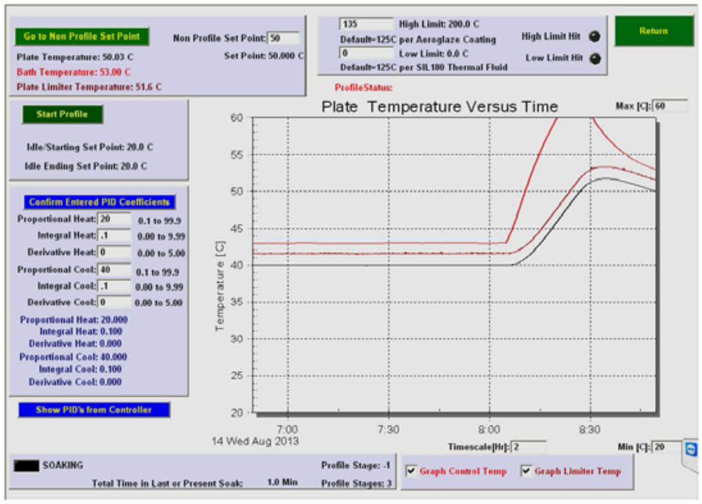
_____**9.3** | TPO | **SELECT** the 'Plate Chiller' and 'Shroud Chiller' buttons to turn them on



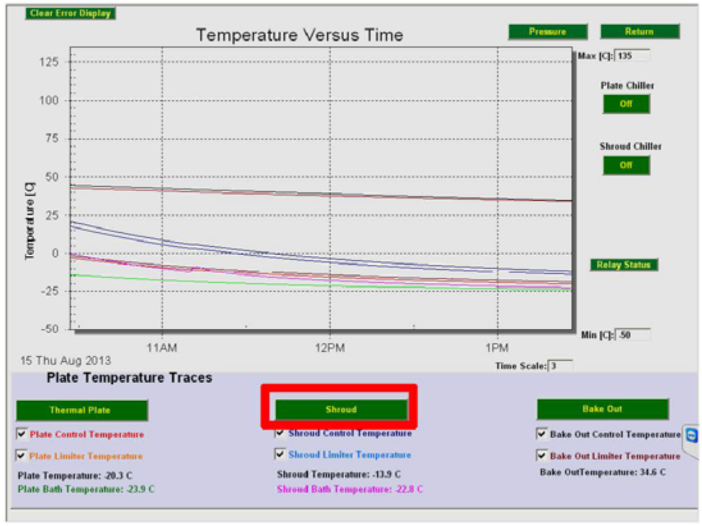
_____**9.4** | TPO | **SELECT** the 'Thermal Plate' button on the Temperature Screen of the touch screen GUI to go to the Plate Temperature Control Screen.



_____**9.5**	TPO	**SET** the following settings under the Plate Temperature Control Screen (Refer to Appendix 3.0 for Non Profile Set Point):
		_____ Non Profile Set Point

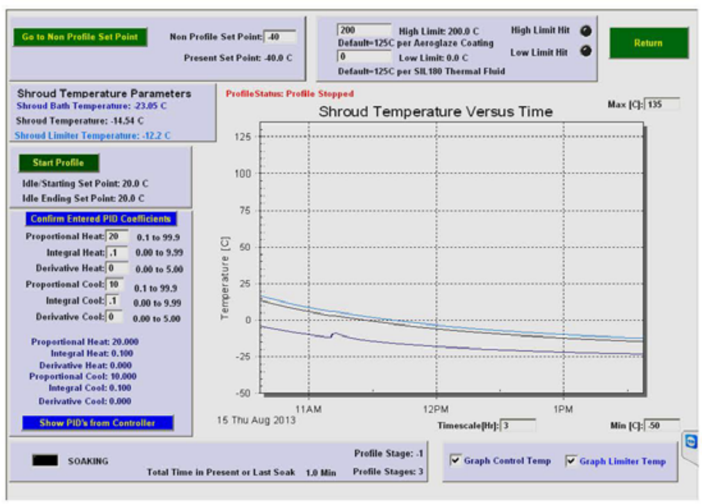


_____**9.6**	TPO	**SELECT** the 'Go to Non Profile Set Point' to set the Thermal Plate temperature.
_____**9.7**	TPO	**SELECT** the 'Return' to go back to the Temperature Screen.
_____**9.8**	TPO	**SELECT** the 'Shroud' button on the Temperature Screen of the touch screen GUI to go to the Shroud Temperature Control Screen.



_____**9.9** TPO **SET** the following settings under the Shroud Temperature Control Screen (Refer to Appendix 3.0 for Non Profile Set Point):

_____ Non Profile Set Point



_____**9.10** TPO **SELECT** the 'Go to Non Profile Set Point' to set the Shroud temperature.

_____**9.11** TPO **SELECT** the 'Return' to go back to the Temperature Screen.

_____**9.12** TPO **VERIFY** that the antennas have reached equilibrium temperature.

_____9.13	TPO	**SELECT** the 'Thermal Plate' button on the Temperature Screen of the touch screen GUI to go to the Plate Temperature Control Screen.
_____9.14	TPO	**SET** the following settings under the Thermal Plate Control Screen in order to end the cycle (Refer to Appendix 3.0 for Non Profile Set Point): _____ Non Profile Set Point
_____9.15	TPO	**SELECT** the 'Go to Non Profile Set Point' to set the Thermal Plate temperature.
_____9.16	TPO	**SELECT** the 'Return' to go back to the Temperature Screen.
_____9.17	TPO	**SELECT** the 'Shroud' button on the Temperature Screen of the touch screen GUI to go to the Shroud Temperature Control Screen.
_____9.18	TPO	**SET** the following settings under the Shroud Plate Control Screen in order to end the cycle (Refer to Appendix 3.0 for Non Profile Set Point): _____ Non Profile Set Point
_____9.19	TPO	**SELECT** the 'Go to Non Profile Set Point' to set the Shroud Plate temperature.
_____9.20	TPO	**SELECT** the 'Return' to go back to the Temperature Screen.
_____9.21	TPO	**VERIFY** that the chamber temperature reached ambient (25°C)
_____9.22	TC	**SIGN** to confirm completion, date and archive for reporting. Procedure Completed ______________________ Date________ Test Conductor END OF PROCEDURES

10.0		**10.0** **<u>TVAC SHUT-DOWN</u>**
______**10.1**	TPO	**SET** the Shroud and Thermal Plate temperatures to ambient (25°C)
______**10.2**	TPO	**VERIFY** that the temperature of the Chamber is at ambient (25°C)
______**10.3**	TPO	**SET** the Shroud and Thermal Plate Circulators Off.
______**10.4**	TPO	**SELECT** the 'Pressure' to go to the Pressure Control Panel.
______**10.5**	TPO	**VERIFY** that nitrogen tank (in the back center of room) has a reading labeled PI-152 which is greater than 50psi
______**10.6**	TPO	**OPEN** Nitrogen valve
______**10.7**	TPO	**SELECT** the 'STOP' on the Pressure Control Panel (N2 Purge Valve will automatically turn to ON) .
______**10.8**	TPO	**OPEN** red handles
		NOTE: When the chamber has finished pumping back up, the door will open
______**10.9**	TPO	**ACCESS** the chamber and the articles under test only after the lab ambient temperature and pressure are reached via controlled operation.
______**10.10**	TPO	**SELECT** 'Relay Status' from the Pressure Control Panel
______**10.11**	TPO	**SET** the N2 Purge Valve to Off.
______**10.12**	TPO	**SELECT** the 'Return to Pressure' to go to the Pressure Control Panel.
______**10.13**	TPO	**CLOSE** Nitrogen valve
______**10.14**	TC	**SIGN** to confirm completion, date and archive for reporting.
		Procedure Completed ______________________ Date________ Test Conductor
		END OF PROCEDURES

12.0		**11.0 <u>EMERGENCY RESPONSE</u>** **NOTE:** Perform the following steps in the event of a major leak, fire or other anomaly which cannot be safely managed by normal securing operations.
12.1	TC	If necessary, **DIAL 911** to notify fire department of emergency
12.2	TPO CL	**MONITOR** the test stand situation using remote cameras, and system instrumentation.
12.3	TPO	**SHUT DOWN** by pressing the manual Emergency Stop button on the Control Box **NOTE:** Pressing the manual Emergency Stop button on the Control Box shuts down all power immediately: Components may suffer damage as a consequence, so this method must NOT be used for System Shutdown.
12.4	TPO / TC / CM	If necessary, **BRIEF** fire department and medics when they arrive.
12.5	TPO	Continue to **MONITOR** Facility until condition has been secured. END OF EMERGENCY PROCEDURES

APPENDIX 1.0 – Test Log

Itm	TIME	EVENT / STATUS	FILENAME
(#)	*(HHMM)*	*(Desc.)*	*(SxMMDDr1)*
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			

Page __ of __

APPENDIX 2.0 – Data Test Log

Date__________ Time___________

Time	EDU #	Thermocouple #	Functional Test Type	Chamber Pressure (Torr)	Chamber Temp (°C)	Deployed Length (mm)	Notes / Event

Thermocouple Data/Locations

1	2	3	4

Page __ of __

APPENDIX 2.0 – Temperature Sensor Locations

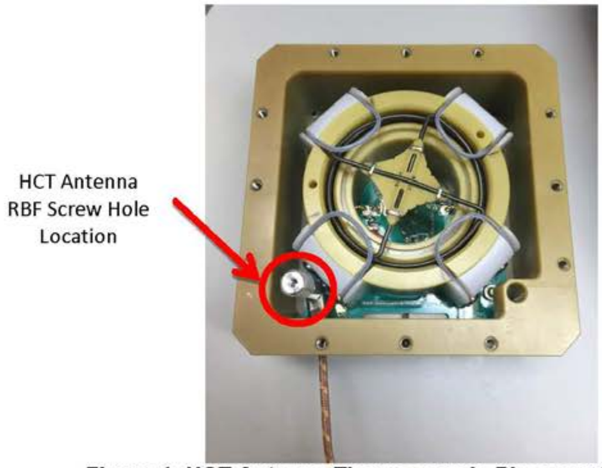


Figure 1. HCT Antenna Thermocouple Placement, Top View

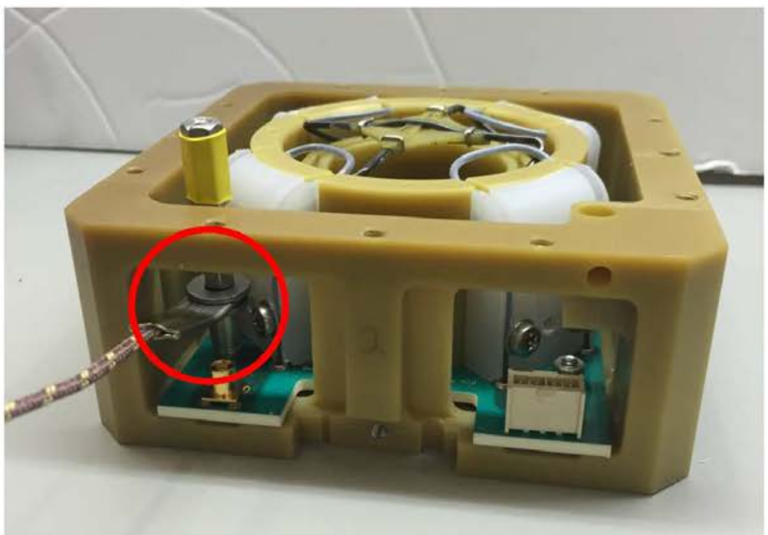


Figure 2. HCT Antenna Thermocouple Placement, Side View

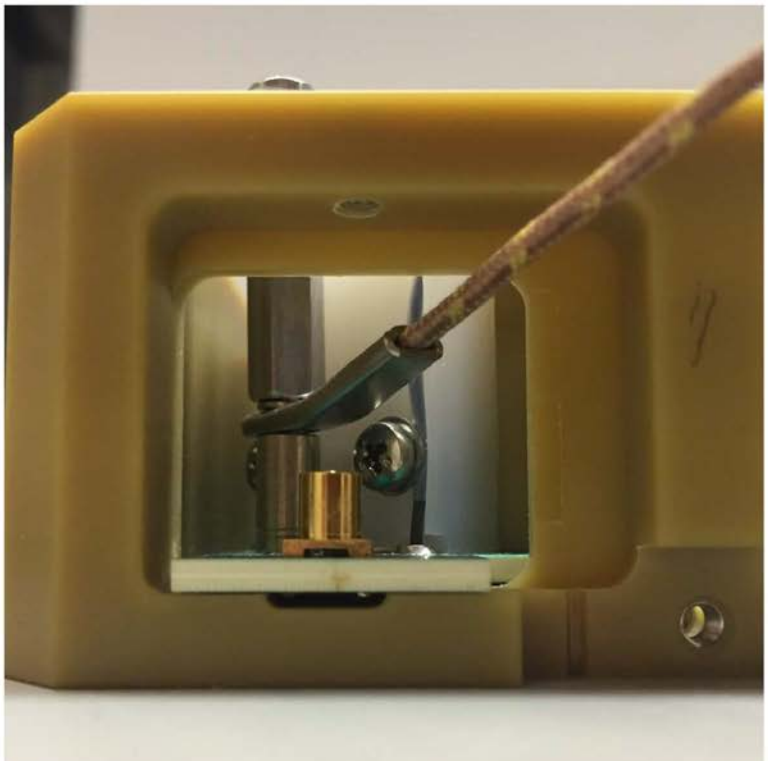


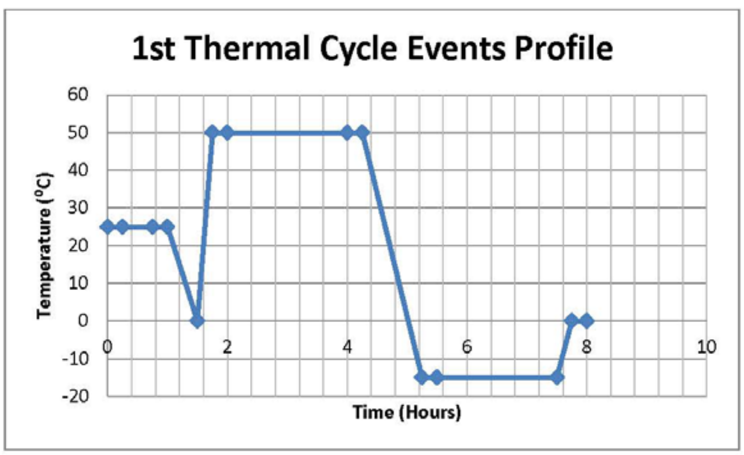
Figure 3. HCT Antenna Thermocouple Placement, Side View Closeup

Table 1. HCT TVAC Testing Thermocouple Numbering and Placement

Thermocouple #	Location
1	HCT EDU1 RBF Screw Hole
2	HCT EDU2 RBF Screw Hole
3	HCT EDU3 RBF Screw Hole
4	HCT EDU4 RBF Screw Hole

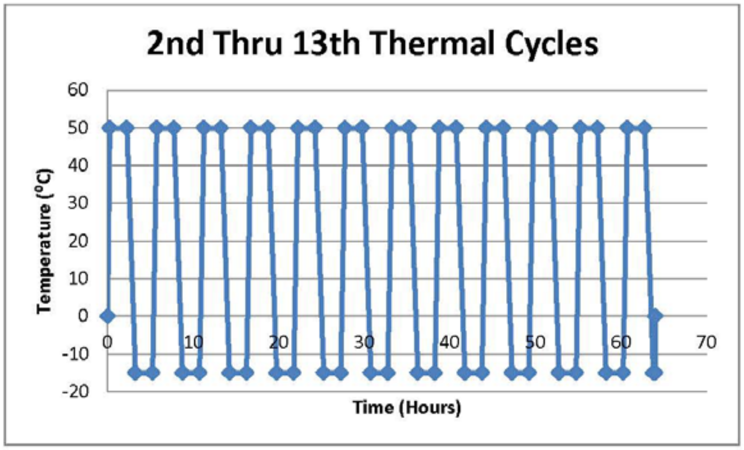
APPENDIX 3.0 – Thermal Cycle Test Profiles

1st Thermal Cycle			
Event	Event Duration (Hr)	Event Time (Hr)	Event Temperature (°C)
Electrical Functional Test (@ atm.)	0.25	0	25
Pump Down	0.5	0.25	25
Electrical Functional Test (@ 1e-5 torr)	0.25	0.75	25
Set Chamber to 0°C	0.5	1	25
Ramp up to 55°C	0.25	1.5	0
Electrical Functional Test	0.25	1.75	50
Begin 2 Hr. Dwell	2	2	50
Electrical Functional Test	0.25	2	50
Mechanical Functional Test	0.25	2	50
End 2 Hr. Dwell	0	4	50
Electrical Functional Test	0.25	4	50
Ramp Down to -25°C	1	4.25	50
Functional Test	0.25	5.25	-15
Begin 2 Hr. Dwell	2	5.5	-15
Electrical Functional Test	0.25	5.5	-15
Mechanical Functional Test	0.25	5.5	-15
End 2 Hr. Dwell	0	7.5	-15
Electrical Functional Test	0.25	7.5	-15
Ramp up to 0°C	0.25	7.75	0
Electrical Functional Test	0.25	8	0

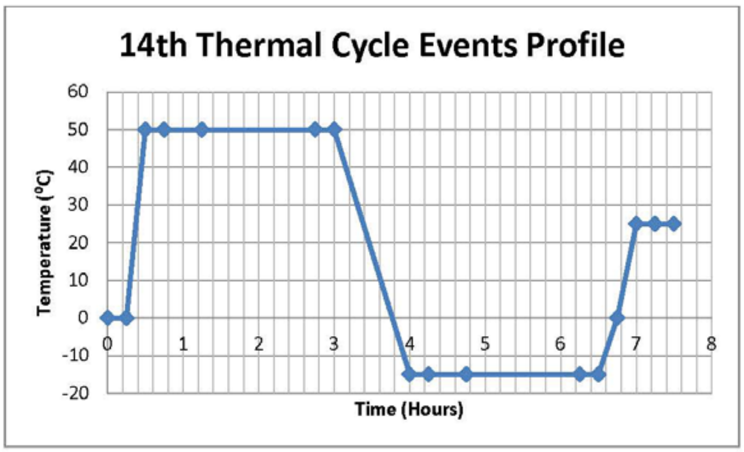


2nd Thru 13th Thermal Cycles			
Event	Event Duration (Hr)	Event Time (Hr)	Event Temperature (^oC)
Begin 2nd Cycle	0	0	0
Ramp up to 55^oC	0.25	0	0
2 Hr. Dwell	2	0.25	50
Ramp down to -25^oC	1	2.25	50
2 Hr. Dwell	2	3.25	-15
Ramp up to 55^oC	0.5	5.25	-15
2 Hr. Dwell	2	5.75	50
Ramp down to -25^oC	1	7.75	50
2 Hr. Dwell	2	8.75	-15
Ramp up to 55^oC	0.5	10.75	-15
2 Hr. Dwell	2	11.25	50
Ramp down to -25^oC	1	13.25	50
2 Hr. Dwell	2	14.25	-15
Ramp up to 55^oC	0.5	16.25	-15
2 Hr. Dwell	2	16.75	50
Ramp down to -25^oC	1	18.75	50
2 Hr. Dwell	2	19.75	-15
Ramp up to 55^oC	0.5	21.75	-15
2 Hr. Dwell	2	22.25	50
Ramp down to -25^oC	1	24.25	50
2 Hr. Dwell	2	25.25	-15
Ramp up to 55^oC	0.5	27.25	-15
2 Hr. Dwell	2	27.75	50
Ramp down to -25^oC	1	29.75	50
2 Hr. Dwell	2	30.75	-15
Ramp up to 55^oC	0.5	32.75	-15
2 Hr. Dwell	2	33.25	50
Ramp down to -25^oC	1	35.25	50
2 Hr. Dwell	2	36.25	-15
Ramp up to 55^oC	0.5	38.25	-15
2 Hr. Dwell	2	38.75	50
Ramp down to -25^oC	1	40.75	50
2 Hr. Dwell	2	41.75	-15
Ramp up to 55^oC	0.5	43.75	-15
2 Hr. Dwell	2	44.25	50
Ramp down to -25^oC	1	46.25	50
2 Hr. Dwell	2	47.25	-15
Ramp up to 55^oC	0.5	49.25	-15
2 Hr. Dwell	2	49.75	50
Ramp down to -25^oC	1	51.75	50
2 Hr. Dwell	2	52.75	-15
Ramp up to 55^oC	0.5	54.75	-15

