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Overview of the Acoustic Testing of the European Service Module Structural Test Article (E-STA)

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Abstract

The European Space Agency (ESA) and their prime contractor Airbus Defense & Space (ADS) are developing the European Service Module (ESM) for integration and utilization with other modules of NASA's Orion Multi-Purpose Crew Vehicle.

As part of this development, ESA, ADS, NASA and the Lockheed Martin Company performed a series of reverberant acoustic tests in April-May 2016 on the ESM Structural Test Article (E-STA), the mechanical mock-up of the ESM designated for mechanical tests. Testing the E-STA under acoustic qualification loads verifies whether it can successfully withstand the medium and high frequency mechanical environment occurring during the vehicle's lift-off and atmospheric phases of flight. The testing occurred at the Reverberant Acoustic Test Facility (RATF) at the NASA Glenn Research Center's Plum Brook Station site in Sandusky, Ohio, USA.

This highly successful acoustic test campaign excited the E-STA to acoustic test levels as high as 149.4 dB Overall Sound Pressure Level. This acoustic testing met all the ESA and ADS's test objectives, including establishing/verifying the random vibration qualification test levels for numerous hardware components of the ESM, and qualifying the ESM's Solar Array Wing electrical power system.

This paper will address the test objectives, the test article's configuration, the test instrumentation and excitation levels, the RATF site and capabilities, the series of acoustic tests performed, and the technical issues faced and overcome to result in a successful acoustic test campaign for the ESM. A discussion of several test results is also included.

Introduction

Orion Multi-Purpose Crew Vehicle

The NASA Orion Multi-Purpose Crew Vehicle (MPCV) will be launched for the first time in 2018 on a new heavy launch vehicle, named the Space Launch System (SLS). The goal of this un-crewed Exploration Mission (EM-1) of about seven days is to pass in proximity to the moon and return to Earth while demonstrating an operational MPCV. The SLS and MPCV constitutes the key components in the realization of future crewed exploration missions in cislunar space and towards asteroids and Mars.

The Orion MPCV, located at the top of the SLS launcher, is composed of different primary components as shown in Figure 1 and Figure 2. A European Service Module (ESM), developed by the European Space Agency (ESA) with Airbus Defense and Space (ADS) as their prime contractor, provides propulsion, power and consumables. The ESM is interfaced with the Crew Module (CM) through a Crew Module Adaptor (CMA). The CMA serves as a structural, electrical, and fluid interface between the CM and ESM. A Launch Abort System (LAS) that removes the crew from the launch vehicle in case of emergency is on top. A Spacecraft Adaptor Jettisonable (SAJ) fairing provides both aerodynamic and thermal protections for the ESM components during first stage flight. Lockheed Martin Company (LMCO) is developing the CM, CMA, LAS, and SAJ for NASA.

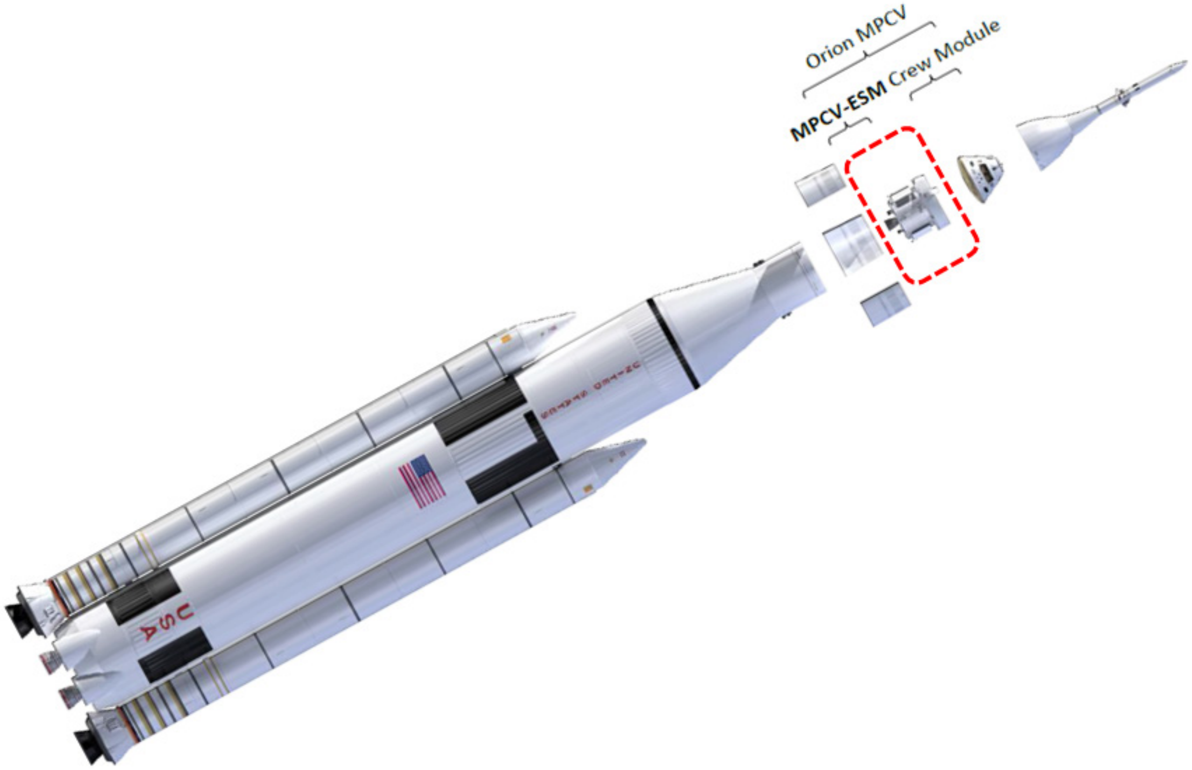
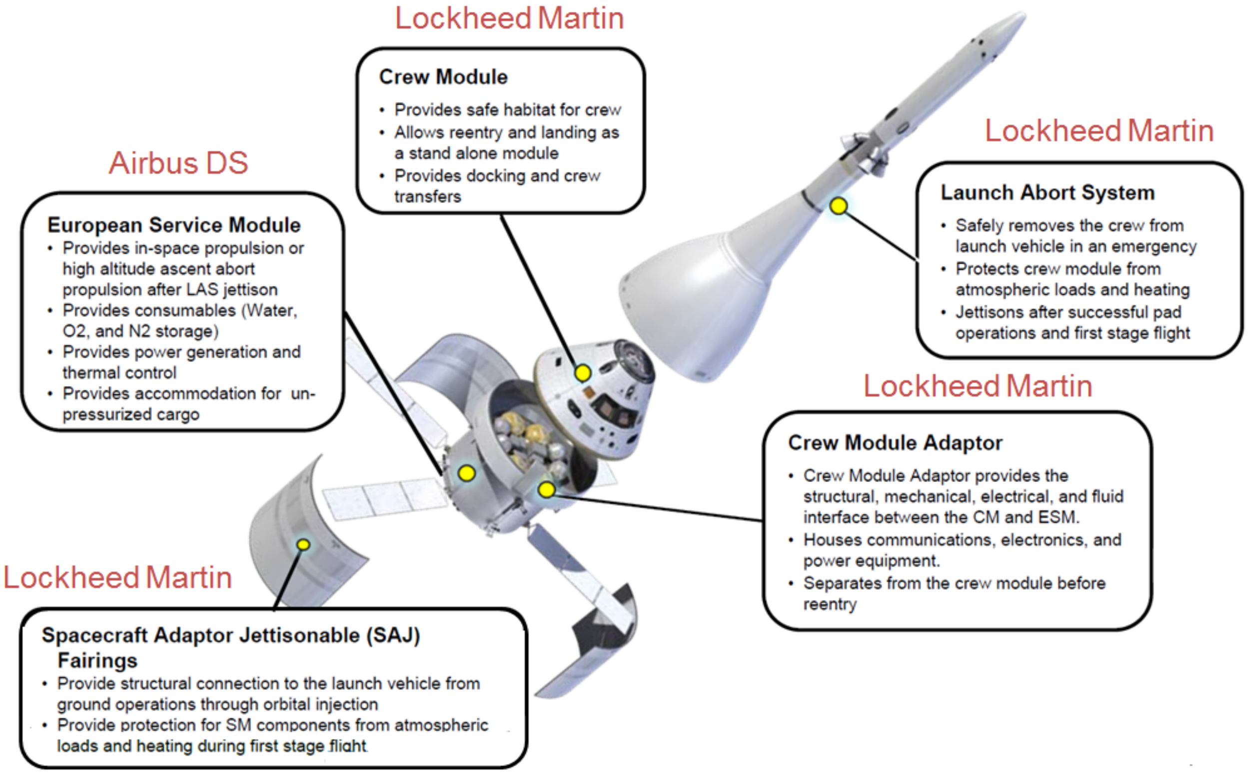


Figure 1.—Space Launch System and Orion MPCV.



Crew Module

- Provides safe habitat for crew
- Allows reentry and landing as a stand alone module
- Provides docking and crew transfers

European Service Module

- Provides in-space propulsion or high altitude ascent abort propulsion after LAS jettison
- Provides consumables (Water, O2, and N2 storage)
- Provides power generation and thermal control
- Provides accommodation for un-pressurized cargo

Launch Abort System

- Safely removes the crew from launch vehicle in an emergency
- Protects crew module from atmospheric loads and heating
- Jettisons after successful pad operations and first stage flight

Crew Module Adaptor

- Crew Module Adaptor provides the structural, mechanical, electrical, and fluid interface between the CM and ESM.
- Houses communications, electronics, and power equipment.
- Separates from the crew module before reentry

Spacecraft Adaptor Jettisonable (SAJ) Fairings

- Provide structural connection to the launch vehicle from ground operations through orbital injection
- Provide protection for SM components from atmospheric loads and heating during first stage flight

Figure 2.—Orion MPCV.

European Service Module (ESM)

As shown in Figure 3, the ESM’s main interfaces to Orion are: (a) the CMA (above), (b) the Spacecraft Adapter (SA) (below), and (c) the SAJ fairings (sides).

The architecture takes into account a double load path in the launcher flight phases: the loads from the launcher are divided and transmitted to the CMA through both the SA/ESM path and through the SAJ fairing path. The flight loads applied on these structures therefore depend on their relative structural stiffness. As the SAJ fairing is jettisoned early during flight but after the main flight load cases, and in order to lighten the ESM as much as possible, the objective is to make the SAJ fairing carry the majority of loads during early flight phases. The stiffness of the ESM structure must therefore be relatively low. On the other hand, after fairing jettisoning, the ESM still has to transmit thrust from the launcher during launcher flight and then during free flight. A minimum stiffness of the ESM is therefore needed.

To ensure its main functions, the ESM consists of different subsystems as shown in Figure 4.

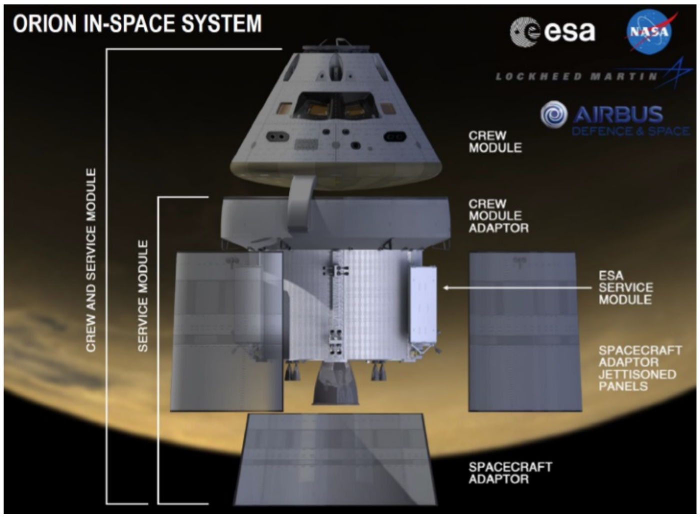


Figure 3.—ESM Main Interfaces.

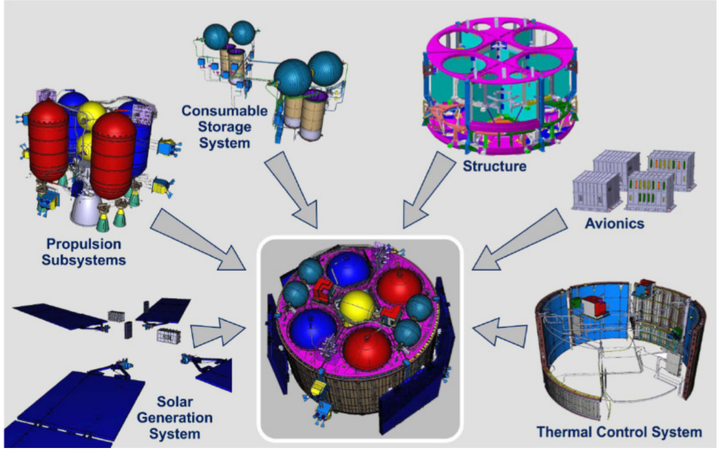


Figure 4.—ESM Subsystems.

