Space Systems Research Center
United States Air Force Academy

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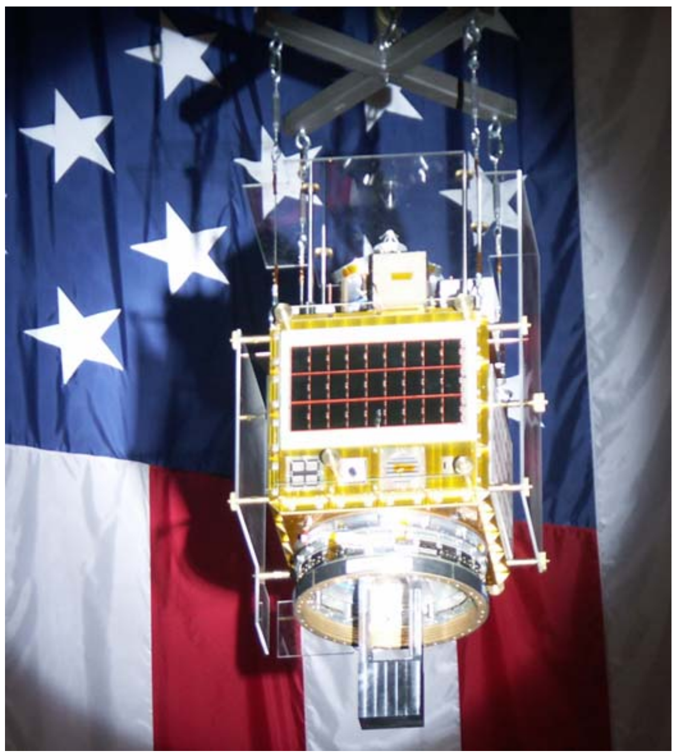
Falcon Sat-3
Qualification Model (QM)
Thermal-Vacuum, Vibration Test, and Mass Properties Measurement Test Report



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Revisions

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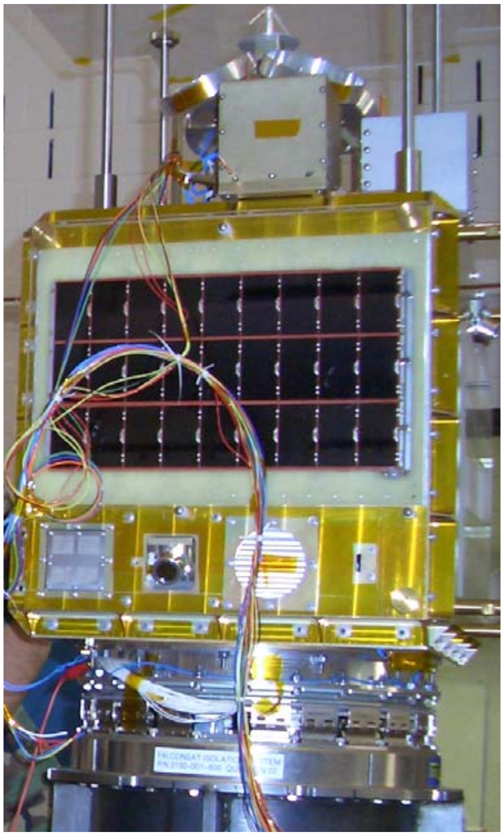
1 Executive summary



The FalconSAT-3 (FS3) Qualification Model (QM) is the third iteration on the campaign to launch for FS3. This test will be a stepping stone in its progress.

The QM test was a development test to support the design of the FS3 spacecraft, which is fourth in a series developed for educational purposes in the Small Satellite Program at the United States Air Force Academy (USAFA). FS3 will be launched on a Lockheed-Martin Atlas-V ESPA, currently scheduled for September 2006. The QM testing is the third of four planned phases of testing, with acceptance testing of the Flight Model (FM) planned for the fall of 2005.

The purpose of the QM test was to build confidence in the final design of FS3. In keeping with the philosophy of true qualification testing, the QM will be built to the design intended for the flight model with the processes intended for the flight model. The major differences will be that only one real MPACS (Micro-Propulsion Attitude Control System) will be integrated with the other four accounted for as mass dummies, the spacecraft harness will be larger to allow easy electrical test access, FLAPS will not be tested, and the boom will be a mass simulator of the SpaceQuest boom design.

All tests and measurements were performed at the Aerospace Engineering Facility (AEF) at Kirtland Air Force Base (KAFB), New Mexico. Testing took place 28 January – 06 February 2005.

The QM model was tested in a Thermal-Vacuum environment beyond the expect bounds imposed by the space environment. It was then tested for low-level sine sweep to determine the fundamental and other natural frequencies, and random vibration and sine burst to confirm strength and structural integrity. Testing was done to qualification levels, with test environments conservatively defined, recognizing that the launch vehicle is relatively new and that this will be the first flight of the ESPA. It is expected that the environments defined by the LV program to change throughout the FS3 development program, and the QM was tested to at least twice the launch environment.

The mass properties of the QM were not accurately measured due to the CG/MOI machine not being at the AEF.

This test report provides the details of the tests that were performed.

2 Scope

2.1 Introduction

This test plan details the Qualification Model (QM) test for FalconSAT-3. This FS3 program intends to verify the Flight Model (FM) design by testing a spacecraft built nearly to FM specifications at levels exceeding the flight acceptance levels required to demonstrate that the spacecraft is robust enough to survive the space environment.

All tests are run under the responsibility of the Responsible Test Engineer, and any changes must be approved by that individual. Any test may be changed, removed from the test plan or added to it as technical and planning concerns may require.

2.2 Vibration tests

The following tests will be performed separately in the X, Y and Z-axes:

- Low-level sine sweep (fully assembled)
- Sine burst (fully assembled)
- Random vibration (fully assembled)

2.3 Mass Properties

The following mass properties will be measured for various spacecraft configurations:

- Mass
- Center of Gravity in X, Y & Z
- Moments of Inertia in X, Y & Z

Note: This was not accomplished because the CG/MOI machine was not at the AEF during the test campaign. Only a rough measurement of mass was performed.

2.4 Thermal Vacuum (T-Vac)

The spacecraft will be tested at 10^{-6} Torr and will be cycled between 50 degrees Celsius and -20 degrees Celsius at least three times, with 4 hours minimum at each extreme per cycle.

3 Test objectives

3.1 Introduction

The main purpose of the QM is to validate the flight model of FalconSat-3 and to develop detailed procedures for the assembly of the spacecraft. Specific objectives are as follows:

- Give cadets hands on experience with spacecraft
- Validate assembly procedures
- Validate structural modifications from SEM 2
- Determine spacecraft response to mechanical vibration loads
- Measure satellite mass properties
- Test functionality in a space simulating environment
- Train in the use of the mounting interfaces to be used with the FM spacecraft

All test configurations and set-ups are to be photographed and described in relevant detail during the tests. Detailed sketches with dimensions are to be made where appropriate to include in the test report.

3.2 Safety

Mechanical tests are inherently dangerous, with heavy lifting and maneuvering required. During the actual tests a lot of energy is imparted into the QM, with risk of items breaking off and moving at high speeds. All personnel should be briefed on test facility safety by an appropriate AEF safety officer. See the individual chapters describing the use of lifting and handling gear for additional safety instructions. A lot of the same dangers need to be considered for the T-Vac test as the satellite will have to be lifted and mounted in the chamber for testing. Extreme caution will be the standard during all set-up phases of the testing to prevent injury to both team members and the spacecraft.

Safety always goes before any test.

3.3 Tests

3.3.1 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 high-level sine burst and random vibration, to determine whether anything in the satellite has changed or broken as a result of the tests by comparing the 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.

3.3.2 Random Vibration

The objective of this test is to verify the capability of the satellite structure and components to withstand the fatigue introduced during the launch vibrations. The spacecraft structure already proved to be dependable during testing of SEM-2 so the primary focus here will be on the payloads, the avionics, and any other components which were not part of SEM-2.

3.3.3 Sine Burst

The objective of this test is to check the static strength of the spacecraft structure to determine whether it can withstand the launch acceleration loads. This test will be performed with the fully integrated QM. To ensure that testing in one axis at a time will adequately stress the FS-3 structure, encompassing the multi-axis design loads specified for ESPA payloads, the single axis acceleration must be higher than is needed to adequately test the spacecraft.

3.3.4 Mass

The mass of the satellite is measured to determine its launch weight, and will be used for attitude control purposes. This value is also required to calculate the Center of Gravity and Moments of Inertia from the output values of the mass properties table. The mass must also meet launch vehicle requirements. The measured mass will be used to update the computer based FEM, and it should be close to the calculated mass, to validate the method of predicting mass.

3.3.5 Moments of Inertia

The Moments of Inertia are measured in three axes. These values are required to analyze the satellite tip-off during deployment in space from the launch vehicle, and for the attitude control algorithms that are used whilst in space. The measured MoI will be used to update the computer based FEM, and it should be close to the calculated MoI, to validate the method of predicting MoI.

3.3.6 Center of Gravity

The Center of Gravity is measured in three axes. This value is required to analyze the satellite tip-off during deployment in space from the launch vehicle, and for the attitude control algorithms. This value must also meet launch vehicle requirements. The measured CoG will be used to update the computer based FEM, and it should be close to the calculated CoG, to validate the method of predicting CoG.

3.3.7 Thermal Vacuum

The objectives of the T-Vac test are to verify that FS3 will be able to operate in a vacuum at temperatures exceeding the temperature extremes expected for the mission, to verify that FS3 will be able to withstand temperature cycling in a vacuum by subjecting the QM to at least three complete cycles from maximum to minimum temperatures, simulate orbit lighting/heating changes using a solar cage, acquire data that will verify/improve the thermal model, simulate operational conditions to improve commissioning and test procedures, ensure the spacecraft will start and operate beyond the temperature extremes, and to measure and record any performance changes for all subsystems and payloads over the temperature range. In addition an actual MPACS payload will test fire each of its three tubes to insure functionality in a space like environment.

3.4 Test success criteria

3.4.1 General

The QM spacecraft will be built as nearly identical to the FM as possible so its success criteria are fairly stringent. All spacecraft primary, secondary, and tertiary structural elements will be identical to flight, the harness will be slightly larger to allow for easier electrical test access, only one MPACs will be integrated (the other four will be mass models), and the lightband and shock ring will be attached. Before departure to Kirtland AFB a full-functional test will be accomplished to insure electrical/software functionality, all connections function per spec, and all systems are within specs.

Test anomalies may require partial disassembly of the QM to enable inspection and or repair, or replacement e.g. of accelerometers/thermocouples. This will only be performed with the agreement of the Responsible Test Engineer.

3.4.2 Sine sweep

- The fundamental frequency of the fully assembled spacecraft should be about 33 Hz (rocking frequency) and a fundamental axial (bouncing) frequency of 92 Hz
- Peak acceleration at fundamental frequency to not shift by more than +/- 20% (variable at Responsible Test Engineer's discretion) during tests, as determined by the low-level sine sweeps before and after the high-level tests
- Fundamental frequency to not shift by more than +/- 5% (variable at Responsible Test Engineer's discretion) during tests, as determined by the low-level sine sweeps before and after the high-level tests
- No damage to the spacecraft should be detectable including no change in the fundamental frequency

3.4.3 Random vibration

- No damage to the spacecraft
- No fasteners losing more than 20% of original torque

3.4.4 Sine Burst

- No apparent/discernable damage to the spacecraft

3.4.5 Mass

- Actual mass within 10% of the predicted value

3.4.6 Moments of Inertia

- Actual moments of inertia within 5% of the predicted values

3.4.7 Center of Gravity

- Lateral COG (X-Y plane) must be within 1/8" radius of the line centered on the center of the separation ring (per tip-off analysis)
- Axial COG (Z axis) must be within 0.5" of predicted value in mass properties report

3.4.8 Thermal Vacuum

- Vacuum of 10^{-6} Torr reached during the hot bake-out cycle and maintained for 4 hours
- Electrical functionality during all phases of T-Vac
- No condensation at spacecraft removal after final hot cycle at 25 degrees Celsius
- Full spacecraft functionality after removal from T-Vac Chamber

4 Test article

4.1 Introduction

The test article is the Qualification Model (QM) of FalconSat-3. The primary structure consists of an 18” cube made of six machined aluminum panels and an aluminum adapter ring attached to the Lightband separation mechanism and the Shock Ring.

The test article includes a qualification level avionics stack and payloads with mass simulators for three of the four MPACS, and mass simulator of the gravity gradient boom (in a stowed configuration) to provide for a spacecraft nearly identical to the forthcoming Flight Model.

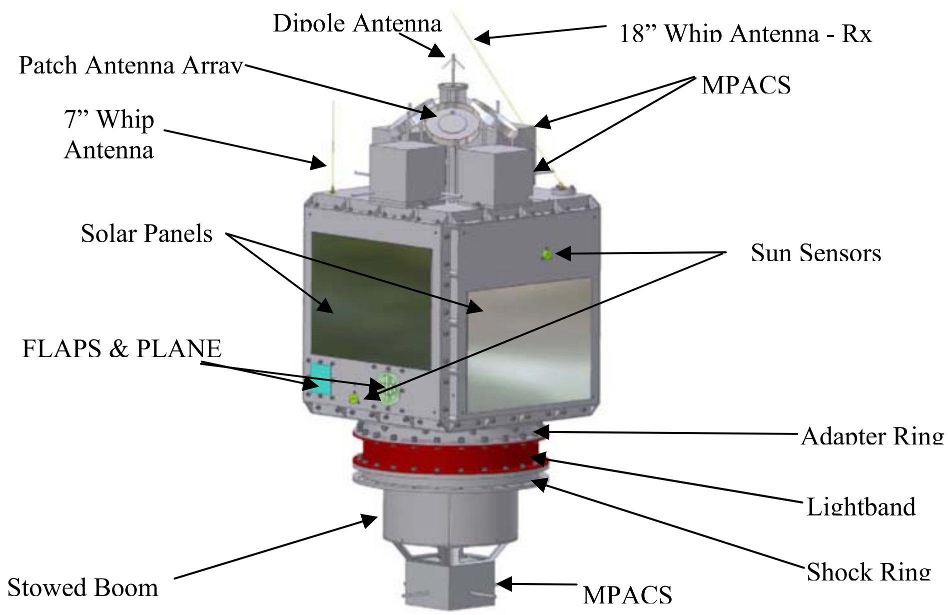


Figure 1 FalconSat-3 External Configuration

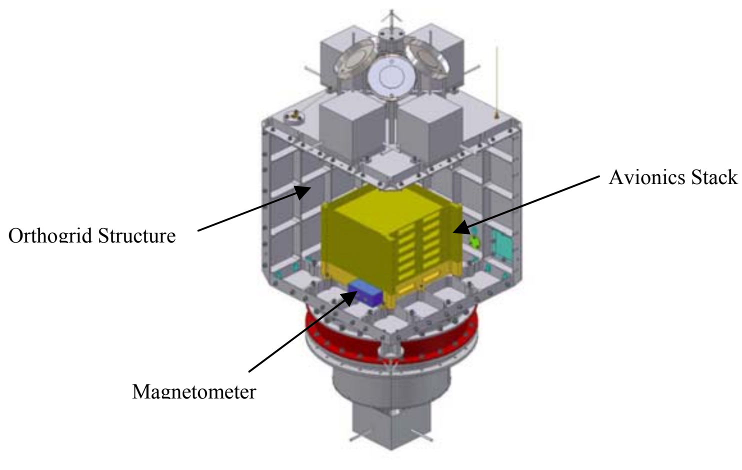


Figure 2 Internal View of FalconSat-3

4.2 Spacecraft axis

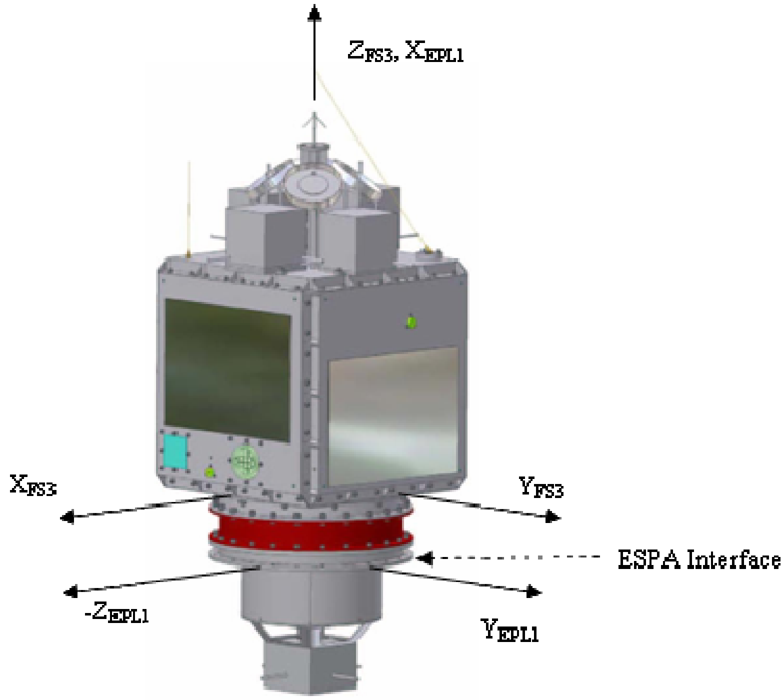


Figure 3 FalconSat-3 Axis Diagram

4.2.1 ESPA local coordinate system

- X_{EPL1}, Y_{EPL1}, Z_{EPL1}
- Origin at center of ESPA mechanical interface

4.2.2 FalconSAT-3 (FS3) / Space Vehicle (SV) coordinate system

- X_{FS3}, Y_{FS3}, Z_{FS3}
- Origin at center of bottom surface of the satellite's base plate

4.2.3 Relationship of FalconSAT-3 to ESPA Local Coordinate System

- $X_{EPL1} = Z_{FS3} + 5.38$ inch
- $Y_{EPL1} = Y_{FS3}$
- $Z_{EPL1} = -X_{FS3}$

4.3 Calculated mass properties

The mass properties of the QM have been calculated from the computer model as shown in Table 1 and Table 2.

MOI	kg-m^2	lbm-in^2	lbf-ft-s^2	lbf-in-s^2
Ixx	3.84	1.31E4	2.83	33.99
Iyy	3.89	1.33E4	2.87	34.46

Izz	1.32	4.51E3	0.97	11.68
Products	~0±TBD	~0±TBD	~0±TBD	~0±TBD

Table 1 Calculated Moments of Inertia

Coordinate	in	m
X	0.13±0.125	0.003±0.003175
Y	0.04±0.125	0.001±0.003175
Z	5.19±1.0	0.13181±0.0254

Table 2 Calculated Center of Gravity

These mass properties include the complete Lightband, the Shock Ring and the stowed boom. The origin for the MoI is the Center of Gravity, the origin for the Center of Gravity is the Bottom Center of the spacecraft base plate, where it interfaces to the Boom Adaptor Ring.