2 Hr. Dwell	2	55.25	50
Ramp down to -25°C	1	57.25	50
2 Hr. Dwell	2	58.25	-15
Ramp up to 55°C	0.5	60.25	-15
2 Hr. Dwell	2	60.75	50
Ramp down to -25°C	1	62.75	50
2 Hr. Dwell	2	63.75	-15
Ramp up to 0°C	0.25	64	-15
End 13th Cycle	0	64	0

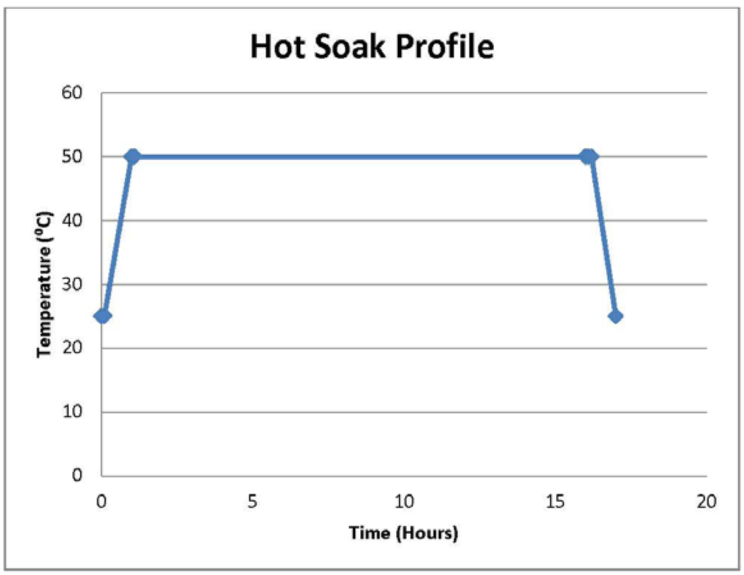


14th Thermal Cycle			
Event	Event Duration	Event Time (Hr)	Event Temperature (°C)
Electrical Functional Test	0.25	0	0
Ramp up to 55°C	0.25	0.25	0
Electrical Functional Test	0.25	0.5	50
Begin 2 Hr. Dwell	2	0.75	50
Electrical Functional Test	0.25	1.25	50
End 2 Hr. Dwell	0	2.75	50
Electrical Functional Test	0.25	2.75	50
Ramp Down to -25°C	1	3	50
Electrical Functional Test	0.25	4	-15
Begin 2 Hr. Dwell	2	4.25	-15
Electrical Functional Test	0.25	4.75	-15
End 2 Hr. Dwell	0	6.25	-15
Electrical Functional Test	0.25	6.25	-15
Ramp up to 0°C	0.25	6.5	-15
Set Chamber to 25°C	0.25	6.75	0
Electrical Functional Test	0.25	7	25
Pump Up	0.25	7.25	25



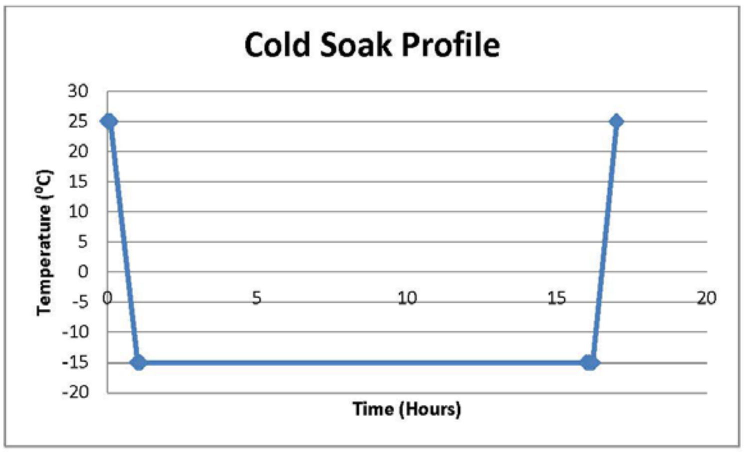
APPENDIX 4.0 – HCT Hot Profile

Action	Duration (Hr)	Total Time (Hr)	Temp (°C)
Set Chamber to 25°C	0	0	25
Perform Electrical Functional Test	0.1	0.1	25
Ramp Down	1	1	50
Perform Electrical Functional Test	0.1	1.1	50
Begin Dwell	16	16	50
Perform Electrical Functional Test	0.1	16.1	50
Perform Mechanical Functional Test	0.1	16.2	50
Ramp Up	1	17	25
End Dwell	0	17	25



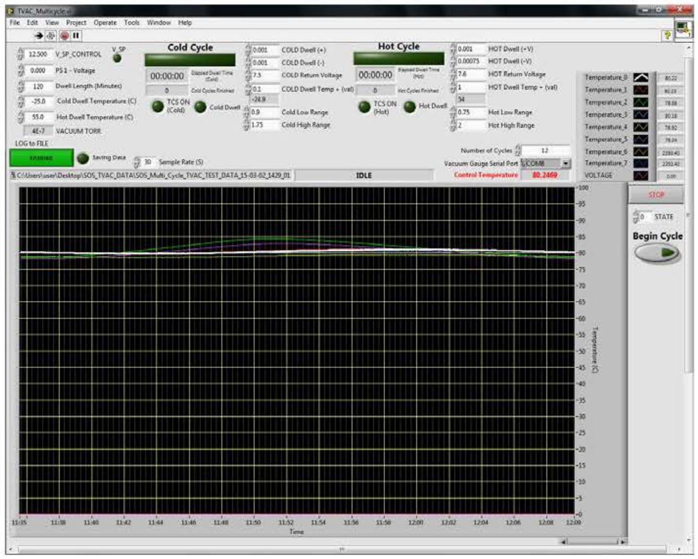
APPENDIX 5.0 – HCT Cold Profile

Action	Duration (Hr)	Total Time (Hr)	Temp (°C)
Set Chamber to 25°C	0	0	25
Perform Electrical Functional Test	0.1	0.1	25
Ramp Down	1	1	-15
Perform Electrical Functional Test	0.1	1.1	-15
Begin Dwell	16	16	-15
Perform Electrical Functional Test	0.1	16.1	-15
Perform Mechanical Functional Test	0.1	16.2	-15
Ramp Up	1	17	25
End Dwell	0	17	25

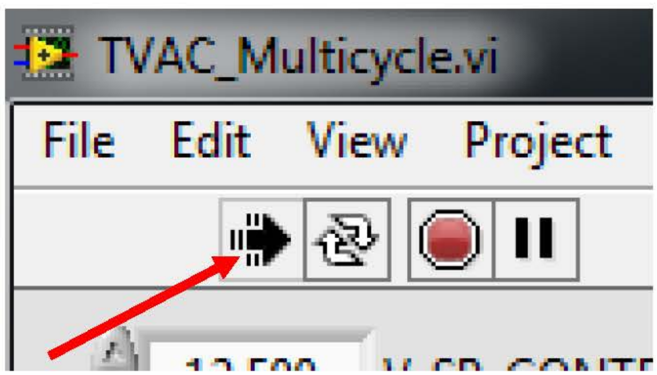


A6. **APPENDIX 6.0 – LabVIEW Procedure**

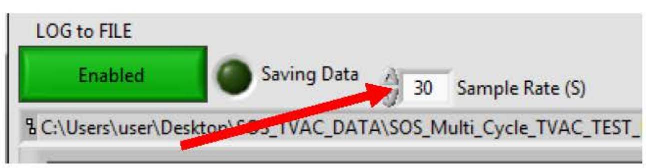
_____**A6.1** TPO **OPEN** the LabVIEW program named TVAC_Multicycle.vi



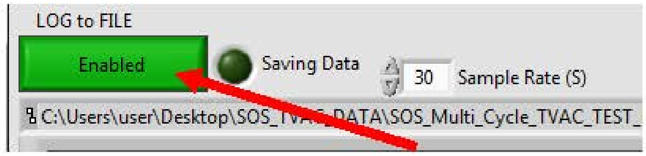
_____**A6.2** TPO **EXECUTE** the program by pressing the following button:



_____**A6.3** TPO **SET/VERIFY** sample rate is 60 seconds

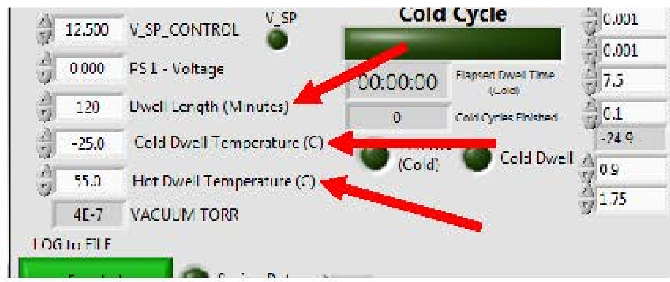


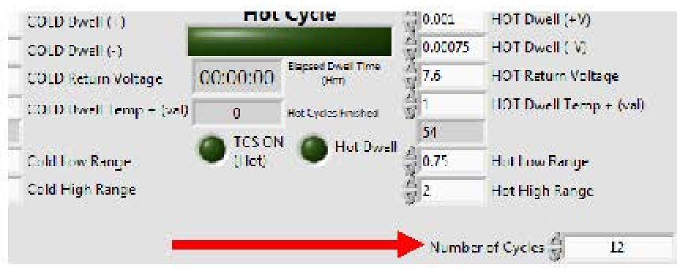
_____**A6.4** TPO **PRESS/VERIFY** 'LOG to FILE' button to begin recording data



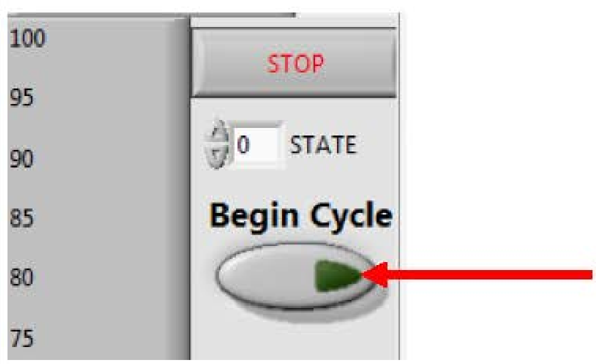
_____**A6.5** TPO **SET** the following settings:

_____ Dwell Length (Minutes) _____ Cold Dwell Temperature (C)
_____ Hot Dwell Temperature (C) _____ Number of Cycles



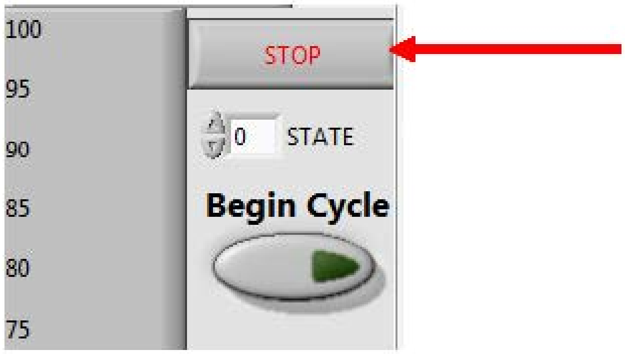


_____**A6.6** TPO **BEGIN** thermal cycling by pressing the 'Begin Cycle' button:



***Note:** Verify that the button turns on, once it does, press it again.

_____**A6.7** TPO **RECORD** cycle date and start time: ______________________

		***Note:** If the program needs to be stopped in the middle of the cycle, press the STOP button.
		
____**A6.8**		**RECORD** cycle date and end time: ____________________
____**A6.9**	TC	**SIGN** to confirm completion, date and archive for reporting.
		Procedure Completed ____________________ Date________ Test Conductor
____**A6.10**		END OF PROCEDURES

Appendix B: Vibe Test Plan

TEST AREA B644 L125A	PROCEDURE: HCT_Antenna_VibeTP
AFIT/ENY	REVISION: 1
HCT Antenna Vibe Plan	DATE REVISED: 7 June 2016
WRIGHT-PATTERSON AFB, OH	NUMBER OF PAGES: 31

AFIT / ENY
VIBRATION FACILITY
OPERATIONS

HCT Antenna Vibration Table Testing

SYSTEM UNDERGOING TESTING	**ASSOCIATED FUNCTIONAL TEST PLAN VERSION**
HCT Antenna	Vibe Functional Test Plan

PREPARED BY:

Test Engineer____ DATE ____________
Test Conductor

REVIEWED / APPROVED BY:

AF Customer____ DATE ____________
Test Director

Revision	Notes	Prepared By
0	- Initial procedure modified from 12U chassis	Carl Kobza 3 Feb 2016
1	- Update document for testing HCT antenna	Carl Kobza 7 June 2016

TABLE OF CONTENTS

PERSONNEL

EXPERIMENTAL VIBRATION FACILITY DATE__________________________

The following personnel are designated as test team members, and are chartered to perform their assignment as follows:

Test Conductor (TC) – Responsible for the timely performance of the test as written. This includes coordinating and directing the activities of the Red Crew and other test support teams. TC is responsible for coordinating all pretest activities and outside support required, including (but not limited to) security, fire, medical, and safety. TC is responsible for initialing completion on each step of the master test procedure.
Name______________________________ Signature_________________________________

Test Director (TD) – Responsible for overall facility and test safety. Responsible for ensuring all test goals are met and all critical data is acquired. Supervises test activities to ensure procedures are followed. Has authority to perform real-time redlines on test procedures as required to ensure test requirements and goals are met.
Name______________________________ Signature_________________________________

Red Crew Leader (RCL) – Responsible for directing the activities of Red Crew members. Reports directly to the TC and ensures all Red Crew tasks are completed. Responsible for ensuring all RCM's have all required certifications and training. Responsible for ensuring all required equipment is available, accessible, and serviceable.
Name______________________________ Signature_________________________________

Test Panel Operator (TPO) – Responsible for operating the facility control systems during test operations as directed by TC. TPO is responsible for notifying the TC of any anomalous conditions.
Name_______________________________ Signature_________________________________

Red Crew Member (RCM) – Reports to the RCL. RCM is responsible for performing test-related tasks as directed by RCL.
Name_______________________________ Signature_________________________________

Name_______________________________ Signature_________________________________

Functional Test Conductor – Responsible for performing functional test in support of test.
Name_______________________________ Signature_________________________________

Name_______________________________ Signature_________________________________

EXCEPTIONS – When filling all positions is not possible, the Test Conductor will assume the duties of any empty position until the completion of the test or a suitable replacement is designated.

ALL TEST TEAM MEMBERS – Responsible for the safe performance of the test. Have read and understood all portions of the test procedure. Any Test Team Member can declare an emergency or unsafe condition.

1.0

1.0 ABBREVATIONS AND ACRYONMS

AFIT	Air Force Institute of Technology
dB	Decibel
DOF	Degree of Freedom
EM	Engineering Model
FOD	Foreign Object Debris
FV	Flight Vehicle
HAZCOM	Hazardous Communication
HCT	Helical Communication Technologies
MPE	Maximum Predicted Environment
PCB	Printed Circuit Board
PPE	Personal Protective Equipment
QM	Qualification Model
RCL	Red Crew Leader
RCM	Red Crew Member
SOS	Space Object Self-tracker
STE	Special Test Equipment
TC	Test Conductor
TD	Test Director
TOP	Test Operating Procedure
TPO	Test Panel Operator
VTP	Vibration Test Procedure

2.0		2.0 **TEST DESCRIPTION AND OBJECTIVES**

2.1 PURPOSE

This procedure provides the means to perform vibration testing for test articles supplied relating to the Helical Communication Technologies (HCT) ANTENNA. The HCT ANTENNA test campaign is a structure and model validation plan intended to mitigate technology concerns for a future integration in a 12U CubeSat chassis in later years. The AFIT Vibration Facility will be configured with the proper special test equipment (STE) to direct, and measure "maximum predicted environments" associated with launching the HCT antenna according to the NASA GEVS Payload Specification (see Appendix 6.0).

2.2

2.2 SCOPE

This procedure prepares the instrumentation and control system as well as verifies the proper mechanical configuration during the pre-test setup (note that the HCT antenna will be tested in the stowed configuration for all phases of this test series). Upon completion of the setup, appropriate levels for Sine, Random and environments will be configured to test the HCT Antenna in X, Y and Z axes. Rationale for each test is as follows:

Sine Sweep: The objective of the Sine sweep is to determine the fundamental and further natural frequencies, modal shapes and modal gain of the structure in the three main axis, and, by repeating this test after the random vibration, to determine whether anything in the satellite has changed/broken as a result of the tests by comparing the Sine sweep responses pre- and post-test. The fundamental frequency must meet launch vehicle requirements as well. This information will aid in analysis of any design changes that may be made if certain components fail.

Random Vibration: The objective of this test is to verify the capability of the satellite structure and components to withstand the fatigue introduced during launch.

Stand-Characterization (AS REQUIRED): The goal of the stand-characterization test is to show that the vertical acceleration of the top of the vibration stand is two orders of magnitude less than the horizontal acceleration, thereby showing that the stand can be accurately considered as a rigid-body.

Test recycling will take place as necessary. The test facility will then be properly secured and reconfigured to a safe state for normal operations. Data will be reviewed and archived. Any facility anomalies or lessons observed will be noted in a final test report.