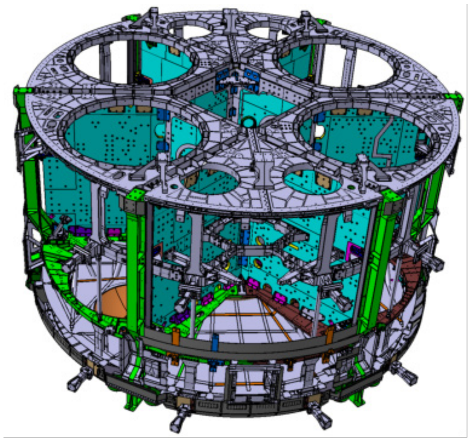


Figure 5.—ESM Primary Structure.

The ESM structure is composed of a primary structure, shown in Figure 5, of six aluminium longerons to transmit loads from the launcher to the CMA, and a central core (tank platform, web assembly, and lower platform) which accommodates all equipment and stiffens the longeron assembly in lateral directions for stability. Secondary structures enables the accommodation and support of the main engine, auxiliary thrusters, tanks, radiators equipment, reaction control system (RCS), solar arrays, and the Micro-Meteoroids and Orbital Debris Protection System (MDPS).

The propulsion subsystem consists of one main engine (30 kN (6744 lbf)) retrieved from the Shuttle program, eight auxiliary thrusters (each 490 N (110 lbf)), and 24 Attitude Control Thrusters (each 220 N (49 lbf)). The consumable storage subsystem entails four gas tanks and four water tanks. The thermal control subsystem is composed of six radiators and its associated control electronics. The electrical power generation subsystem consists of the four Solar Array Wings (SAW), its drive mechanism and electronics.

The total mass of the ESM is about 13.5 metric tons (29,762 lbm), carrying 9 metric tons (19,842 lbm) of propellants, 230 kg (507 lbm) of water, and 120 kg (265 lbm) of O_2 and N_2 gas.

ESM Structural Test Article (E-STA)

E-STA is the term used to designate the mechanical mock-up of the ESM used for mechanical tests, as well as the ESM-level dynamic environments test campaign conducted on this test article.

The E-STA was composed of flight primary and secondary structures, with flight or highly representative equipment items representing various subsystems such as the propulsion, power, avionics, thermal control, and consumable storage. The E-STA had four SAWs, including one flight SAW, denoted as the SAW Qualification Model (SAW QM), and three dummy SAWs.

The main goals of this E-STA test campaign were:

- To validate ESM mechanical models across the full frequency range: Finite Element Model (FEM) through sine tests, Boundary Element Model (BEM) and Statistical Energy Analysis (SEA) models through acoustic tests, and shock transmissibility models through shock tests. These validated ESM models are planned to be used to qualify the ESM with respect to mechanical environments, together with equipment-level qualification tests.
- To reduce risk and gain confidence by a direct demonstration of ESM structural ability to withstand qualification-level dynamic environments and by demonstrating the absence of unexpected behaviours of the structural assembly.

The E-STA was mainly assembled in Turin, Italy just after the end of the static test performed mid-2015 on its structure (denoted as S-STA) by structure manufacturer Thales Alenia Space Italy (TAS-I). It was then shipped to NASA's Glenn Research Center's (GRC) Plum Brook Station (PBS) in Sandusky, Ohio, USA at the end of 2015 to be integrated with adjacent structures representative of the full Orion stack for subsequent dynamic environmental testing.

The E-STA test campaign (Di Vita et al. 2016) performed at NASA's GRC PBS included the following activities:

1. Solar Array Wing deployment test—pre-environmental (baseline) test check-out,
2. Acoustic tests in reverberant acoustic chamber,
3. Random and sine vibration tests on a large shaker system,
4. Separation shock tests—both SAJ fairing separation shock, and SA separation shock,
5. Solar Array Wing deployment test—post-environment tests check-out,
6. Final inspections.

At the end of this test program, the E-STA was made available for the upcoming MPCV-Structural Test Article (M-STA) test campaign.

Reverberant Acoustic Test Facility (RATF)

The acoustic testing for the E-STA System was conducted at the NASA GRC PBS Reverberant Acoustic Test Facility (RATF), located in the Space Power Facility (SPF). The NASA PBS is located in Sandusky, Ohio, USA. An aerial photograph of the SPF (Sorge 2012), which also holds the world's largest thermal/vacuum chamber and one of the world's largest vibration shaker facility, is shown in Figure 6.

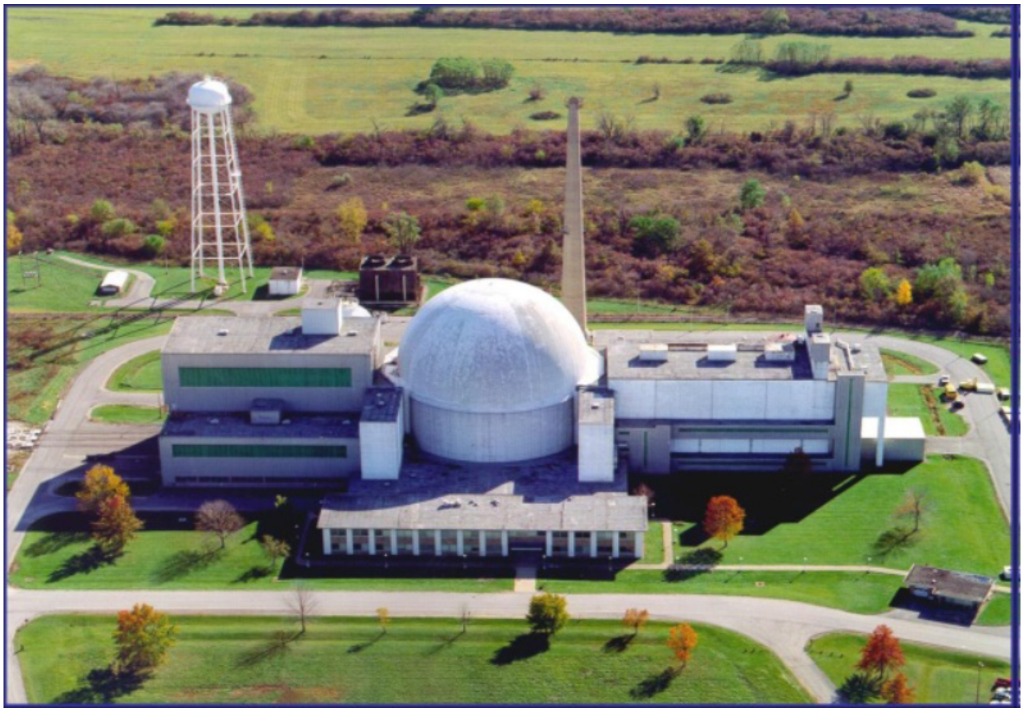


Figure 6.—Aerial Photograph of the Space Power Facility.

The RATF is a 2,860 m^3 (101,189 ft^3) reverberant acoustic chamber (Hughes et al. 2011) capable of achieving an empty-chamber acoustic overall sound pressure level (OASPL) of 163 dB. The RATF includes various supporting sub-systems including gaseous nitrogen generation system, horn room with acoustic modulators and horns, acoustic control system (ACS), and hydraulic supply system. The chamber can be operated as a Class 100,000 clean room once the access doors are closed and the facility is cleaned. The combinations of servo-hydraulic and electro-pneumatic noise modulators utilize gaseous nitrogen (GN_2) capable of producing a tailored wide-range of acoustic spectrums over a frequency range from the 25 to 10,000 Hz one-third octave bands (OTOB). The nitrogen generation system automatically vaporizes liquid nitrogen into GN_2 as required up to 1,981 standard cubic meters per minute (70,000 scfm).

Photographs of the RATF horn wall and the E-STA in the test chamber are shown in Figure 7 and Figure 8, respectively.

A maximum of 19 control microphones (CM) can be placed around the test article for closed-loop control using the ACS. The ACS, control microphones, or other response instrumentation (accelerometers, microphones) may be input into the Analog Abort Computer (AAC) to provide automatic shutdown capability in the time domain. Each of twenty-three (23) servo-hydraulic acoustic modulators is coupled with individual horns of six different cut-off frequencies (from 25 to 160 Hz). Each of thirteen (13) electro-pneumatic acoustic modulators is coupled with individual horns of one cut-off frequency (at 250 Hz). This combination of 36 modulators and 36 horns provides for an extremely variable and tailored acoustic spectrum capability.

Figure 7.—RATF Horn Wall.

Figure 8.—E-STA in RATF Reverberation Chamber.

The RATF chamber's internal dimensions are 11.4 m (37.5 ft) wide by 14.5 m (47.5 ft) deep by 17.4 m (57 ft) high. The East side of the RATF's acoustic chamber has a two-part door system consisting of a large rolling door and a hinged door which provides access to the acoustic chamber up to 10.5 m (34.5 ft) in width and 17.4 m (57 ft) in height. Threaded inserts are located in the RATF floor for attachment of test article mounting fixtures.

Data is acquired at the RATF via the Facility Data Acquisition System (FDAS), a 1,024-channel high-speed digital system. The RATF has been tested up to a maximum OASPL of 163 dB for an empty chamber, and has been utilized for various aerospace industry customers since 2013.

Pre-Test Considerations

Acoustic Test Objectives

The objectives of the E-STA acoustic tests were the following:

- Verify the mechanical resistance of the ESM under acoustic qualification loads. The goal here was to gain confidence by a direct demonstration of the ESM ability to withstand the predicted flight acoustic qualification environment and by checking the absence of unexpected behavior at high levels.
- Validate the dynamic models of the ESM modal behavior of the equipped ESM in the acoustic frequency range by comparing the simulated ESM acoustic response to test results. These models will be used during the verification cycle to confirm the structural margins, and to confirm the mechanical environment specified to the ESM components, ensuring the qualification of the ESM as flight-ready.
- Measure responses at the ESM's equipment mounting points under qualification loads and validate the mechanical environment specifications of the various ESM equipment items in relevant acoustic frequency range. Measure induced stresses on some specific structural equipment items (radiators and SAW), and confirm the acoustic stresses requirements specified to these equipment items.
- Directly qualify the SAW Subsystem to its acoustic environment.
- Prepare for the pre-flight acoustic test planned for the Orion EM-1 spacecraft by performing a high-level acoustic test in an empty propellant tank configuration (dry tank), which is the configuration planned for the future EM-1 ground tests.

The driving acoustic input for both the ESM structural response and for the SAW qualification was the acoustic environment in the internal cavity between ESM lateral sides and the SAJ fairings; this cavity is denoted as the *SM Outer Cavity*. This cavity is revealed in the photograph of Figure 9. Since the SAJ fairings used for the E-STA tests were from an earlier heritage fairing design, (with possible differences in acoustic transmissibility and main modes), one of the main challenges of this test campaign was to tune the external acoustic levels produced by the test chamber to reach targeted levels in this SM Outer Cavity, coping with nonlinearities of the SAJ fairing behavior, while making sure not to damage the SAW.

Acoustic tests are of major importance for spacecraft qualification and acceptance as secondary structures and equipment items are particularly sensitive to mechanical loads in the acoustic frequency range. Additionally, acoustic models are still very complex and difficult to handle. It is thus very important to correlate model simulations with actual test data to fully validate a spacecraft's ability to withstand launch.

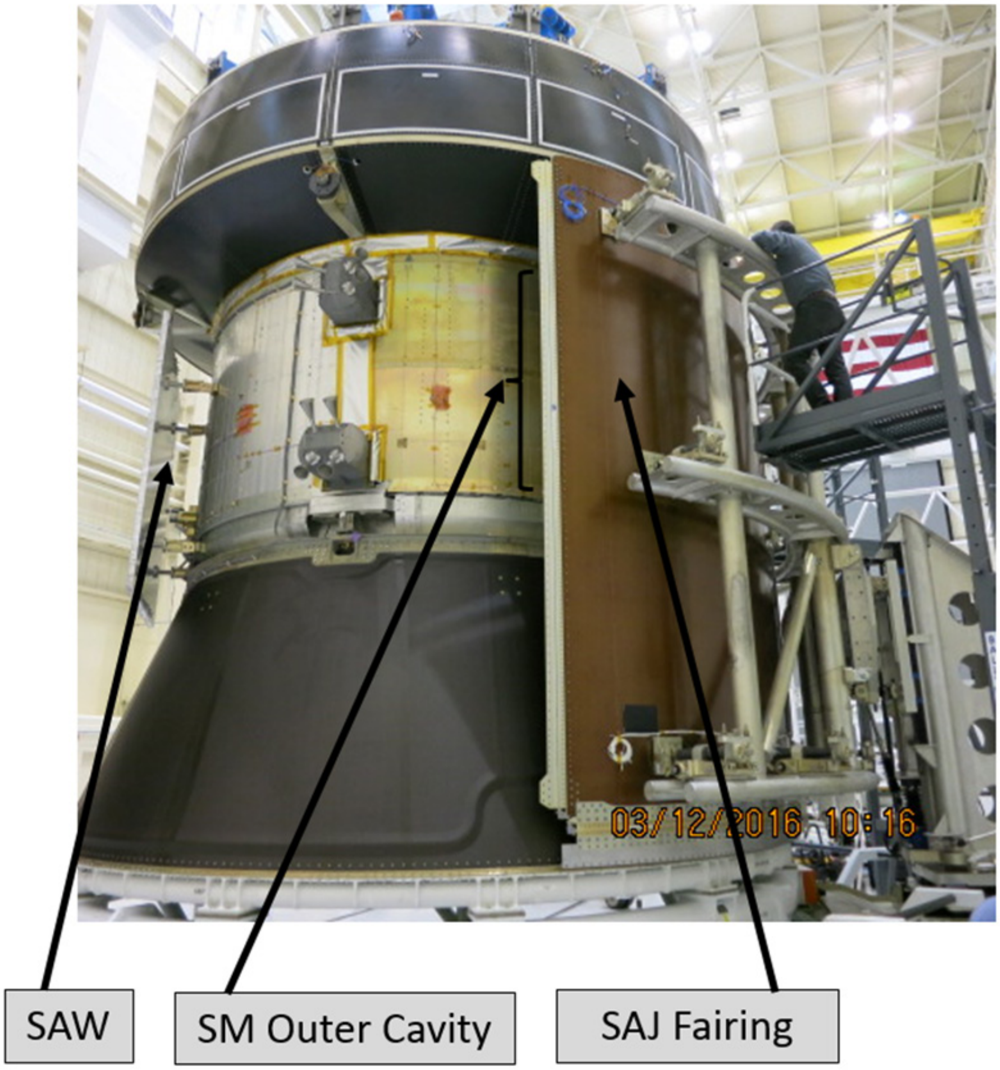


Figure 9.—The SM Outer Cavity is the Internal Acoustic Volume Between the ESM Lateral Sides and the SAJ Fairings. The SAJ Fairings are Partially Installed in this Photo to Reveal this Cavity, Which Contains the SAWs.