The total spacecraft mass is calculated to be 49.6 kg ±10%

4.4 Mechanical dimensions of test article

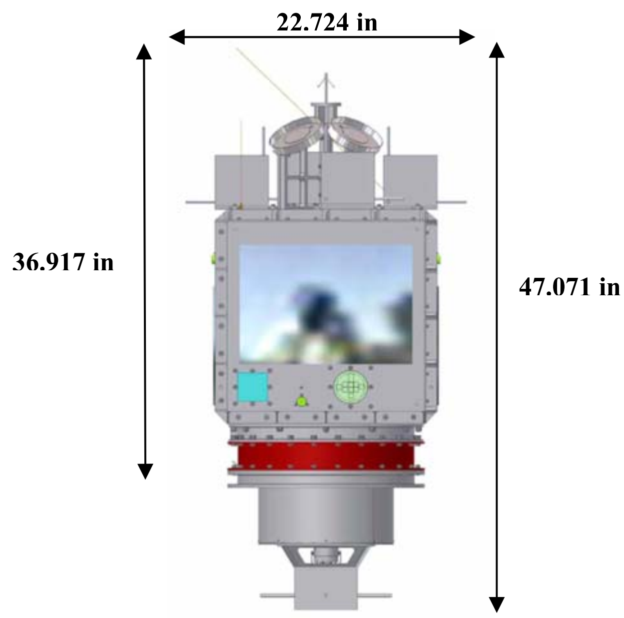


Figure 4 QM Overall Dimensions

4.5 Mechanical Interface to Vibration Table

The test article will be mounted on the vibration table using a USAFA supplied extender and interface plate. The interface plate bolts to both the vibration slip table and directly to the head. The bolts between the interface and the vibration table will be assembled and torqued by AEF staff. The interface has attachment points for straps to facilitate lifting.

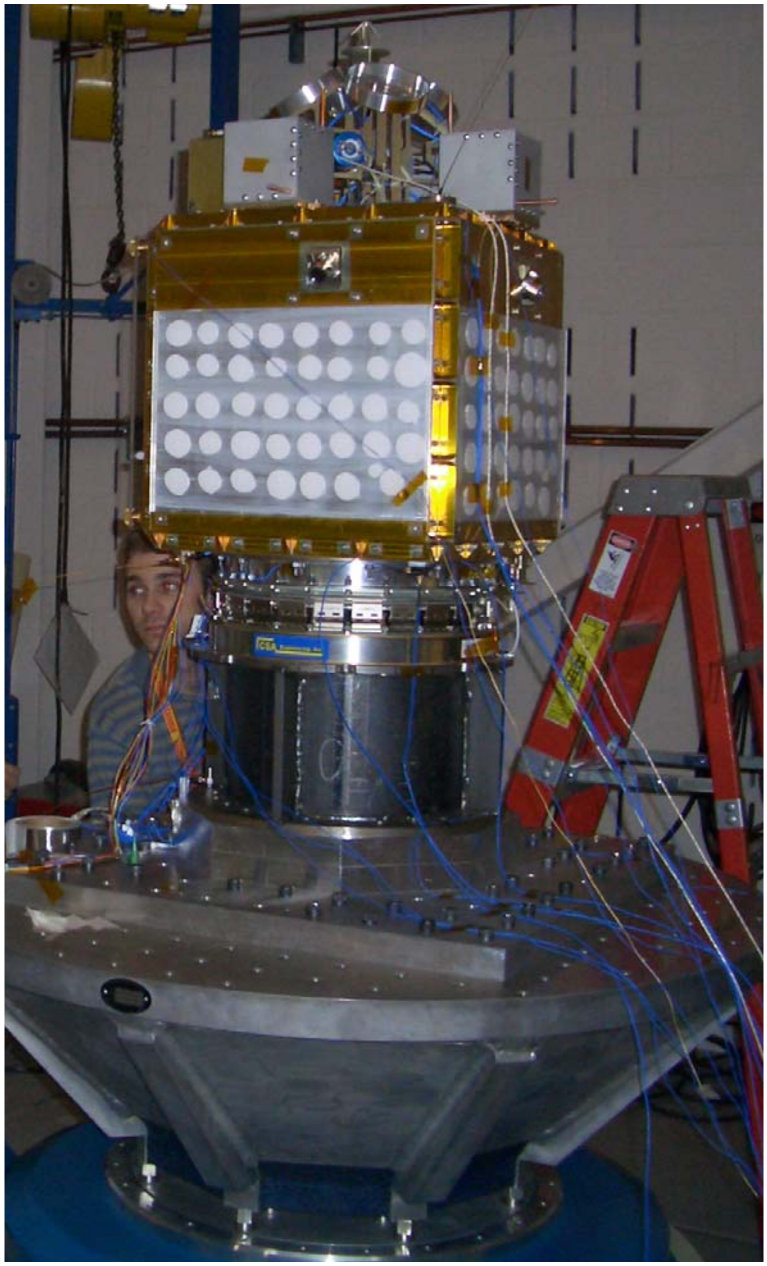


Figure 5 QM Mounted on Vibration Table

4.6 Mechanical Interfaces to Mass Properties Table

The QM must be mounted in both horizontal and vertical direction for the mass properties tests. Two mounting brackets are available for this test, both interface to the table. The interfaces are compatible with FS3 SEM-2, QM and FM. The interfaces must be measured separately using the mass properties table to enable the final QM properties to be calculated from the combined measurements.

4.6.1 Vertical Mounting

The vertical mounting bracket supports the spacecraft onto the mass properties table to measure the following:

- Moment of Inertia around Z from SC origin (Izz)
- Center of Gravity in the X axis from SC origin
- Center of Gravity in the Y axis from SC origin

The vertical mounting interface is also used to support the Horizontal interface during spacecraft assembly.

Figure 6 Vertical Stand (Shown Mounted Under Horizontal Stand)

4.6.2 Horizontal Mounting

The horizontal mounting bracket allows the spacecraft to be mounted onto the mass properties table to measure the following:

- Moment of Inertia around X from CoG (Ixx)
- Moment of Inertia around Y from CoG (Iyy)
- Center of Gravity in the Z axis from SC origin

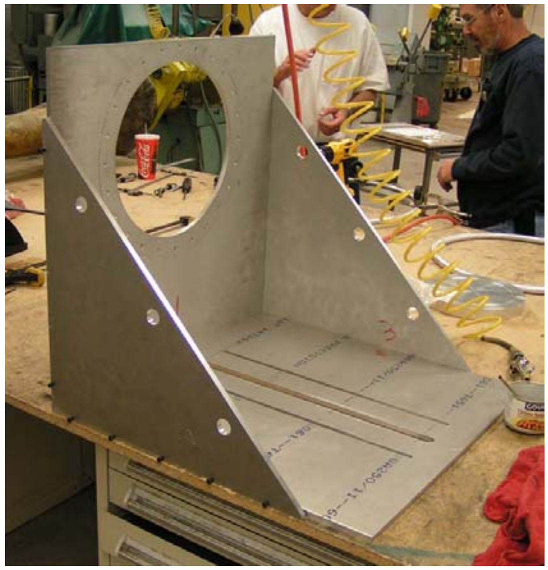


Figure 7 Horizontal Mounting Interface

The horizontal mounting bracket facilitates the rotation of the QM between horizontal and vertical. The composite must be held at all times when lifted, to prevent any unwanted rotation; and no personnel should stand under a suspended load at any time. The interface is mounted onto the vertical interface for support and to clear the spacecraft boom when assembled. The horizontal mount has an additional leg to support it: this must be assembled before the interface is positioned onto the vertical stand. The satellite is then lowered onto the interface, and eight nuts are assembled onto the studs that are cleared by the vertical stand. Two long (6-10 feet) straps are connected to the highest side holes. The composite is then lifted whilst personnel holds on to the interfaces. When the assembly has been lifted several feet off the ground it is rotated to the horizontal position and then moved over to the Mass Properties table. The interface has slotted mounting holes to allow the satellite to be mounted at its CoG over the rotation axis of the table. When the composite has been mounted and bolted onto the table the vertical support and the additional leg can be removed. Do not remove the lifting straps before the composite is securely bolted on the table.

To measure the inertia in the cross axis the procedure must be reversed, the satellite rotated 90 degrees on the stand, and the composite re-mounted onto the table.

Figure 8 Horizontal Stand on Vertical Stand Ready for Spacecraft to be Integrated to it

4.7 Lifting Gear

The spacecraft will be supplied with a lifting system that allows support in various axes for handling during the vibration test. The lifting gear consists of a set of steel cables that attach through holes in the side panels of the spacecraft with shackles. Ensure the shackles are screwed shut during lifting. The spacecraft may be lifted on its side with three points of attachment or hanging straight up and down with the top panel upwards with found points of attachment. Never stand under a suspended load. Ensure loads are stable before and during lifting and moving operations. Ensure that crane operators confirm that spacecraft and interfaces are safe to lift and not bolted to any fixed support before lifting. Ensure that crane operators confirm that spacecraft is stable and safe before releasing lifting gear from spacecraft.

Do not lift the spacecraft through its lifting points with either the vibration interface or the horizontal mass properties interface attached. Only the vertical mass properties interface is light enough to be lifted with the spacecraft. The other interfaces have lifting points themselves that allow lifting with or without the spacecraft attached.

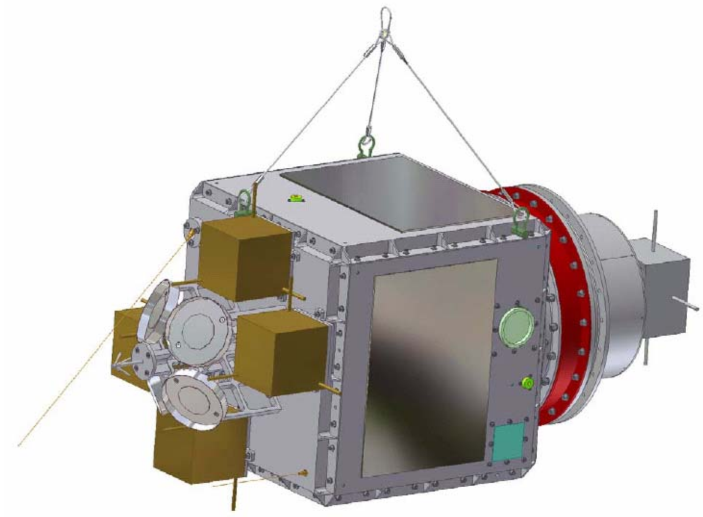


Figure 9 Lifting Cable Attachment Pattern – Horizontal Configuration (Vertical was Used for QM Test Campaign)

4.8 Test Configurations

The QM will only be tested in one completed configuration (no with/without the shock ring which was done for SEM-2). The QM will be mounted to the shaker fixture with an USAFA supplied extender tube, as the boom protrudes below the mounting interface of the Shock Ring. This extender fixture will allow mounting of the QM in the completed configuration

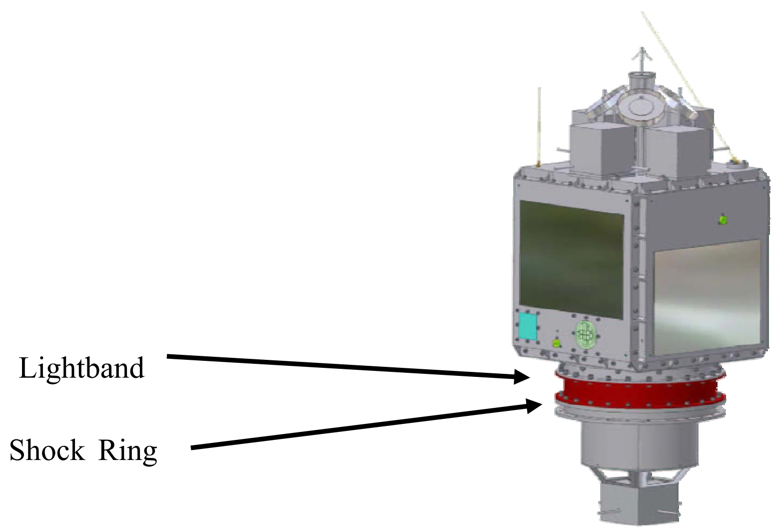


Figure 10 Lightband and Shock Ring Location

4.9 Instrumentation Requirements

4.9.1 Accelerometers

The following layout for the accelerometers is what was used for the QM vibration testing. Channels 1 and 2 were used as control channels for the vibration table's control system for all tests. Please see Table 3 below for the Z-Axis Tests configuration, Table 4 for the X-Axis Tests configuration, Table 5 for the Y-Axis Tests configuration, and finally Table 6 for the Stand Characterization Test configuration.

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30816	9.83	Fixture Base – Rear	Control
2	30817	10.07	Fixture Base – Forward	Control
3	37448X	10.00	Top Panel Center X	
4	37448Y	10.74	Top Panel Center Y	
5	37448Z	9.80	Top Panel Center Z	
6	13228	9.42	+X Panel, X Axis	
7	ANJE1	10.19	+X Panel, Z Axis	
8	AAM32Z	9.346	Base Plate Corner Z	
9	AD808X	9.392	Stack Top X	
10	AD808Y	10.46	Stack Top Y	
11	AD808Z	9.406	Stack Top Z	
12	30818	9.70	Boom Plate Z	
13	37449X	10.39	MPACS X	
14	37449Y	9.91	MPACS Y	
15	37449Z	10.52	MPACS Z	
16	2965	10.4	Top of S-Band Stand Z	
17	21522	10.39	PLANE X	
18	30819	9.60	PLANE Z	

Table 3 Z-Axis Vibration Tests Accelerometer Information

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30816	9.83	Fixture Base – Rear	Control
2	30817	10.07	Fixture Base – Forward	Control
3	37448X	10.00	Top Panel Center X	
4	37448Y	10.74	Top Panel Center Y	
5	37448Z	9.80	Top Panel Center Z	
6	13228	9.42	+X Panel, X Axis	
7	ANJE1	10.19	+X Panel, Z Axis	
8	AAM32X	10.3	Base Plate Corner X	

9	AAM32Y	9.651	Base Plate Corner Y	
10	AAM32Z	9.346	Base Plate Corner Z	
11	AD808X	9.392	Stack Top X	
12	AD808Z	9.406	Stack Top Z	
13	30818	9.70	Boom Adaptor Plate X	
14	37449X	10.39	MPACS X	
15	37449Y	9.91	MPACS Y	
16	37449Z	10.52	MPACS Z	
17	21523	9.95	Top of S-Band Stand X	
18	21522	10.39	PLANE X	

Table 4 X-Axis Vibration Tests Accelerometer Information

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30816	9.83	Fixture Base – Forward	Control
2	30817	10.07	Fixture Base – Rear	Control
3	37448X	10.00	Top Panel Center X	
4	37448Y	10.74	Top Panel Center Y	
5	37448Z	9.80	Top Panel Center Z	
6	13228	9.42	+X Panel, X Axis	
8	AAM32X	10.3	Base Plate Corner X	
9	AAM32Y	9.651	Base Plate Corner Y	
10	AAM32Z	9.346	Base Plate Corner Z	
11	AD808X	9.392	Stack Top X	
12	AD808Y	10.46	Stack Top Y	
13	AD808Z	9.406	Stack Top Z	
14	37449X	10.39	MPACS X	
15	37449Y	9.91	MPACS Y	
16	2965	10.4	Top of S-Band Stand Z	
17	21522	10.39	PLANE X	

Table 5 Y-Axis Vibration Tests Accelerometer Information

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30817	10.07	Front Y-Axis	Control
2	30819	9.60	Front Z-Axis	Control
3	30816	9.83	Back Y-Axis	
4	21523	9.95	Back Z-Axis	

Table 6 Stand Characterization Test Accelerometer Information

4.9.2 Thermocouples

The thermocouple locations were as follows:

Channel	Serial #	Location
17	55	BAT TRAY +X
18	53	BAT TRAY +Y
19	77	BAT TRAY -X
20	72	BAT TRAY -Y
21	69	BCR TRAY -X
22	70	TX TRAY -X
23	50	TX TRAY +Y
24	51	RX TRAY -X
25	52	TOP PLATE (INTERNAL)
26	49	Inside side panel +X
27	47	MPACS +X
28	76	MPACS +Y
29	75	MPACS -X
30	59	MPACS -Y
31	61	FLAPS
32	46	PLANE
33	83	SUN SENSOR +X
34	81	SUN SENSOR +Y
35	80	SUN SENSOR -X
36	62	SUN SENSOR +Y
37	54	ADAPTER RING +X
38	82	ADAPTER RING +Y
39	35	LIGHT BAND +X
40	65	LIGHT BAND +Y
41	57	S-PATCH +X +Y
42	68	S-PATCH +X -Y
43	37	S-PATCH -X +Y
44	58	S-PATCH -X -Y
45	74	SHOCK RING +X
46	84	SHOCK RING +Y
47	79	SHOCK RING -X
48	73	SHOCK RING -Y
49	36	SIDE PANEL +X
50	43	SIDE PANEL +Y
51	39	SIDE PANEL -X
52	38	SIDE PANEL -Y
53	67	TOP PLATE (EXTERNAL)
54	48	PPT 2

Table 7 Thermocouple Locations

4.10 Spacecraft shipping

The QM spacecraft was shipped between USAFA and AEF by mounting it directly to the Falcon-Sat 3 shipping container. The shipping container provided for slight damping of the motion encountered by the spacecraft one the trip down to Kirtland AFB. The spacecraft was completely enclosed by the sides of the container to maintain cleanliness and was also enclosed in a plastic electrostatic discharge protected envelop.

This entire assembly was subsequently loaded onto a trailer for transportation.

Figure 11 Shipping Container with FS-3 QM Mounted in it

4.11 USAFA Supplied Items

Many tools, equipment, and materials not listed below were taken to the AEF to support the QM Test Campaign. The following test and support articles were expected to be brought by USAFA:

Item	Notes
QM	Assembled QM Structural Engineering Model
QM shipping support	Allows QM to be transported
Vibration interface	Mounts between QM and the shaker table
Bolts between vibration I/F and QM	Not the bolts between vibration interface and shaker!
Horizontal mass properties stand	Mounts between QM and Mass properties table
Bolts to mount QM onto Hor. stand	Not the bolts between Horizontal Stand and table
Vertical mass properties stand	Mounts between QM and Mass properties table
Bolts to mount QM onto Vert. stand	Not the bolts between Vertical Stand and table
Lifting cables to lift QM	Connects to AEF crane hook
Tools to assemble USAFA supplied bolts	No tools to assemble bolts into AEF tables and shakers
Avionics equipment	All equipment needed to operate the spacecraft, record telemetry, and run functional tests (ie: computers, oscilloscopes, etc)

Table 8 USAFA Supplied Items

5 Structural Tests Results: Z-Axis

5.1 Test Configuration

5.1.1 Test Set-up

The test article consisted of the QM in its fully assembled configuration. The QM was bolted to the FalconSAT-3 test fixture which was bolted to the table in the same configuration as described in Section 4.5. The test configuration is shown in Figure 15 below:

Figure 12: Configuration for Z-axis test (shown attached to test table)

5.1.2 Accelerometer Locations

Accelerometers for this portion of the test were placed as shown in Table 9.