2.3

2.3 OBJECTIVES/SUCCESS CRITERIA

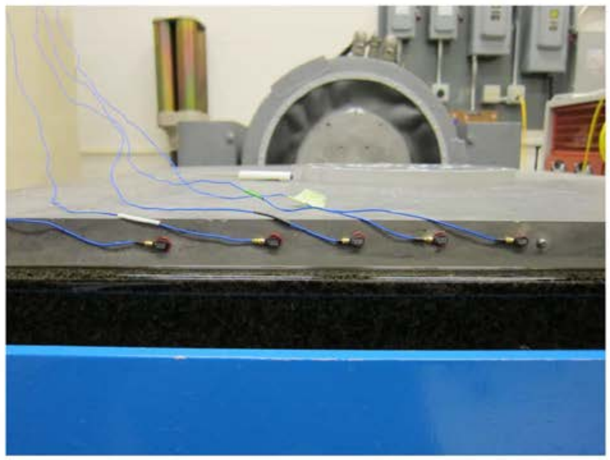
Complete Success

1. No items are free during tip test

		2. No structural failures 3. Antenna passes electrical and mechanical functional tests <u>Marginal Success</u> 1. No structural items are free during tip test (bolts, brackets, etc.) 2. Structural failures occur, but they do not inhibit satellite operation 3. Antenna passes electrical and mechanical functional tests <u>Unsuccessful</u> 1. Structural items are free during tip test 2. Structural failures occur that inhibit satellite operations 3. Antenna does not pass electrical and mechanical functional tests
3.0		**3.0 <u>DOCUMENTATION</u>** The completion of each applicable event shall be verified by initialing to the left of the item number. Deviations from these procedures will be coordinated with the Test Conductor. (NOTE: TD has the local authority to approve red-line revisions to this procedure).
_____**3.1**		3.1 REFERENCE DOCUMENTS HCT Handling Instructions HCT Functional Test Plan
_____**3.2**		3.2 SPECIFICATIONS The following list of specifications shall be used as a guide: NASA GEVS (GSFC-STD-7000A - 22 April 2013)
_____**3.3**		3.3 DRAWINGS NONE
4.0		**4.0 <u>TEST REQUIREMENTS AND RESTRICTIONS</u>**
_____**4.1**		4.1 TRAINING The following training is required for personnel using these procedures: All personnel: Job Site General Lab Safety Briefing
_____**4.2**		4.2 MAXIMUM PERSONNEL: Control Room: 15
_____**4.3**		4.3 LIST OF EQUIPMENT HCT antenna (2) (stowed), 12U CubeSat Chassis, spare tool set,

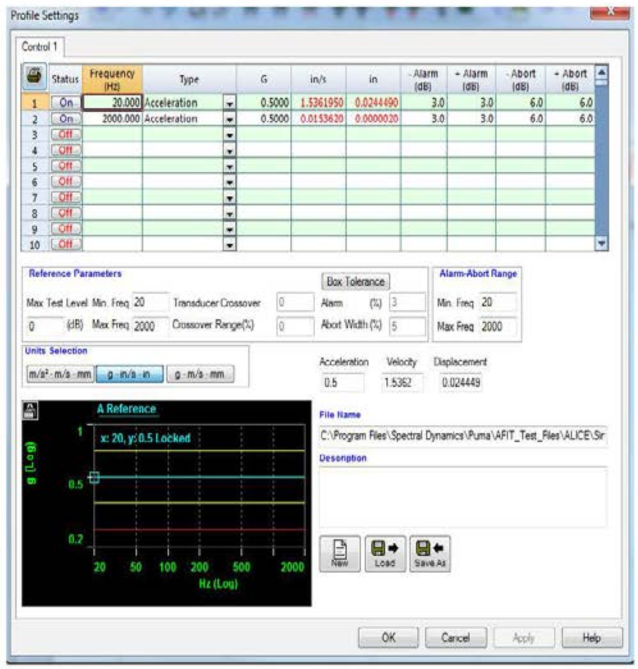
		fasteners, high-speed camera, spare components Ensure all tools associated with this experiment/test/operation are accounted for prior to initiating system/item test. Ensure all FOD is picked up from around the test facility.
5.0		**5.0 SAFETY REQUIREMENTS**
_____**5.1**		5.1 PERSONNEL PROTECTIVE EQUIPMENT REQUIREMENTS Standard PPE: Safety goggles or glasses (as required), hearing protection (when required), boots – soles and heels made of semi-conductive rubber containing no nails. All jewelry will be removed by test members while working on the test facility. No ties or other loose clothing permitted (at TD discretion).
_____**5.2**		5.2 EMERGENCY PROCEDURES In the event of an emergency that jeopardizes the safety of the operators or other personnel perform Section 11.0 emergency procedures at the end of this document.
_____**5.3**		5.3 TEST AREA ACCESS DURING OPERATIONS The test facility room will be limited to test personnel only. Personnel will not be allowed access to the test area unless cleared by the TD.
_____**5.4**		5.4 SPECIAL INSTRUCTIONS A qualified technician should provide orientation for operation and maintenance of the vibration table and the proper faculty member / instructor should be consulted on test-series set points prior to test operations commencing. Test Crew members shall place all cellular telephones on "silent mode" or turn off prior to completing any portion of this procedure. Test Crew Members shall notify the TD of any leaks from hydraulic system, or pneumatic system pipe or tubing connections.
6.0		**6.0 PRE-TEST SETUP**
_____**6.1**	TC	**VERIFY** all pages in this procedure are intact and complete.
6.2	TC	**READ** procedure and input any specific information required to perform operation.
_____**6.3**	TC	**VERIFY** with Facility Management that no open Work Orders / Issues are listed for the Vibration Test Facility impeding operations.
_____**6.4**	TC	**PERFORM** Setup Brief with Test Crew Members and note any redline changes on Appendices.

_____6.5	TC	**VERIFY** Test Team has donned standard PPE (and noted restrictions / special instructions).
_____6.6	TC	**INITIATE** the following Procedures/Appendices(s):
		NOTE: All appendices can be completed independently from one another – there is no order to completion.
		Appendix 1– Control System Setup
		Appendix 2 – Mechanical Setup
_____6.7	TC	**VERIFY** that Appendices are complete.
		_____ Appendix 1 _____ Appendix 2
_____6.8	TC	**PERFORM** Pre-Operation Brief with Test Crew Members
		_ Objective _ Personnel and assigned roles/duties _ Safety: materials, PPE, communication, etc. _ Sequence of events _ Emergency procedures
_____6.8.1	TC	**RECORD** Pre-Test Brief Time ________
_____6.8.2	TC	**VERIFY** all personnel involved with the operation have signed this procedure.

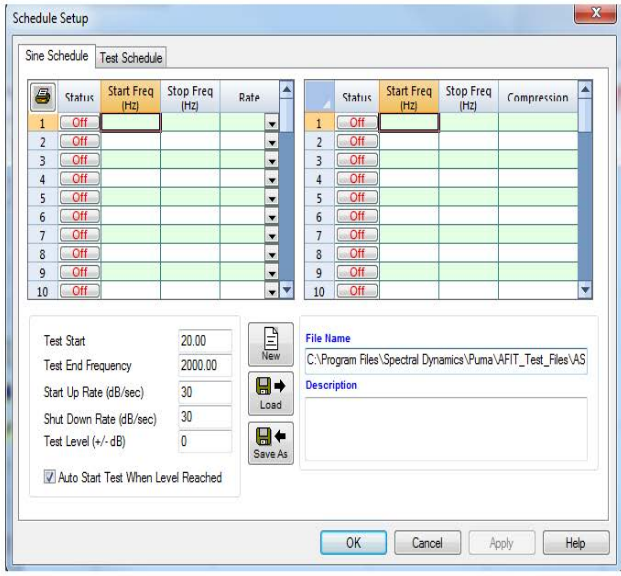
_____**6.9**	TC	**EXECUTE** Pre-Test functional test according to designated Functional Test Plan, per cover sheet
_____**6.10**	TD	**PERFORM** Pre-Test accelerometer verification test by positioning the accelerometers (minimum of 5) on the edge of the slip table as shown in the figure below (skip this step if not using the slip table). 

7.0		**7.0 TEST SERIES FLOW / PLAN** **NOTE:** Refer to the screenshots in Sections 8.0 and 9.0 for test levels and timing.
7.1		7.1 3-AXIS VIBRATIONAL TESTING
_____**7.1.1**	TC	**VERIFY** HCT Antenna/Accelerometer Positioning is correct for 3-axis test, per Appendix 5.0
_____**7.1.2**	TC	**EXECUTE** Sine Sweep Test, Section 8.0
_____**7.1.3**	TC	**EXECUTE** Random Vibe Test, Section 9.0
_____**7.1.4**	TC	**EXECUTE** Sine Sweep Test, Section 8.0
_____**7.1.5**	TC	**REPEAT** 7.1.3 - 7.1.4 for each desired dB level according to Appendix 3.0
_____**7.1.6**	TC	**EXECUTE** electrical and deployment functional test according to designated Functional Test Plan
_____**7.1.7**	TC	**RECORD** data/results in Appendix 4.0
7.4	TC	**GO TO** Section 10.

8.0		8.0 **SINE-SWEEP TEST**
		OPEN "HCT_sine_half_g_Up" file
_____8.1	TPO	
_____8.2	TPO	**SELECT** "Profile Settings" and verify/enter the following parameters:



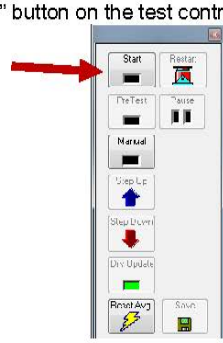
_____8.3 TPO SELECT "Schedule Setup" and verify/enter the following parameters:



_____8.4 RCL VERIFY all test personnel are clear of the test equipment and are still wearing proper PPE.

CAUTION: Test to commence with the completion of the next step. Anomalous conditions witnessed by ANY test team member are to be reported to TC immediately for command decision (unity of command). TPO to be ready to initiate an ABORT command if directed by TC.

_____8.5 TPO SELECT "START" button on the test control window



_____**8.6**	TPO	**SELECT** "Post Analysis" menu, "Save Plot to ASCII file" save file in format: **Sy_r1_MMDD_HHmm_U.xxx** Where, S := Type of Test (**S**ine-Sweep) y := Test-stand Axis (x-Axis; y-Axis; z-axis) r1:= Run number (r1, r2, r3, etc.) MM := Two-digit month DD := Two-digit day HH := Two-digit hour (24-hour time) mm := Two-digit minute U := Sine direction (**U**p or **D**own)
_____**8.7**	RCL	Upon completion of test, initiate quick visual inspection for post-test anomalous conditions. Take photo.
_____**8.8**	TPO	**SAVE** a screenshot of the graph tool.
_____**8.9**	TPO	**RECORD** Test / Initial Results in Data Log, Appendix 4
_____**8.10**	TC	**RETURN** to next process flow, Section 7.0
		END OF SINE-SWEEP TEST

9.0 **9.0 RANDOM-VIBE TEST**

_____**9.1** TPO **SELECT** “Profile Settings” and load the appropriate profile

OPEN the appropriate axis’ profile
___ “HCT_Random_3_Axis.pro”

_____**9.2** TPO **VERIFY/ENTER** the following parameters according to the NASA GEVS active profile found in Appendix 6 (Frequencies and accelerations are axis specific).

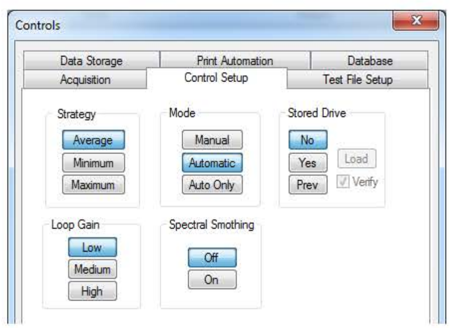
_____**9.3** TPO **SELECT** “Schedule Setup” and verify/enter the following parameters (Adjust *Level (dB)* to the correct level for each test:

	Status	Level (dB)	Time at Level	Time to Level	Alarm Action
2	On	0.000 (adjust)	0000:001:000	0000:000:000	Abort
3	Off				

NOTE: Initial Test Limit should read 15 when testing -12dB (should read 12 for all other tests)

Y: ___ -12 dB ___ -6 dB ___-3 dB ___ 0 dB

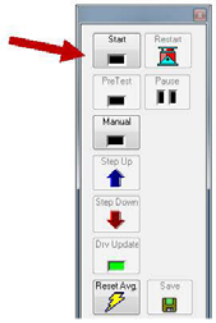
_____**9.4** RCL **SELECT** “Controls”, then the “Control Setup” tab, and **VERIFY/SELECT** “Automatic” Mode.



_____**9.5** RCL **VERIFY** all test personnel are clear of the test equipment and are still wearing correct PPE.

CAUTION: Test to commence with the completion of the next step. Anomalous conditions witnessed by ANY test team member are to be reported to TC immediately for command decision (unity of command). TPO to be ready to initiate an ABORT command if directed by TC.

_____**9.6**	TPO	**SELECT** "START" button on the test control window



_____**9.7**	TPO	**SELECT** "Post Analysis" menu, "Save Plot to ASCII file" save file in format: **Ry_r1_MMDD_HHmm_DB.xxx** Where, S := Type of Test (**<u>R</u>**andom) x := Test Axis (x-Axis; y-Axis; z-axis) r1:= Run number (r1, r2, r3, etc.) MM := Two-digit month DD := Two-digit day HH := Two-digit hour (24-hour time) mm := Two-digit minute DB := Decibel Level (absolute value: -12, -6, -3, 0)
_____**9.8**	TPO	**EXECUTE** electrical and deployment functional test according to designated Functional Test Plan.
_____**9.9**	TPO	If functional test fails, **STOP** test, correct error, and restart test from the beginning, otherwise **CONTINUE.**
_____**9.10**	RCL	Upon completion of test, initiate quick visual inspection for post-test anomalous conditions. Take photo.
_____**9.11**	TPO	**SAVE** a screenshot of the graph tool.
_____**9.12**	TPO	**RECORD** Test / Initial Results in Data Log, Appendix 4.0
_____**9.13**	TC	**RETURN** to next process flow, Section 7.0
		END OF RANDOM VIBE TEST

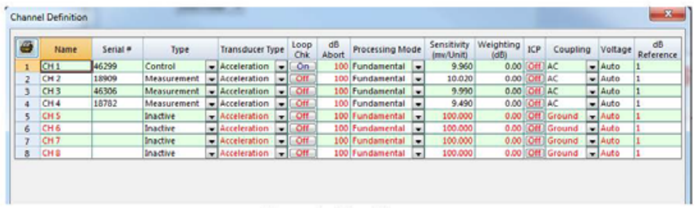
10.0		10.0 **SHAKER-TABLE SHUT-DOWN**
_____10.1	RCM	**PRESS STOP** on cooling system M-Series Control Panel
_____10.2	RCM	**CLOSE** shop-air isolation hand-valve
_____10.3	RCM	**TURN OFF** Slip Table power
_____10.4	RCM	**TURN OFF** Circuit Breaker No. 7 (Power Station 480V, 3-Phase, 3W) *Wait 3 minutes for cooling system to self-shutoff.
_____10.5	TC	**SIGN** to confirm completion, date and archive for reporting.
		Procedure Completed ______________________ Date________ Test Conductor
		END OF SHAKER TABLE SHUT-DOWN

11.0		**11.0 <u>EMERGENCY RESPONSE</u>** **NOTE:** Perform the following steps in the event of a major leak, fire or other anomaly which cannot be safely managed by normal securing operations. TC shall have authority (On-Scene Command) over the situation until relieved from support organizations.
_____**11.1**	TC	If necessary, **EVACUATE** and/or **Dial 9-911** to notify fire department of emergency
_____**11.2**	TPO	If possible/safe and necessary, **Press** emergency shutoff (Red button located on the wall next to doorway)
_____**11.3**	TPO	If possible/safe, **ABORT** any test currently in process
_____**11.4**	RCM	If possible/safe, **CLOSE** shop-air isolation hand-valve
_____**11.5**	RCM	If possible/safe, **TURN OFF** Circuit Breaker No. 7 (Power Station 480V, 3-Phase, 3W)
_____**11.6**	ANY	If necessary, **Brief** fire department and medics when they arrive.
_____**11.7**	TD	Continue to Monitor Facility until condition has been secured. END OF EMERGENCY RESPONSE

APPENDIX 1.0 – Control System Setup
Date__________ Time___________

NOTE: If there are any deviations to the verification steps below, note these exceptions and report them to the TD.