Test Article Configuration

The E-STA test article was a partially-representative Orion stack constituted with:

- ESM module Structural Test Article (E-STA), as shown in Figure 10,
- SA—near-flight design test article, representative of the Exploration Flight Test – 1 (EFT-1) heritage design
- CMA—near-flight design test article, representative of the EFT-1 heritage design
- SAJ fairings—near-flight design test article, representative of the EFT-1 heritage design
- Partial CM and LAS mass simulator—the entire mass simulator which was designed to ensure mass and center of gravity location representativeness was not installed for this acoustic test, only for the subsequent vibration tests.

EFT-1 was the first flight test of the un-crewed Orion MPCV launched in December 2014 by a Delta IV Heavy rocket. EFT-1 tested numerous Orion systems such as separation events, control, re-entry, and recovery operations. Some design improvements have been made for the EM-1 flight design since the EFT-1 heritage design.

For the E-STA acoustic test, various nonflight openings in structures surrounding the E-STA module were acoustically closed out by adequate materials (mass-load vinyl panels, metallic close-out panels, etc.) to ensure a good representativeness in terms of acoustic transmissibility.

The E-STA was assembled from:

- A flight structure (primary and secondary structures), based on a preliminary design baselined between ESM Structure Preliminary Design Review (PDR) and Critical Design Review (CDR),
- Some flight or highly-representative equipment items (also based on a preliminary design baselined between ESM Subsystem PDR and CDR):
    - Propulsion Subsystem: Propellant tanks, Orbiting Maneuvering System (OMS-E) Main Engine, some Auxiliary Thrusters, main propellant lines,
    - Power and Avionics systems: one SAW Qualification Model, and one Solar Array Drive Mechanism (SADM) Engineering Model,
    - Thermal Control Subsystem (TCS): one large radiator panel,
    - Consumables Storage Subsystem (CSS): two water tanks,
    - MDPS systems: aluminum aft bumper and some aluminum gap closure, second internal soft-material layer,
- Mass dummies representing the other equipment items.

Two fluidic tank configurations were tested in the frame of these Acoustic Tests: full propellant loads (wet) of 8.9 metric tons (19,624 lb), and an empty propellant tank configuration (dry). Due to safety and cost concerns, the flight propellants (MMH and MON3) were replaced by benign referee fluids (de-ionized water and HFE-7100) for the wet tank configuration. Flight water tanks were full of water for all tests. The propellant tanks and the flight water tanks were pressurized with nitrogen at an intermediate pressure. The other tanks were replaced by mass dummies, representative of their filled configurations.

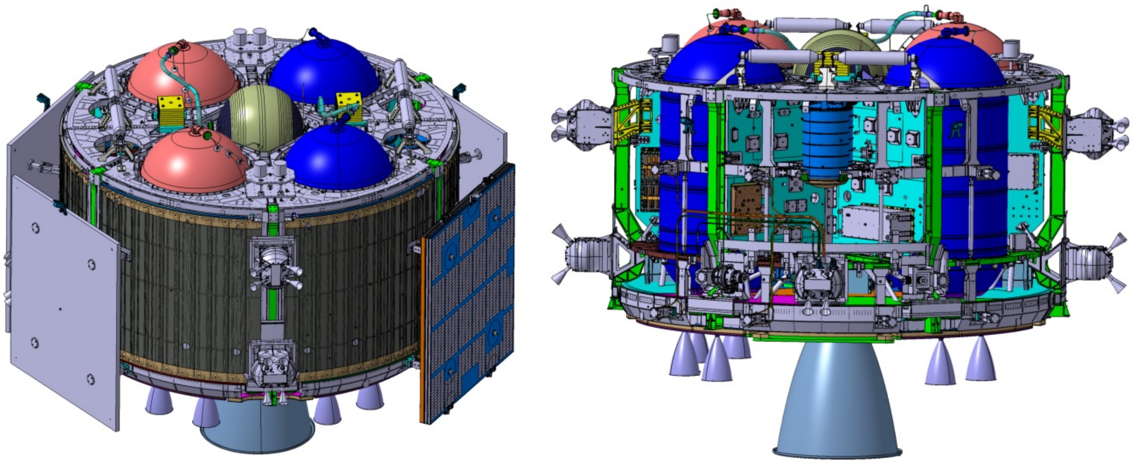


Figure 10.—E-STA General View of E-STA.

The E-STA was installed near the center of the PBS RATF, as shown by Figure 11 and Figure 12. The E-STA was bolted on a test fixture which was made of two parts: the actual test stand to raise the test article high enough in the chamber to avoid floor reflection effects (the Acoustic Test Stand or ATS) and a structure acoustically representative of the SLS launch vehicle's upper stage interface with the Orion spacecraft (the MPCV Stage Adapter (MSA) Simulator, or MSAS).

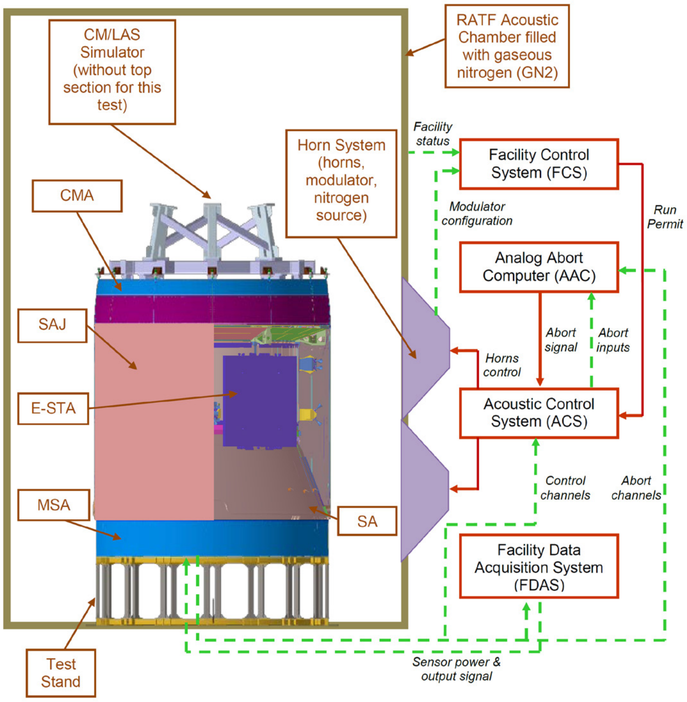


Figure 11.—Acoustic Test Configuration Schematic.

Figure 12.—E-STA Test Configuration Photo (through fish eye camera lens).

Instrumentation

The test article was heavily instrumented, since the sensors planned for the subsequent vibration tests were already installed prior to the acoustic tests.

A total of 746 instrumentation channels were installed on the test article and inside the acoustic chamber, as defined in Table 1.

All ESM equipment items were instrumented with 3-axes (triaxial) accelerometers on structure side next to equipment item base, and for the most representative ones on top of the equipment as well. Structures with larges surfaces were also instrumented with mono-axis (uniaxial) accelerometers.

In terms of microphone measurements:

- Eight (8) control microphones (CM) were located in the chamber around the test article and were used to control the diffuse acoustic field generated by the RATF's horn system. As seen in Figure 13, each of the quadrants of the chamber had two of the eight CM, and the CM were placed in a spiral configuration representing eight different levels along the test article's height. This approach to the control microphone configuration resulted in excellent consistency amongst the individual control microphones. Figure 14 provides a visual example of this consistency, where one can see that the range of the measured sound pressure levels (SPL) of the eight CM (for the full level wet tank acoustic test) is typically only 1 to 2 dB in the 80 to 2,500 Hz OTOBs, with a maximum difference amongst the eight CM of 2.6 dB in the 160 Hz OTOB. At and below the 63 Hz OTOB a somewhat greater variation is observed, although all the levels are still within the allowable E-STA test tolerances.
- Most of the remaining response microphones (RM) were spread in the main cavities surrounding the ESM itself: above the ESM (under the crew module heatshield), under the ESM (inside the SA and the MSAS), and around the ESM (in the SM Outer Cavity). Due to the importance of achieving the critical and targeted acoustic levels in the SM Outer Cavity (especially for the SAW Qualification) a large number (16) of response microphones were located in this SM Outer Cavity.

TABLE 1.—ACOUSTIC TEST INSTRUMENTATION SUMMARY

Number of channels							
Type	Total	ESM	SA	SAJ	CMA	CM/LAS	Facility
Total	746	578	9	59	53	35	12
Microphone	49	6	3	18	5	5	12
Mono-axis accelerometers	132	7	6	41	48	30	0
3-axes accelerometers	516	516	0	0	0	0	0
Strain gauges	49	49	0	0	0	0	0

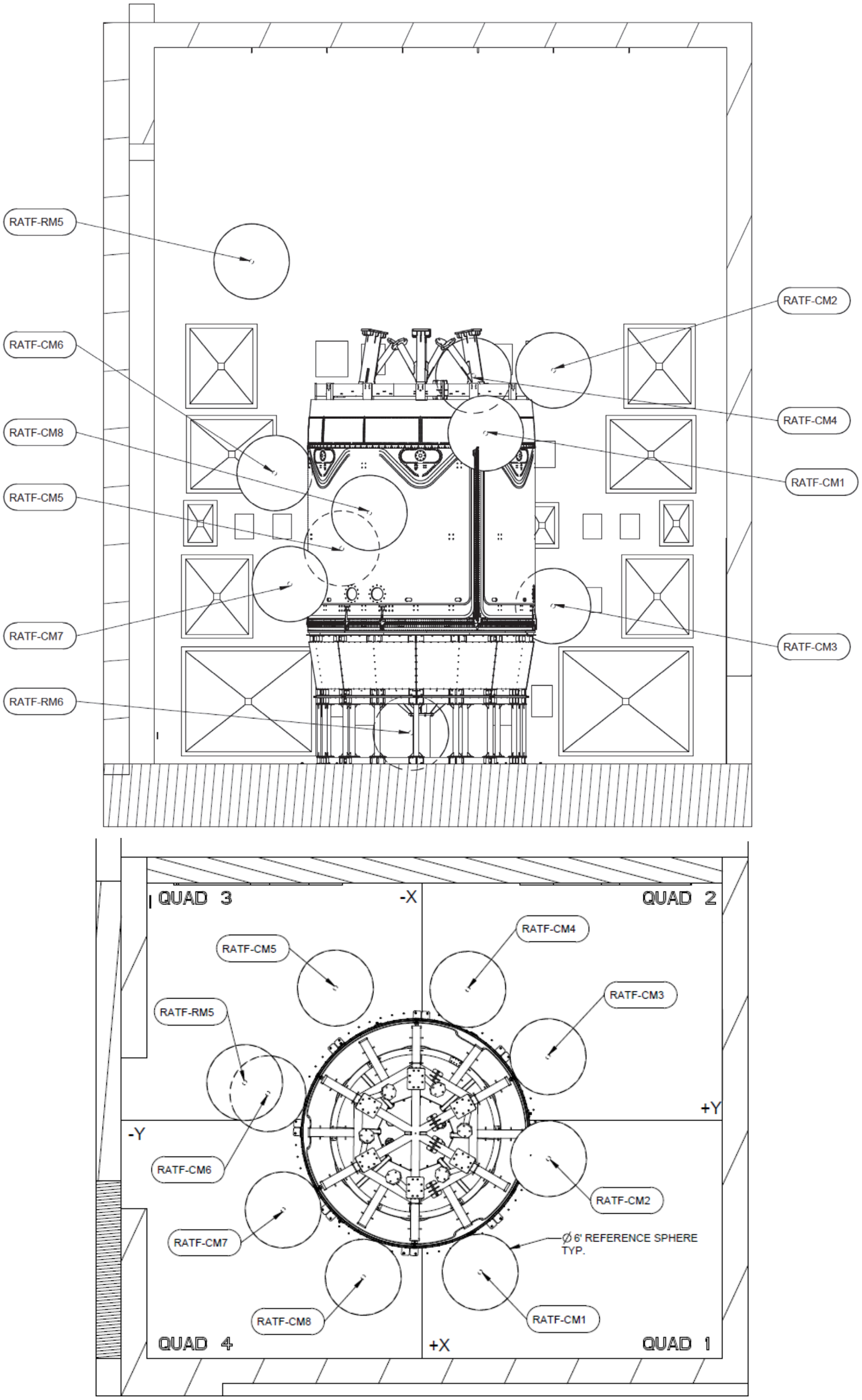


Figure 13.—RATF's Control Microphones (CM).