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30816	9.83	Fixture Base – Rear	Control
2	30817	10.07	Fixture Base – Forward	Control
3	37448X	10.00	Top Panel Center X	
4	37448Y	10.74	Top Panel Center Y	
5	37448Z	9.80	Top Panel Center Z	
6	13228	9.42	+X Panel, X Axis	
7	ANJE1	10.19	+X Panel, Z Axis	
8	AAM32Z	9.346	Base Plate Corner Z	
9	AD808X	9.392	Stack Top X	
10	AD808Y	10.46	Stack Top Y	
11	AD808Z	9.406	Stack Top Z	
12	30818	9.70	Boom Plate Z	
13	37449X	10.39	MPACS X	
14	37449Y	9.91	MPACS Y	
15	37449Z	10.52	MPACS Z	
16	2965	10.4	Top of S-Band Stand Z	
17	21522	10.39	PLANE X	
18	30819	9.60	PLANE Z	

Table 9: Z-axis test accelerometer locations

5.2 Summary of Results, Z-Axis

Test	Objectives	Success Criteria	Result
Sine Sweep	1. Validate fundamental frequency of 92 Hz found in SEM-2 testing 2. Peak acceleration at fundamental frequency not to shift more than 20% during tests 3. Fundamental frequency not to shift more than 5% during tests 4. No damage to spacecraft should be detectable	1. Successful measurements 2. Acceleration shift < 20% 3. Fundament frequency shift < 5% 4. No damage	1. Primary mode is at about 88 Hz, 2nd mode is at about 140 Hz. 2. Shift of about 13% 3. Shift of about 1% 4. Pass

Sine Burst	1. No apparent/discernable damage to spacecraft	1. Spacecraft maintains structural integrity and functionality following RSS of 10.6 g's in three axes (15 g's) sine burst	1. Verified up to 14.995 g's → pass
Random Vibration	1. No damage to spacecraft 2. No fastener losing > 20% of original torque	1. Spacecraft maintains structural integrity and functionality following random vibration to two times the expected flight environment 2. Representative sample of fasteners do not lose more than 20% of original torque	1. Pass 2. Pass

5.3 Test data

The tests produced output graphs from the various accelerometers. From these graphs the response of the structure was determined. In the cases when the only output available was hardcopy plots, the main values were captured off the recording equipment before they were cleared off the system and noted on the copies by hand when they could not be printed directly.

5.4 Initial Sine Sweep, Z-Axis

5.4.1 Objective

The initial sine sweep was conducted to determine the fundamental and further natural frequencies, modal shapes, and modal gain of the structure. The sine sweep also provided a baseline from which subsequent tests were judged. Additional sine sweeps were conducted following each test to ensure that no damage was done to the spacecraft (indicated by no change in the fundamental frequency).

5.4.2 Success Criteria

The success criteria for the sine sweep were to characterize the natural frequencies of the QM flight configuration in the Z axis and to validate the values found in the SEM-2 test campaign (fundamental axial, bouncing, frequency of 92 Hz)

5.4.3 Test Levels

The following table outlines the frequencies and accelerations that were used for all sine sweeps completed during testing in this particular configuration.

Frequency range (Hz)	Acceleration (g)	Sweep rate (octaves/minute)
20-1000	0.1 g	2

Table 10 Sine sweep vibration specification

5.4.4 Results

From this initial sine sweep, the following fundamental and secondary frequencies were determined.

Mode	Frequency (Hz)
First	88.7
Second	140

Table 11 Initial sine sweep frequency results

These frequencies are illustrated in the following figure which depicts the initial sine sweep response near the center of the top panel:

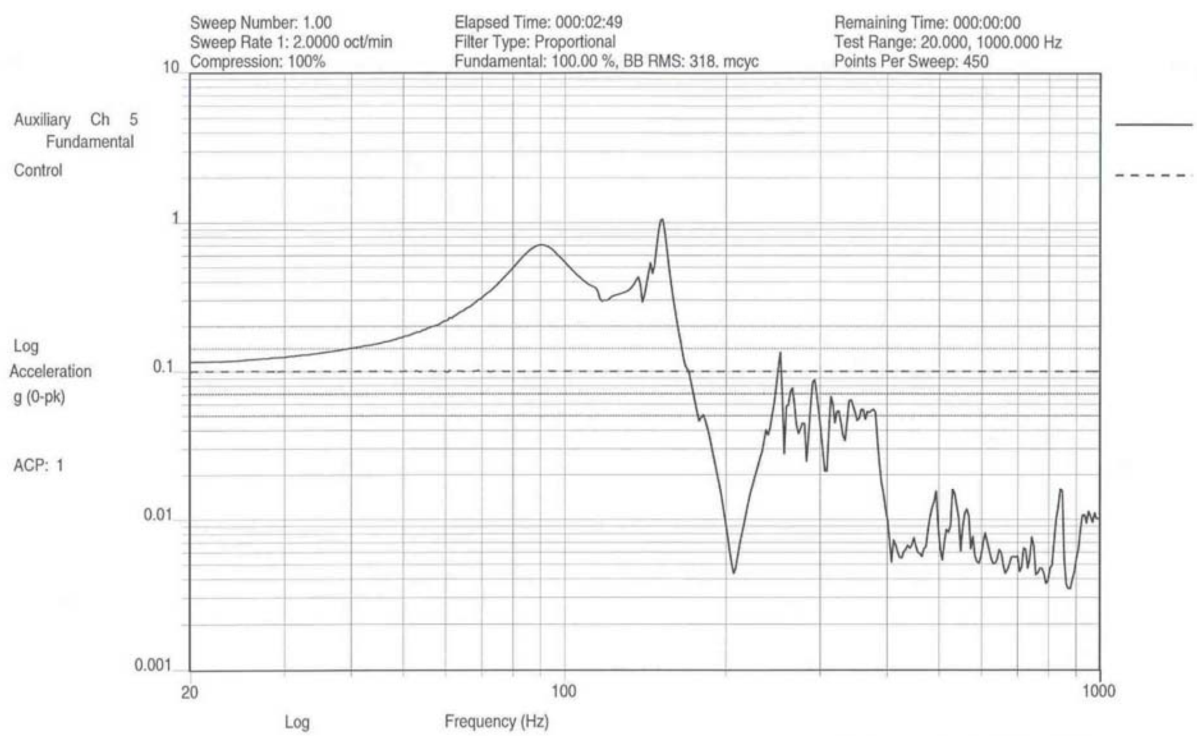


Figure 13: Initial Sine Sweep, Z-Axis, Top Center Z

5.5 Sine Burst Test, Z-Axis

5.5.1 Objective

The sine burst test was completed in order to verify that the spacecraft meets the ESPA static load requirement of 10.6 g limit load in axial and lateral axes simultaneously.

5.5.2 Success Criteria

The success criteria for this test was to ensure that the spacecraft maintains structural integrity following RSS of 10.6 g's in three axes (15 g's) sine burst.

5.5.3 Test Level

The sine burst test was performed with the following frequency and maximum acceleration specification seen below. The test was able to verify up to 14.995 g's. The test was performed in a number of steps starting from -12 dB, to -9 dB, -6 dB, -3 dB then 0 dB (the final test level) to allow the vibration equipment to analyze the system response and adjust the input levels appropriately.

Frequency	Acceleration (g)
25 Hz	14.995

Table 12 Z-Axis Sine burst Vibration Specification

5.5.4 Results

The following plot shows the response of the QM spacecraft near the center of the top panel during the sine burst test in the Z-axis:

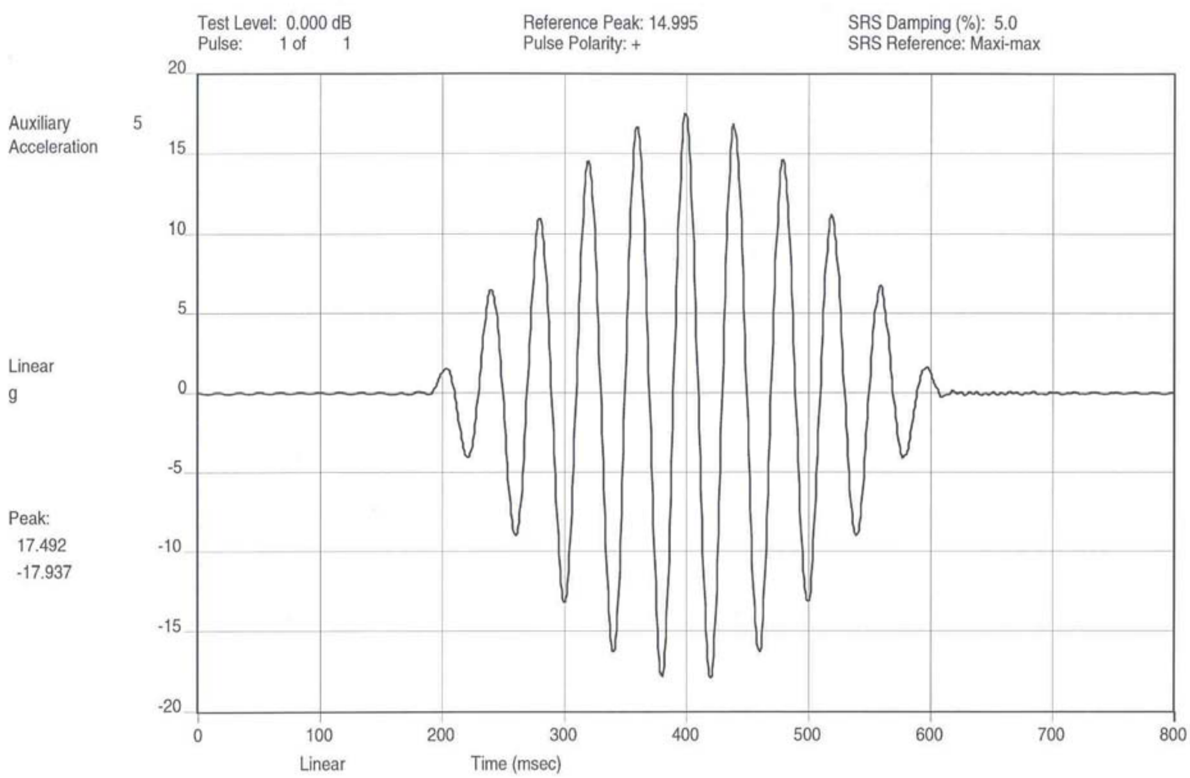


Figure 14: Sine Burst, Z-Axis, Top Center Z

Following this sine burst test, a swine sweep was conducted to the levels indicated in Table 10 Sine sweep vibration specification. The plot below illustrates the sine sweep results for the center of the top panel following this test. The fundamental frequency following this test remained almost unchanged, indicating structural integrity. Additionally, the functionality test following all the Z-axis tests was successful. Plots remain unchanged, for the most part, from one accelerometer to the next.

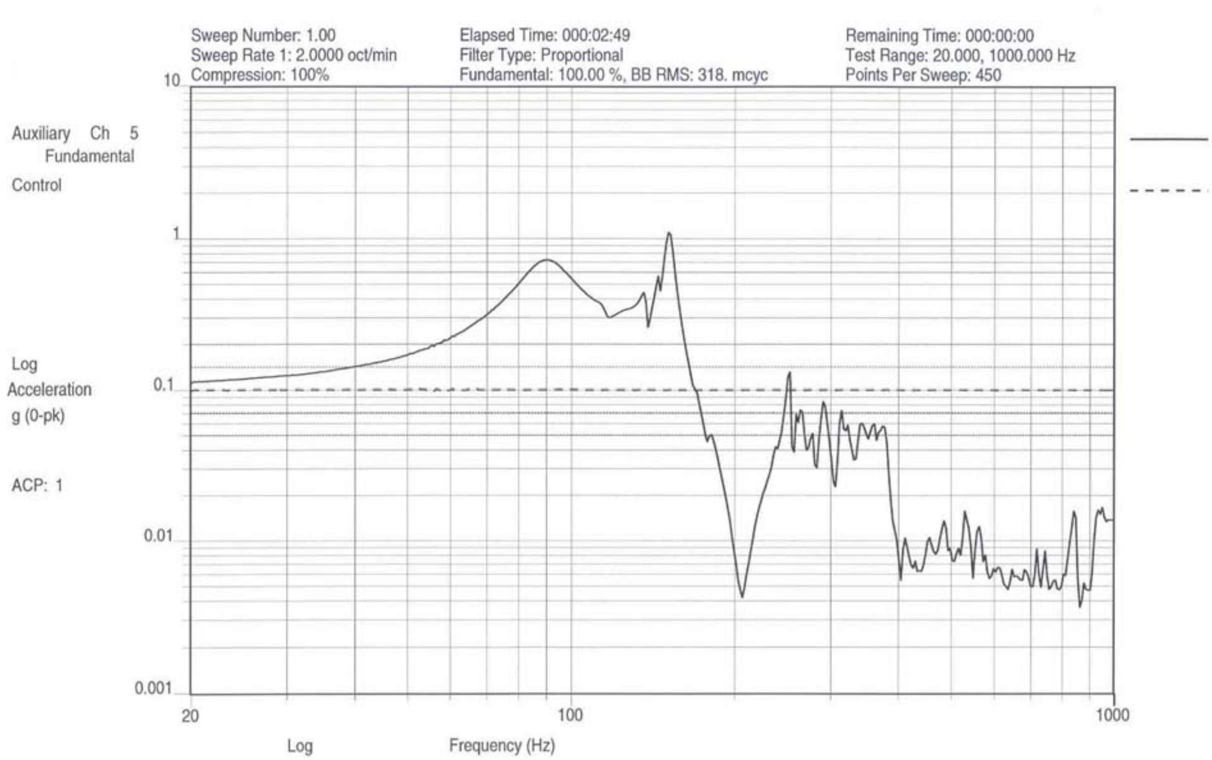


Figure 15: Post Sine Burst Sine Sweep, Z-Axis, Top Center Z

The following table illustrates responses of several key components to this test:

Component	**Response (g's)**
Top Panel Z	17.5
Base Plate Corner Z	17
Stack Top Z	16
Boom Adaptor Plate Z	16

Table 13: Sine Burst Test Results

5.6 Qualification-Level Random Vibration Test, Z-Axis

5.6.1 Objective

The qualification-level random vibration test was conducted to verify the capability of the satellite structure and components to withstand the fatigue introduced during the launch vibrations per ESPA interface requirement.

5.6.2 Success Criteria

To verify the structure's ability to withstand the fatigue, a representative sample of fasteners must not lose more than 20% of their original torque. Data must be collected as referred to above. Also, structural integrity during the test and electrical functionality after the test must be achieved.

5.6.3 Test Level

Random vibration qualification levels are shown in Table 14 and Figure 16 below. These levels represent +3 dB above the flight level (two times the intensity). The test duration was 2 minutes per axis.

Frequency (Hz)	Acceleration PSD (g^2/Hz)
20	0.0256
20-50	+6 dB/octave
50-800	0.16
800-2000	-4.5 dB/octave
2000	0.0256
Duration	**2 minute per axis**
Overall g rms	**14.12**

Table 14 FS-3 Qualification random vibration level

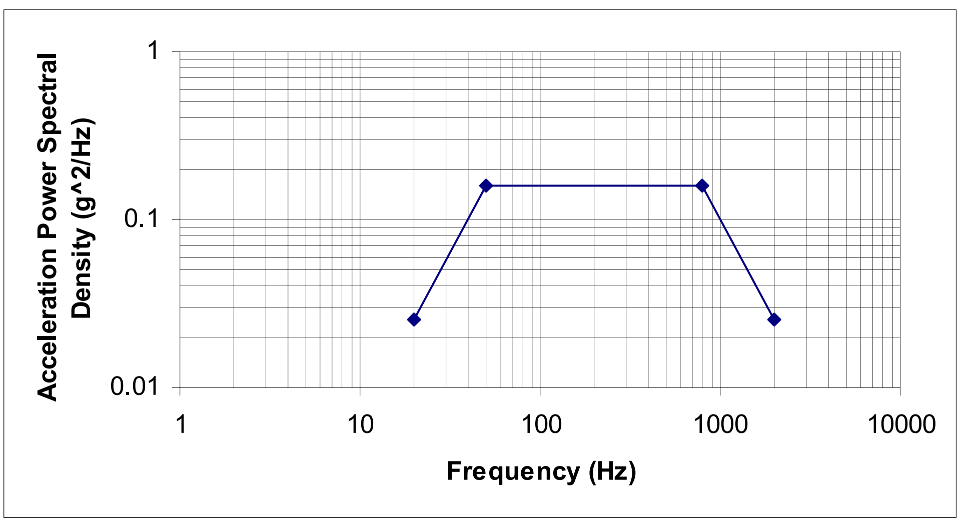


Figure 16: FalconSAT-3 Qualification-Level Power Spectral Density

5.6.4 Results

The following plot shows the response of the QM spacecraft near the center of the top panel during the random vibration test in the Z-axis:

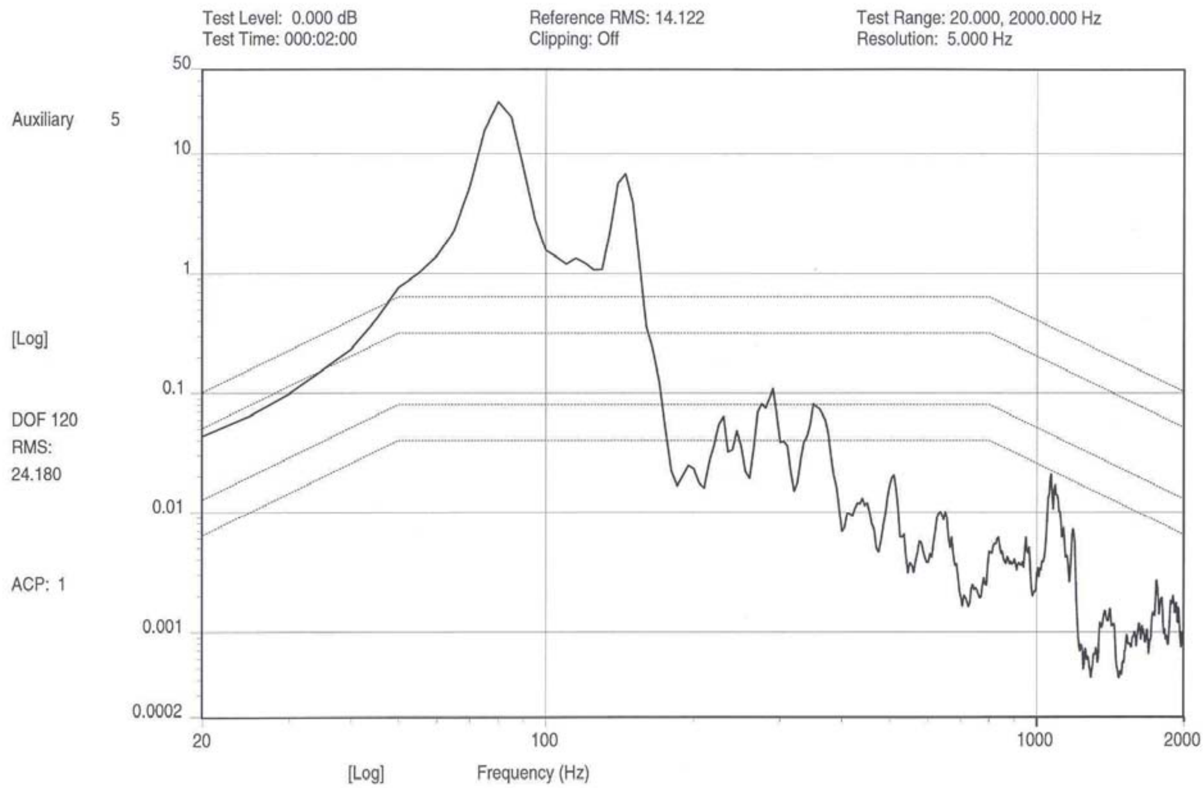


Figure 17: Random Vibration, Z-Axis, Top Center Z

Following this random vibration test, a swine sweep was conducted to the levels indicated in Table 10 Sine sweep vibration specification. The plot below illustrates the sine sweep results for the top panel following this test. The fundamental frequency following this test remained almost unchanged, indicating structural integrity. Additionally, the functionality test following all the Z-axis tests was successful. Plots remain unchanged, for the most part, from one accelerometer to the next.