1.0		CONTROL SYSTEM SETUP
_____**1.1**	TPO	**TURN ON** Spectral Dynamics control system computer
_____**1.2**	TPO	**SELECT** "Puma" shortcut on desktop
_____**1.3**	TPO	**SELECT** test type (Sine, Random Vibe)
_____**1.4**	TPO	**SELECT** Channel Definition Menu
_____**1.5**	TPO	**Verify / Enter** the following parameters from the PUMA channel definitions (Accel serial # and channel will vary. Use corresponding sensitivity for each accel.):



Channel Definition

	Name	Serial #	Type	Transducer Type	Loop Chk	dB Abort	Processing Mode	Sensitivity (mv/Unit)	Weighting (dB)	ICP	Coupling	Voltage	dB Reference
1	CH 1	46299	Control	Acceleration	On	100	Fundamental	9.960	0.00	Off	AC	Auto	1
2	CH 2	18909	Measurement	Acceleration	Off	100	Fundamental	10.020	0.00	Off	AC	Auto	1
3	CH 3	46306	Measurement	Acceleration	Off	100	Fundamental	9.990	0.00	Off	AC	Auto	1
4	CH 4	18782	Measurement	Acceleration	Off	100	Fundamental	9.490	0.00	Off	AC	Auto	1
5	CH 5		Inactive	Acceleration	Off	100	Fundamental	100.000	0.00	Off	Ground	Auto	1
6	CH 6		Inactive	Acceleration	Off	100	Fundamental	100.000	0.00	Off	Ground	Auto	1
7	CH 7		Inactive	Acceleration	Off	100	Fundamental	100.000	0.00	Off	Ground	Auto	1
8	CH 8		Inactive	Acceleration	Off	100	Fundamental	100.000	0.00	Off	Ground	Auto	1

Figure 1: Sine Sweep

Channel Definition

	Name	Serial #	Type	Engineering Units	Loop Chk	Sensitivity (mv/Unit)	Transducer Units	Weighting (dB)	RMS Abort	ICP	Coupling	dB Reference	Reference Chans
1	CH 1	18787	Control	No EU's - g's or	On	103.700	g	0.00	30.0000	Off	AC	1	NONE
2	CH 2	46299	Measure	g (in/sec, in)	Off	99.600	g	0.00	30.0000	Off	AC	1	1
3	CH 3	18909	Measure	g (in/sec, in)	Off	100.200	g	0.00	30.0000	Off	AC	1	1
4	CH 4	18782	Measure	g (in/sec, in)	Off	94.900	g	0.00	30.0000	Off	AC	1	1
5	CH 5		Inactive	g	Off	100.000	g	0.00	30.0000	Off	Ground	1	NONE
6	CH 6		Inactive	g	Off	100.000	g	0.00	30.0000	Off	Ground	1	NONE
7	CH 7		Inactive	g	Off	100.000	g	0.00	30.0000	Off	Ground	1	NONE
8	CH 8		Inactive	g	Off	100.000	g	0.00	30.0000	Off	Ground	1	NONE

Figure 2: Random Vibe

_____**1.6**	TPO	**Verify / Enter** Accelerometer Values

Name	Serial #	Type	Sensitivity (mv/Unit)	Coupling
CH 1		Control		AC
CH 2		Measurement		AC
CH 3		Measurement		AC
CH 4		Measurement		AC
CH 5		Measurement		AC
CH 6		Measurement		AC
CH 7		Measurement		AC
CH 8		Measurement		AC

_____**1.7** TPO Sign and Return to TD upon completion of Appendix

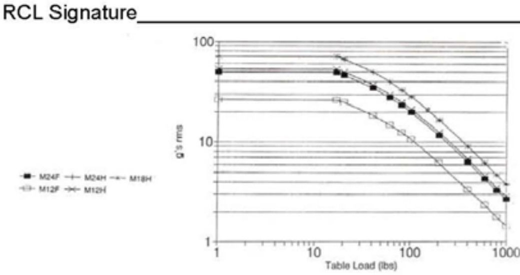
TPO Signature____

END OF APPENDIX 1.0 – Control System Setup

APPENDIX 2.0 – Mechanical Setup

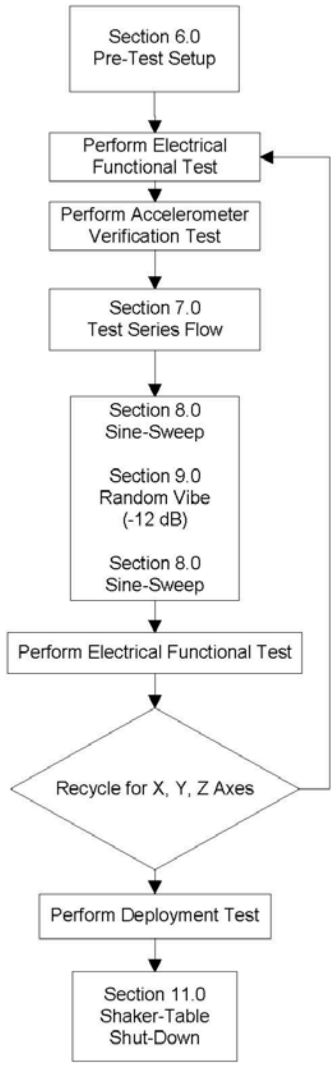
Date__________ Time___________

2.0		**STE SETUP**
_____**2.0.1**	_____	Verify Red Crew has donned Standard PPE and has hearing protection ready/available
_____**2.0.2**	RCM	**SECURE** into vibe fixture (thumb-screws hand-tight) ____ Y Axis
_____**2.0.3**	RCM	**AFFIX** accelerometers per Appendix 5.0
2.1		**SHAKER-TABLE SETUP**
_____**2.1.3**	RCM	**SLOWLY OPEN** shop-air isolation hand-valve to **OPEN**
_____**2.1.4**	RCM	Verify >90 psig on shaker-table inlet gauge
		TURN ON Circuit Breaker No. 7 (Power Station 480V, 3-Phase, 3W)
_____**2.1.5**	RCM	**PRESS START** on cooling system M-Series Control Panel
_____**2.1.6**	RCM	**VERIFY** all lights are **GREEN** (except clipping) on Control Panel and **GAIN** is set to 6.0
_____**2.1.7**	RCL	Sign and Return to TD upon completion of Attachment.
		RCL Signature___________________________________



END OF ATTACHMENT 2

APPENDIX 3.0 – TOP Process Flow Diagram



APPENDIX 4.0 – Test Log

ITEM	TIME	EVENT / STATUS	FILENAME
(#)	(HHMM)	(Description)	(Sx_r1_MMDD_HHMM)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			

APPENDIX 5.0 –Accelerometer Positioning

5.0		3-AXIS SETUP
_____ **5.1**		**SECURE** Test Fixture to vibration table with appropriate axis of HCT Antenna in the direction of motion as shown in Figure 3. **NOTE:** All accelerometers need to be positioned in-line with the shaker-axis (same orientation as the control accelerometer).
_____ **5.2**	RCL	**POSITION** accelerometers in the following locations based on test axis and full or empty chassis: (If insufficient working sensors, drop the highest numbers first, ensure at least 6 operational sensors)

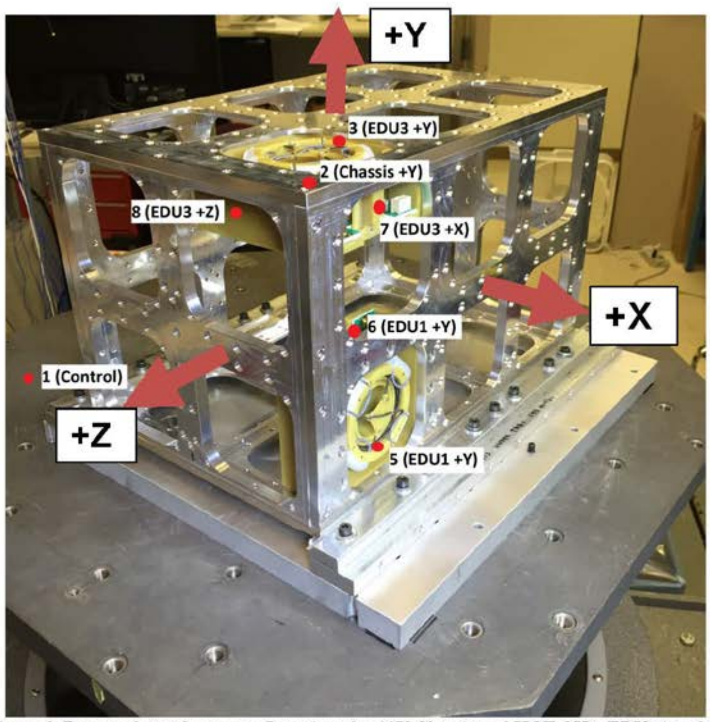


Figure 3. Proposed Accelerometer Locations for 12U Chassis and HCT QHA EDUs 1 and 3

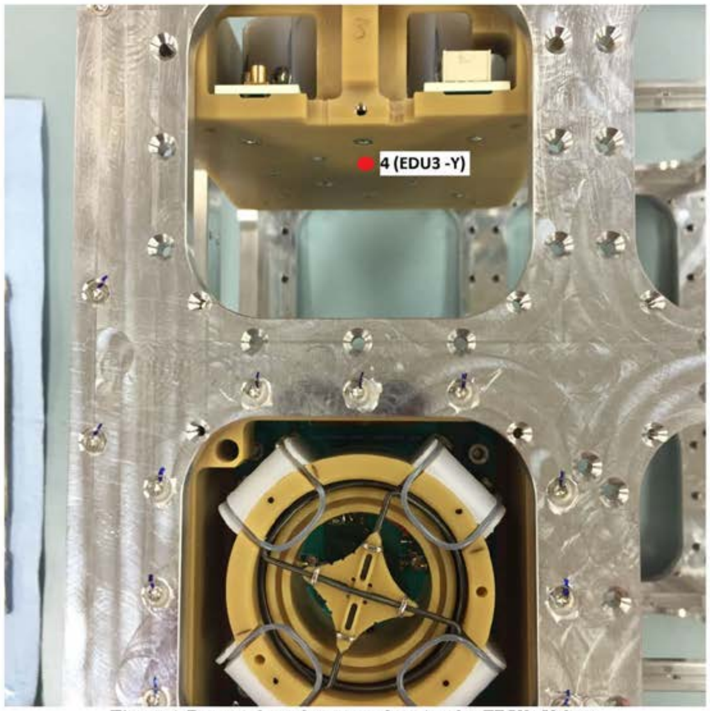


Figure 4. Proposed accelerometer location for EDU3 -Y face

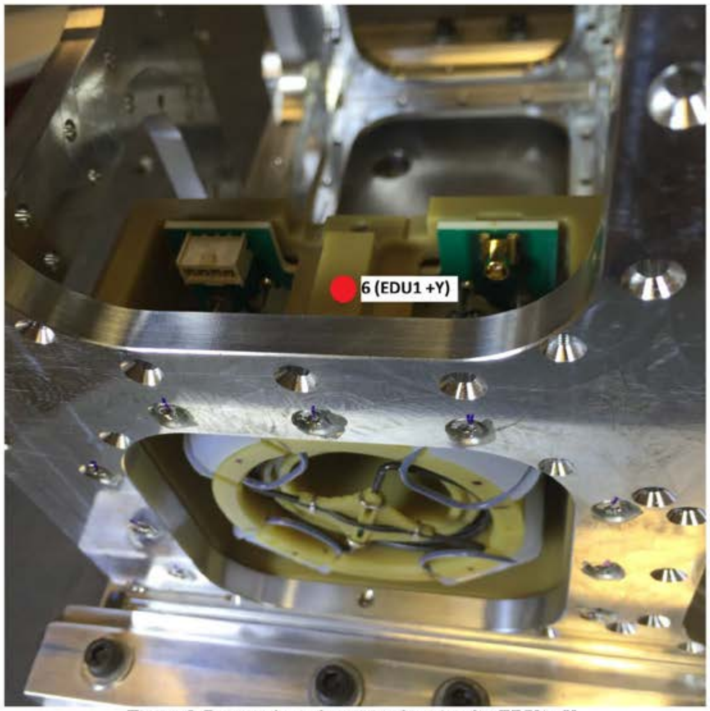


Figure 5. Proposed accelerometer location for EDU1 +Y

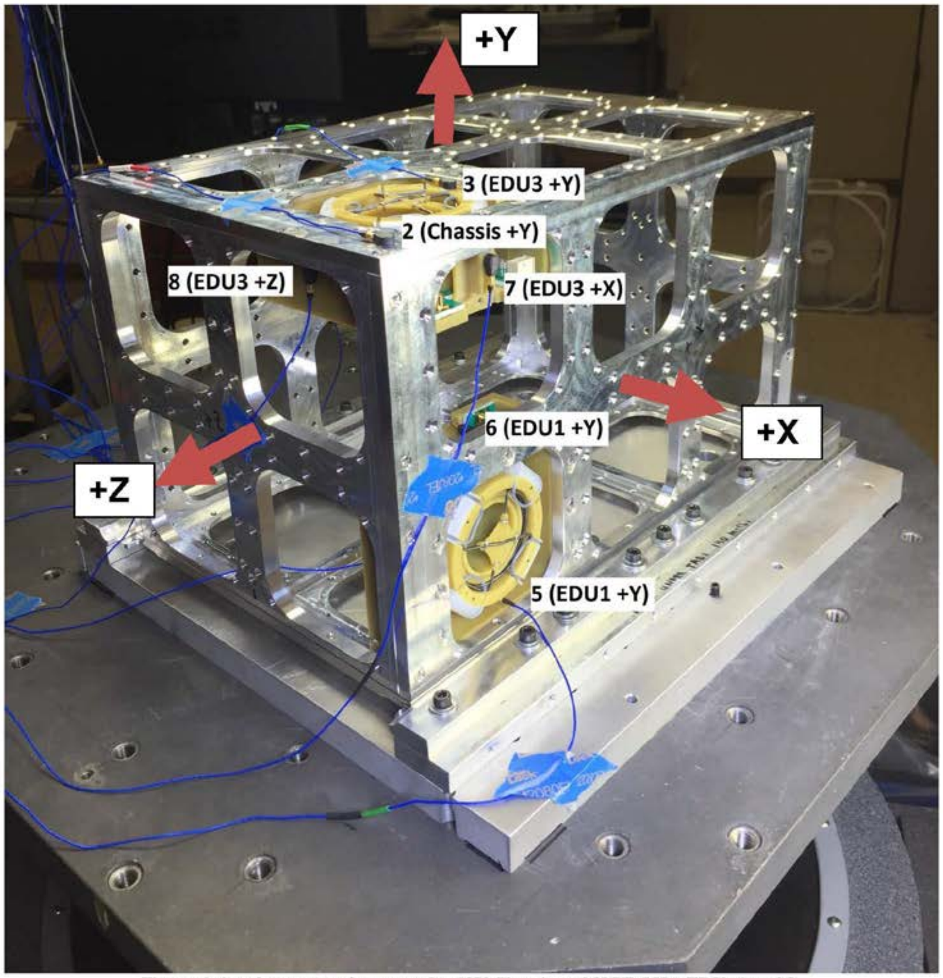


Figure 6. Accelerometer placement for 12U Chassis and HCT QHA EDUs 1 and 3

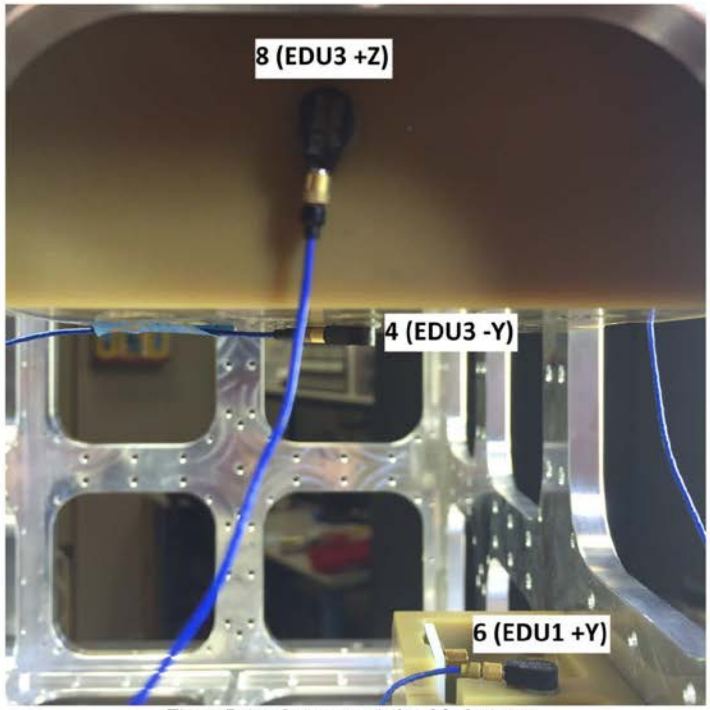


Figure 7. Accelerometers 4, 6 and 8 placement

APPENDIX 6.0 - Excerpt from GSFC-STD-7000A

Table 2.4-3
Generalized Random Vibration Test Levels
Components (ELV)
22.7-kg (50-lb) or less

Frequency (Hz)	ASD Level (g^2/Hz) Qualification	ASD Level (g^2/Hz) Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

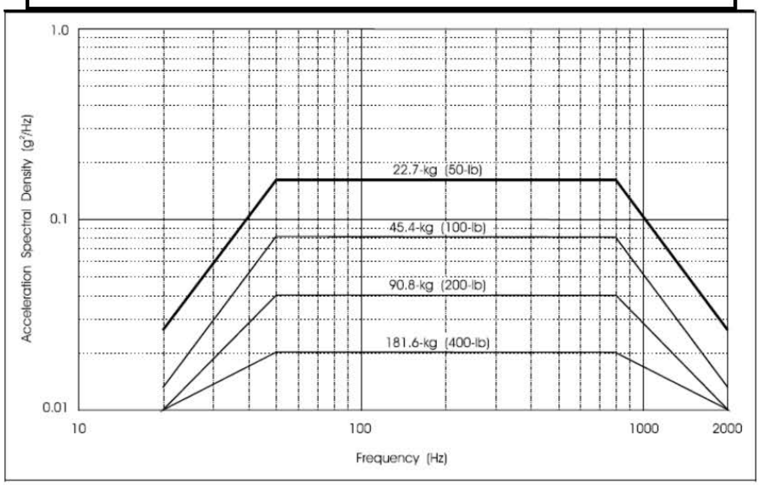


Table 2.4-4
Component Minimum Workmanship
Random Vibration Test Levels
45.4-kg (100-lb) or less

Frequency (Hz)	ASD Level (g^2/Hz)
20	0.01
20-80	+3 dB/oct
80-500	0.04
500-2000	-3 dB/oct
2000	0.01
Overall	6.8 g_{rms}

The plateau acceleration spectral density level (ASD) may be reduced for components weighing between 45.4 and 182 kg, or 100 and 400 pounds according to the component weight (W) up to a maximum of 6 dB as follows:

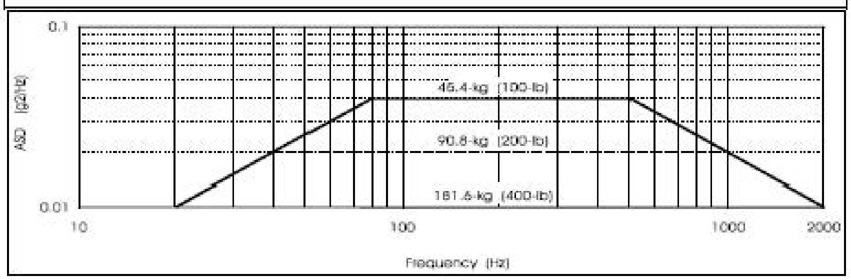
		Weight in kg	Weight in lb
dB reduction	=	10 log(W/45.4)	10 log(W/100)
$ASD_{(plateau)}$ level	=	0.04•(45.4/W)	0.04•(100/W)

The sloped portions of the spectrum shall be maintained at plus and minus 3 dB/oct. Therefore, the lower and upper break points, or frequencies at the ends of the plateau become:

F_L = 80 (45.4/W) [kg] F_L = frequency break point low end of plateau
= 80 (100/W) [lb]

F_H = 500 (W/45.4) [kg] F_H = frequency break point high end of plateau
= 500 (W/100) [lb]

The test spectrum shall not go below 0.01 g^2/Hz. For components whose weight is greater than 182-kg or 400 pounds, the workmanship test spectrum is 0.01 g^2/Hz from 20 to 2000 Hz with an overall level of 4.4 g_{rms}.



Appendix C: Functional Test Plan

HCT Antenna Functional Test Plan

Carl Kobza USAF AETC AFIT/ENY
Chris Sheffield USAF AETC AFIT/ENY

25 April 2016

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY
Wright-Patterson Air Force Base, Ohio

Signature Page

Authored		
Action Taken	Kobza, Carl - Structural Engineer	Date
Approval		
Action Taken	Sheffield, Chris - Bus Engineer	Date

1. Introduction

1.1. Purpose

This test procedure provides electrical and mechanical deployment functional testing and checkout of the Helical Communications Technologies (HCT) antenna Engineering Design Units (EDUs) and flight units.

1.2. Scope

This plan provides procedures to test the HCT antenna's electrical circuit functionality through electrical functional tests and verify the hardware operates correctly by performing mechanical deployment tests.

1.3. Objective

This plan should be performed before, during, and after environmental testing events to establish performance baselines and evaluate impacts of testing on the HCT antenna.

2. Resource Requirements

2.1. Facilities

Room 127 of AFIT building 644 is required to support material and equipment; access to room 125 of AFIT building 644 is required for functional testing during thermal vacuum (TVAC) and vibration testing.

2.2. Personnel Requirements

2.2.1. Test Conductor (TC) - Controls test plan, administers test procedures and ensures compliance as well as establishes changes of the test plan as required.