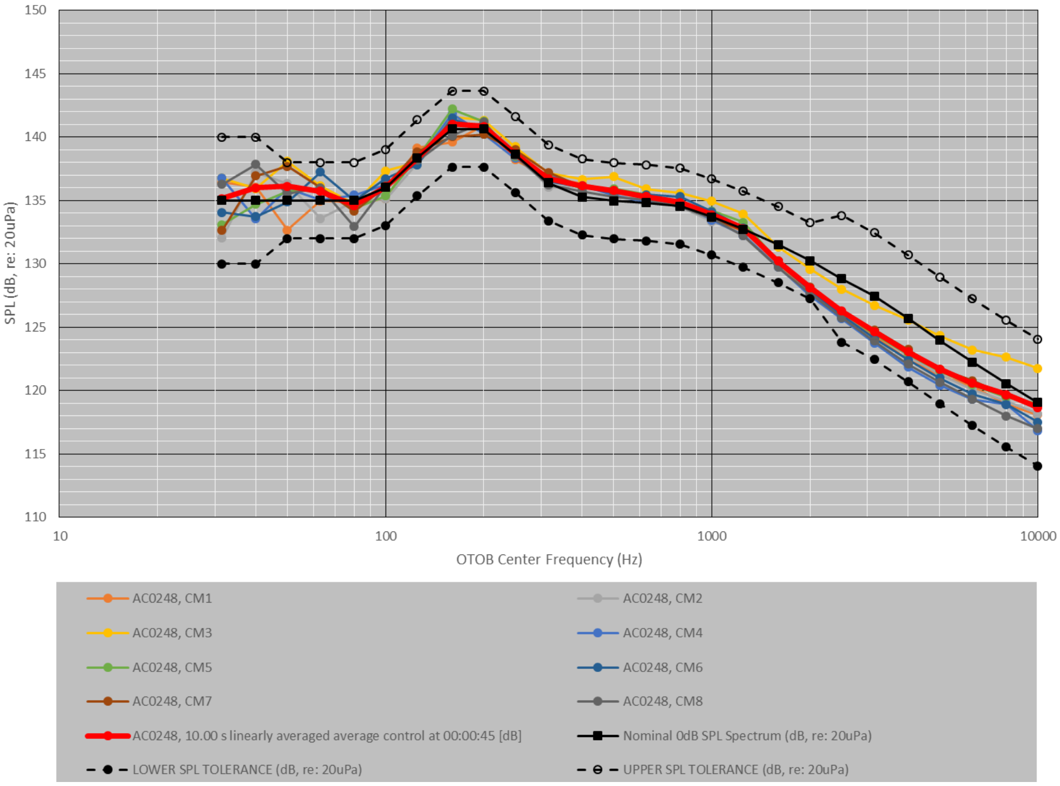


Figure 14.—Control Microphone Performance for AC0248.

Derivation of External Test Excitation Levels

Traditionally, acoustic environments as specified by the launch vehicle providers are treated as diffuse excitations. That is, reverberant acoustic test chambers such as NASA GRC’s RATF can generally replicate the given diffuse acoustic environment in test. However, recent results from subscale acoustic model test firings from the SLS program showed that the acoustic environment surrounding the Orion spacecraft is characterized by a mixture of diffuse and propagating waves. This presented an acoustic test environment formulation challenge. Since propagating waves cannot be directly replicated in a reverberant acoustic chamber a flight response-based approach was developed by NASA to develop the E-STA acoustic test excitation. That is, the test excitation should be chosen to replicate a targeted flight response of a structure or cavity based on analytical model predictions.

The first step in the response-based approach is to select a key response, be it structural or cavity, to be matched between test and flight model. Alternatively, a compromise between multiple responses could be used. The response of the SM Outer Cavity was chosen for the E-STA acoustic test because it is the main driver of ESM environments, and particularly the SAW response.

The response-based approach is contingent on analytical models to accurately predict the targeted response. For the derivation of the E-STA acoustic test excitation, the latest available ESM flight models were used to predict its flight response, whereas E-STA test models were used to predict the expected test response. In both the ESM and E-STA configurations, both BEM (from 30 to 315 Hz) and SEA models (from 80 to 2,000 Hz) were utilized.

The ESM flight models were excited by the flight acoustic environments specified by the SLS Program which are the mixtures of diffuse and propagating waves. Five different flight events were analyzed: liftoff, transonic, maximum dynamic pressure (max Q), liquid engine start, and hold down. Alternatively, the E-STA test models are to be excited by one pure diffuse acoustic field (DAF). The pure DAF is yet to be specified at this point because this is the spectrum to be determined via the response-based method.

There are three key assumptions made in deriving the environment. First, we assume that the ESM flight and the E-STA test models are each representative of their respective design configurations. Second, we assume that the ESM flight and the E-STA test models are similar in configuration and in their expected response to acoustic excitation. Third, we assume E-STA responses are linear within the SPL range analyzed.

With these assumptions, a scale-up approach becomes viable. The test model DAF is set at an arbitrary value. For simplicity, the DAF was set at a flat 100 dB spectrum. This generates a particular response in the SM Outer Cavity. Now we consider the flight models. There is a different SM Outer Cavity response for each of the five load cases applied. An envelope is taken to reduce all five cases to one response. At this point, there is one test response and one flight response at the SM Outer Cavity (the targeted response). At each OTOB, the difference between the two SPLs is added to the original arbitrary test DAF (100 dB at every OTOB in this analysis). In theory, due to linearity, applying this newly defined “Equivalent DAF” spectrum should now generate nearly exactly the same response in the SM Outer Cavity in the E-STA models (and in the actual test) as in the flight models with its mixture of diffuse and propagating wave excitations.

Ideally, the test article would be excited in test by the Equivalent DAF exactly as-is at this point in the analysis. However, each reverberant chamber has limitations as to what particular spectrum shapes it can generate, and the response-based method typically creates a very jagged curve that is difficult to generate in the actual test chamber. After consulting with the NASA RATF facility engineer and ESA and ADS, the equivalent DAF was smoothed such that it had only two distinct and well-separated peaks. Additionally, the first peak was lowered in magnitude because the facility is limited as to how much sound power it can generate at such low frequencies, such as in the 31.5 Hz OTOB. This process does remove some of the flight-like traits of the environment and introduces a small amount of over-and under-testing in some OTOBs, but the new, smoothed Equivalent DAF remains a valid qualification environment. Figure 15 shows the smoothed Equivalent DAF as compared to the equivalent DAF generated by the ESM flight models.

Finally, the analysis used surface pressures to define environments. RATF requires a free-field spectrum. This conversion from surface pressures to free-field pressures was performed using known procedures. Figure 16 shows the response-based starting external excitation test spectrum (free-field), with an OASPL of 148.1 dB.

It is expected that the production of the free field external acoustic environment during actual testing will result in the SM Outer Cavity reaching flight-like acoustic levels during the test. The use of the response based test spectrum developed by this method accounts for the flight environment that is comprised of a field that is partially diffuse and directional. The methodology, highly dependent upon confidence in the models, results in duplicating flight predicted responses, in this case achieving the targeted flight SM Outer Cavity acoustic levels.

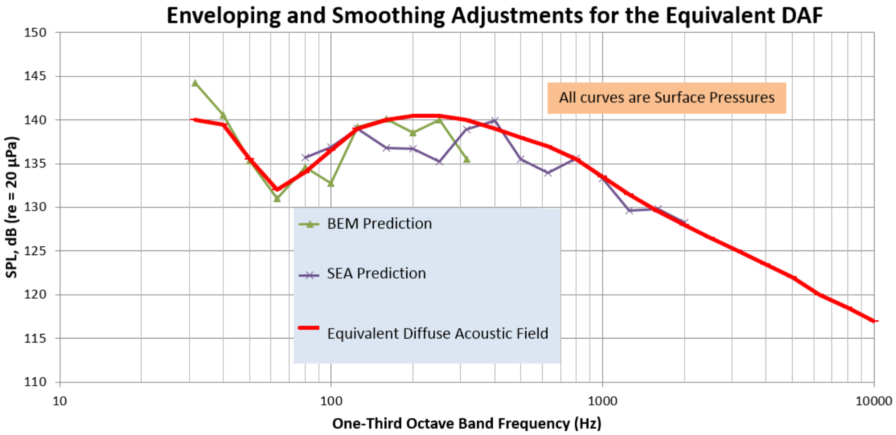


Figure 15.—E-STA Qualification External Diffuse Acoustic Field (surface pressures).

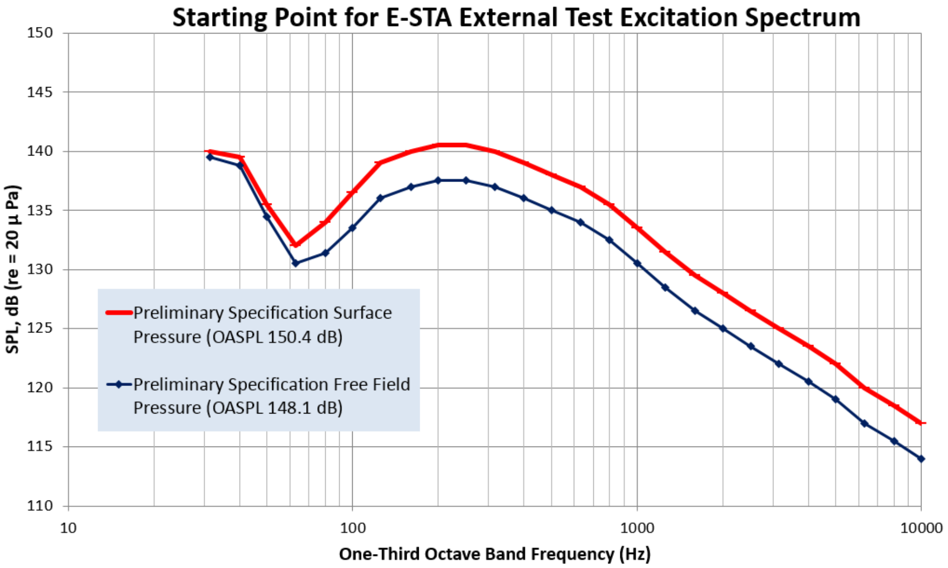


Figure 16.—Response-based Starting External Excitation (free-field).

E-STA Acoustic Testing

Test Matrix

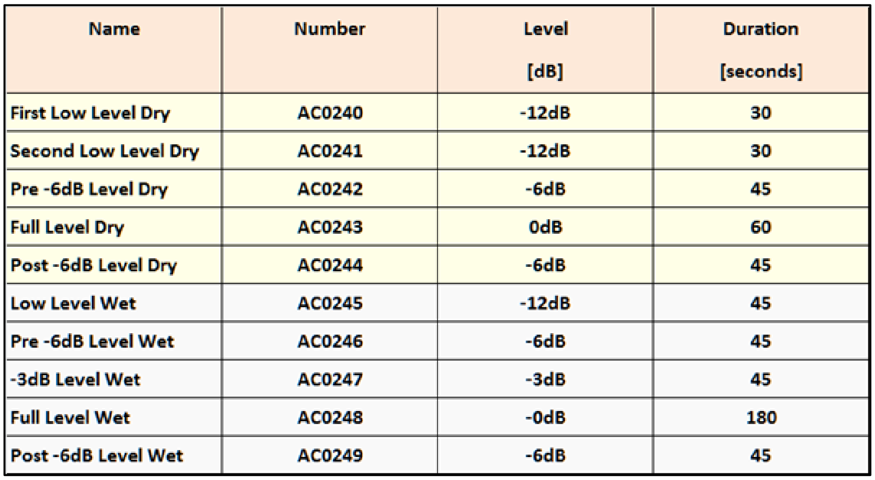
A general overview of all the runs performed is mentioned in Table 2. The external noise spectrum within the RATF was adjusted prior to each test in order to match the targeted noise level in the SM Outer Cavity which is the driving excitation source for the ESM components.

A total of 10 acoustic tests were performed. The first five E-STA tests were performed with dry (empty) propellant tanks. These dry tests were performed because it is expected that future acoustic testing of the actual flight ESM hardware will be with dry propellant tanks for both safety and schedule reasons. The last five E-STA tests were performed with wet (full) propellant tanks, as that tank condition represents the actual flight lift-off loading condition requiring qualification verification.

For both the dry and wet tank configurations, lower level tests were first performed in order to learn how the test article was responding to the acoustic excitation therein preventing any possible unforeseen structural response that could result in damage to the test article. Understanding the noise reduction of the SAJ Fairings (the reduction of SPLs from the external chamber excitation level to the internal SM Outer Cavity level) was of key importance, and allowed slight modifications of the external excitation levels to be made prior to each successive test. This logic provided confidence in proceeding to the next higher test level before ultimately reaching the full 0 dB test level which was considered the qualification level. The two full level 0 dB qualification tests were AC0243 (dry) and AC0248 (wet), and reached OASPL’s of 147.9 and 149.4 dB, respectively.