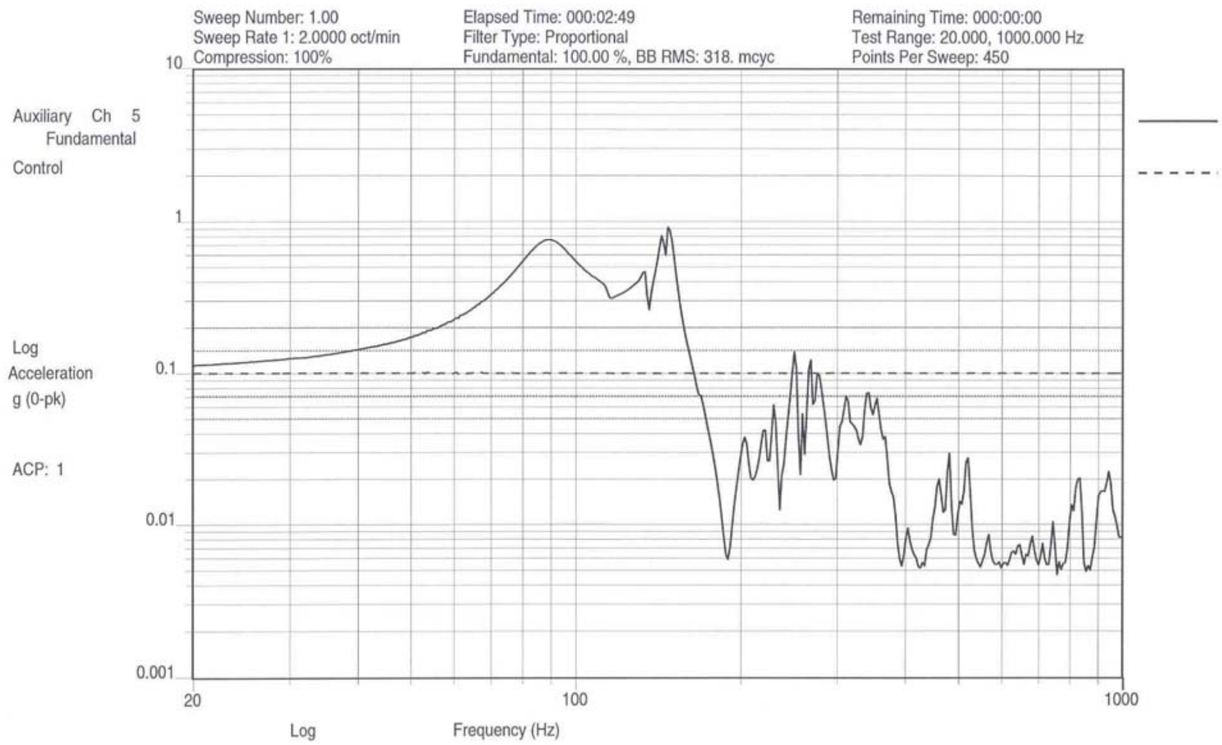


Figure 18: Post Qualification-Level Random Vibe Sine Sweep, Z-Axis

6 Structural Tests Results: X-Axis

6.1 Test Configuration

6.1.1 Test Set-up

The test article consisted of the QM in its fully assembled configuration. The QM was bolted to the FalconSAT-3 test fixture which was bolted to the table in the same configuration as described in Section 4.5. The test configuration is shown in Figure 19 below:

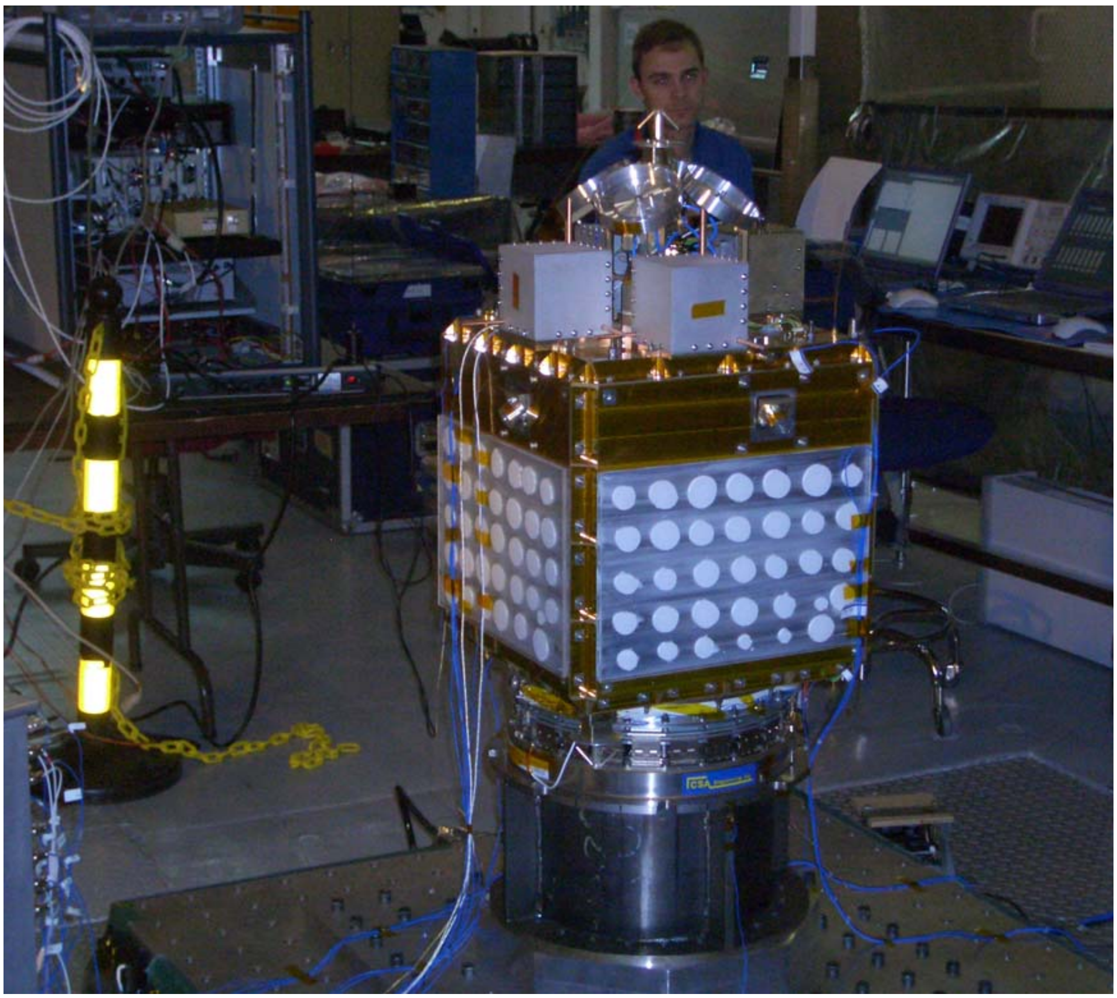


Figure 19: Configuration for X-axis test (shown attached to horizontal test table)

6.1.2 Accelerometer Locations

Accelerometers for this portion of the test were placed as shown in Table 15 below.

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30816	9.83	Fixture Base – Rear	Control
2	30817	10.07	Fixture Base – Forward	Control
3	37448X	10.00	Top Panel Center X	
4	37448Y	10.74	Top Panel Center Y	
5	37448Z	9.80	Top Panel Center Z	
6	13228	9.42	+X Panel, X Axis	
7	ANJE1	10.19	+X Panel, Z Axis	
8	AAM32X	10.3	Base Plate Corner X	
9	AAM32Y	9.651	Base Plate Corner Y	
10	AAM32Z	9.346	Base Plate Corner Z	
11	AD808X	9.392	Stack Top X	
12	AD808Z	9.406	Stack Top Z	
13	30818	9.70	Boom Adaptor Plate X	
14	37449X	10.39	MPACS X	
15	37449Y	9.91	MPACS Y	
16	37449Z	10.52	MPACS Z	
17	21523	9.95	Top of S-Band Stand X	
18	21522	10.39	PLANE X	

Table 15: X-axis test accelerometer locations

6.2 Summary of Results, X-Axis

Test	Objectives	Success Criteria	Result
Sine Sweep	1. Validate fundamental rocking frequency of 33 Hz found in SEM-2 testing 2. Peak acceleration at fundamental frequency not to shift more than 20% during tests 3. Fundamental frequency not to shift more than 5% during tests 4. No damage to spacecraft should be detectable	1. Successful measurements 2. Acceleration shift < 20% 3. Fundament frequency shift < 5% 4. No damage	1. Primary mode is at about 26 Hz, 2^{nd} mode is at about 93 Hz. 2. Shift of about 15% 3. Shift of about 5.9% 4. Pass

Sine Burst	1. No apparent/discernable damage to spacecraft	1. Spacecraft maintains structural integrity and functionality following RSS of 10.6 g's in three axes (15 g's) sine burst	1. Verified up to 15.000 g's → pass
Random Vibration	1. No damage to spacecraft 2. No fastener losing > 20% of original torque	1. Spacecraft maintains structural integrity and functionality following random vibration to two times the expected flight environment 2. Representative sample of fasteners do not lose more than 20% of original torque	1. Pass 2. Pass

6.3 Test data

The tests produced output graphs from the various accelerometers. From these graphs the response of the structure was determined. In the cases when the only output available was hardcopy plots, the main values were captured off the recording equipment before they were cleared off the system and noted on the copies by hand when they could not be printed directly.

6.4 Initial Sine Sweep, X-Axis

6.4.1 Objective

The initial sine sweep was conducted to determine the fundamental and further natural frequencies, modal shapes, and modal gain of the structure. The sine sweep also provided a baseline from which subsequent tests were judged. Additional sine sweeps were conducted following each test to ensure that no damage was done to the spacecraft (indicated by no change in the fundamental frequency).

6.4.2 Success Criteria

The success criteria for the sine sweep were to characterize the natural frequencies of the QM flight configuration in the X axis and to validate the values found in the SEM-2 test campaign (rocking frequency of 33 Hz)

6.4.3 Test Levels

The following table outlines the frequencies and accelerations that were used for all sine sweeps completed during testing in this particular configuration.

Frequency range (Hz)	Acceleration (g)	Sweep rate (octaves/minute)
20-1000	0.25 g	2

Table 16 Sine sweep vibration specification

6.4.4 Results

From this initial sine sweep, the following fundamental and secondary frequencies were determined.

Mode	Frequency (Hz)
First	27.4
Second	93

Table 17 Initial sine sweep frequency results

These frequencies are illustrated in the following figure which depicts the initial sine sweep response near the center of the top of the stack:

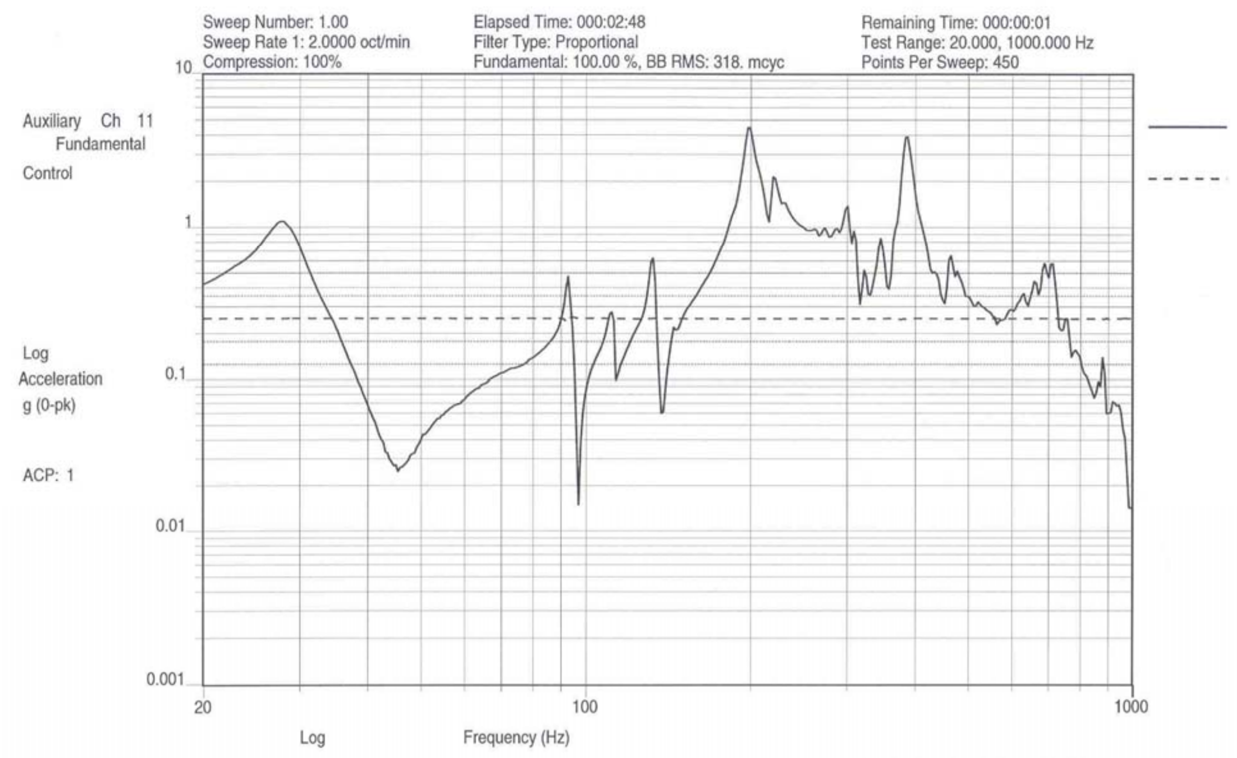


Figure 20: Initial Sine Sweep, X-Axis, Stack Top X

6.5 Sine Burst Test, X-Axis

6.5.1 Objective

The sine burst test was completed in order to verify that the spacecraft meets the ESPA static load requirement of 10.6 g limit load in axial and lateral axes simultaneously.

6.5.2 Success Criteria

The success criteria for this test was to ensure that the spacecraft maintains structural integrity following RSS of 10.6 g's in three axes (15 g's) sine burst.

6.5.3 Test Level

The sine burst test was performed with the following frequency and maximum acceleration specification seen below. The test was able to verify up to 15.000 g's. The test was performed in a number of steps starting from -12 dB, to -9 dB, -6 dB, -3 dB then 0 dB (the final test level) to allow the vibration equipment to analyze the system response and adjust the input levels appropriately.

Frequency	Acceleration (g)
20 Hz	15.000

Table 18 X-Axis Sine burst Vibration Specification

6.5.4 Results

The following plot shows the response of the QM spacecraft near the center of the top of the stack during the sine burst test in the X-axis:

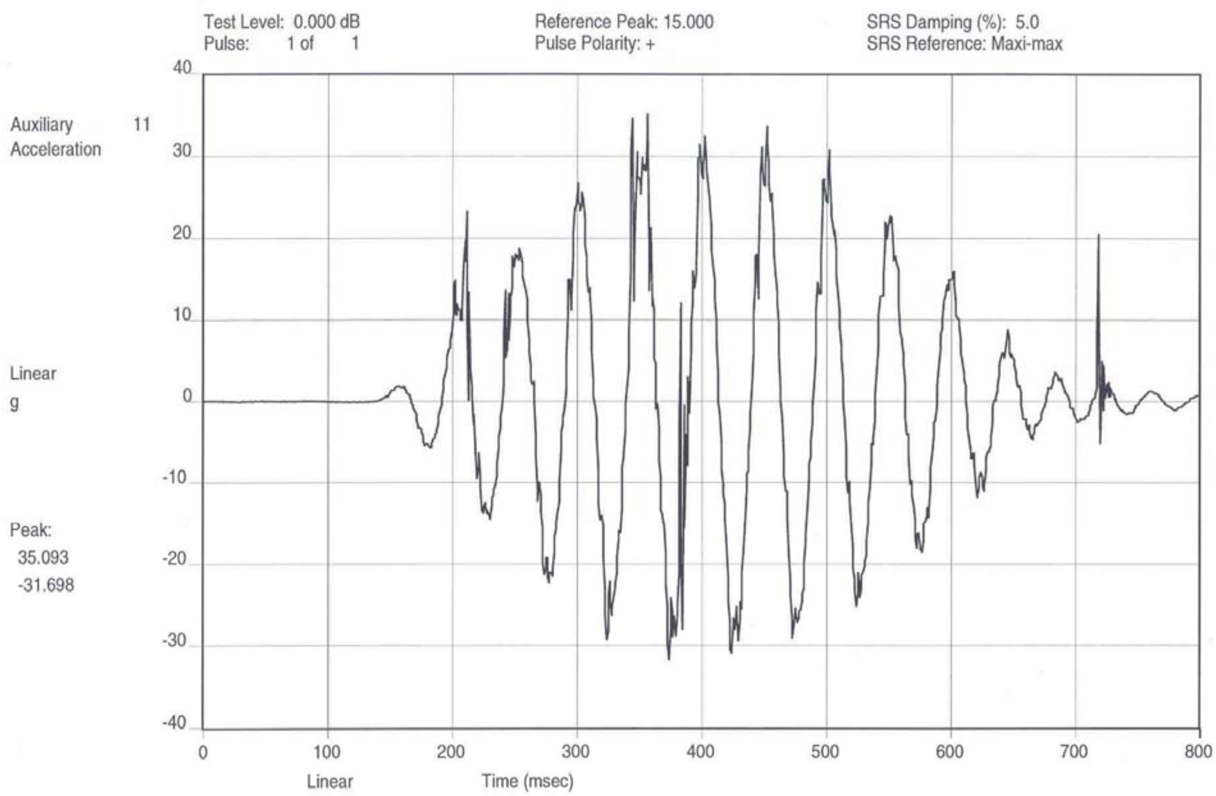


Figure 21: Sine Burst, X-Axis, Stack Top X

Following this sine burst test, a swine sweep was conducted to the levels indicated in Table 16. The plot below illustrates the sine sweep results for the center of the top of the stack following this test. The fundamental frequency following this test dropped slightly, just outside of our 5% margin. However there was no noticeable damage to the spacecraft and the functionality test following all the

X-axis tests was successful. Plots remain unchanged, for the most part, from one accelerometer to the next.