2.2.2. Test Technician(s) – Performs actions administered by the Test Conductor.

2.2.3. Quality Assurance Engineer (QA) – Provides double check of TC and Test Technician actions and performs QA Provisions.

Table 1 - Test Personnel

Position	Team Member	Initials
Test Conductor		
Test Technician		
Quality Assurance		

2.3. Quality Assurance (QA) Provisions

The designated Quality Assurance Engineer shall perform the following:

2.3.1. Inspect all test setup and configurations in real-time.
2.3.2. Provide judgment on appropriateness of any real-time changes to this procedure.
2.3.3. Review data and accept at completion of this procedure.
2.3.4. Ensure documentation of the results of this procedure.

2.4. Safety Compliance

2.4.1. For operations occurring during normal duty days, all accidents and hazardous incidents shall be reported to Facility Safety.

2.4.2. During non-standard hours, all accidents and incidents shall be reported to the Facility Safety Officer on the next working day.

2.5. Hazardous Operations

2.5.1. General Laboratory Safety, Ear/Eye Protection (PPE)

2.6. Material/Equipment/Software Requirements

2.6.1. Material, equipment and software requirements are as follows: computer, LabView software, HCT antenna EDU, wiring harness, power supply, and Power Selection Interface box.

3. Test Configuration

3.1. Test Setup

3.1.1. See initial setup (section 4.1.).

3.2. Test Results

3.2.1. All results and data will be recorded. Pass/fail criteria is based on successful individual test completion within the proper test sequence. Additional observations, notes, and any changes to the procedure will be annotated and submitted with the final test package.

3.3. Test Software

3.3.1. LabView (file name: HCT_ANTENNA_TVAC)

4. Test Procedure

4.1. Initial Setup

Step	Activity	TC Initials/Date	QA/Date
1.	Remove "remove before flight" cover from HCT antenna		
2.	Connect Power Supply to Laptop		
3.	Start Labview and verify Power Supply is connected		
4.	Switch the Power Selection Interface to "OFF"		
5.	Connect Power Supply to Power Selection Interface		
6.	Connect Power Selection Interface to DB-25 connector		
7.	Turn on Power Supply		
8.	In LabView set maximum current to 7 Amps		
9.	Measure resistance on antenna circuit		
10.	In LabView set voltage so that the antenna will receive 8.4V		
11.	Set file location and name		

4.2. Functional Tests

4.2.1. Electrical Functional Test Demonstration

Step	Activity	TC Initials/Date	QA/Date

1.	Use LabView VI for the following steps: Set test duration to two seconds		
2.	Select which EDU to deploy		
3.	Select EDU orientation		
4.	Select temperature profile		
5.	Attach the positive and negative wires on the box to the desired antenna number intended to test		
6.	Switch the Power Selection Interface to "ON"		
7.	Run the VI		
8.	Click "Start Test"		
9.	Stop the VI when test has concluded		

4.2.2. Mechanical Functional Deployment Test Demonstration

Step	Activity	TC Initials/Date	QA/Date
1.	Use LabView VI for the following steps: Set test duration to 120 seconds		
2.	Select which EDU to deploy		
3.	Select EDU orientation		
4.	Select temperature profile		
5.	Attach the positive and negative wires on the box to the desired antenna number intended to deploy		
6.	Switch the Power Selection Interface to "ON"		
7.	Run the VI		
8.	Click "Start Test"		
9.	Stop the VI when test has concluded		