For both the dry and wet tank configurations, a second –6 dB level test was performed following the full level 0 dB test. The purpose of the second –6 dB level test was to provide a comparison to the first –6 dB level test that was performed prior to the full level 0 dB test. The comparison of the two –6 dB level tests allows an assessment of the health of the hardware following each of the full level 0 dB qualification level tests.

TABLE 2.—OVERVIEW OF THE ACOUSTIC TEST RUNS; LEVEL REPRESENTS Δ dB RELATIVE TO THE FULL LEVEL



Name	Number	Level [dB]	Duration [seconds]
First Low Level Dry	AC0240	-12dB	30
Second Low Level Dry	AC0241	-12dB	30
Pre -6dB Level Dry	AC0242	-6dB	45
Full Level Dry	AC0243	0dB	60
Post -6dB Level Dry	AC0244	-6dB	45
Low Level Wet	AC0245	-12dB	45
Pre -6dB Level Wet	AC0246	-6dB	45
-3dB Level Wet	AC0247	-3dB	45
Full Level Wet	AC0248	-0dB	180
Post -6dB Level Wet	AC0249	-6dB	45

Modification of the External Test Levels

As stated in the previous section, the experimental tuning of the external spectrum to meet the target inside the SM Outer Cavity was difficult particularly because of a low frequency nonlinearity in the noise reduction of the SAJ Fairing. Tuning the external field during low levels runs was difficult because of this nonlinearity and because of the high background noise inherent to the test facility.

This issue was monitored closely since the frequency range in which the nonlinearity occurred was consistent with the SAW modes which induced the highest fatigue to the SAW.

For the dry tank configuration, two –12 dB level tests were performed. The second –12 dB test, AC0241, was needed due to the fact that during AC0240:

- The external SPLs were lower than targeted above 250 Hz OTOB, probably due to higher than expected test-article absorption,
- The observed SAJ Fairing noise reduction was not completely in line with predictions (in low frequency, especially around 63 Hz OTOB),
- The targeted SM Outer Cavity levels in very low frequency (31.5 and 40 Hz OTOBs) were not reachable while keeping the more important frequencies of 63 and 80 Hz OTOBs at their desired levels,
- High background noise, close to lower level target levels perturb the ACS's ability to reach target level.

Therefore, for this AC0241 run, additional electro-pneumatic noise modulators were utilized in order to boost the high frequency power, and modification of the target spectrum to improve the controllability at and above 50 Hz OTOBs were both implemented. The use of these high frequency noise modulators and tweaking the target spectrum based on previous test measurements continued throughout the E-STA acoustic test series.

Regarding the AC0247 run at –3 dB in the wet tank configuration, it was performed mainly as a risk mitigation in order to confirm the noise reduction of the SAJ, and finalize the external input spectrum in order to ensure the correct SM Outer Cavity acoustic level during the qualification run.

In general, main difficulties encountered during the low level acoustic test runs were:

- RATF background noise perturbing ACS (at –12 and –6 dB lower test levels),
- Nonlinearity of the noise reduction of the SAJ Fairing (better understood during the wet tank configuration testing),
- Deviation in acoustic levels at low frequencies (< 40 Hz OTOB).

As a result, the external levels were slightly increased between the dry and wet tank configurations in order to better target the noise levels inside the SAJ Fairing cavity. The evolution of the measured noise inside the SM Outer Cavity for both the dry and wet tank configurations are plotted Figure 17 and Figure 18, respectively.

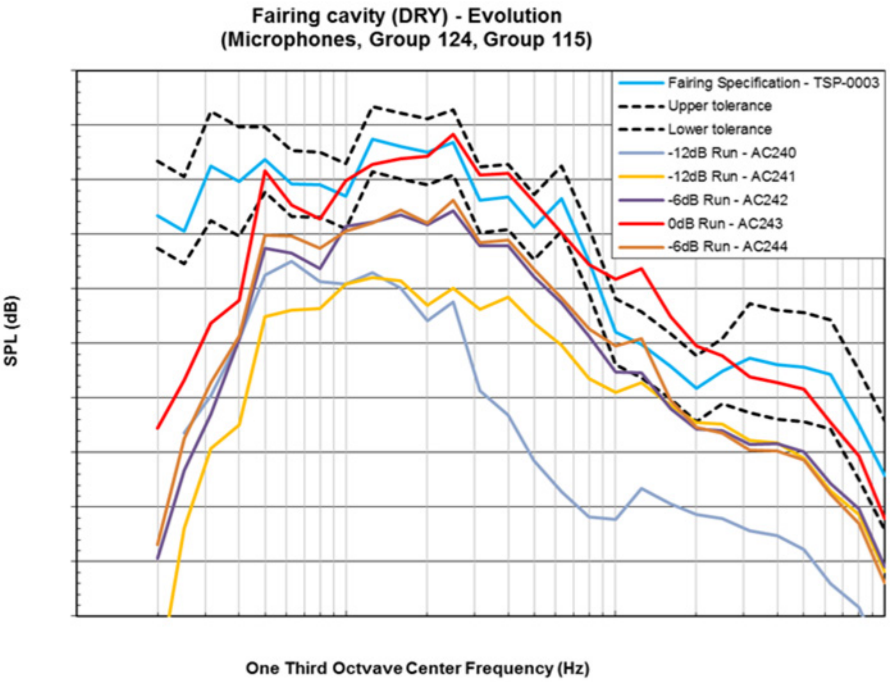


Figure 17.—Evolution of the Acoustic Test Levels Within the SM Outer Cavity for Dry Tank Configuration.

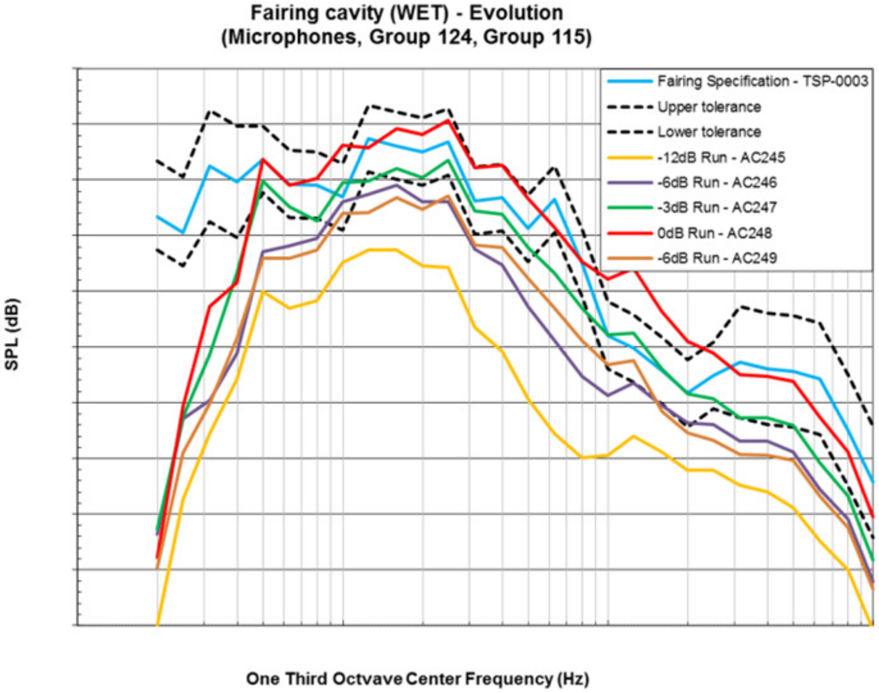


Figure 18.—Evolution of the Acoustic Test Levels Within the SM Outer Cavity for Wet Tank Configuration.

Spatial Consistency of SM Outer Cavity Levels

As stated previously, achieving the targeted SPL in the SM Outer Cavity was critical in achieving the test objectives of exciting the E-STA components correctly, especially for the flight-like SAW QM. To properly measure this critical environment, four microphones (known as Group 124) were positioned near the SAW QM panels, and twelve microphones (known as Group 115) were positioned near the other three dummy SAW panels.

The spatial consistency of these SM Outer Cavity microphones was found to be extremely good for all tests. Figure 19 compares the average of all valid (13 of the 16) SM Outer Cavity microphones (4 from Group 124, and 9 of the 12 from Group 115) inside the fairing (the purple ESM objective curve) with the average of the four microphones (Group 124) located in front of the SAW QM (the red SAW objective curve) for the full level 0 dB Qualification test with the wet tank configuration (AC0248). As shown by this figure, the acoustic field is very homogeneous within the SM Outer Cavity. It was concluded that there is no significant difference in the SM Outer Cavity acoustic environment around the circumference of the E-STA, and that the flight-like SAW QM was exposed to the same acoustic levels as were the three dummy SAWs.

Figure 20 shows the dispersion of the four microphones (Group 124) located in front the SAW QM for test AC0248. One can see clearly on the plot that the spatial dispersion is very acceptable.

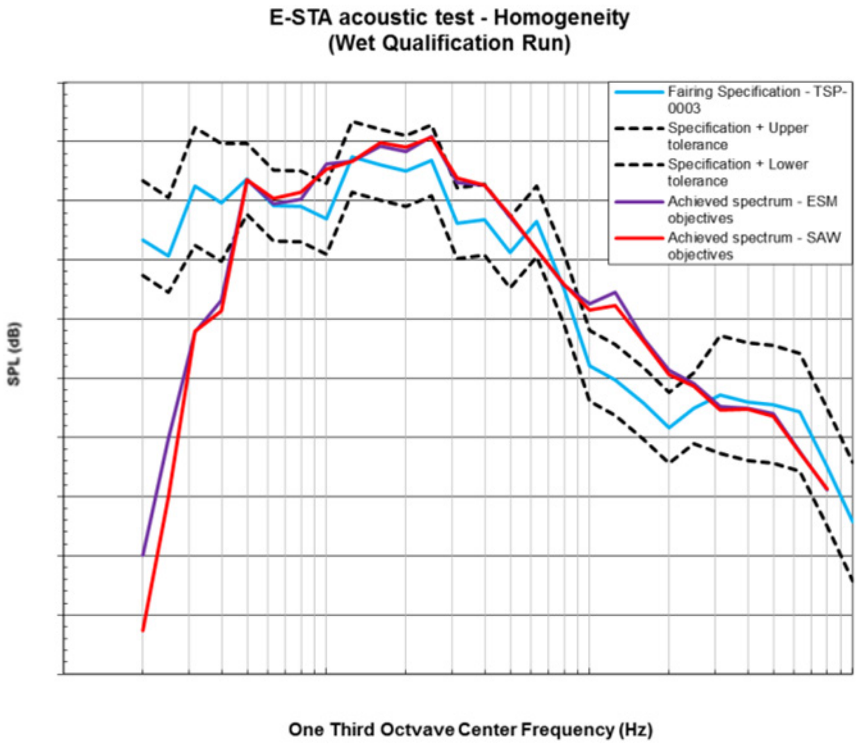


Figure 19.—Homogeneity of the Acoustic Field Within the SM Outer Cavity for AC0248.

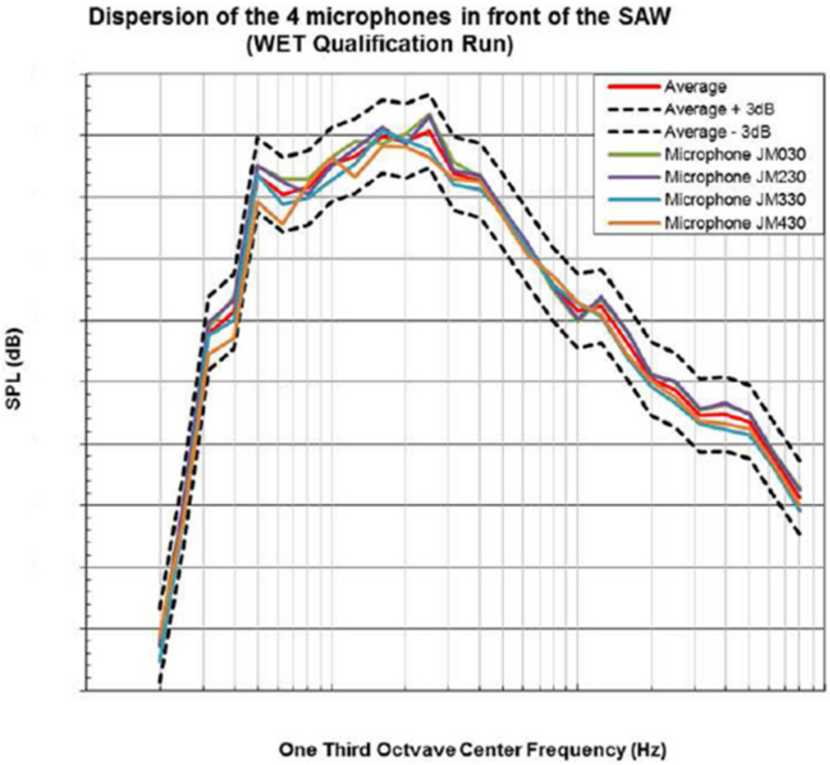


Figure 20.—Homogeneity of the Acoustic Level Measured at the SAW QM (Group 124) for AC0248.

Solar Array Wing (SAW) Qualification

As previously stated, one of the main objectives of this test campaign was the qualification of the SAW subsystem by this acoustic test. Indeed, instead of qualifying the SAW on subsystem level, it has been decided for planning purpose to qualify it on the ESM assembly level. To achieve this task, different scenarios of combined acoustic levels and test durations applicable to the SAW have been established through numerical predictions and analyzed by the SAW subcontractor from the fatigue damage perspective.