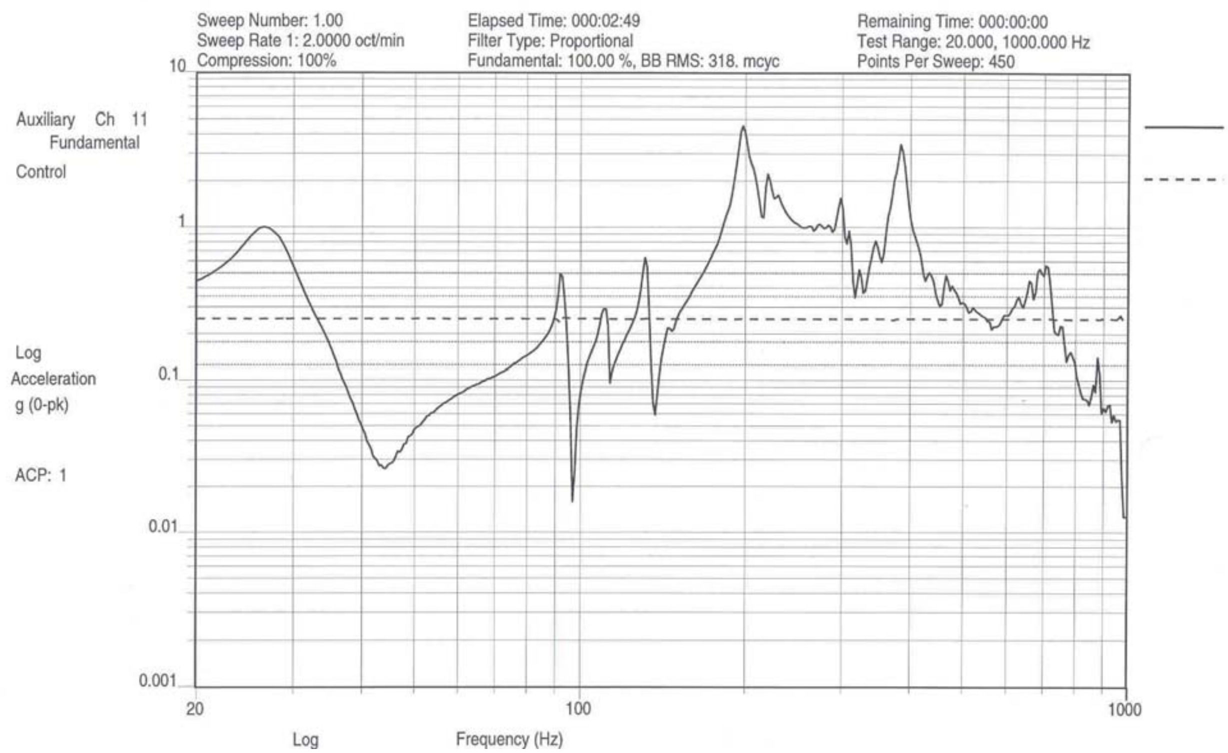


Figure 22: Post Sine Burst Sine Sweep, X-Axis, Stack Top X

The following table illustrates responses of several key components to this test:

Component	**Response (g's)**
Base Plate Corner X	22
Stack Top X	35
Boom Adaptor Plate X	20
Top Panel Center X	44

Table 19: Sine Burst Test Results

6.6 Qualification-Level Random Vibration Test, X-Axis

6.6.1 Objective

The qualification-level random vibration test was conducted to verify the capability of the satellite structure and components to withstand the fatigue introduced during the launch vibrations per ESPA interface requirement.

6.6.2 Success Criteria

To verify the structure's ability to withstand the fatigue, a representative sample of fasteners must not lose more than 20% of their original torque. Data must be collected as referred to above. Also, structural integrity during the test and electrical functionality after the test must be achieved.

6.6.3 Test Level

Random vibration qualification levels are shown in Table 20 and Figure 23 below. These levels represent +3 dB above the flight level (two times the intensity). The test duration was 2 minutes per axis.

Frequency (Hz)	Acceleration PSD (g^2/Hz)
20	0.0256
20-50	+6 dB/octave
50-800	0.16
800-2000	-4.5 dB/octave
2000	0.0256
Duration	**2 minute per axis**
Overall g rms	**14.12**

Table 20 FS-3 Qualification random vibration level

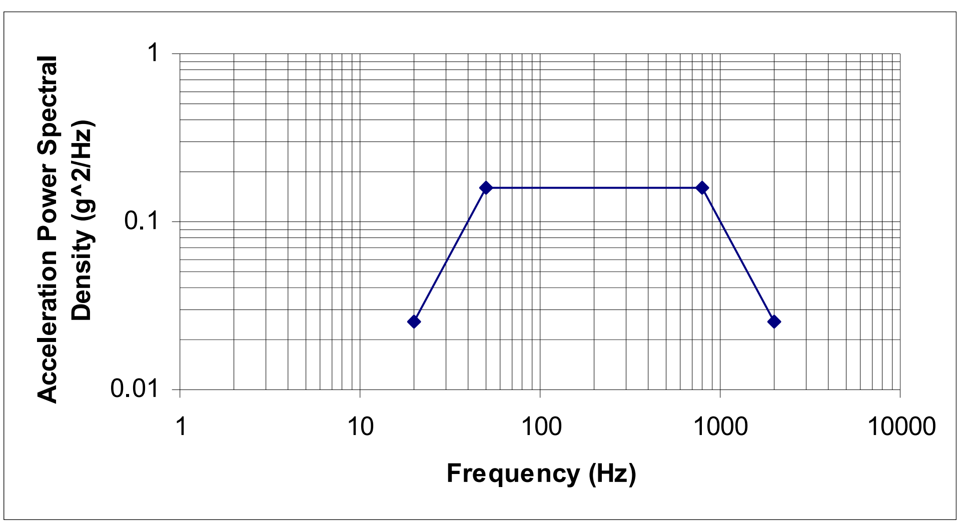


Figure 23: FalconSAT-3 Qualification-Level Power Spectral Density

6.6.4 Results

The following plot shows the response of the QM spacecraft near the center of the top of the stack during the random vibration test in the X-axis:

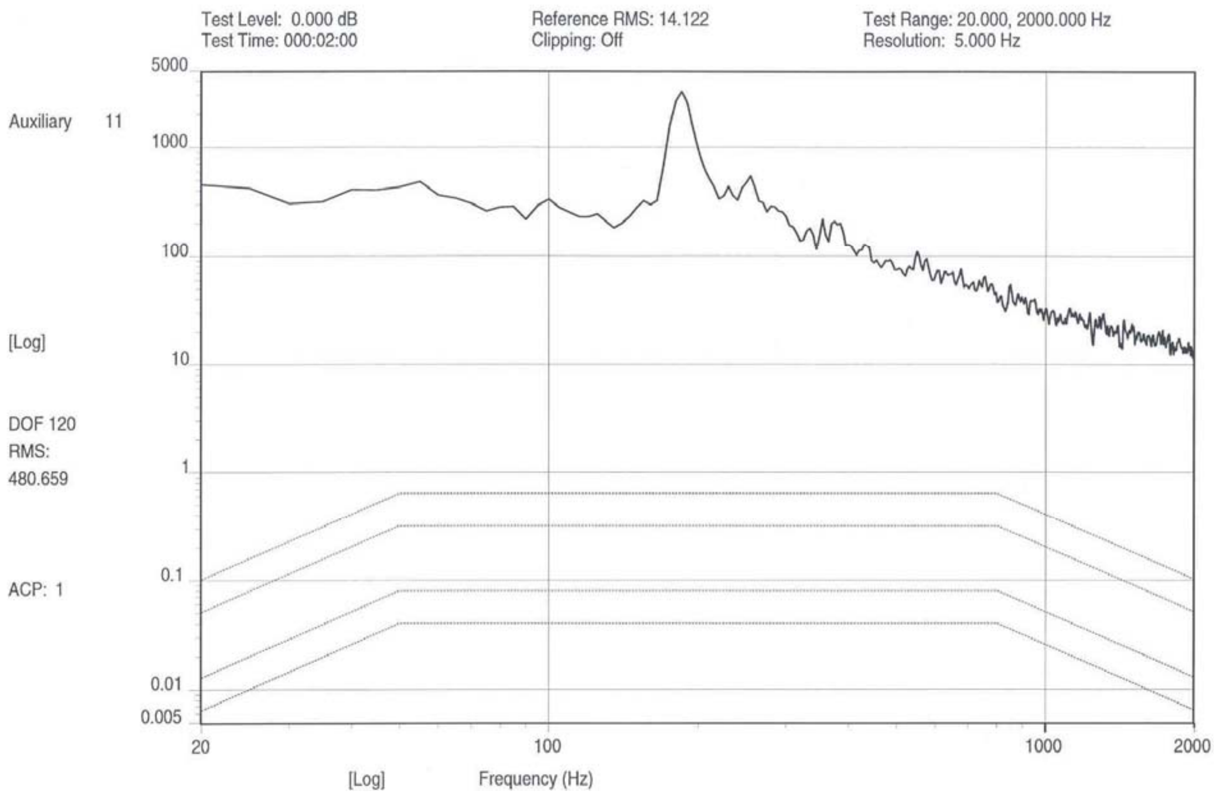


Figure 24: Random Vibration, X-Axis, Stack Top X

Following this random vibration test, a swine sweep was conducted to the levels indicated in Table 16. The plot below illustrates the sine sweep results for the top of the stack following this test. The fundamental frequency following this test dropped slightly, just outside of our 5% margin. However there was no noticeable damage to the spacecraft and the functionality test following all the X-axis tests was successful. Plots remain unchanged, for the most part, from one accelerometer to the next.

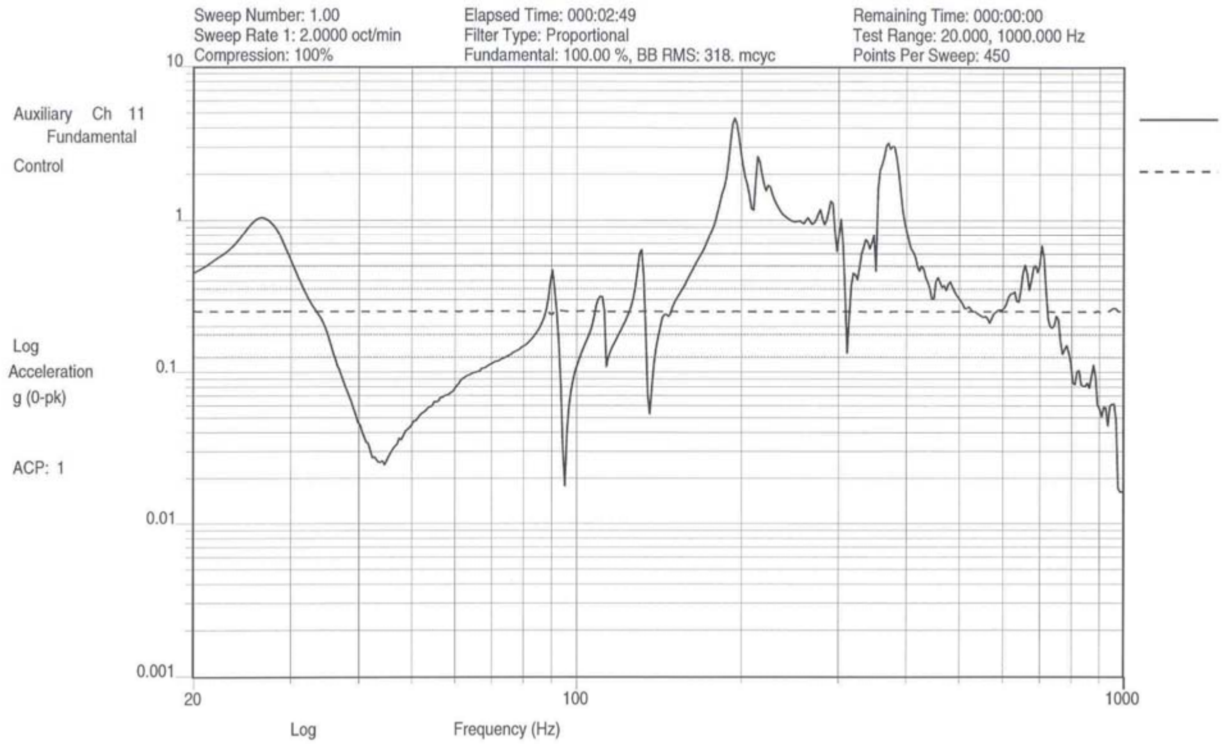


Figure 25: Post Qualification-Level Random Vibe Sine Sweep, X-Axis

7 Structural Tests Results: Y-Axis

7.1 Test Configuration

7.1.1 Test Set-up

The test article consisted of the QM in its fully assembled configuration. The QM was bolted to the FalconSAT-3 test fixture which was bolted to the table in the same configuration as described in Section 4.5.

7.1.2 Accelerometer Locations

Accelerometers for this portion of the test were placed as shown in Table 21 below.

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30816	9.83	Fixture Base – Forward	Control
2	30817	10.07	Fixture Base – Rear	Control
3	37448X	10.00	Top Panel Center X	
4	37448Y	10.74	Top Panel Center Y	
5	37448Z	9.80	Top Panel Center Z	
6	13228	9.42	+X Panel, X Axis	
8	AAM32X	10.3	Base Plate Corner X	
9	AAM32Y	9.651	Base Plate Corner Y	
10	AAM32Z	9.346	Base Plate Corner Z	
11	AD808X	9.392	Stack Top X	
12	AD808Y	10.46	Stack Top Y	
13	AD808Z	9.406	Stack Top Z	
14	37449X	10.39	MPACS X	
15	37449Y	9.91	MPACS Y	
16	2965	10.4	Top of S-Band Stand Z	
17	21522	10.39	PLANE X	

Table 21: Y-axis test accelerometer locations

7.2 Summary of Results, Y-Axis

Test	Objectives	Success Criteria	Result
Sine Sweep	1. Validate fundamental rocking frequency of 33 Hz found in SEM-2 testing 2. Peak acceleration at fundamental frequency not to shift more than 20% during tests 3. Fundamental frequency not to shift more than 5% during tests 4. No damage to spacecraft should be detectable	1. Successful measurements 2. Acceleration shift < 20% 3. Fundament frequency shift < 5% 4. No damage	1. Primary mode is at about 25 Hz, 2nd mode is at about 104 Hz. 2. Shift of about 22.3% 3. Shift of about 4.3% 4. Pass
Sine Burst	1. No apparent/discernable damage to spacecraft	1. Spacecraft maintains structural integrity and functionality following RSS of 10.6 g's in three axes (15 g's) sine burst	1. Verified up to 15.000 g's → pass
Random Vibration	1. No damage to spacecraft 2. No fastener losing > 20% of original torque	1. Spacecraft maintains structural integrity and functionality following random vibration to two times the expected flight environment 2. Representative sample of fasteners do not lose more than 20% of original torque	1. Pass 2. Pass

7.3 Test data

The tests produced output graphs from the various accelerometers. From these graphs the response of the structure was determined. In the cases when the only output available was hardcopy plots, the main values were captured off the recording equipment before they were cleared off the system and noted on the copies by hand when they could not be printed directly.

7.4 Initial Sine Sweep, Y-Axis

7.4.1 Objective

The initial sine sweep was conducted to determine the fundamental and further natural frequencies, modal shapes, and modal gain of the structure. The sine sweep also provided a baseline from which subsequent tests were judged. Additional sine sweeps were conducted following each test to ensure that no damage was done to the spacecraft (indicated by no change in the fundamental frequency).

7.4.2 Success Criteria

The success criteria for the sine sweep were to characterize the natural frequencies of the QM flight configuration in the Y axis and to validate the values found in the SEM-2 test campaign (rocking frequency of 33 Hz)

7.4.3 Test Levels

The following table outlines the frequencies and accelerations that were used for all sine sweeps completed during testing in this particular configuration.

Frequency range (Hz)	Acceleration (g)	Sweep rate (octaves/minute)
20-1000	0.25 g	2

Table 22 Sine sweep vibration specification

7.4.4 Results

From this initial sine sweep, the following fundamental and secondary frequencies were determined.

Mode	Frequency (Hz)
First	26.431
Second	104

Table 23 Initial sine sweep frequency results

These frequencies are illustrated in the following figure which depicts the initial sine sweep response near the center of the top of the stack:

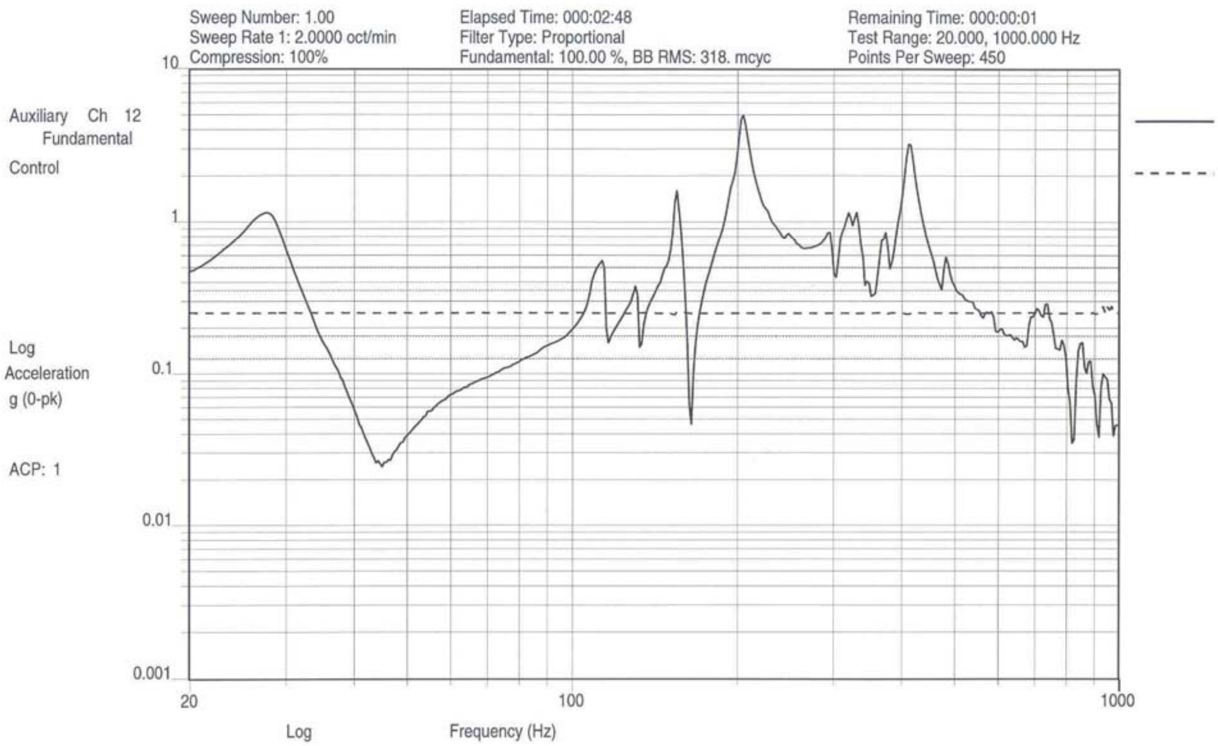


Figure 26: Initial Sine Sweep, Y-Axis, Stack Top Y

7.5 Sine Burst Test, Y-Axis

7.5.1 Objective

The sine burst test was completed in order to verify that the spacecraft meets the ESPA static load requirement of 10.6 g limit load in axial and lateral axes simultaneously.

7.5.2 Success Criteria

The success criteria for this test was to ensure that the spacecraft maintains structural integrity following RSS of 10.6 g's in three axes (15 g's) sine burst.

7.5.3 Test Level

The sine burst test was performed with the following frequency and maximum acceleration specification seen below. The test were able to verify up to 15.000 g's. The test was performed in a number of steps starting from -12 dB, to -9 dB, -6 dB, -3 dB then 0 dB (the final test level) to allow the vibration equipment to analyze the system response and adjust the input levels appropriately.