Appendix D: FEA Mode Shapes

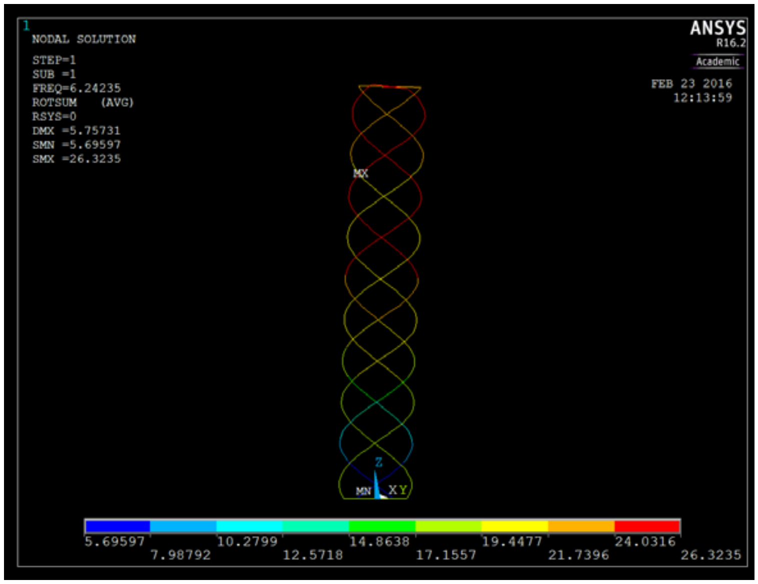


Figure 89. FEA identified 1st mode: 1st bending mode

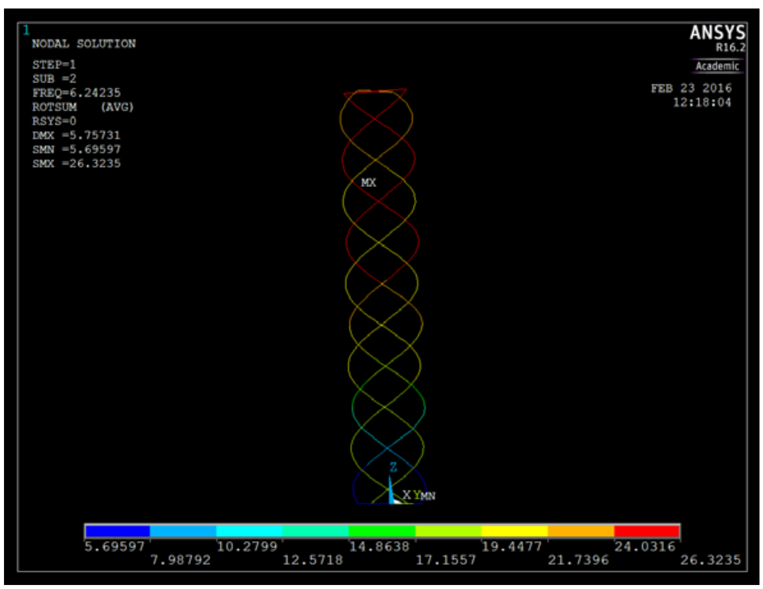


Figure 90. FEA identified 2nd mode: 2nd bending mode

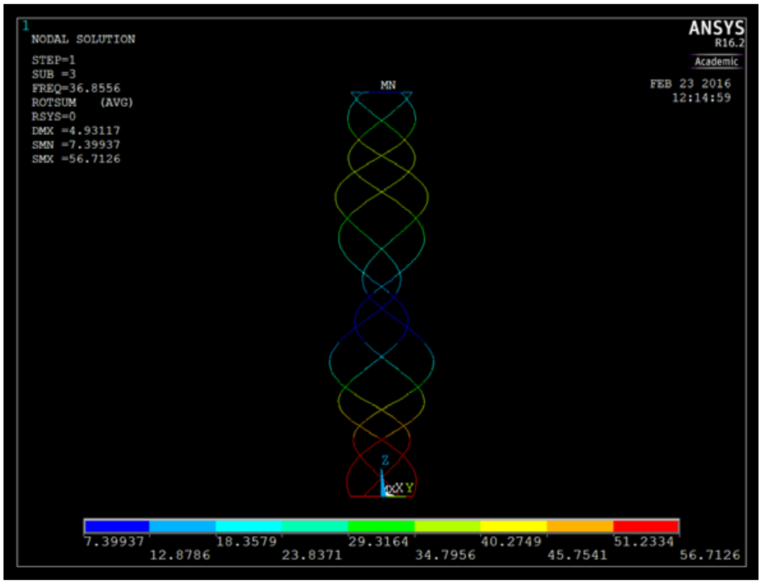


Figure 91. FEA identified 3rd mode: 1st breathing mode

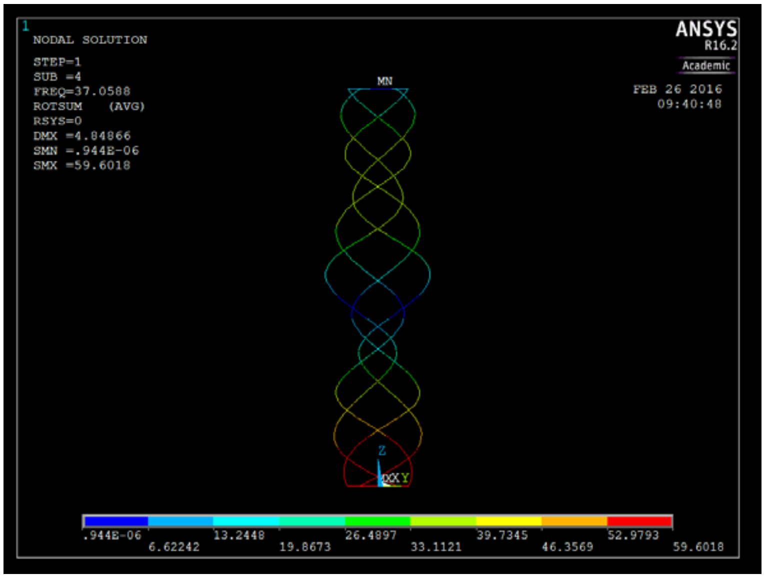


Figure 92. FEA identified 4th mode: 2nd breathing mode

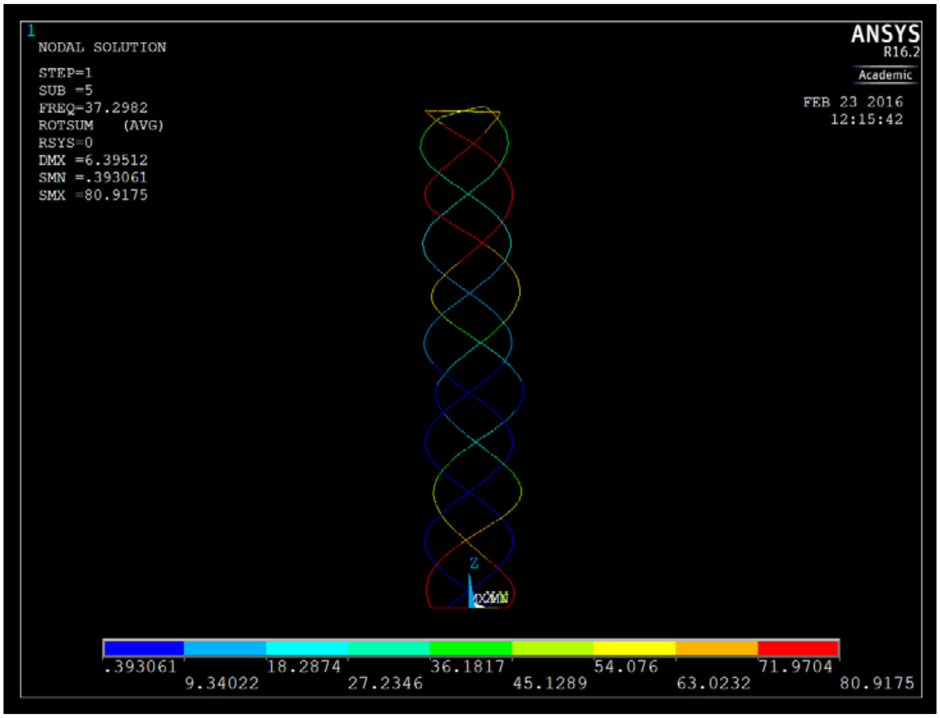


Figure 93. FEA identified 5th mode: 1st torsional mode

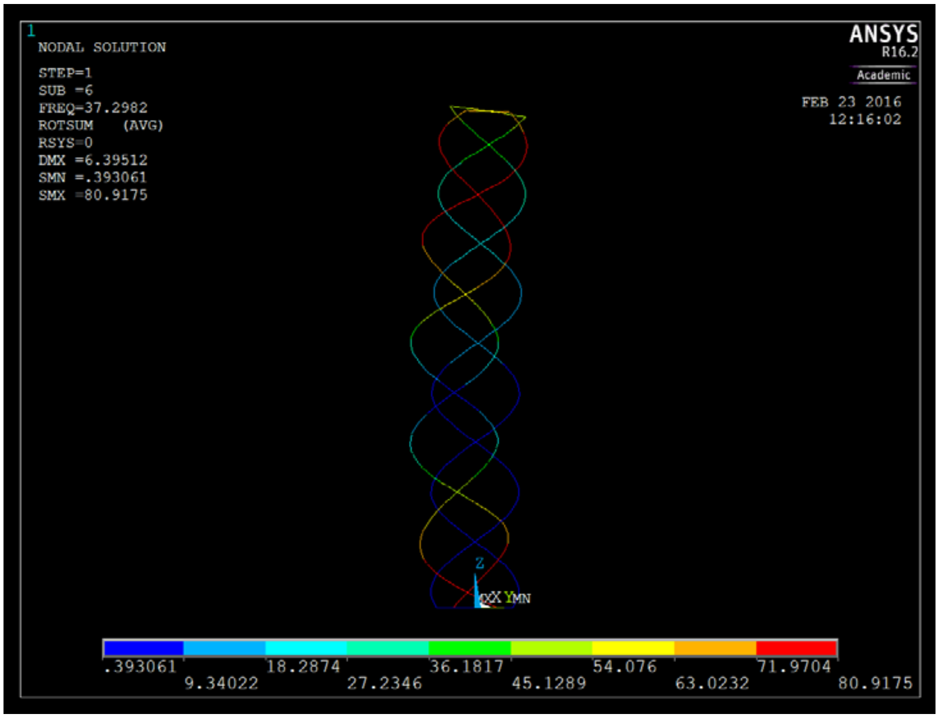


Figure 94. FEA identified 6th mode: 2nd torsional mode

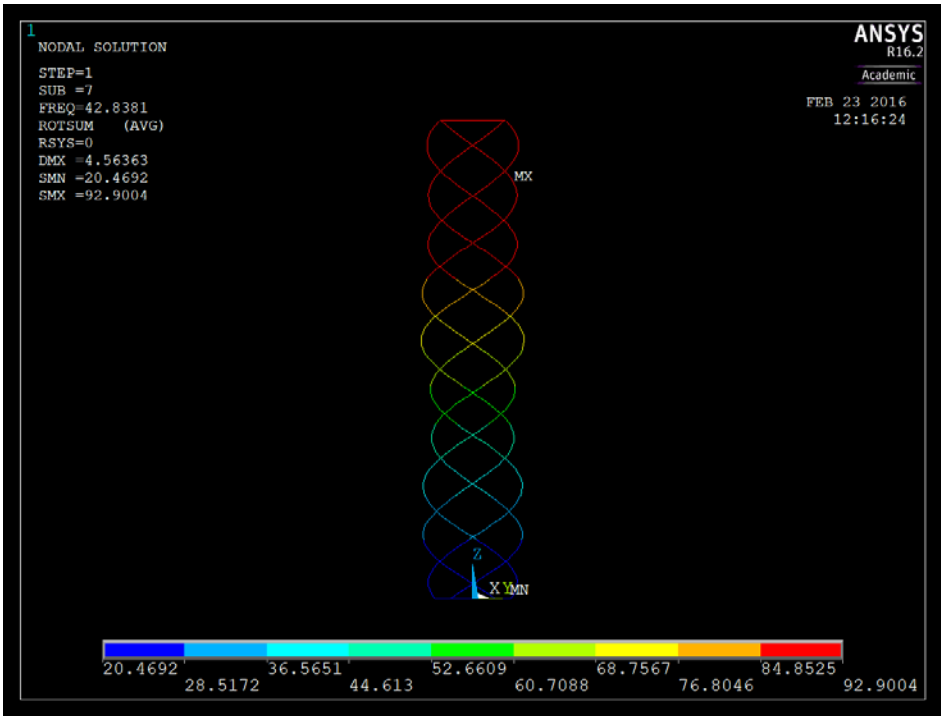


Figure 95. FEA identified 7th mode: 1st "pogo" mode

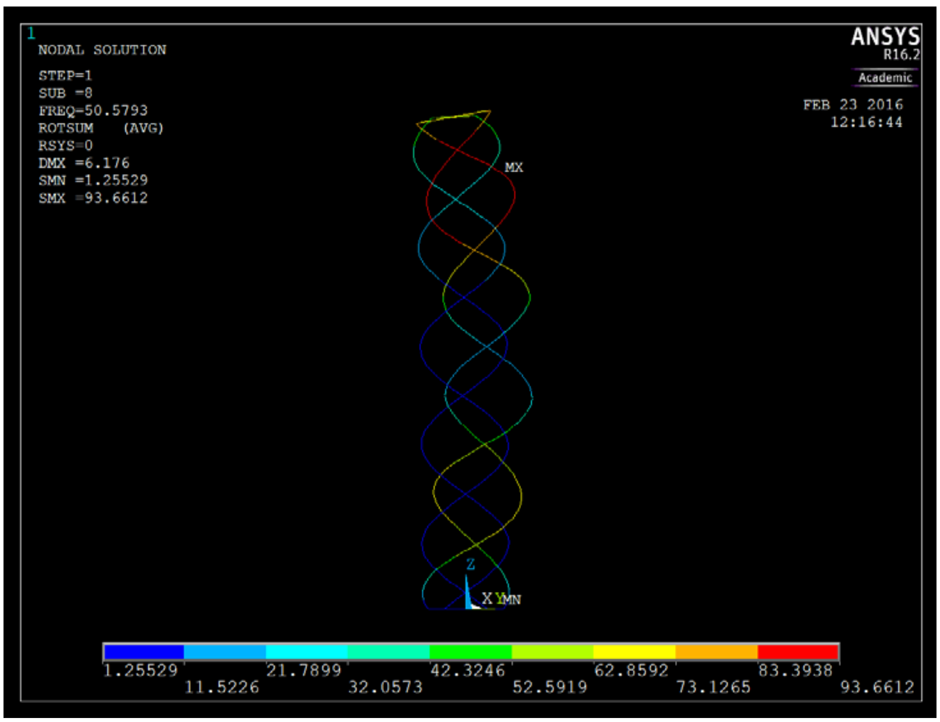


Figure 96. FEA identified 8th mode: 3rd torsional mode

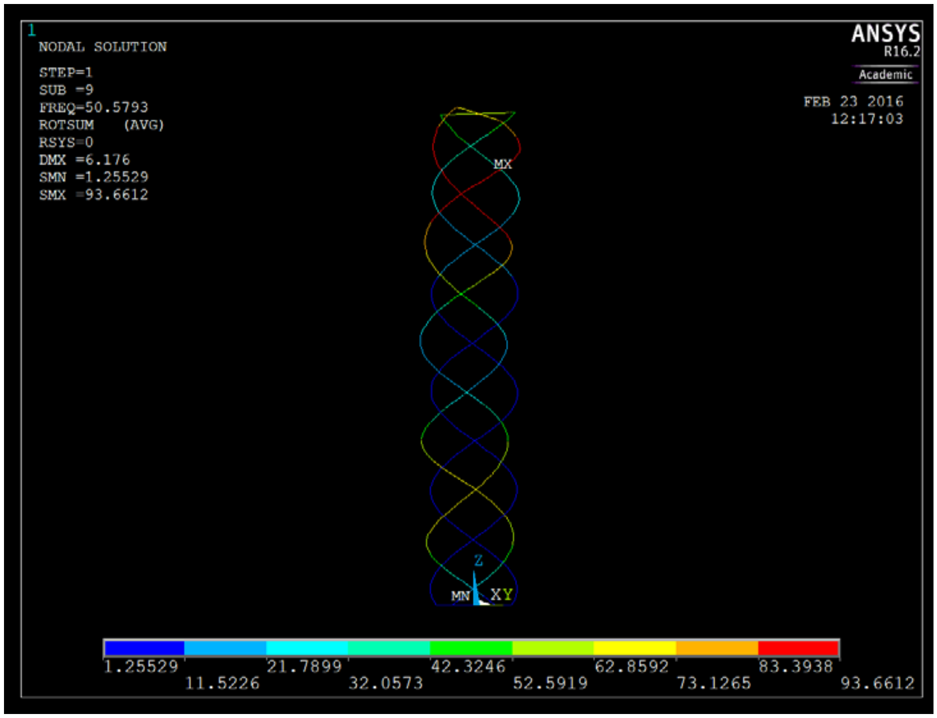


Figure 97. FEA identified 9th mode: 4th torsional mode

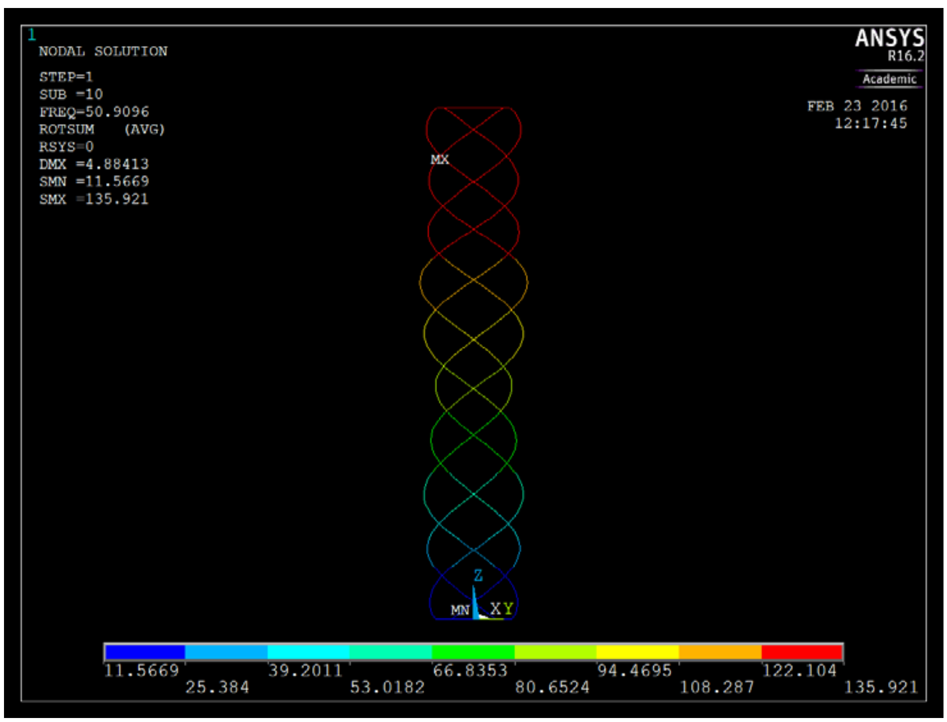


Figure 98. FEA identified 10th mode: 2nd "pogo" mode

Appendix E: Laser Vibrometer Measured Frequencies

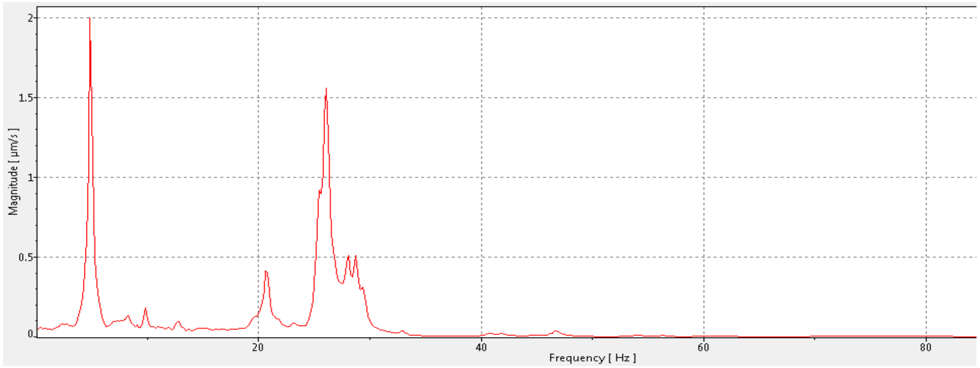
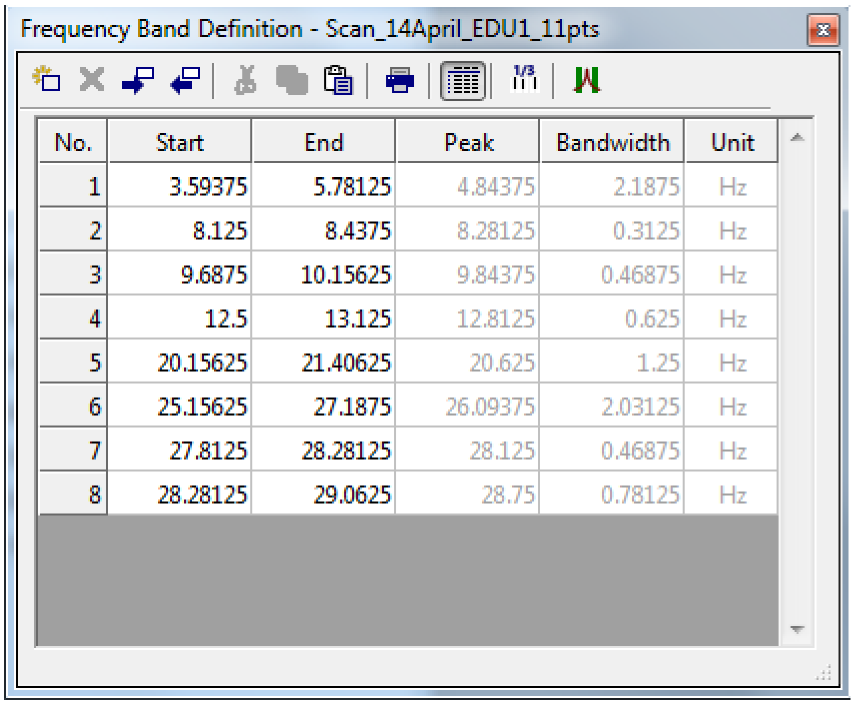


Figure 99. EDU 1 pre-testing laser vibrometer measured frequencies



Frequency Band Definition - Scan_14April_EDU1_11pts

No.	Start	End	Peak	Bandwidth	Unit
1	3.59375	5.78125	4.84375	2.1875	Hz
2	8.125	8.4375	8.28125	0.3125	Hz
3	9.6875	10.15625	9.84375	0.46875	Hz
4	12.5	13.125	12.8125	0.625	Hz
5	20.15625	21.40625	20.625	1.25	Hz
6	25.15625	27.1875	26.09375	2.03125	Hz
7	27.8125	28.28125	28.125	0.46875	Hz
8	28.28125	29.0625	28.75	0.78125	Hz

Figure 100. EDU 1 pre-testing identified natural frequencies

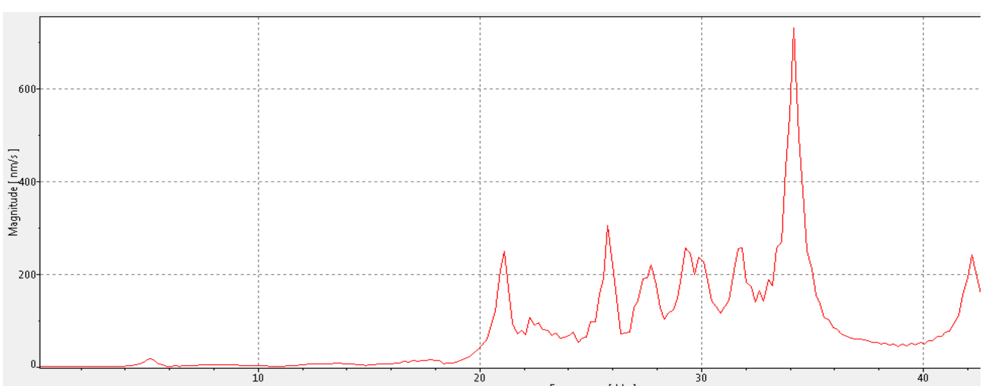
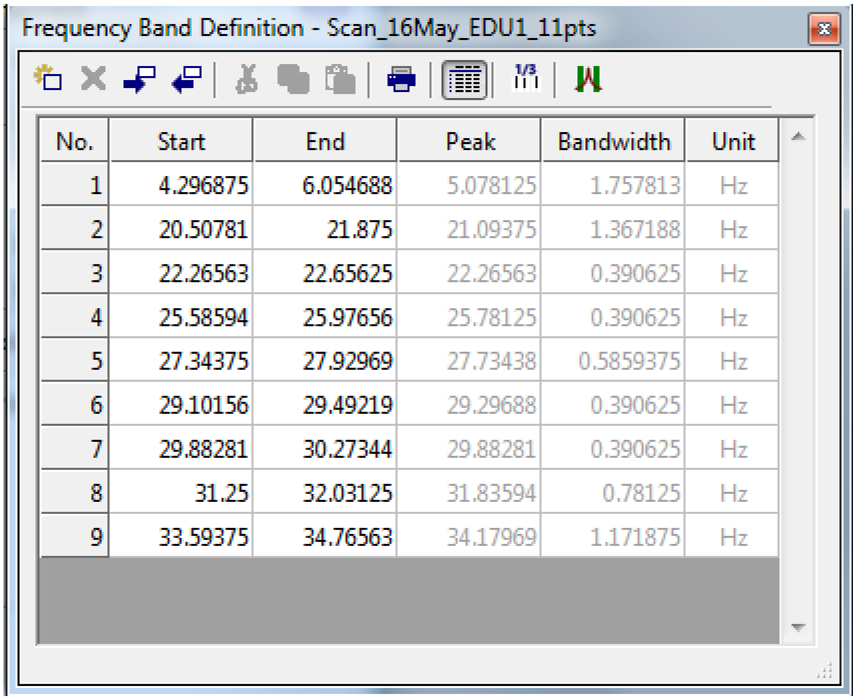


Figure 101. EDU 1 post-testing laser vibrometer measured frequencies



Frequency Band Definition - Scan_16May_EDU1_11pts

No.	Start	End	Peak	Bandwidth	Unit
1	4.296875	6.054688	5.078125	1.757813	Hz
2	20.50781	21.875	21.09375	1.367188	Hz
3	22.26563	22.65625	22.26563	0.390625	Hz
4	25.58594	25.97656	25.78125	0.390625	Hz
5	27.34375	27.92969	27.73438	0.5859375	Hz
6	29.10156	29.49219	29.29688	0.390625	Hz
7	29.88281	30.27344	29.88281	0.390625	Hz
8	31.25	32.03125	31.83594	0.78125	Hz
9	33.59375	34.76563	34.17969	1.171875	Hz

Figure 102. EDU 1 post-testing identified natural frequencies

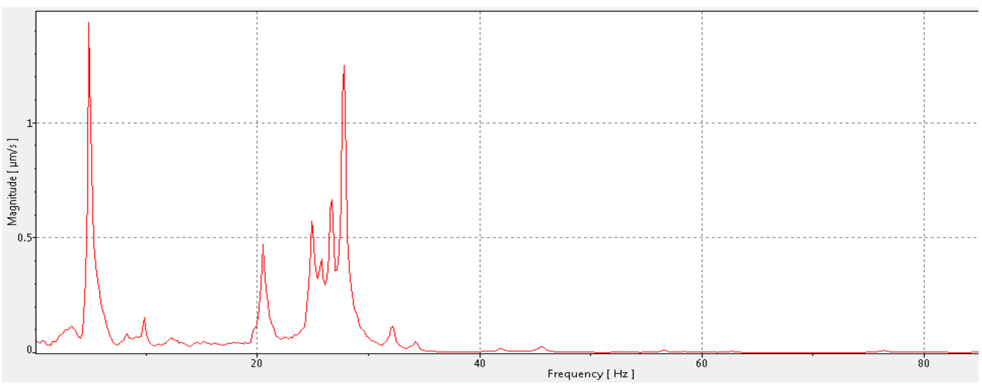
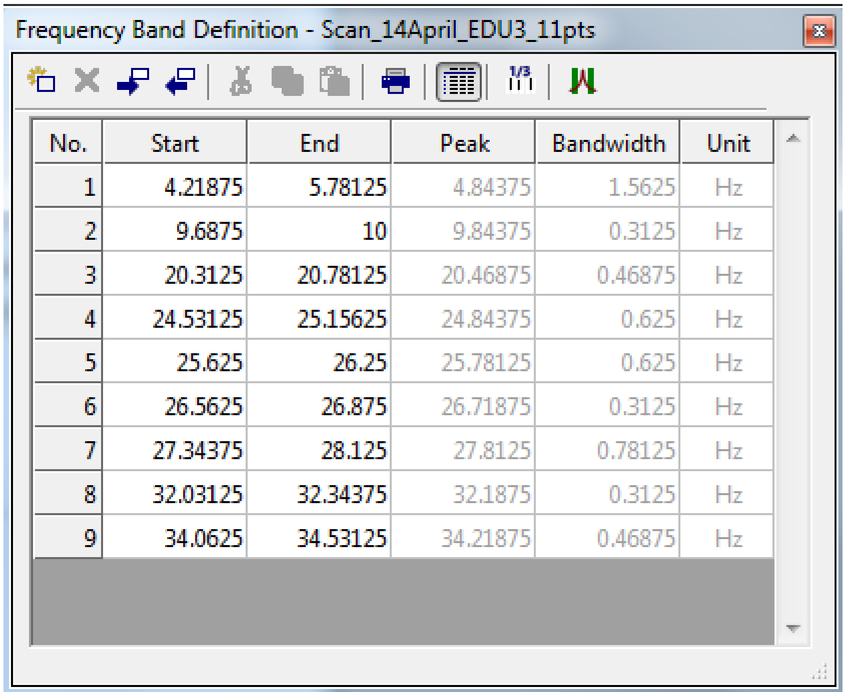


Figure 103. EDU 3 pre-testing laser vibrometer measured frequencies



Frequency Band Definition - Scan_14April_EDU3_11pts

No.	Start	End	Peak	Bandwidth	Unit
1	4.21875	5.78125	4.84375	1.5625	Hz
2	9.6875	10	9.84375	0.3125	Hz
3	20.3125	20.78125	20.46875	0.46875	Hz
4	24.53125	25.15625	24.84375	0.625	Hz
5	25.625	26.25	25.78125	0.625	Hz
6	26.5625	26.875	26.71875	0.3125	Hz
7	27.34375	28.125	27.8125	0.78125	Hz
8	32.03125	32.34375	32.1875	0.3125	Hz
9	34.0625	34.53125	34.21875	0.46875	Hz

Figure 104. EDU 3 pre-testing identified natural frequencies

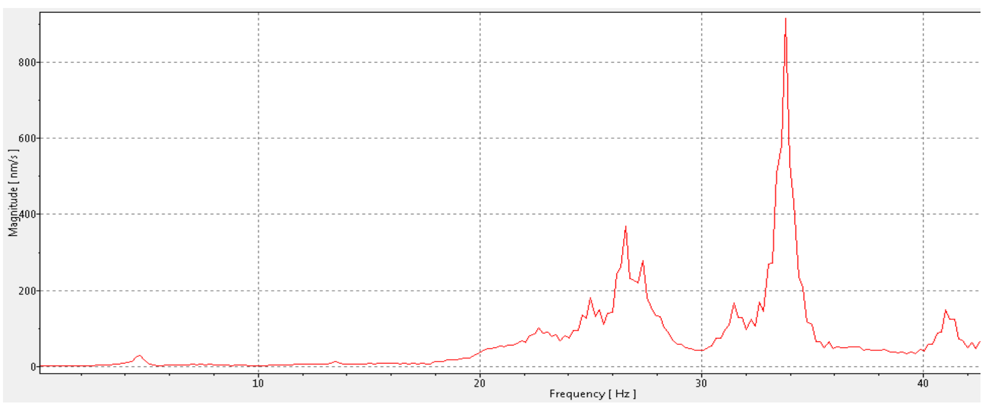
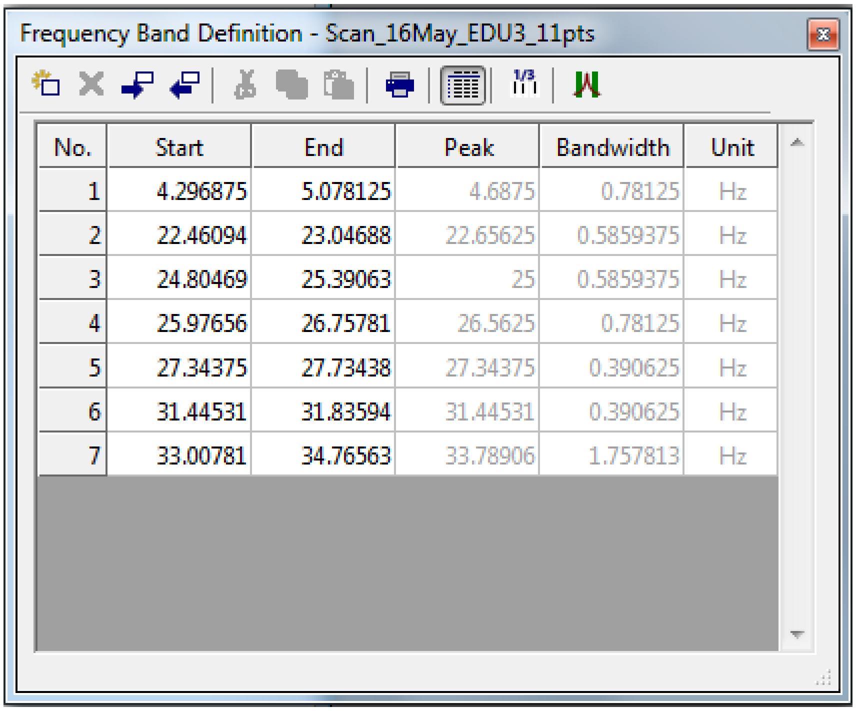