The key to successfully qualifying the SAW in this E-STA acoustic testing was to tune the external acoustic field in order to get the right SM Outer Cavity acoustic levels in the important SAW frequency bands (50 to 160 Hz) within allowable test tolerances. As explained in the previous section, lower level test were necessary to accurately tune the external levels to meet the required levels in front of the SAW. The achieved equivalent spectrum in terms of fatigue compared to the targeted one and associated test tolerances are presented in Figure 21.

The following issues were encountered:

- In the low frequency part of the spectrum (< 40 Hz OTOB), due to the room modes of the RATF, the achieved levels were far from the target. This point was acceptable, since the main relevant resonances of the ESM from an acoustic point of view are at higher frequencies.
- Around 63 Hz OTOB, the noise reduction of the SAJ Fairing presented a moderate nonlinearity that tended to increase the noise reduction with the increase of acoustic loading.

Moreover, external test levels were increased between the dry and wet tank configurations tests in order to better target the required spectrum inside the SM Outer Cavity.

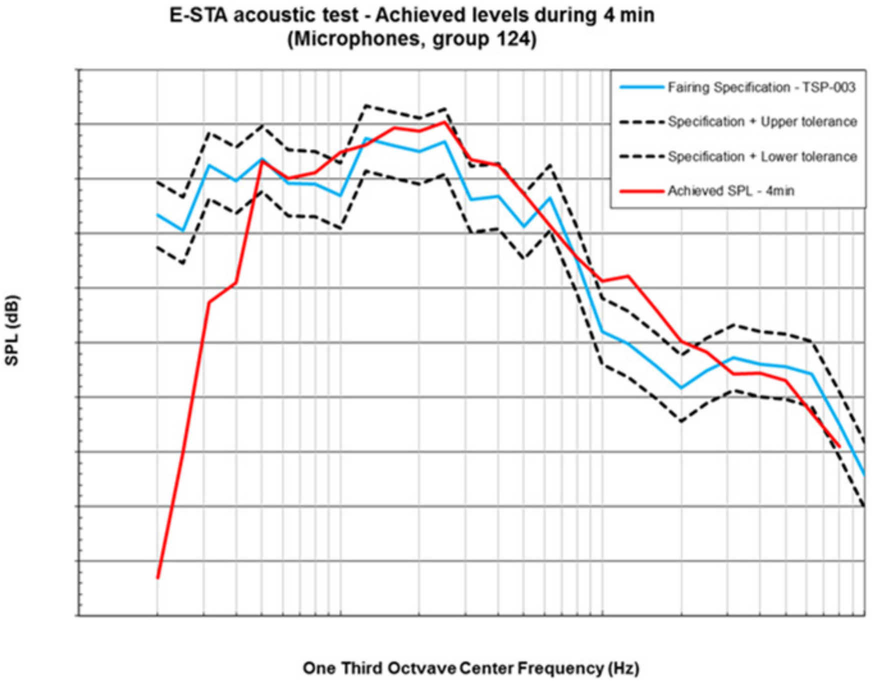


Figure 21.—Achieved Equivalent Acoustic Level at the SAW QM (Group 124).

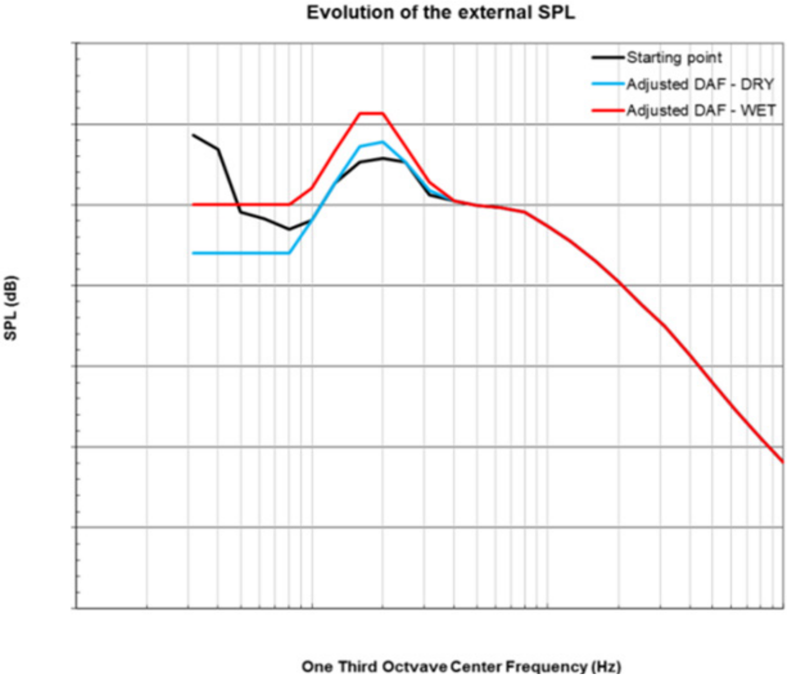


Figure 22.—Evolution of the External Excitation Noise.

As an indication, the final external noise spectrum for qualification runs AC0243 (dry) and AC0248 (wet) as well as the starting point based on E-STA predictions are given in Figure 22.

Since the key frequency range was 50 to 160 Hz for SAW qualification purpose, the main external excitation modifications were concentrated in that range. The OTOB at 50 Hz was the most complicated one to handle since one of the main modes of the solar arrays which generates the fatigue is around 60 Hz.

The average of the four microphones (Group 124) located in front the SAW QM has been used to verify that achieved acoustic levels were in accordance with the required ones. The following relation using the two full level 0 dB tests (AC0243 and AC0248) has been used to compute an achieved equivalent SPL from a fatigue point of view:

$$SPL_{eq}(f) = 10\ \log_{10}\left(\left(\frac{t_{DRY}}{t_{TOT}}10^{(6*SPL_{DRY}(f)/10)} + \frac{t_{WET}}{t_{TOT}}10^{\,(6*SPL_{WET}(f)/10)}\right)^{1/6}\right)$$

Where:

- $SPL_{eq}(f)$ is the equivalent SPL from a fatigue point of view
- t_{DRY}, t_{WET} and t_{TOT} represent respectively the dry tank test, the wet tank test and the total test run durations
- $SPL_{DRY}(f)$ and $SPL_{WET}(f)$ represent the achieved levels during the dry and wet tank tests

The achieved OASPL was slightly above the target (+0.7 dB), while the OTOB levels stayed above or within the allowable test tolerances.

Therefore, the test objective to qualify the SAW QM to its acoustic environment in this E-STA test was met. The desired acoustic levels and test durations met (or exceeded) the targeted goals.

Solar Array Wing (SAW) Fatigue Life Assessment

Regarding the structural response of the SAW, accelerometers in the out-of-plane direction located on the SAW QM have been analyzed. Those random responses are given in Figure 23 as an indication of the levels reached on the SAW QM and to check the model representativeness.

The model predictions are conservative above 50 Hz up to 400 Hz on the SAW panel response. The energy coming from the acoustic loading on the SAW is transmitted to the ESM through structure borne vibration. This path is therefore conservative above 50 Hz where main modes of the SAW inducing fatigue are present. For fatigue aspect, the modes responsible for the largest damage are located below 100 Hz.

The post-processing of the strain gauges test measurements after the qualification test revealed high margins regarding the allowable micro-strains due to inherent conservatism of the predictions/ specifications process. Therefore, there were no issues about stresses due to acoustic loading on the SAW QM assembly. The total expected accumulated damage for the SAW has been conservatively assessed at 8.4 percent of its fatigue life (from both the E-STA acoustic and E-STA sine vibration testing).

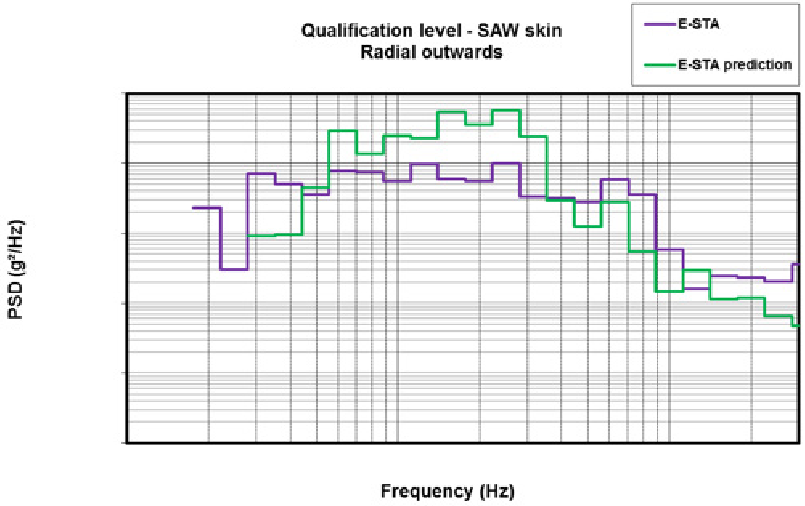


Figure 23.—Envelope of Structural Response on SAW Panel 3 (normal direction).

Post-Test Assessments

Recall that three of the E-STA acoustic test objectives were to: (a) verify the mechanical resistance of the ESM under acoustic qualification loads, (b) validate dynamic models of the ESM, and (c) measure structural responses at the ESM's equipment under qualification load in order to validate their component levels random vibration test specifications. The E-STA test data is also used to authorize potential notching to the component random vibration test input level.

In order to achieve these objectives and insure the protection of the ESM going forward, the ESM health has been verified and assessed by the following criteria:

- Comparisons of pre and post –6 dB of the second qualification runs (AC0248) are compared to check if significant discrepancies are observed in the mechanical behaviour.
- Comparison of acceleration Power Spectral Density (PSD) on key components (mainly all the flight-like ones, since dummies are robust with regards to random environments) with their random specification. These components have been identified in order to get a global mapping of the ESM random responses, as well as on the most sensitive ESM components.
- Comparison of loads measured on the qualification runs (AC0243 and AC0248) with allowables using criteria on Quasi Static Loads (QSL) to assess the health of the dummy equipment. The QSL were assessed by computing the Grms value up to 200 Hz. The measured Grms acceleration is only an estimation of the QSL since sensors are not located exactly at the center of gravity of the equipment.

Pre and Post –6 dB Test Comparisons

Figure 24 provides several examples of a comparison between the two –6 dB runs for accelerometer sensors located on the Hold Down Release Mechanism (HDRM) of the SAW, on the middle of the MON Propellant Tank Downstream, on the SAW Panel 2, and on the dummy SADM.

Any discrepancies have been explained by external SPL differences between both –6 dB tests. Therefore, no abnormal behaviour has been identified.

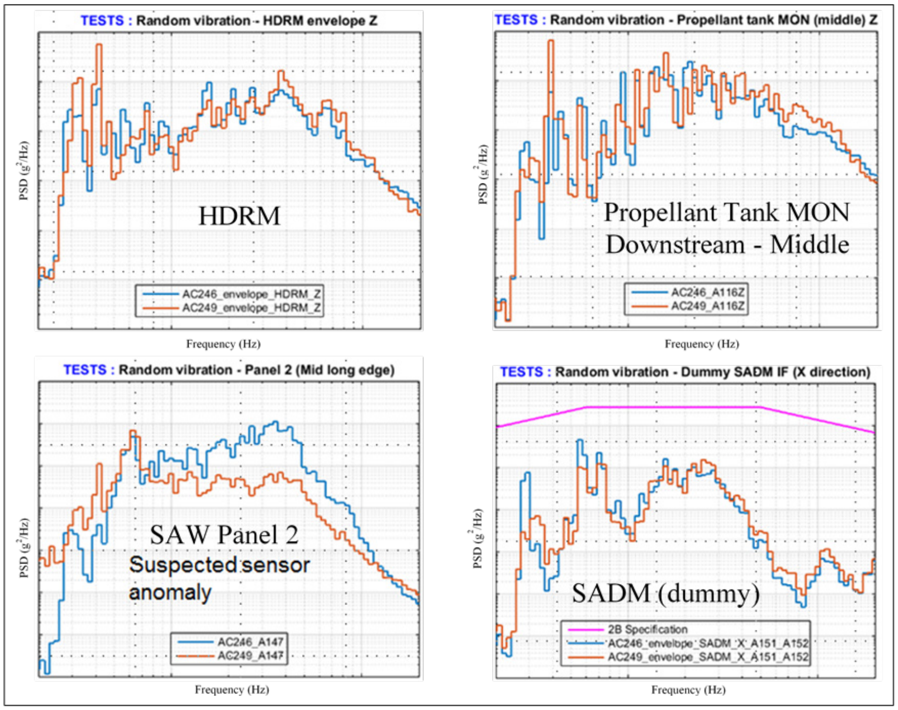


Figure 24.—Comparison of the two –6 dB Test Runs Before and After AC0248 for four Components.

Regarding the sensor on the SAW Panel 2, the accelerometer A247 provided suspicious data during the acoustic test AC0248 (0 dB wet tank) and the subsequent –6 dB check-out test. Endoscope and visual inspections have been performed and confirmed that the sensor was detached.

Global health status of the E-STA has been confirmed after the E-STA acoustic test campaign, and as well as the global E-STA test campaign by the final inspection.