Frequency	Acceleration (g)
20 Hz	15.000

Table 24 Y-Axis Sine burst Vibration Specification

7.5.4 Results

The following plot shows the response of the QM spacecraft near the center of the top of the stack during the sine burst test in the Y-axis:

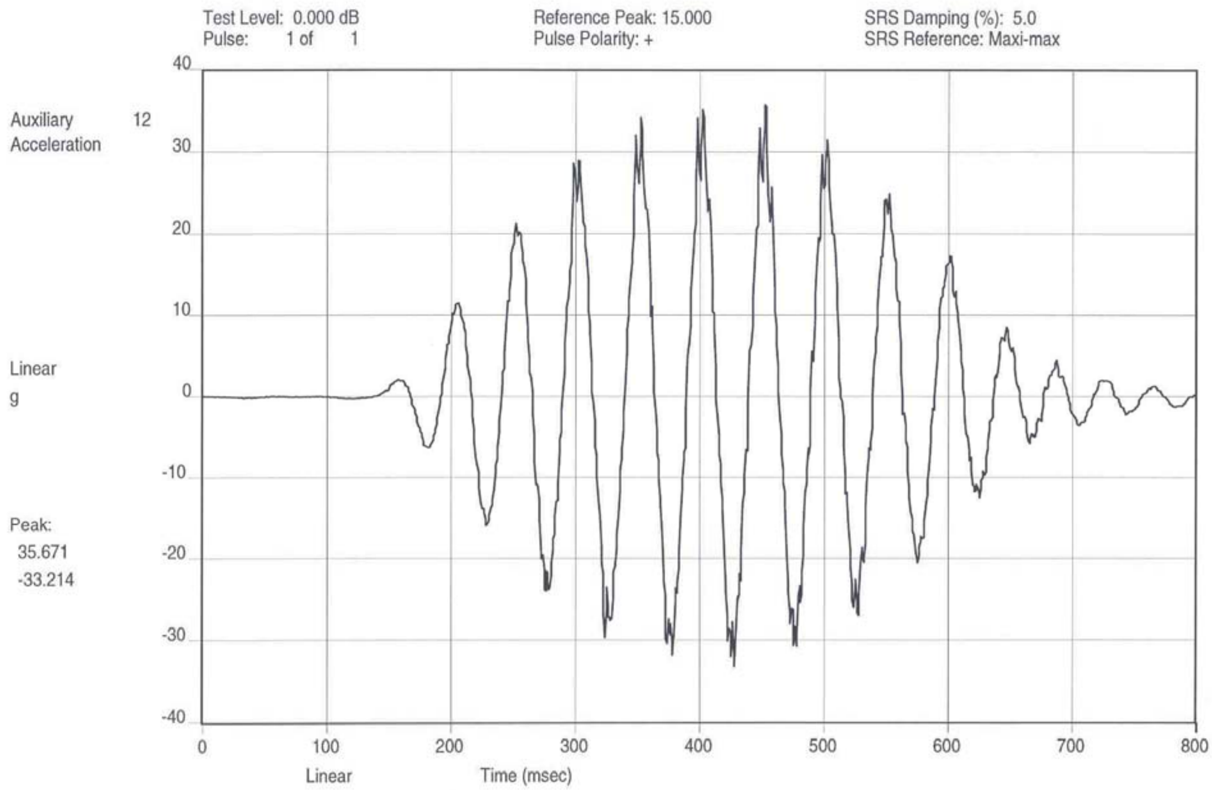


Figure 27: Sine Burst, Y-Axis, Stack Top Y

Following this sine burst test, a swine sweep was conducted to the levels indicated in Table 22. The plot below illustrates the sine sweep results for the center of the top of the stack following this test. The fundamental frequency following this test dropped slightly, just inside of our 5% margin. However there was no noticeable damage to the spacecraft and the functionality test following all the Y-axis tests was successful. Plots remain unchanged, for the most part, from one accelerometer to the next.

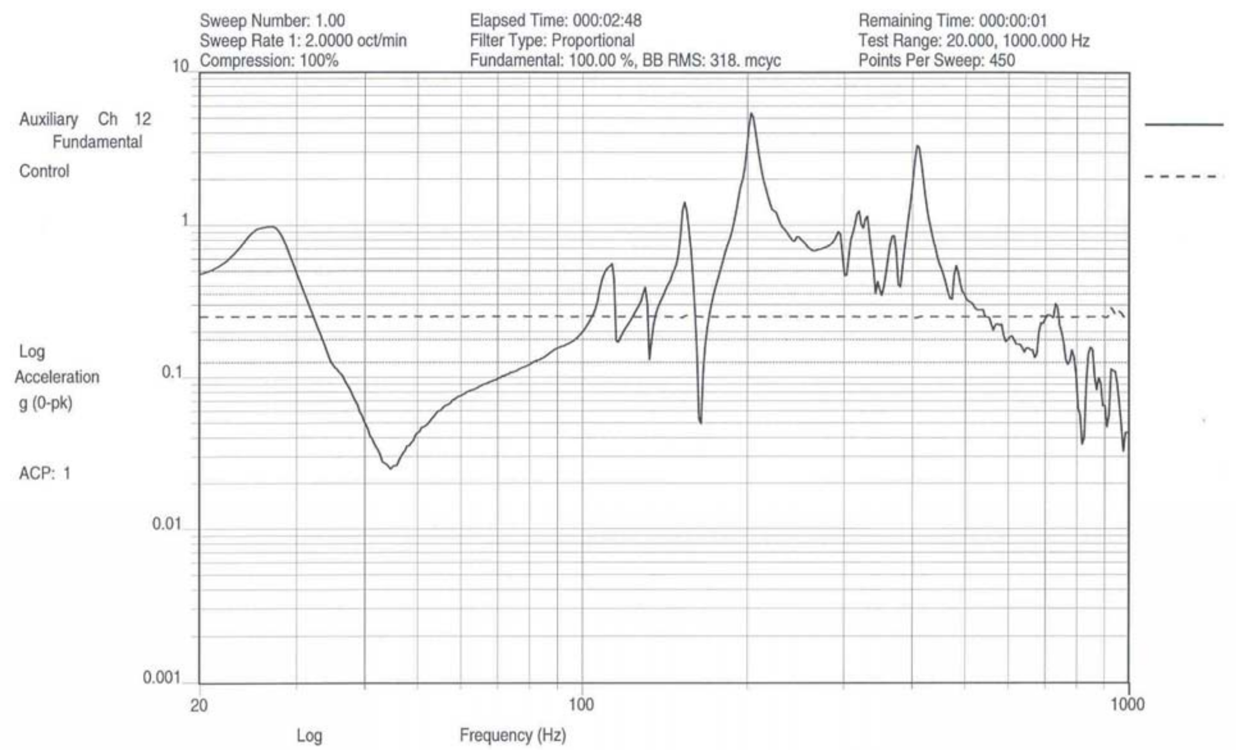


Figure 28: Post Sine Burst Sine Sweep, Y-Axis, Stack Top Y

The following table illustrates responses of several key components to this test:

Component	Response (g's)
Base Plate Corner Y	22
Stack Top Y	36
MPACS Y	51
Top Panel Center Y	46

Table 25: Sine Burst Test Results

7.6 Qualification-Level Random Vibration Test, Y-Axis

7.6.1 Objective

The qualification-level random vibration test was conducted to verify the capability of the satellite structure and components to withstand the fatigue introduced during the launch vibrations per ESPA interface requirement.

7.6.2 Success Criteria

To verify the structure's ability to withstand the fatigue, a representative sample of fasteners must not lose more than 20% of their original torque. Data must be collected as referred to above. Also, structural integrity during the test and electrical functionality after the test must be achieved.

7.6.3 Test Level

Random vibration qualification levels are shown in Table 26 and Figure 29 below. These levels represent +3 dB above the flight level (two times the intensity). The test duration was 2 minutes per axis.

Frequency (Hz)	Acceleration PSD (g^2/Hz)
20	0.0256
20-50	+6 dB/octave
50-800	0.16
800-2000	-4.5 dB/octave
2000	0.0256
Duration	**2 minute per axis**
Overall g rms	**14.12**

Table 26 FS-3 Qualification random vibration level

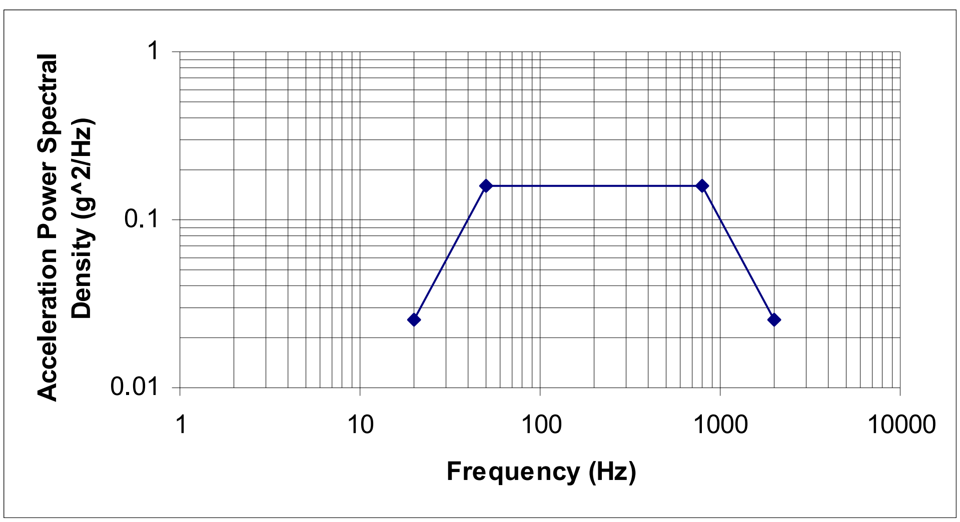


Figure 29: FalconSAT-3 Qualification-Level Power Spectral Density

7.6.4 Results

The following plot shows the response of the QM spacecraft near the center of the top of the stack during the random vibration test in the Y-axis:

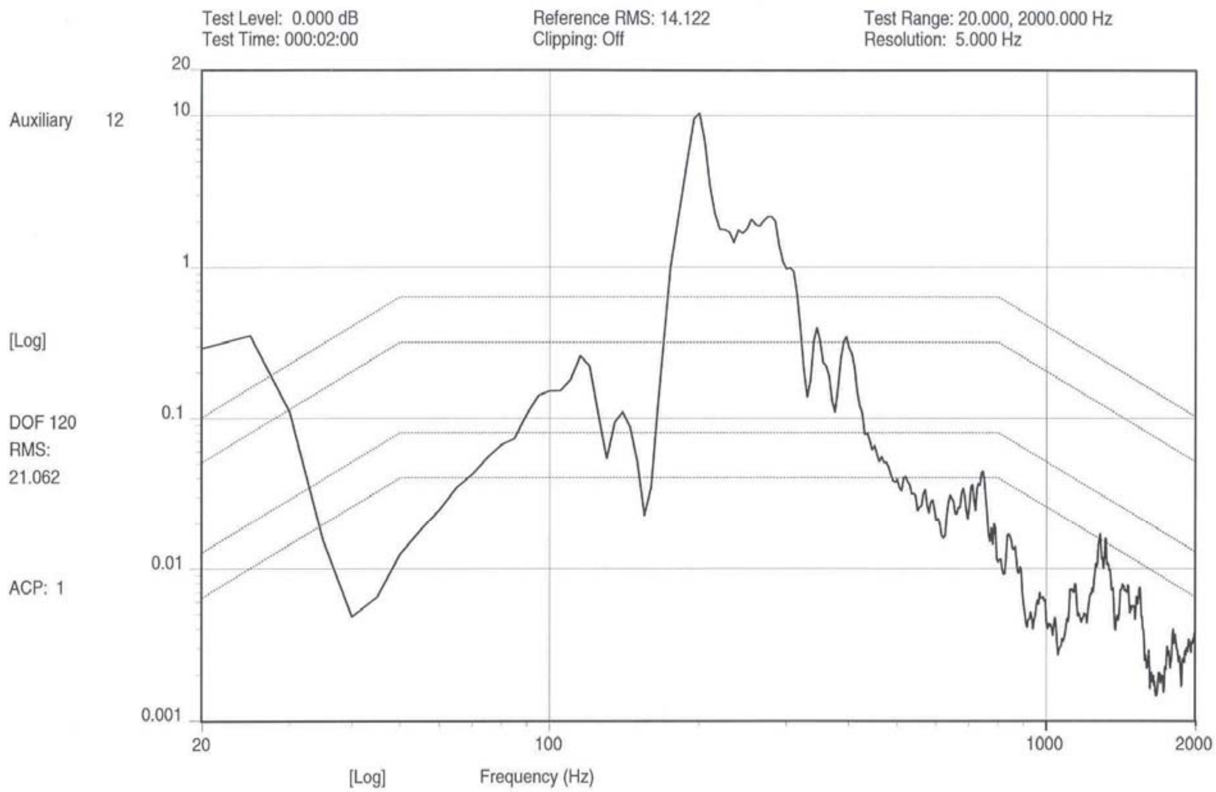


Figure 30: Random Vibration, Y-Axis, Stack Top Y

Following this random vibration test, a swine sweep was conducted to the levels indicated in Table 22. The plot below illustrates the sine sweep results for the top of the stack following this test. The fundamental frequency following this test dropped slightly, just inside of our 5% margin. However there was no noticeable damage to the spacecraft and the functionality test following all the Y-axis tests was successful. Plots remain unchanged, for the most part, from one accelerometer to the next.

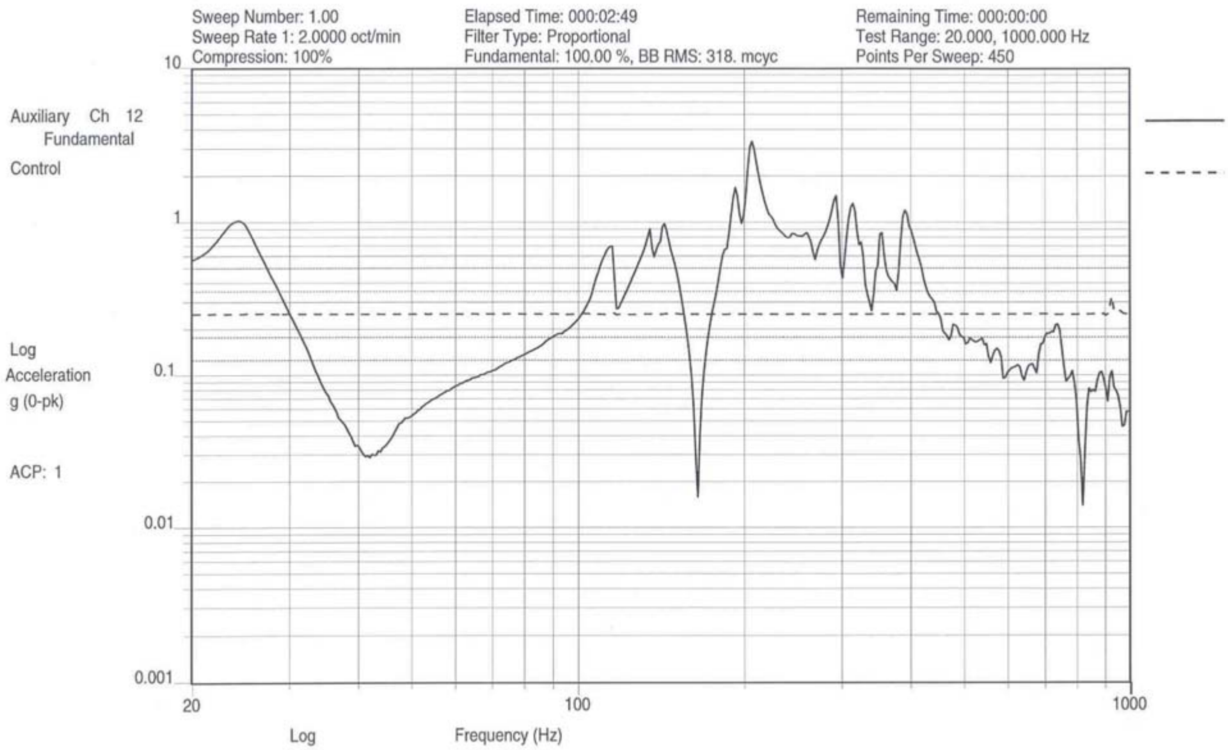


Figure 31: Post Qualification-Level Random Vibe Sine Sweep, Y-Axis

8 Stand Characterization Test Results: Y-Axis

8.1 Test Configuration

8.1.1 Test Set-up

After the Z, X, and Y-Axis vibration testing was complete the vibration interface stand which connects the QM to the vibration table was re-instrumented in accordance with Table 27 below. A sine sweep test was run while the spacecraft was still attached to the stand. After this test, the spacecraft was lifted off of the vibration interface stand and the sine sweep was repeated for just the stand with the same instrumentation.

8.1.2 Accelerometer Locations

Accelerometers for this portion of the test were placed as shown in Table 21 below.

Channel	Serial #	Sensitivity (mV/g)	Location	Type
1	30817	10.07	Front Y-Axis	Control
2	30819	9.60	Front Z-Axis	Control
3	30816	9.83	Back Y-Axis	
4	21523	9.95	Back Z-Axis	

Table 27: Stand Characterization Test Accelerometer Locations

8.2 Test Objectives

The objective for this portion of the test campaign was to show that the vibration interface used during all phases of vibration testing, which is needed because of the protrusion of the gravity gradient boom, does not affect the results of the testing to a significant level. This concern was raised by our launch contractor in an effort to make sure the vibration results are as accurate as possible. The goal of this test was 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.

8.3 Sine Sweep with Spacecraft

8.3.1 Test Levels

A sine sweep of the test fixture with the spacecraft still mounted on it was performed with the frequency and acceleration specifications shows in Table 28 below.

Frequency range (Hz)	Acceleration (g)	Sweep rate (octaves/minute)
20-1000	0.25 g	2

Table 28 Sine sweep vibration specification

8.3.2 Test Results

Figure 32 shows the acceleration of the top-front of the vibration stand in the Y axis direction. Figure 33 shows the acceleration of the top-front of the vibration stand in the Z axis direction. The results from the top-rear accelerometers are not included because they are very close to the results of the top-front ones. As can be seen the Z axis results are not quite two orders of magnitude below the Y axis results but are very close to that specification at low frequencies.