Figure 105. EDU 3 post-testing laser vibrometer measured frequencies



Frequency Band Definition - Scan_16May_EDU3_11pts

No.	Start	End	Peak	Bandwidth	Unit
1	4.296875	5.078125	4.6875	0.78125	Hz
2	22.46094	23.04688	22.65625	0.5859375	Hz
3	24.80469	25.39063	25	0.5859375	Hz
4	25.97656	26.75781	26.5625	0.78125	Hz
5	27.34375	27.73438	27.34375	0.390625	Hz
6	31.44531	31.83594	31.44531	0.390625	Hz
7	33.00781	34.76563	33.78906	1.757813	Hz

Figure 106. EDU 3 post-testing identified natural frequencies

Appendix F: Vibe Test Accelerometer Data

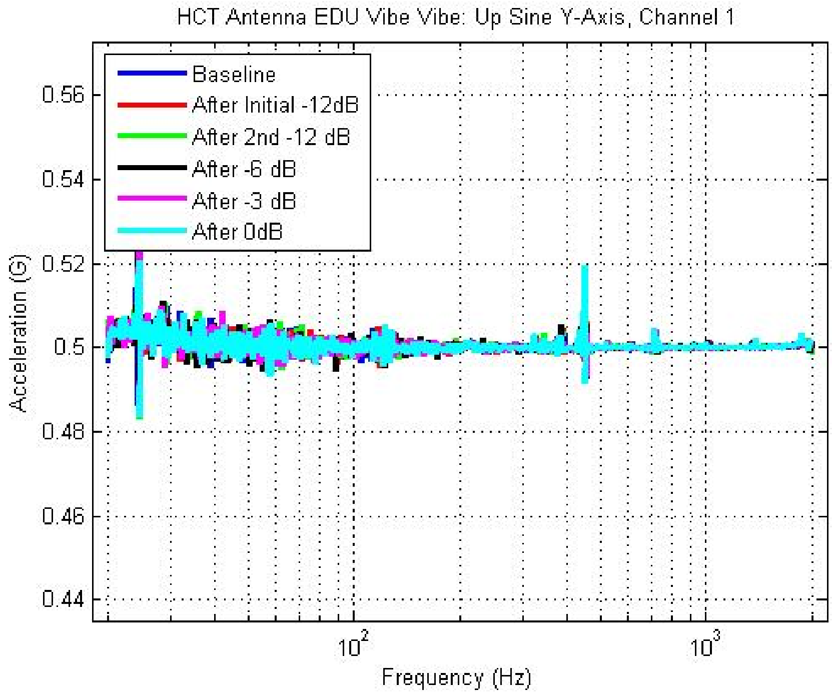


Figure 107. Channel 1 sine sweep results

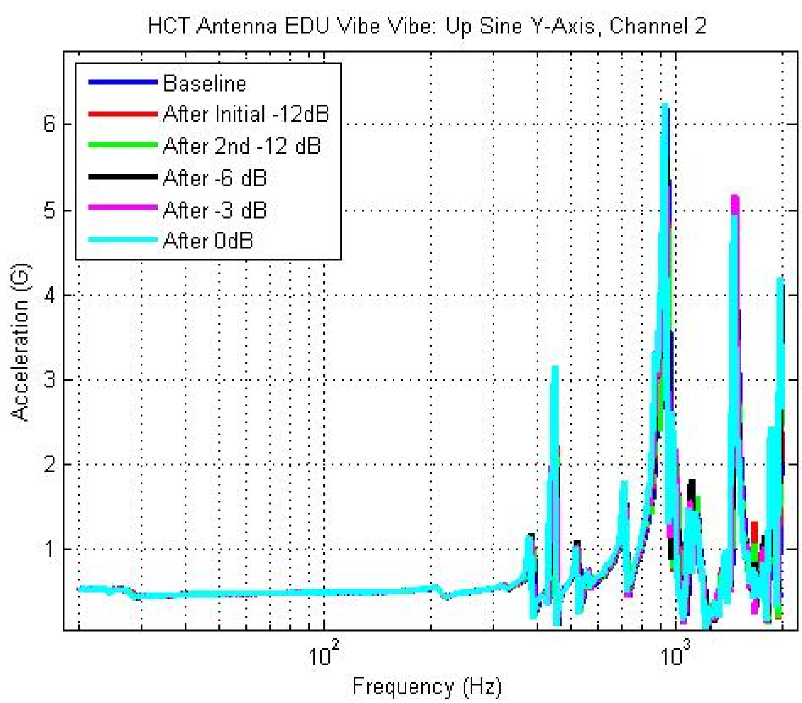


Figure 108. Channel 2 sine sweep results

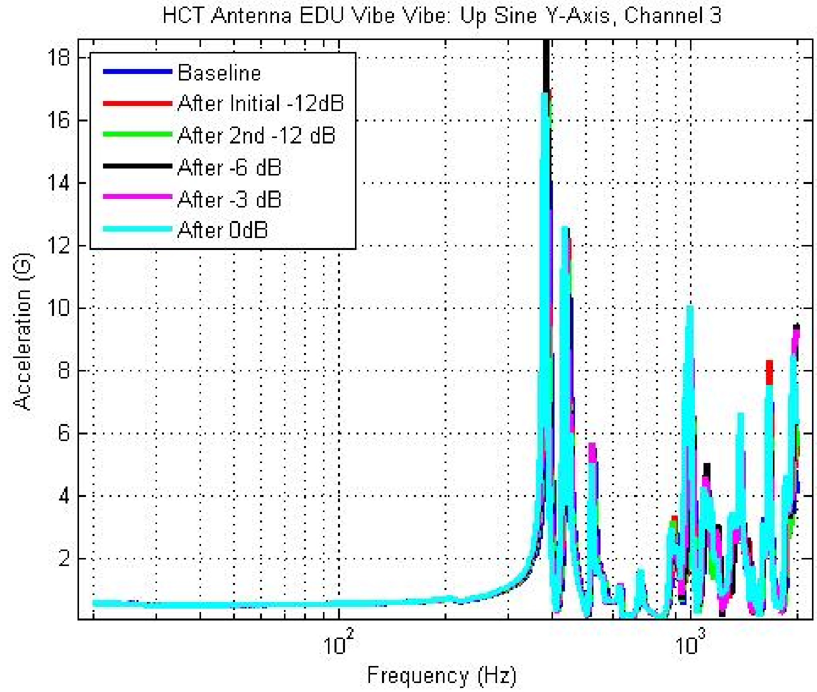


Figure 109. Channel 3 sine sweep results

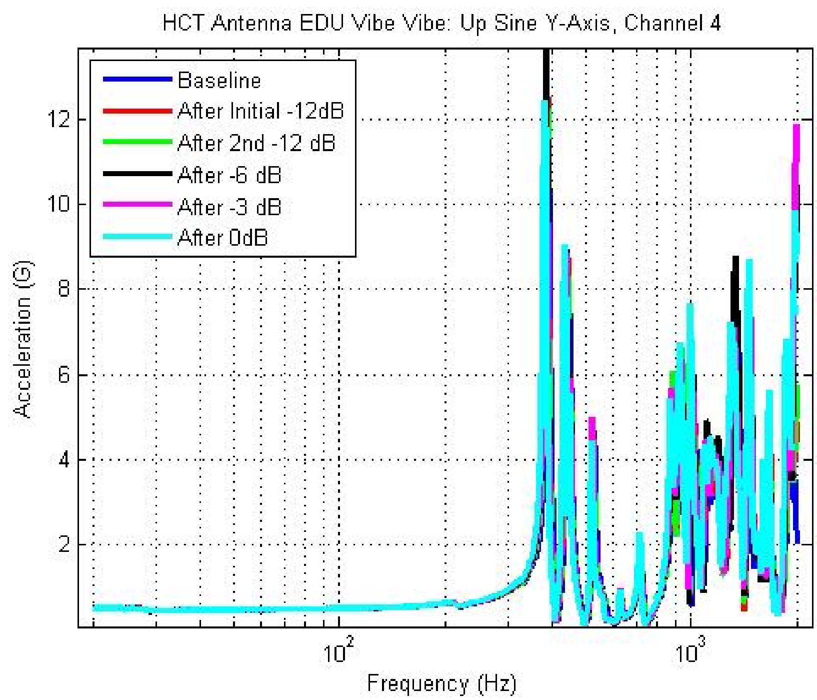


Figure 110. Channel 4 sine sweep results

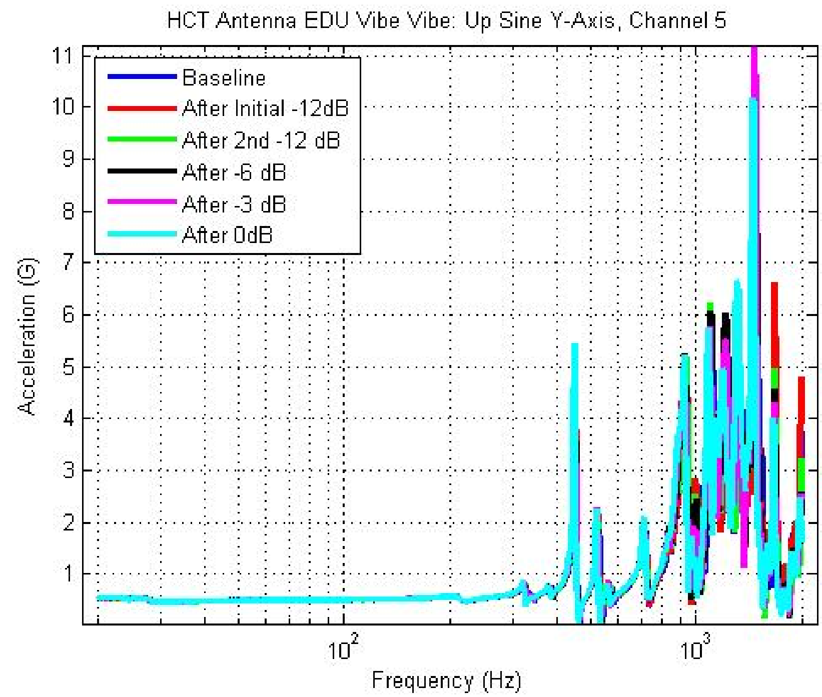


Figure 111. Channel 5 sine sweep results

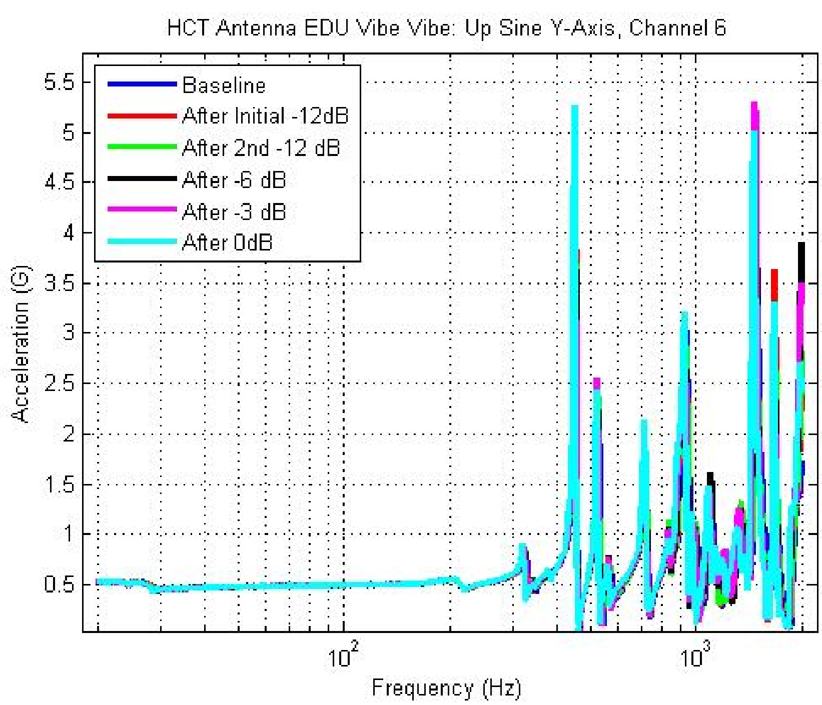


Figure 112. Channel 6 sine sweep results

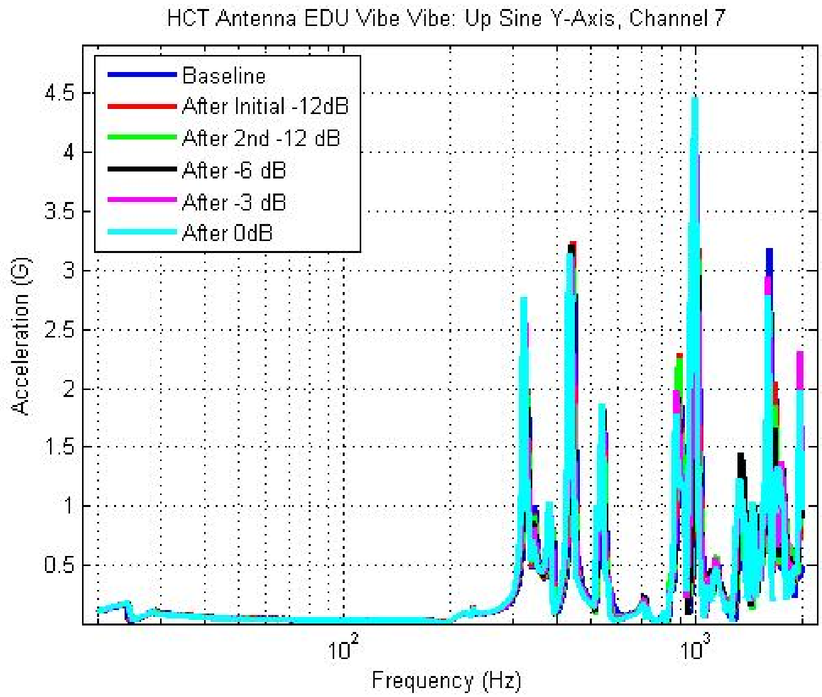


Figure 113. Channel 7 sine sweep results

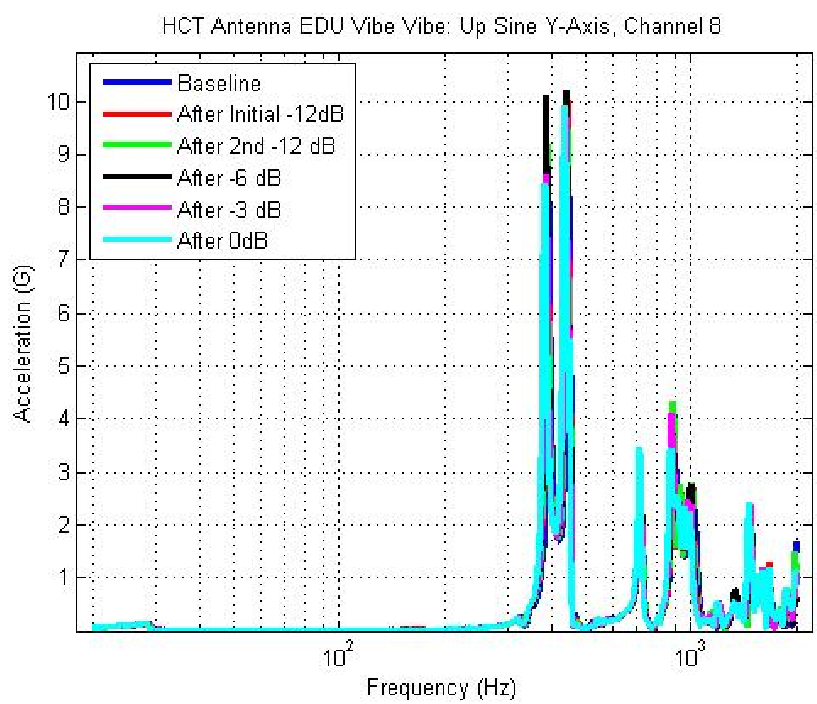


Figure 114. Channel 8 sine sweep results

Appendix G: Deployment Currents

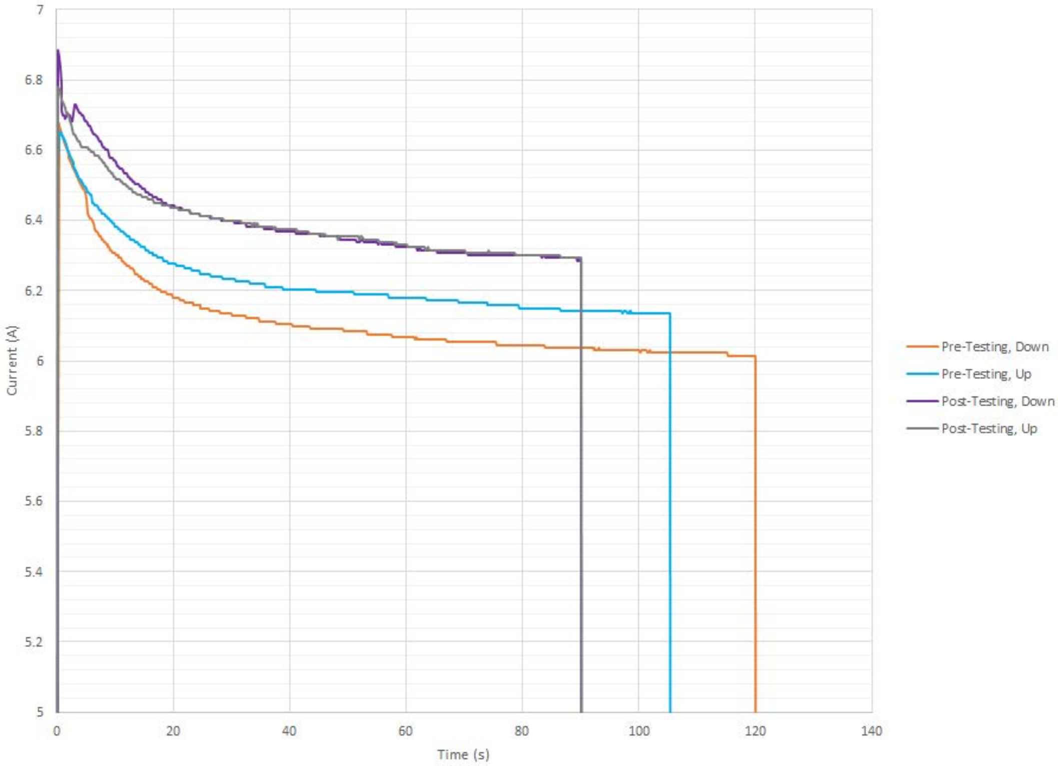


Figure 115. EDU 1 pre-and post-environmental tests deployment current

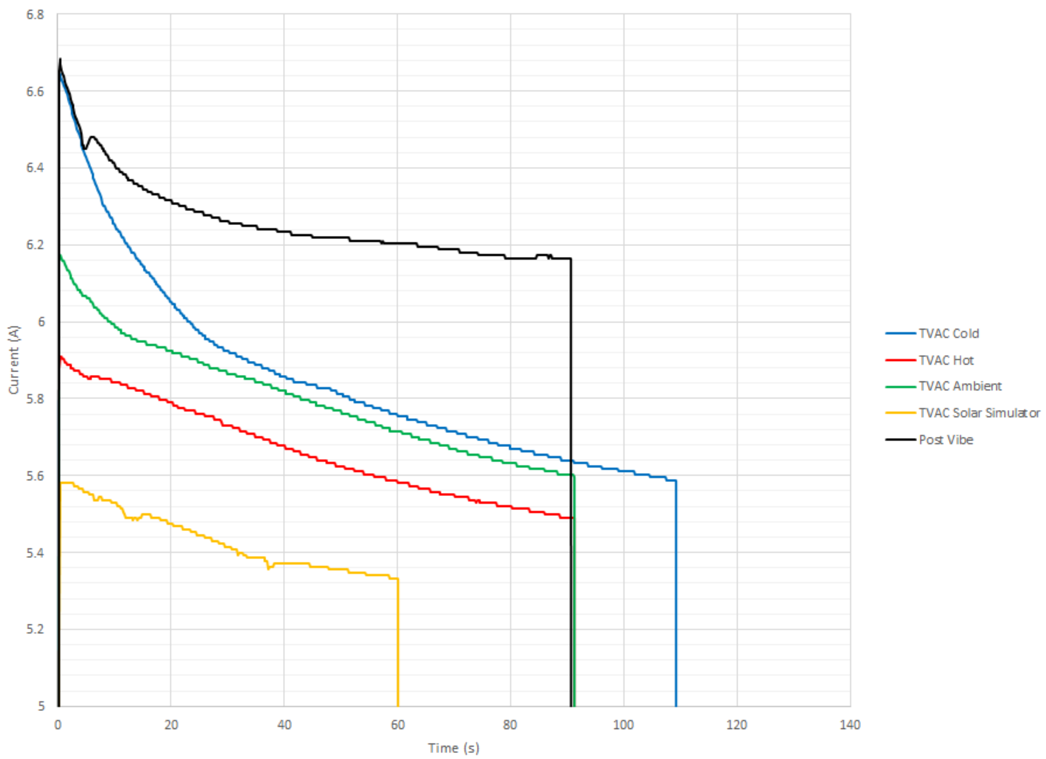


Figure 116. EDU 1 deployment current for all environmental tests

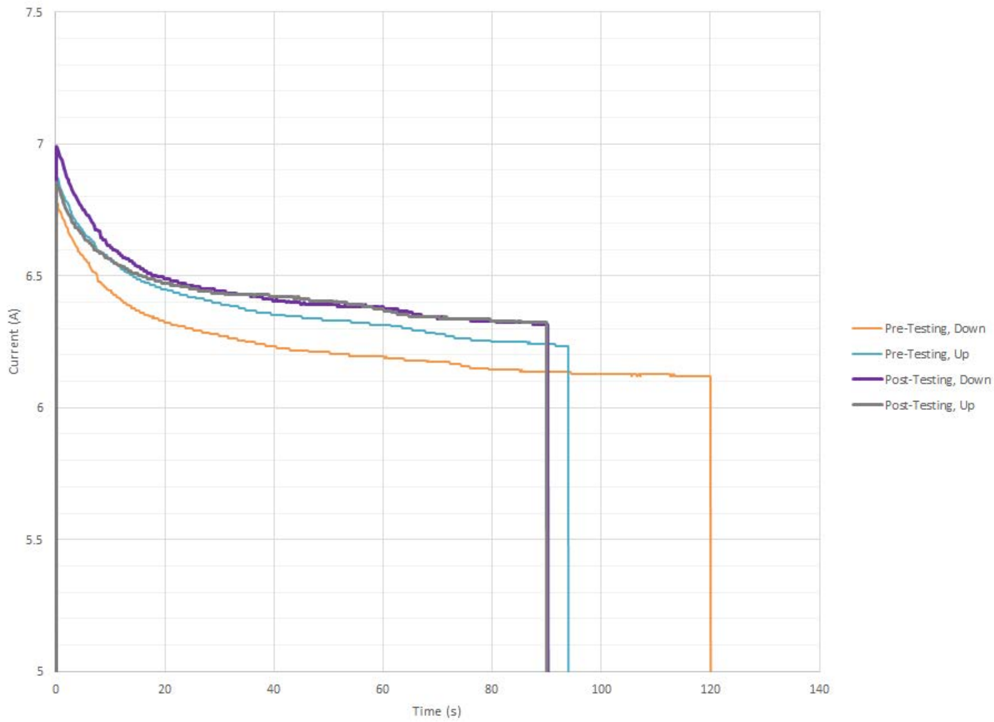


Figure 117. EDU 2 pre- and post-environmental deployment current

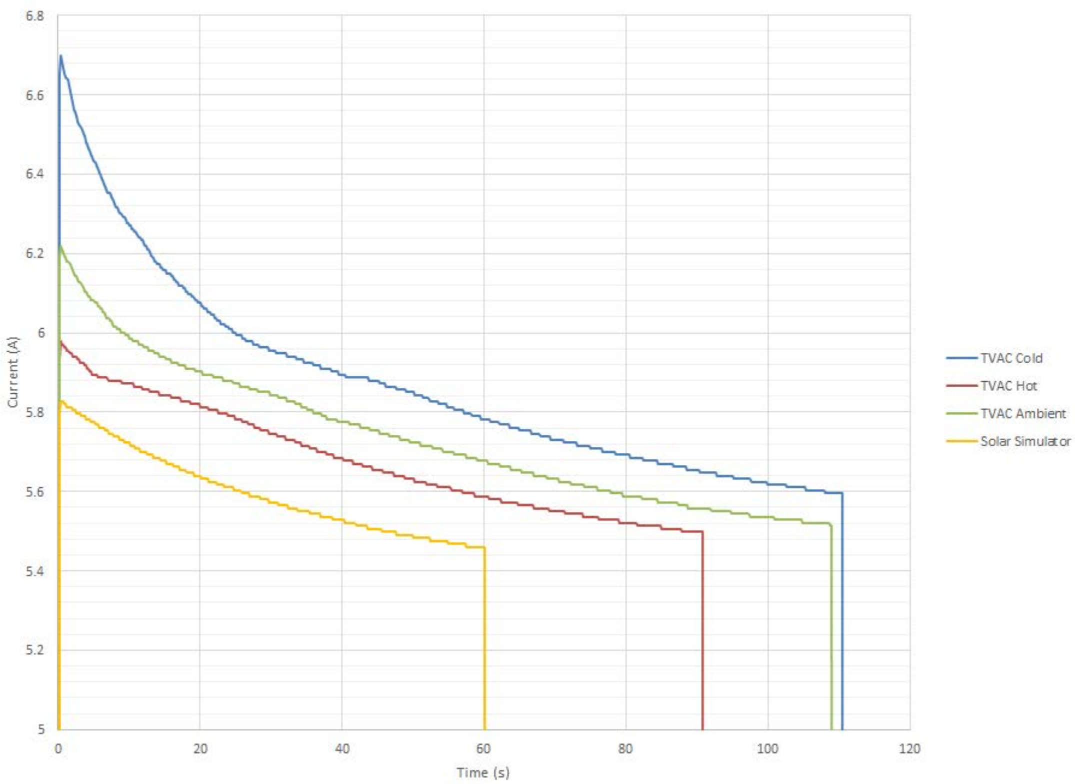


Figure 118. EDU 2 deployment currents for all environmental tests

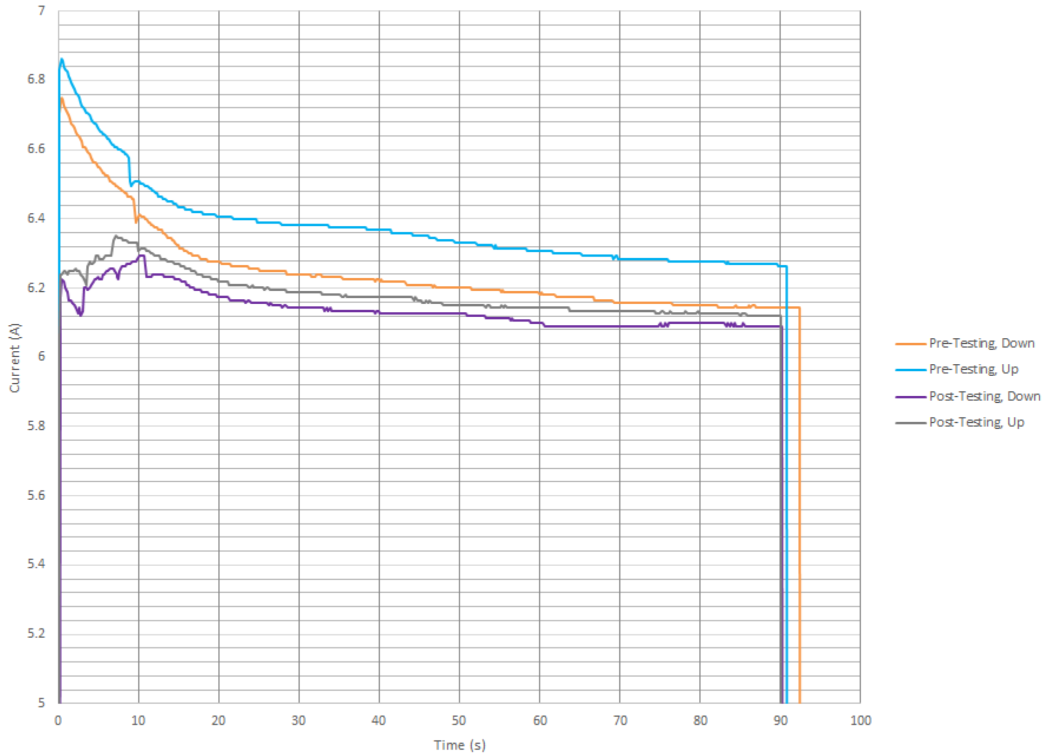


Figure 119. EDU 3 pre- and post-environmental tests deployment currents

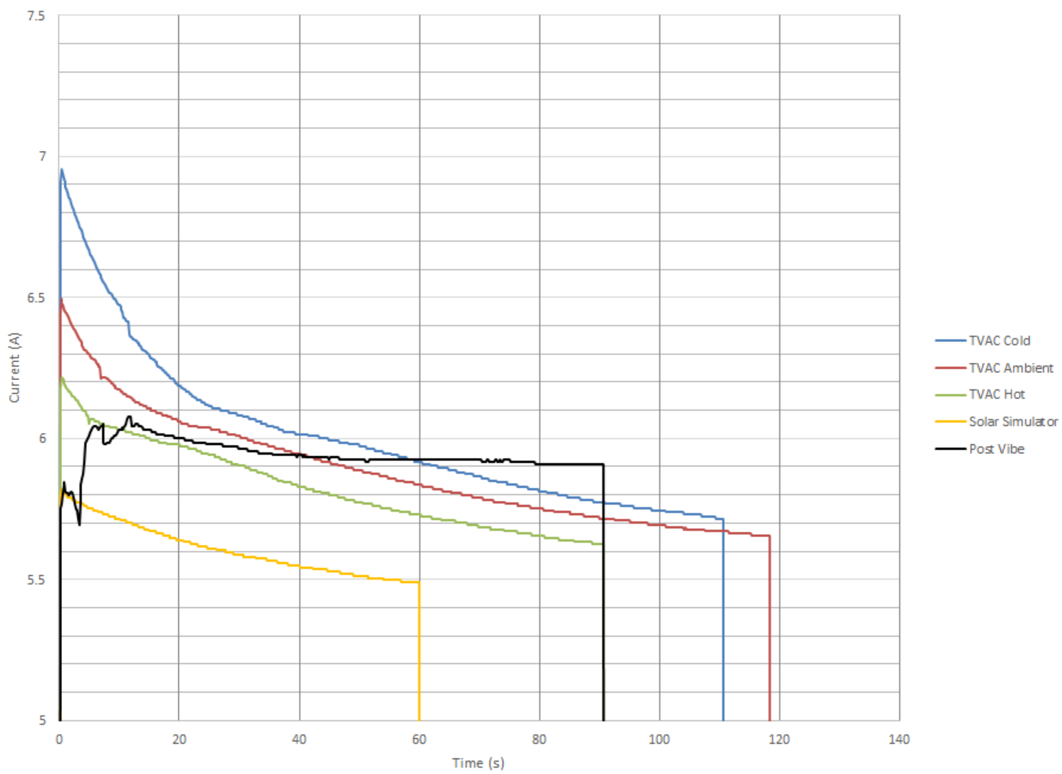