Structural Response Comparisons

The loads due to the vibroacoustic environment are a result of responses induced from direct acoustic impingement on the hardware and/or mechanically transmitted random vibration into the hardware.

To verify the environment, the logic is based on tests supported by analyses. For this E-STA test acoustic campaign, NASA GRC was responsible for the predictions. A combination of BEM (31.5 to 315 Hz) and SEA (80 to 8,000 Hz) was utilized in making the structural response predictions. Several areas in the ESM were not modelled in SEA due to unclear supporting subsystems.

Three examples of comparison of test data, predictions, and component test specification follows.

Pressurant Control Assembly (PCA)—on Tank Platform

The Pressurant Control Assembly’s (PCA) major task is to control the flow of high pressure Helium gas into a downstream volume. Within the larger propellant tank volume, the fluid expands and increases the tank pressure.

On E-STA, the PCA was a mechanical dummy with the correct mass and inertia as shown at top of Figure 25. Two PCA were accommodated on the tank platform along the Z axis. They are represented in the model by a lump mass rigidly connected to the platform.

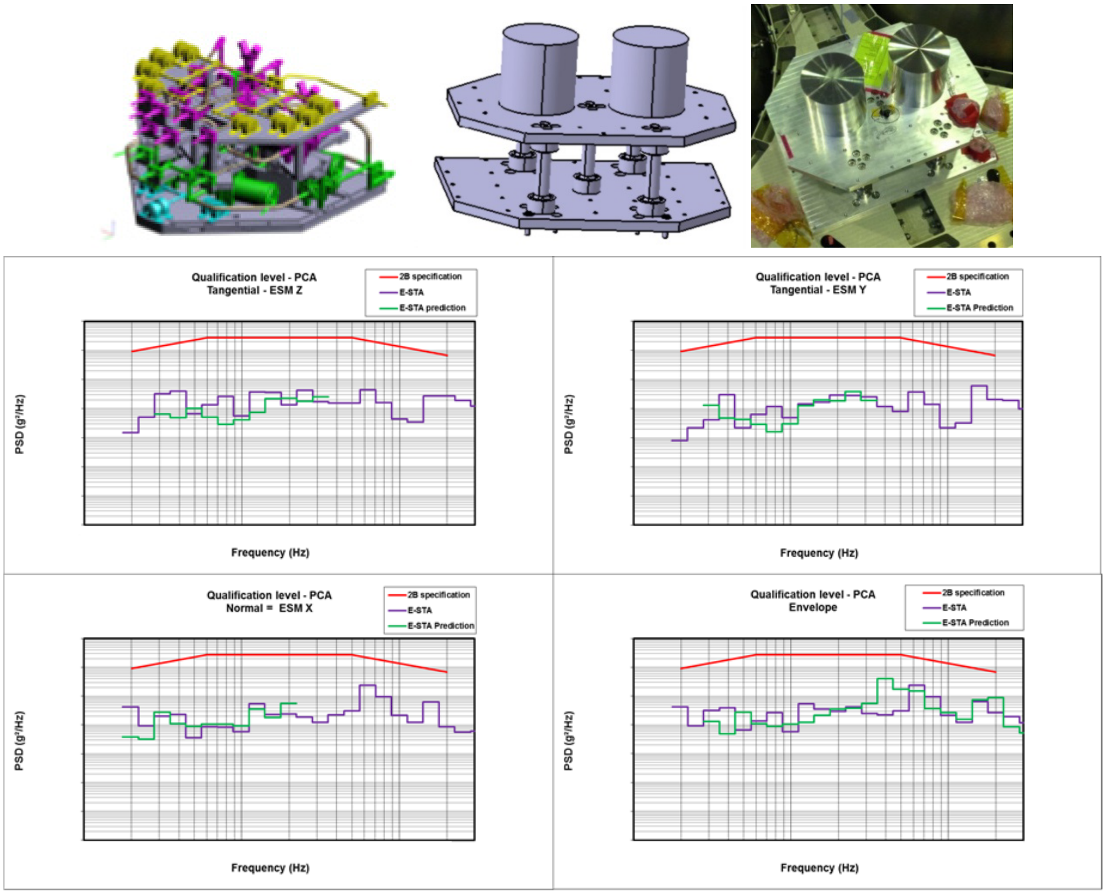


Figure 25.—Comparison Between Predictions and Measurement Near PCA Mounting Points.

The random response at PCA interface located on tank platform (primary structure) is globally well represented by its modelling prediction, and remains under its test specification as shown in Figure 25. The random response is higher in the normal (x) direction due to the bending of the tank bulkhead. Considering the margin, reduction of the random vibration test specification is possible to avoid overtesting of the equipment at the component level.

Solar Array Drive Electronic (SADE)—Shear Web

The Solar Array Drive Assembly (SADA) is composed of the SADM and the Solar Array Drive Electronic (SADE). The SADE is an electronic box that drives two SADMs. The SADM is a device that would drive the solar array wings along two axes.

For the E-STA testing, two SADE were accommodated on the shear webs. They are represented in the model by a lump mass rigidly connected to the shear webs, as seen in the top of Figure 26.

The random response at SADE interface located on shear webs is globally well represented by the model's predictions, as shown in Figure 26. Local modes in high frequencies are not modelled with the SEA. This envelope is given by the normal direction. The SADE's random vibration test specification is verified by this acoustic qualification testing.

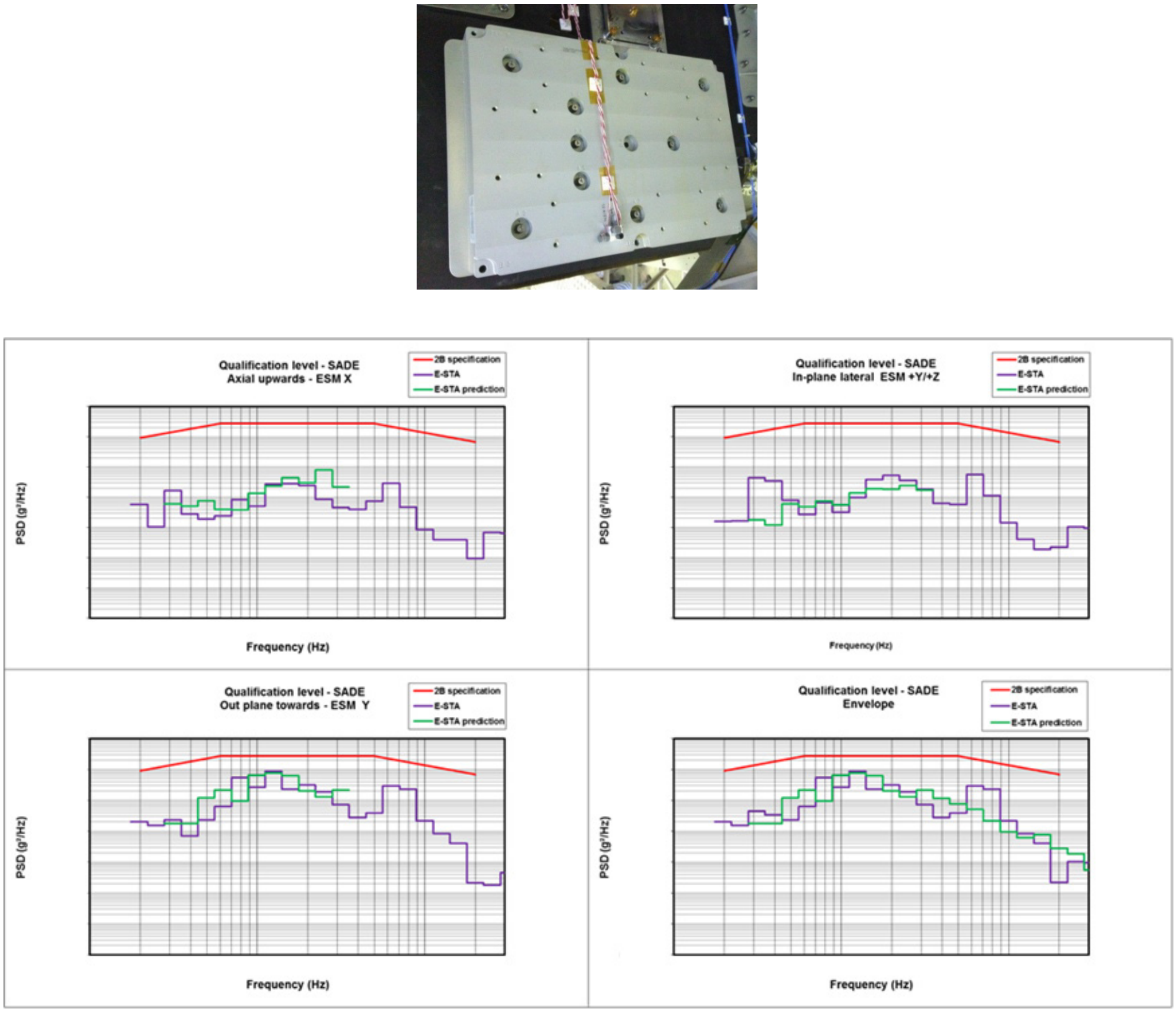


Figure 26.—Comparison Between Predictions and Measurement Near SADE Mounting Points.

Orbital Maneuvering System Engine (OMS-E)

The propulsion of the ESM is driven by three systems. The OMS-E (derived from the Shuttle program) as shown at the top of Figure 27, eight auxiliary thrusters, and 24 small RCS engines.

Responses between 50 to 80 Hz are overestimated by the modelling predictions, as seen in Figure 27. However, the random response of the OMS-E support is globally very well represented by the model and remains under its component test specification. The acoustic test thus enables verification of this random vibration qualification test specification.

Generally speaking it was found that the dynamic representativeness of the ESM model for acoustic/random needs, both the FEM and SEA models presented a good global correlation with regards to acoustic test measurements. Main discrepancies have been noted on the propellant tanks mainly due to the modelling of the fluid, and on the Propulsion subsystem due to the maturity of the model delivered by ADS at the time of the NASA predictions.

In addition to the random vibration measured to validate the specification for equipment qualification, stresses were also measured on some structural parts of the primary structures and some area directly in contact with the acoustic field. For primary structures, stresses were really low. Acoustic is not the sizing load case for primary structures. For Solar Arrays and Radiators, stresses were also low and well below the allowable levels.

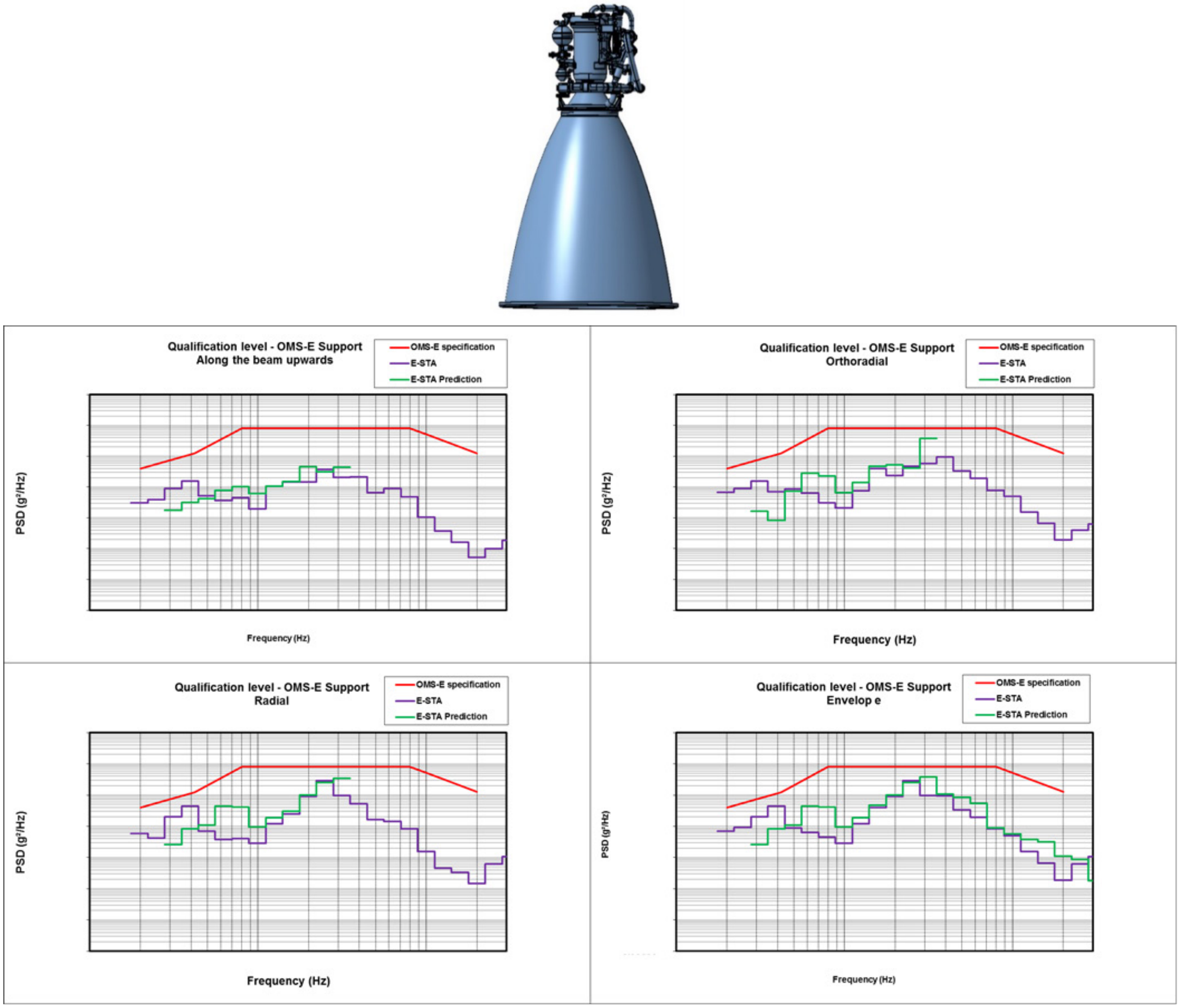


Figure 27.—Comparison Between Predictions and Measurement on OMS-E Support.