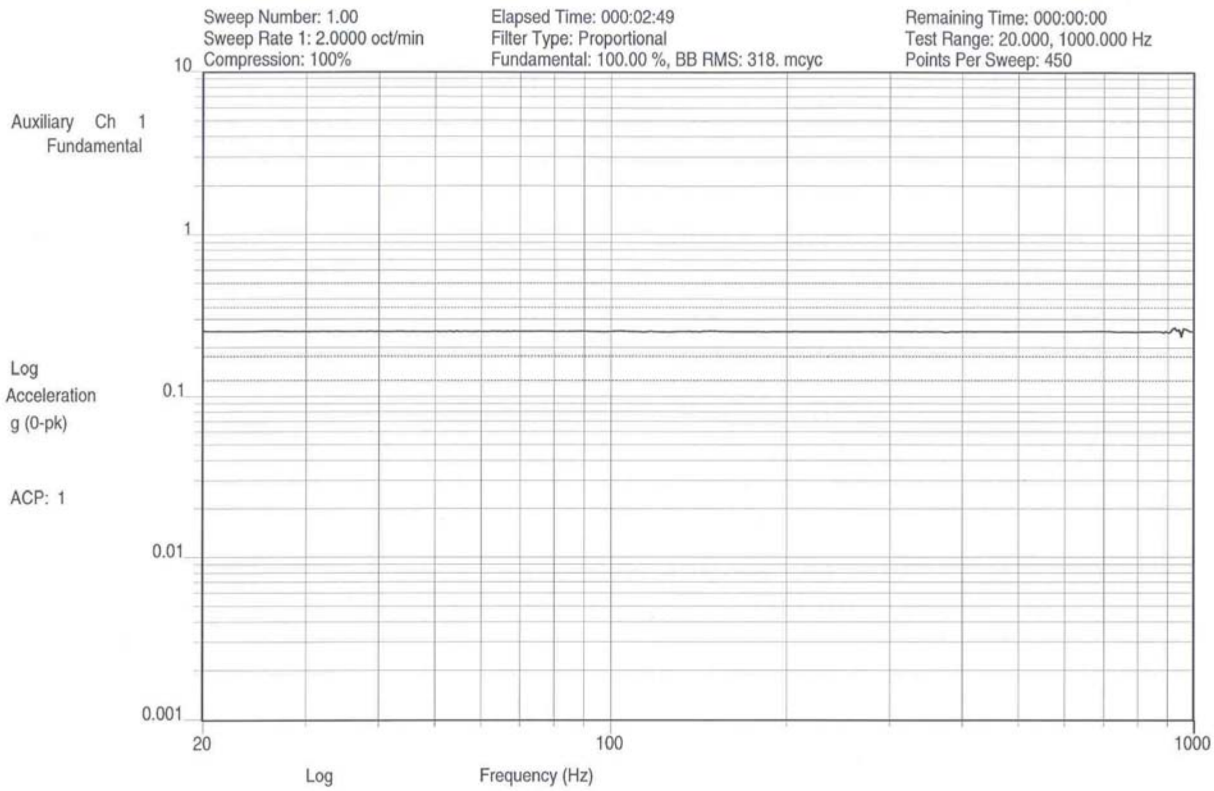


Figure 32: Stand Characterization Test – With Satellite – Top-Front Y Axis

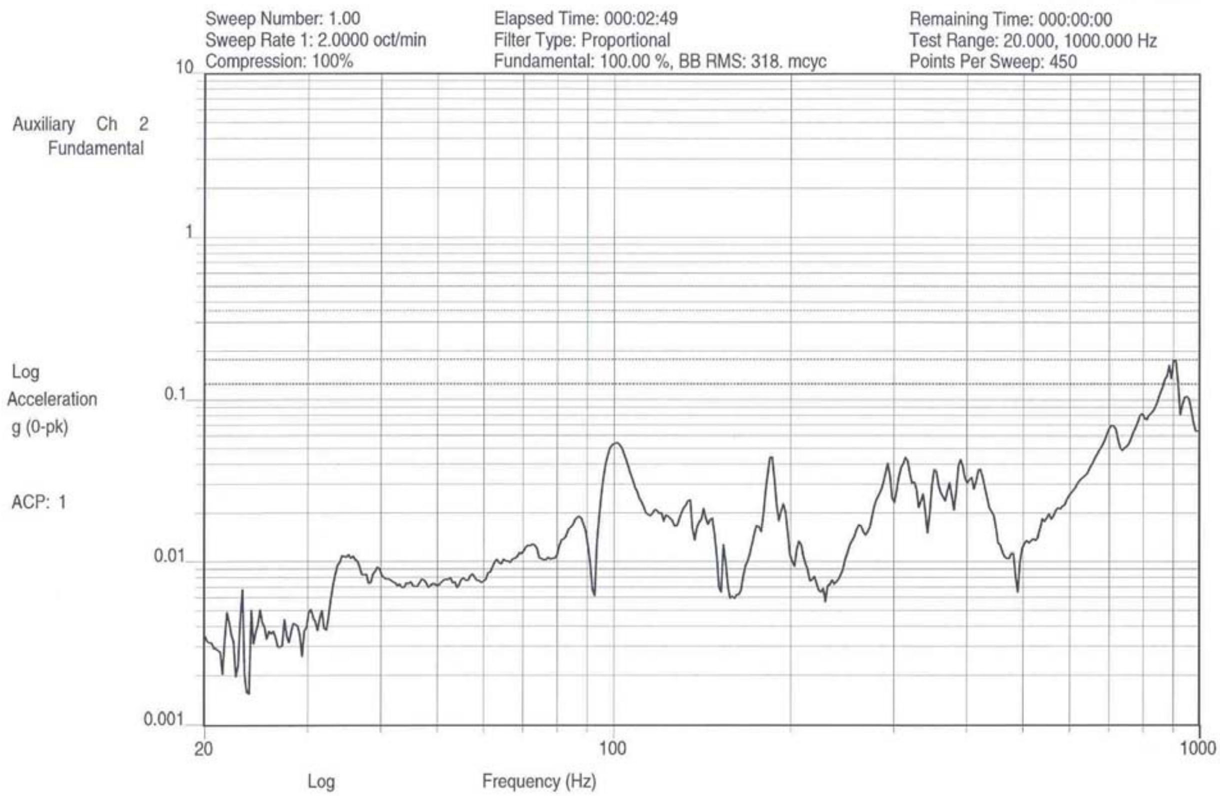


Figure 33: Stand Characterization Test – With Satellite – Top-Front Z Axis

8.4 Sine Sweep without Spacecraft

8.4.1 Test Levels

A sine sweep of the test fixture without the spacecraft mounted on it was performed with the frequency and acceleration specifications shows in Table 29 below.

Frequency range (Hz)	Acceleration (g)	Sweep rate (octaves/minute)
20-1000	0.25 g	2

Table 29 Sine sweep vibration specification

8.4.2 Test Results

Figure 34 shows the acceleration of the top-front of the vibration stand in the Y axis direction. Figure 35 shows the acceleration of the top-front of the vibration stand in the Z axis direction. The results from the top-rear accelerometers are not included because they are very close to the results of the top-front ones. As can be seen the Z axis results are not quite two orders of magnitude below the Y axis results but are very close to that specification at low frequencies.

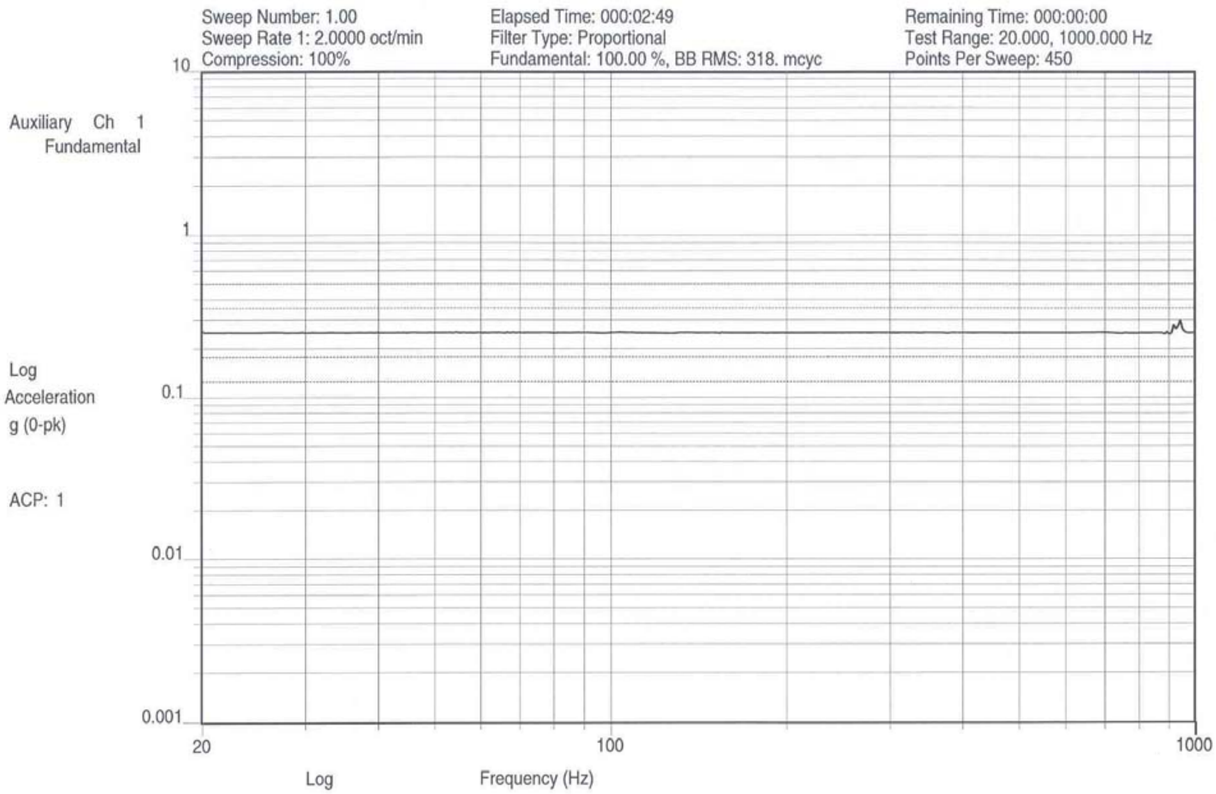


Figure 34: Stand Characterization Test – Without Satellite – Top-Front Y Axis

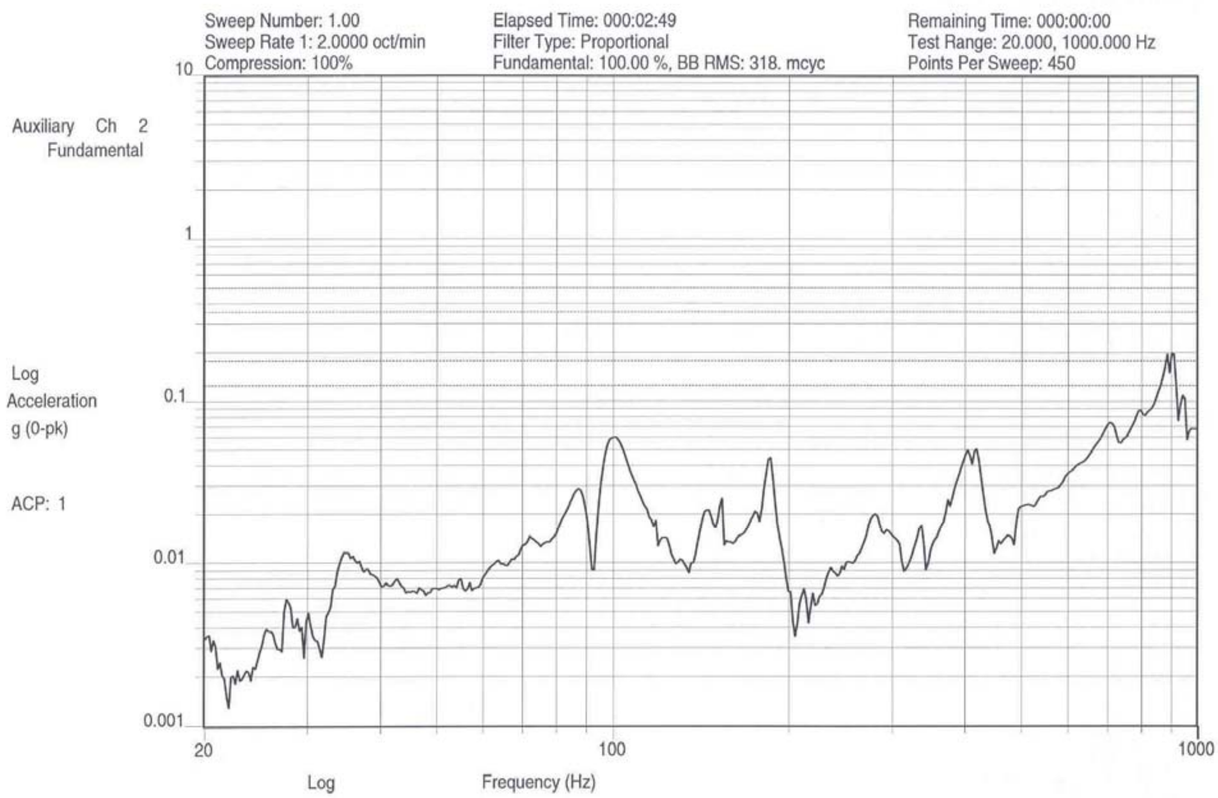


Figure 35: Stand Characterization Test – Without Satellite – Top-Front Z Axis

9 Mass properties measurements

9.1 Introduction

The mass properties of the spacecraft were not obtained because the AEF's CG/MOI table was not at the testing facility. It had been shipped out to support another mission. However, a rough value for the mass of the spacecraft was obtained using a scale that was attached to the crane.

9.2 Mass

The Falcon-Sat 3 QM, when attached to the crane scale, weighed in at 126.8 *km*. When the mass of all the protective side panels was removed the final mass came out to be 116 *km* which is within 10% of the expect mass of 109.1 *kg*.

9.3 Center-of-Gravity (CG)

Results will be included here after the testing takes place.

9.4 Moments-of-Inertia (MOI)

Results will be included here after the testing takes place.

10 Thermal-Vacuum Testing

10.1 Introduction

The objectives of the thermal vacuum test were to:

- Verify that FS3 will be able to operate in a vacuum beyond the temperature extremes expected for the mission by testing the QM in a vacuum to temperatures that exceed those of the space environment.
- Verify that FS3 will be able to withstand temperature cycling in a vacuum by subjecting the QM to at least three complete cycles from maximum to minimum temperatures.
- Characterize RF performance at temperature extremes
- Test onboard and ground software
- Simulate operational conditions to verify and improve commissioning and test procedures

10.2 Success Criteria

The TVAC test success criteria were:

- Vacuum of 10^{-6} Torr reached during the hot bake-out cycle and maintain for 4 hours
- Electrical functionality during all phases of T-Vac
- No condensation at spacecraft removal after final hot cycle at 25 degrees Celsius
- Full spacecraft functionality after removal from T-Vac Chamber

10.3 Test Environment

Target Pressure: 1.0 x 10^{-6} torr

Test conditions were selected to approximate the space environment and the extremes (with extra margin on both ends for qualification level testing requirements) are:

- Maximum temperature: +50°C
- Minimum temperature: -20°C

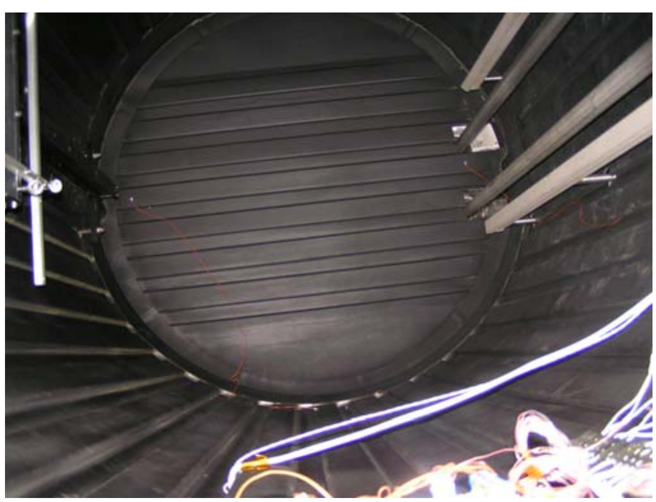


Figure 36 Internal view of the AEF's T-Vac chamber

10.4 Thermocouples

The thermocouple locations were as follows:

Channel	Serial #	Location
17	55	BAT TRAY +X
18	53	BAT TRAY +Y
19	77	BAT TRAY -X
20	72	BAT TRAY -Y
21	69	BCR TRAY -X
22	70	TX TRAY -X
23	50	TX TRAY +Y
24	51	RX TRAY -X
25	52	TOP PLATE (INTERNAL)
26	49	Inside side panel +X
27	47	MPACS +X
28	76	MPACS +Y
29	75	MPACS -X
30	59	MPACS -Y
31	61	FLAPS
32	46	PLANE
33	83	SUN SENSOR +X
34	81	SUN SENSOR +Y
35	80	SUN SENSOR -X
36	62	SUN SENSOR +Y
37	54	ADAPTER RING +X
38	82	ADAPTER RING +Y
39	35	LIGHT BAND +X
40	65	LIGHT BAND +Y
41	57	S-PATCH +X +Y
42	68	S-PATCH +X -Y
43	37	S-PATCH -X +Y
44	58	S-PATCH -X -Y
45	74	SHOCK RING +X
46	84	SHOCK RING +Y
47	79	SHOCK RING -X
48	73	SHOCK RING -Y
49	36	SIDE PANEL +X
50	43	SIDE PANEL +Y
51	39	SIDE PANEL -X
52	38	SIDE PANEL -Y
53	67	TOP PLATE (EXTERNAL)
54	48	PPT 2

Table 30 Thermocouple Locations

10.5 Results

There were three major findings during the thermal-vacuum test:

1) The hot bake-out cycle showed no "burps" in the chamber pressure thereby indicating that the spacecraft was incredibly clean. The test facility personnel backed up this finding and told the team the same. The clean spacecraft may largely be attributed to the team's Contamination Control Plan which insures cleanliness when executed properly.
2) PLANE quit working during the first cold-cycle. The cause is still not none and is being examined and subsequently fixed by the Physics Department here at the United States Air Force Academy.
3) All indications have shown that MPACS did not fire when commanded to. The hardware was sent back to the manufacturer who is fixing an internal component and then is going to run the hardware through another vibration and thermal-vacuum campaign to qualify it.