Figure 120. EDU 3 deployment currents for all environmental tests

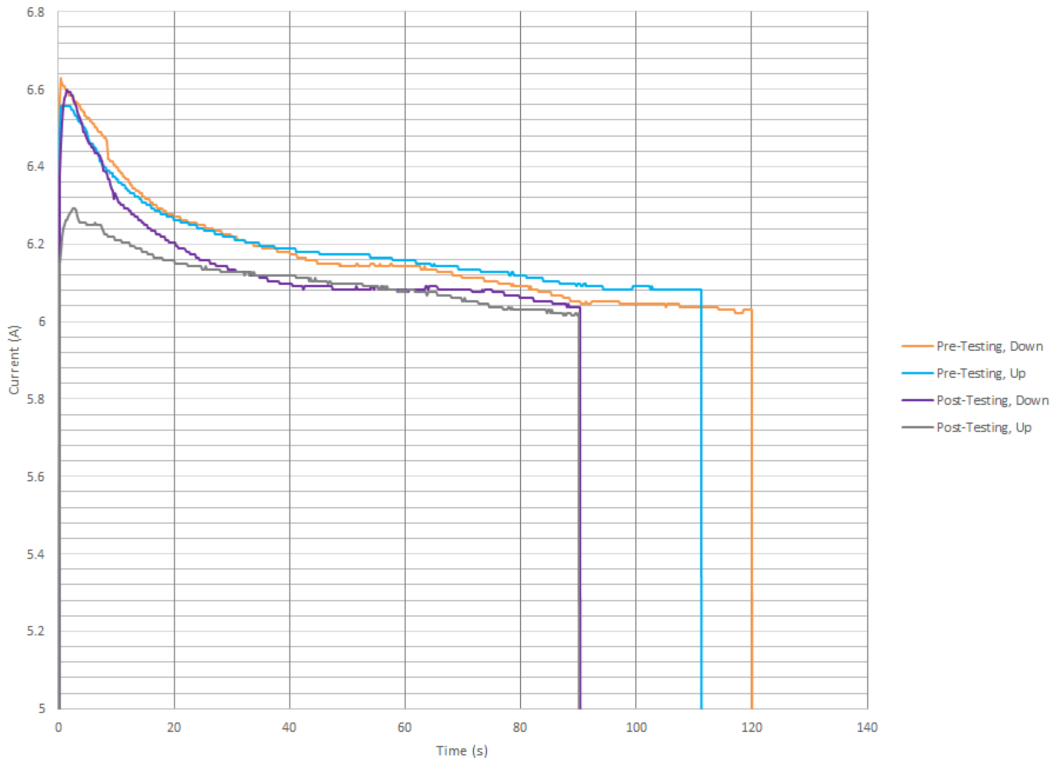


Figure 121. EDU 4 pre- and post-environmental tests deployment current

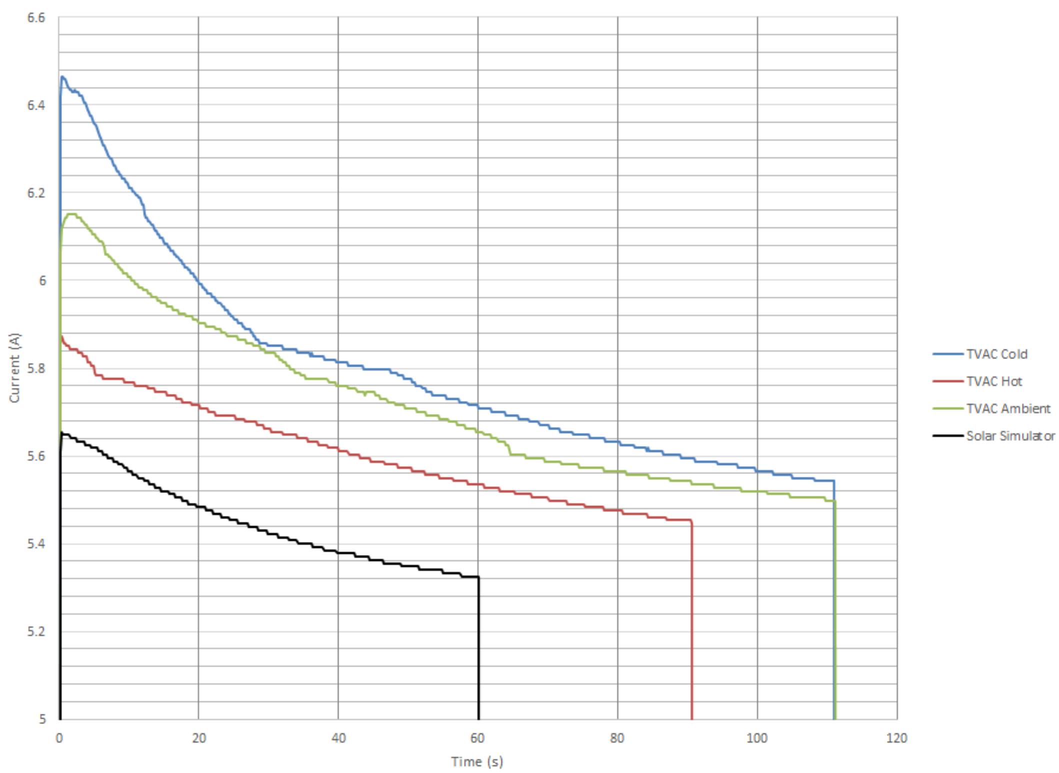


Figure 122. EDU 4 deployment currents for all environmental tests

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14. ABSTRACT
Increasingly capable CubeSat missions require antenna with improved Radio Frequency performance over the traditional CubeSat antennas. Deployable quadrifilar helical antennas (QHA) enable an acceptable stowing volume and deploy to provide increased gain and bandwidth over traditional patch and dipole antennas. Extensive ground testing is required to ensure the antenna is space qualified and to characterize the antenna deployment in the space environment. AFIT requires a QHA to perform a future CubeSat geolocation mission and contracted Helical Communication Technologies (HCT) to design and manufacture a Shape Memory Alloy (SMA) L-band deployable QHA. Vibration, thermal vacuum, laser vibrometer, and Voltage Standing Wave Ratio (VSWR) experiments were conducted on the HCT antenna to verify the hardware in a simulated launch environment and to characterize the SMA deployment in the simulated space environment.

The HCT QHA successfully passed all required NASA General Environmental Verification Standards space qualification testing. Several anomalies experienced by the QHA encourage a redesign. The deployed antenna length varied from 250-290 mm and future RF testing is required to determine if the antenna geometry variations are significant enough to impact the geolocation mission.

This research documents the test results for a QHA deployable CubeSat antenna testing and aids the development of CONOPS for the future AFIT CubeSat mission utilizing the HCT QHAs.

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