Conclusion

In the context of this E-STA acoustic development test performed to support ESM environmental qualification, several conclusions can be addressed.

The acoustic testing of the E-STA was successfully completed in April-May 2016 through the performance of ten reverberant acoustic tests. The E-STA had flight primary and secondary structures, and flight or highly representative equipment items for the various subsystems. Half of these test runs were performed using dry (empty) propellant tanks, and half were performed using wet (filled) propellant tanks. Qualification test levels as high as 149.4 dB OASPL were reached during the testing.

The testing incorporated the use of a flight response based excitation. An analytical modeling approach was developed to arrive at an external test excitation level which would produce the desired acoustic SPL in the SM Outer Cavity, the cavity between the ESM structure and the SAJ Fairing walls. Reaching these targeted SM Outer Cavity levels were necessary for test success.

Several test challenges were met and overcome during the course of the acoustic testing. The most important test challenge was to understand the nonlinear behavior of the SAJ Fairing's noise reduction in order to successfully reach the targeted SPL of the SM Outer Cavity. Test data from lower level acoustic runs were analyzed in order to slightly modify the RATF's external noise levels in order to account for these nonlinearities. These modifications resulted in ultimately achieving the desired sound levels inside the SM Outer Cavity. It was observed that the spatial consistency of the numerous SM Outer Cavity microphones was extremely homogenous.

Reaching these correct SM Outer Cavity levels allowed all the test objectives defined by ESA and Airbus to be fully met. It allowed the test verification of the mechanical resistance of the ESM, a validation of the ESM modeling, and a validation of the ESM component's random vibration test levels. Several examples are provided. Additionally, a direct and successful acoustic qualification of the Solar Array Wing was accomplished. All test objectives were met.

Lastly, this test was a rewarding and great collaboration between multiple organizations (Figure 28) including ESA, Airbus, NASA, and Lockheed Martin.

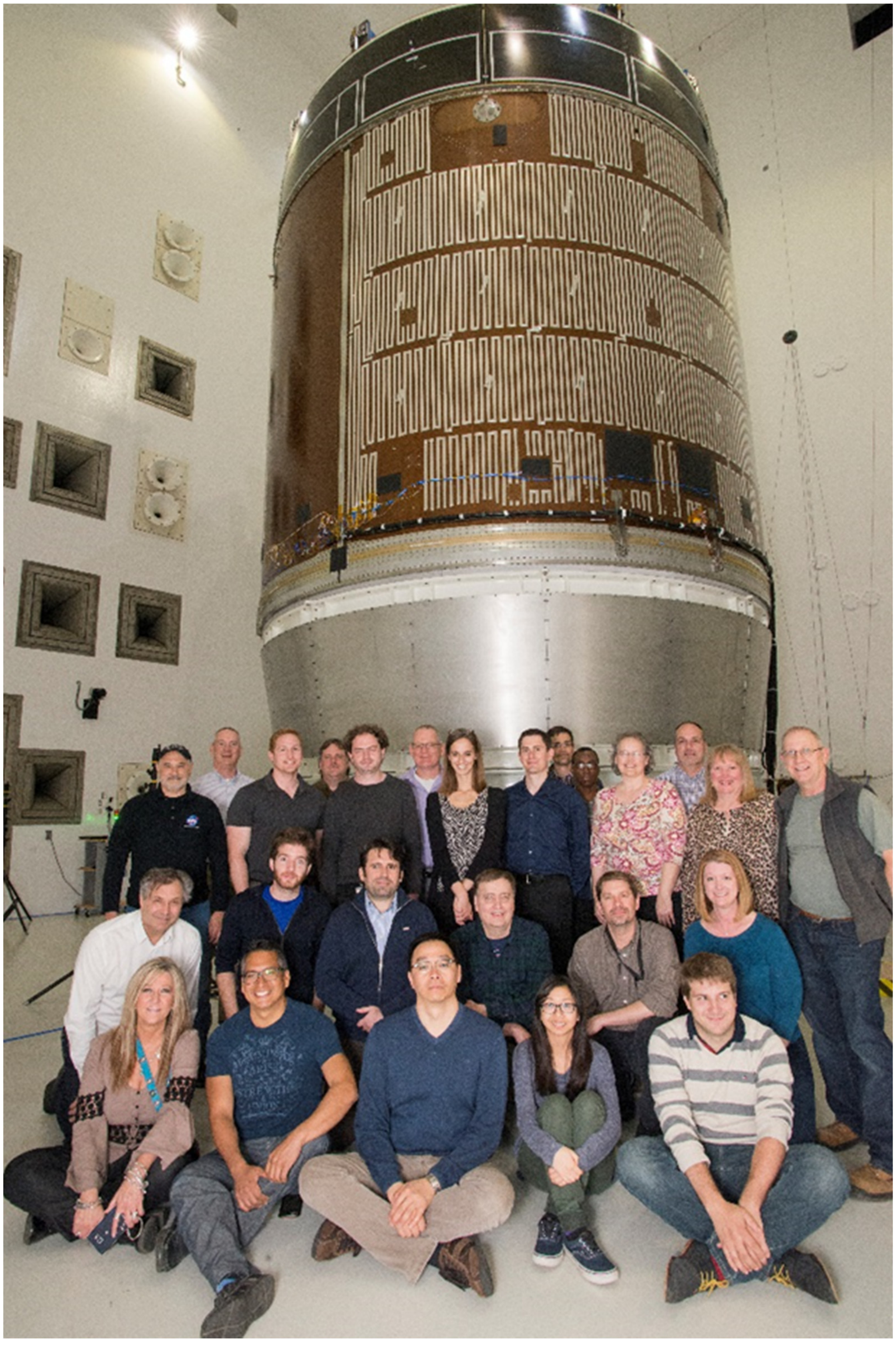


Figure 28.—A Successful E-STA Acoustic Test Campaign.

Biographies

Samantha Bittinger received a BS in Mechanical Engineering from The University of Akron in 2012 and an MS in Interdisciplinary Engineering from Purdue University in 2016. She has been working for NASA Glenn Research Center supporting the Orion Multi-Purpose Crew Vehicle program in the loads and dynamics discipline for the past five years. Her areas of expertise are in vibroacoustics, modal analysis, and vehicle-level finite element model integration. She is the recipient of two Space Flight Awareness Team Awards for design and test concepts.

Jean-François Durand was hired in 2003 by the European car manufacturer PSA Peugeot-Citroën in the frame of a PhD in the field Mechanics at the University of Paris Est (director Pr. Christian Soize). He worked on the topic of stochastic uncertainties modeling for automotive vibroacoustics. The purpose was to take into account the manufacturing dispersions as well as the model uncertainties along the development process of vehicles based on a dual experimental/numerical approach. After receiving his PhD in 2006, he moved to Airbus-Safran Launchers where he worked on various topics related to dynamics on the Ariane5 program: methodologies development, qualification process improvement, research activities, project synthesis and work package management. He is currently in charge of the acoustic activities related to the Ariane6 program as well as supporting the MPCV-ESM program regarding high frequency test and analysis.

François Duval graduated from ISAE-SUPAERO (Superior Institute for Aerospace Engineering) in Toulouse (France) where he obtained a Master of Science degree in space vehicles engineering in 2008. His formation included a one-year internship working on advanced projects of suborbital planes for space tourism at Dassault-Aviation in Saint-Cloud (France). He was hired by Airbus Safran Launchers in Les Mureaux (France) in 2008 to work on military projects within the Vehicle Design Office. There he worked for 3 years on assembly specifications and drawings preparation, configuration control and directly supported assembly activities: assembly procedures and tools validation, anomalies assessment and waivers justification. He subsequently spent 3 years as technical lead for various advanced project activities, coordinating multi-disciplinary engineering activities, still within the military vehicles design office. Finally in 2014 he moved to Airbus Safran Launchers Vehicule Tests department to be in charge of the technical management of the E-STA test campaign for Orion-ESM program.

Vince Fogt is an aerospace engineer for the NASA Johnson Space Center. Mr. Fogt has over 27 years of experience in aerospace, including random vibration, acoustic testing, modal testing, dynamic model correlation, and shock testing. He has held several positions within the NASA manned spaceflight programs including chairman of the Space Shuttle Program payload structures working group, ISS loads and dynamics test and verification lead, and X-38 loads lead. Currently, Mr. Fogt is serving as the technical discipline lead for vibroacoustics and shock in the JSC Loads and Dynamics Branch and the MPCV vehicle integration office. He holds a BS degree Aeronautical and Astronautical Engineering University of Illinois, and a Masters of Civil Engineering from Rice University.

Isaac Hayden, Graduated with a Bachelors and Masters Degree in Aerospace Engineering from University of Colorado Boulder. Worked in structural and mechanical design, as well as integration and testing, for Cube Satellites for four years at Colorado Space Grant Consortium. Currently a Systems Engineer at Lockheed Martin, working on NASA's Orion program.

Since 2007, **Aron Hozman** has been working for NASA and is the Vibroacoustic Test Manager and Test Lead at the Plum Brook Station in Sandusky, Ohio. Aron contributed to the design, evaluations, and test operations of NASA Plum Brook's Mechanical Vibration Facility and the Reverberant Acoustic Test Facility. Prior to coming to NASA, Aron worked in the areas of dynamic testing and in dynamic criteria development and data analysis for 20 years at Boeing's Satellite Division in El Segundo, California. Aron was also instrumental in the design and test operations of Boeing's El Segundo acoustic reverberant chamber. Aron has a Bachelor's degree from the University of Michigan in Electrical Engineering, and a Master's degree from the University of Texas at Austin in their Graduate Engineering Acoustics Program.

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Anthony Thirkettle joined ESA in 2006 and worked on a number of successful projects notably the VEGA small European launcher and the IXV re-entry vehicle. Anthony has been the principal mechanical engineer for the MPCV-ESM at the European Space Agency (ESA) since 2012. In 2010 Anthony co-founded Giaura (now Skytree), a space spin-off company using carbon dioxide air capture technology. Prior to joining ESA, Anthony worked for AOES B.V. as a mechanical engineering consultant and for QinetiQ in the United Kingdom as an aircraft performance analyst. Anthony has a Master's degree in aeronautical engineering from the University of Bristol.

Appendix—Acronyms

AAC	Analog Abort Computer
ACS	Acoustic Control System
ADS	Airbus Defense & Space
ASL	Airbus Safran Launchers
ATS	Acoustic Test Stand
BEM	Boundary Element Method
CDR	Critical Design Review
CM	Crew Module
CM	Control Microphones
CMA	Crew Module Adapter
CSS	Consumables Storage Subsystem
DAF	Diffuse Acoustic Field
DAU	Data Acquisition Unit
EM-1	Exploration Mission 1
ESA	European Space Agency
ESM	European Service Module
E-STA	European Service Module – Structural Test Article
EFT-1	Exploration Flight Test 1
FDAS	Facility Data Acquisition System
FEM	Finite Element Model
GN_2	Gaseous Nitrogen
GRC	Glenn Research Center
G_{rms}	Acceleration Root Mean Square
HDRM	Hold Down Release Mechanism
HFE-7100	Methoxy-nonafluorobutane
JSC	Johnson Space Center
LAS	Launch Abort System
LMCO	Lockheed Martin Company
Max Q	Maximum Dynamic Pressure
MDPS	Micro-Meteoroids and Orbital Debris Protection System
MMH	Monomethylhydrazine
MON3	Mixed Oxides of Nitrogen
MPCV	Multi-Purpose Crew Vehicle
MSA	MPCV Stage Adapter
MSAS	MPCV Stage Adapter Simulator
M-STA	MPCV Structural Test Article
NASA	National Aeronautics and Space Administration
N_2	Nitrogen
OASPL	Overall Sound Pressure Level
OMS-E	Orbiting Maneuvering System Engine
OTOB	One-Third Octave Band
O_2	Oxygen
PBS	Plum Brook Station
PCA	Pressurant Control Assembly
PDR	Preliminary Design Review
PSD	Power Spectral Density
QSL	Quasi-Static Load
RATF	Reverberant Acoustic Test Facility
RCS	Reaction Control System

RM	Response Microphones
SA	Spacecraft Adapter
SADA	Solar Array Drive Assembly
SADE	Solar Array Drive Electronics
SADM	Solar Array Drive Mechanism
SAW	Solar Array Wing
SAW QM	Solar Array Wing Qualification Model
scfm	standard cubic feet per minute
SEA	Statistical Energy Analysis
SLS	Space Launch System
SPF	Space Power Facility
SPL	Sound Pressure Level
S-STA	Static Structural Test Article
TAS-I	Thales Alenia Space, Italy
TCS	Thermal Control System

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