The following plots show the temperature cycles which were endured by the QM spacecraft:

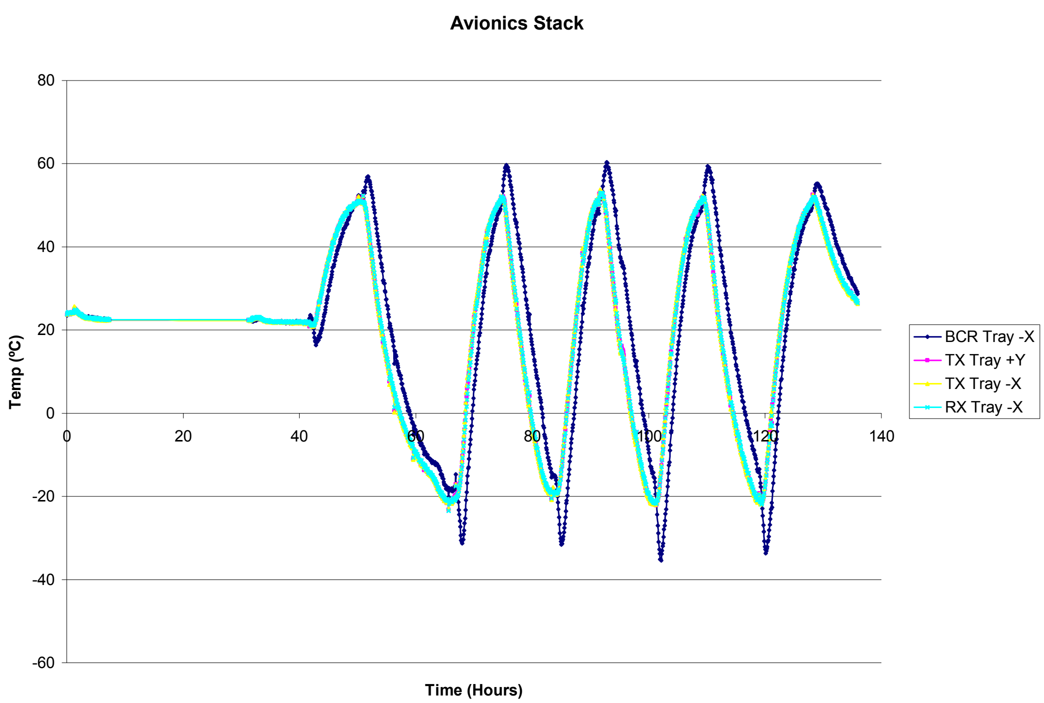


Figure 37 Avionics Stack Temperature Plot, T-Vac Testing

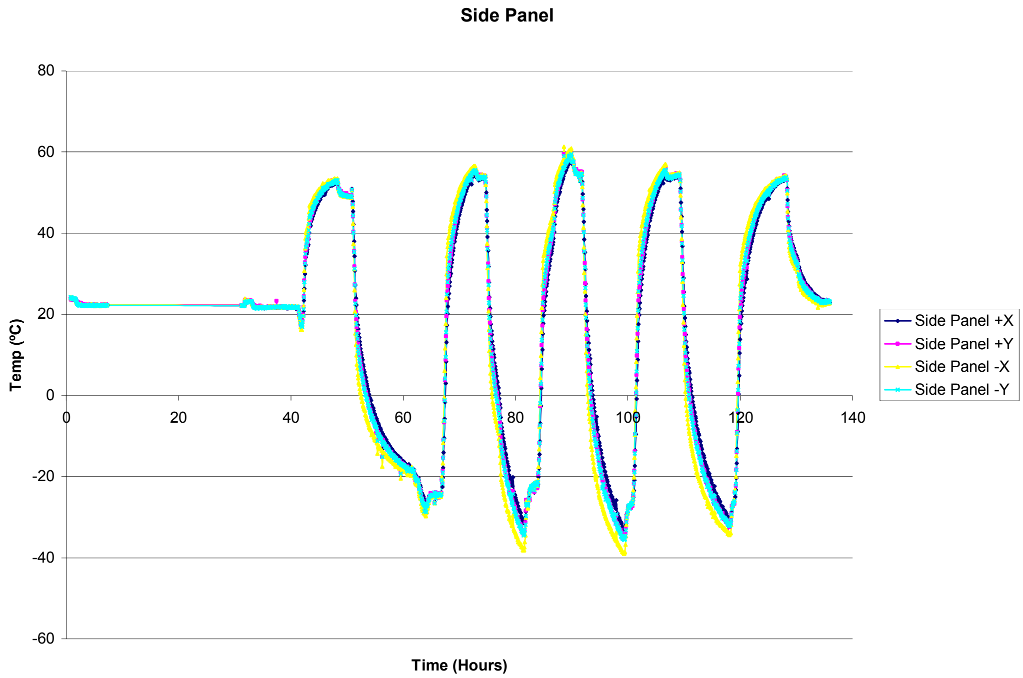


Figure 38 Side Panels Temperature Plot, T-Vac Testing

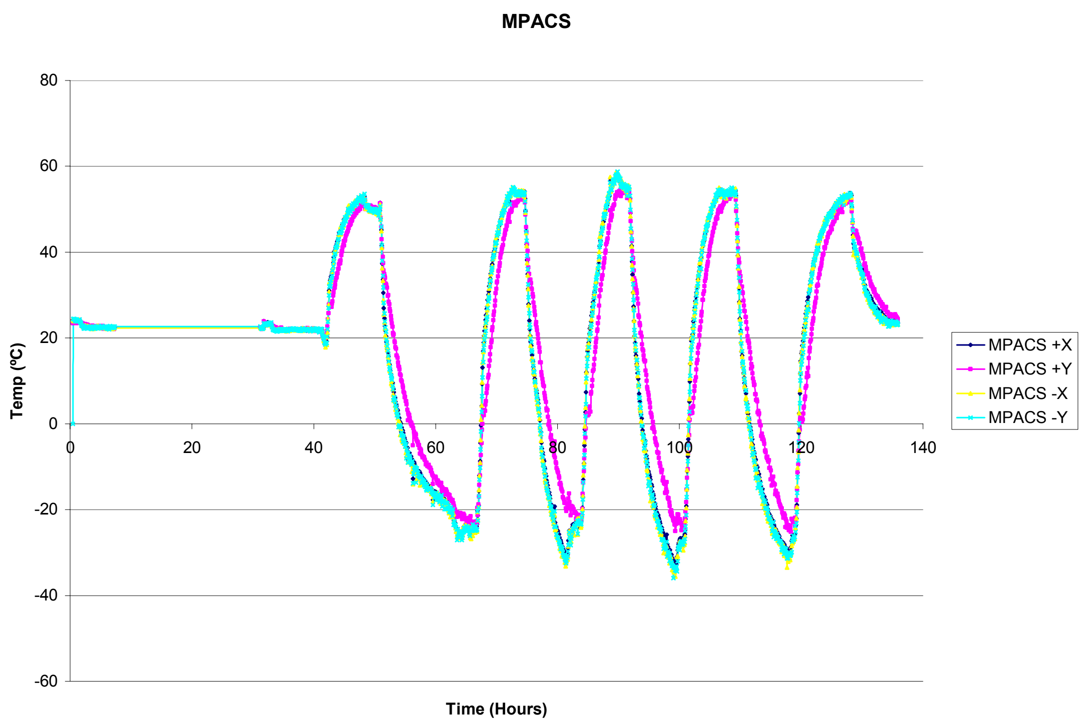


Figure 39 MPACS Temperature Plot, T-Vac Testing

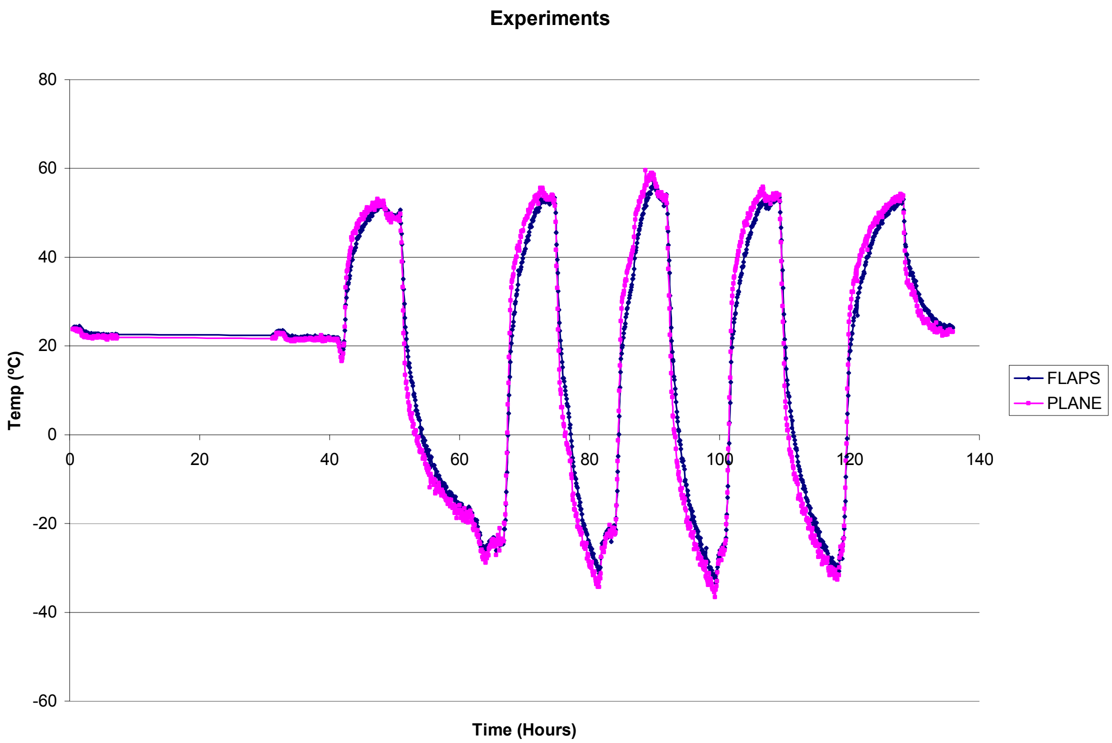


Figure 40 Experiments Temperature Plot, T-Vac Testing

11 Test facility

All testing is to be done at in the Aerospace Engineering Facility (AEF) at Kirtland Air Force Base (KAFB), New Mexico.

The tests are scheduled to take place from 28 January to 06 February 2005.

Time	Activity
07:30	Sign-in, work starts
11:30	Lunch
13:00	Work starts
16:30	End of workday

Table 31 Rough Daily Work Schedule

This schedule is subject to updates, depending on AEF input. USAFA may (and probably will) request that work is performed outside these times as well.

12 Test personnel

The following personnel will be responsible for activities relating to the QM tests.

Lt.Col. Timothy Lawrence, USAFA: Director Space Systems Research Center, Head of Mission

Lt Col Dan Miller, USAFA: FS-3 Faculty Program Manager, Responsible Test Engineer & Responsible for Cadet supervision

Don Waite: Responsible for engineering support

Prof. Maarten Meerman, Schriever Chair, USAFA: General test overview and support

Dale Stoller, AEF Kirtland: Test Conductor, responsible for safety, test equipment, instrumentation, providing initial test and measurement data and controlling the shaker, mass property equipment, and thermal vacuum chamber.

C1C Benjamin Visser, FS-3 Cadet AIT Testing Chief and FS-3 Chief Engineer: Responsible for all USAFA supplied test equipment, and for ensuring all measurement data is collected, and all tests are documented in writing, sketches and photographs

C1C Aaron Lynch, FS-3 Cadet Program Manager: Cadet responsible for planning the daily operations

13 Lessons Learned

The following is a general list of lessons learned throughout the QM Test Campaign:

- Bring extra duct tape, grounding straps with alligator clips, trash bags, and pipe cleaners
- Things needed for the Flight Model Test:
    - A list of exactly what needs to be recorded during the periodic times
        - Example: Record Battery Voltage ever 30 minutes
        - Have a template to put information directly into (Excel??)
    - A single document of the power up and functionality test procedures
        - Cadet Haywas was concerned when he found three copies of how to run ComFS3 (several with errors)
        - This would also be a good place to put what to measure when
    - Well ordered standardized checklist (hard copy) for people to follow
    - Bring an alarm clock or timer so that people are sure to do
    - Consolidated files (max of 5 documents with clear uses)
    - A dedicated document computer in order to avoid the USB Drive transfer
    - Backing up the data is important, and something that was never mentioned
- Bring all harness documentation

14 Test Log

Saturday 29 Jan 2005	
Time:	Description:
0730	Arrived at testing facility
0745	Unloaded satellite equipment from trailer
0830	Falcon-Sat 3 removed from case
0845	Alcohol scrub down of satellite test stand
0900	RF GSE setup
0900	Setup all the computers, printer, spectrum analyzers, etc
0910	Grounding of FS-3
0930	Begin unwrapping of FS-3
0945	FS-3 attached to crane
1010	FS-3 bolted onto test stand. Satellite had two of the outer plastic panels removed in order to fit
1015	Quick tension check of all screws
1030	Hooked up satellite for ground functional test
1030	Troubleshot problems with s-band signal. No signal from satellite.
1042	Connected RF umbilical
1043	Turned spacecraft power on
1044	Turned power off
1200	Figured out boot loader did not function right – fixed problem
1510	Removed QM from bottom support, rotated 90 degrees to place on forklift
1520	Swapped out cables which would fit inside the T-Vac chamber
1530	Hanging of QM on vacuum chamber rail; removed rest of test stand
1550	Hooked up antenna cables
1610	Hooked up thermocouples to channel box inside of chamber
1740	Finished up thermocouple placement
1740	Pictures taken of satellite
1745	Boot loader still does not work, auto-booted okay however
1750	Power turned off

1805	Door to T-Vac chamber closed
1806	Chamber turned on for pump-down and bake-out
2039	Out-gassing expected; lab tech thinks chamber might have a leak

Sunday 30 Jan 2005	
Time:	Description:
0039	Technicians determined chamber had a lead. Pressure had been down to 8.8 x 10^(-5) torr, then spiked to 4.4 x 10^(-4) torr within about 60 seconds
0040	Chamber pressurization turned off, depressurized, Col Miller notified
0213	Re-pressurization for cleaning of pump
0448	Pump-down began again after completion of cleaning pump
0714	Pressure at 1.3e-5 torr
1125	Pressure at 5.2e-5 torr, shroud temperature 52 degrees C
1654	Pressure at 1.4e-5 torr, shroud temperature 56 degrees C
1704	Performed hot bake-out functionality test
1938	Spacecraft shut-down, cold-cycle start
2359	Pressure at 7.3e-7 torr, shroud temperature -20 degrees C

Monday 31 Jan 2005	
Time:	Description:
0645	Told AEF to lower shroud temperature (Lt Col Lawrence)
0802	Pressure at 8.2e-6 torr, shroud temperature -34 degrees C
0933	Raised shroud temperature due to low battery temperature
1001	Performed cold-cycle functionality test
1128	Cranking up the heat for the hot cycle
1412	Pressure at 9.8e-6 torr, shroud temperature 60 degrees C
1526	Performed hot-cycle functionality test
1600	Lowered shroud temperature to start next cold-cycle
2148	Pressure at 6.8e-6 torr, shroud temperature -30 degrees C, figured out it would take forever for satellite to get down to -20 degrees C so turned down shroud temp to -50 for awhile
2359	Battery box around 1 degrees C

Tuesday 01 Feb 2005	
Time:	Description:
0300	Battery box around -20 degrees C, pressure at 2.7e-6 torr, raising chamber temp to -20 degrees C from -30 degrees C
0310	Performed cold-cycle functionality test
0434	Turning shroud temperature up to 60 degrees C to start hot-cycle
1130	Battery temperature 51 degrees C, pressure 8.0e-6 torr
1135	Performed hot-cycle functionality test
1234	Turning shroud temperature down to start cold-cycle
1543	Pressure at 1.6e-6 torr, shroud temperature -48 degrees C
2021	Spacecraft finally cooled to -20 degrees C
2021	Performed cold-cycle functionality test
2129	Turning shroud temperature up to start hot-cycle
2330	Shroud at 61 degrees C, pressure 3.8e-6 torr, spacecraft temp still rising

Wednesday 02 Feb 2005	
Time:	Description:
0450	Pressure at 4.2e-6 torr, spacecraft temp finally up to about 50 degrees C
0455	Performing hot-cycle functionality test
0600	Turning shroud temperature down to start cold-cycle
1430	Spacecraft temperature down to about -20 degrees C, pressure 3.3e-7 torr
1436	Performing cold-cycle functionality test
1540	Turning shroud temperature up to start hot-cycle
2330	Spacecraft temperature about back up to 50 degrees C, pressure 3.3e-6 torr
2347	Performing hot-cycle functionality test

Thursday 03 Feb 2005	
Time:	Description:
0100	Turning shroud temperature back to about room temperature
0600	Shroud temperature 22 degrees C, pressure 7.3e-7 torr, spacecraft temperature about 30

	degrees C
0627	Performing room-temperature functionality test
0727	Testing complete, bringing pressure back up to sea level
0911	Vent chamber to atmosphere
0920	Chamber doors opened
0921	Performing quick PPT test to see if they will fire, all current indications show that they did not fire at all during testing
0939	All three sticks failed to fire
0940	Spacecraft turned off completely
0950	Inspected satellite; looked really good, slight specks on solar panels
0955	Attached rail adaptor to remove satellite from thermal shroud
0957	Grounded the spacecraft
1000	Taking thermocouples off, channel 49 appeared loose
1030	Finished removing thermocouples, all RF cables removed
1035	Taped internal thermocouples to solar panel mass dummies
1045	Installed solar array covers
1055	Installed remaining Plexiglas covers
1115	Used forklift to assist in installation of turn-over jig
1120	Slightly raised spacecraft with forklift (2”)
1135	Carefully removed spacecraft from T-Vac chamber with forklift
1142	Turned satellite upward (MPACS towards ceiling)
1143	Connected lifting harness
1145	Transferred satellite across the room using the crane
1200	Placed satellite on four legged stand
1212	Removed old shock ring
1226	Inspected solar arrays for any cracks
1230	Used crane to move satellite onto vibe table
1235	Attached satellite to new shock ring and in doing so the vibe table
1245	Finished connecting the light band to the shock ring
1315	+Y MPACS removed
1330	+Y side panel removed to remove internal thermocouples and to install internal

	accelerometers
1405	Mr. White verified that the harness was intact before accelerometers were added
1450	Placement of the accelerometers for the Z-axis test
1530	Side panel replacement started
1543	Reattaching MPACS mass dummy
1545	Side panel replacement finished
1548	MPACS mass dummy reattachment finished
1620	Remove protective side panel covers
1630	Replace whip antennas
1640	Light band tensioner box broken, used torque wrench to tighten light band by hand to 30 ft-lbs
1643	Plugged in the umbilical
1644	Power on, functionality tested positive
1744	Satellite turned off; ready for Z-axis vibe testing; retire for the day

Friday 04 Feb 2005	
Time:	Description:
0600	Came back to the lab, checked over spacecraft
0616	Waiting for CSA to finish up so test can begin
0621	Ensured assembly and configuration procedures were completed
0622	Correct procedures for power-up and bootloader
0624	C1C Novotney working on the satellite
0637	CSA placing thermocouples on shock ring
0644	Prepared for the first vibration test
0651	Z-axis initial sine sweep
0658	Z-axis sine burst: 15 G at 25 Hz
0714	Z-axis sine sweep number 2
0723	Z-axis random vibration – auto-terminated because wire to control accelerometer was broken
0754	Z-axis random vibration test completed
0757	Z-axis final sine sweep

0759	CaJacob and Knauf replace protective side panel covers
0801	Umbilical is reconnected
0807	Satellite functionality test – successful
0839	Satellite shut down
0904	Sgt Wickersheim brings crane over to the QM spacecraft
0909	Lifting harness attached to the satellite
0915	Remove screws from shock ring to vibe stand
0917	Remove bolts from base plate
0942	Satellite lifted from vibe table via crane
0950	Satellite placed on integration test stand
0957	Vibe table interface moved to the horizontal vibe surface and re-secured
1201	Preparing for horizontal vibration test
1225	Crane moved over to QM integration stand
1227	Lifting harness attached to QM
1231	QM unsecured from integration stand
1233	QM lifted
1235	Integration stand moved out of the way
1300	Mounting QM spacecraft onto the vibration interface
1350	Spacecraft protective side panel covers removed
1408	SMA internal chassis connector found to be loose for VHF whip antenna – needed to be torqued back down
1410	Accelerometers reconnected into proper channels for +X axis testing
1438	Spacecraft ready for X-axis vibration tests
1445	X-axis initial sine sweep – failed at 0.1 and 0.25 G's – faulty accelerometer – was replaced
1531	X-axis initial sine sweep completed
1540	X-axis sine burst
1555	X-axis sine sweep number two
1605	X-axis random vibration
1612	Spacecraft functional test completed
1644	X-axis final sine sweep
1650	Start of prep for Y-axis vibe testing – need to rotate QM by 90 degrees

1700	Mass of QM recorded to be 116 lbs
1733	QM secured to shock ring again
1748	Antenna lengths measured: VHF = 19.8" and both UHF = 7.8"
1752	Ready for Y-axis vibration testing
1759	Y-axis initial sine sweep
1807	Y-axis sine burst
1814	Y-axis sine sweep number two
1826	Y-axis random vibration
1835	Y-axis final sine sweep
1837	Fairly significant shift in fundamental frequency detected between first and last sine-sweeps
1843	Protective side panel covers replaced
1848	Spacecraft functionality test performed
1907	Antennas replaced
1917	All data backed up to C1C CaJacob's USB drive
1920	Packing up started for return trip to USAFA

Saturday 05 Feb 2005	
Time:	Description:
0800	Packing commences again
0900	Spacecraft back in its closed up shipping container
0915	All equipment loaded back into trailer for trip back to USAFA
0930	Team departs after what seems to be a successful testing campaign 1 day ahead of schedule