SLS Scale Model Acoustic Test Liftoff Results and Comparisons

Janice Houston
Douglas Counter
Clothilde Giacomoni
NASA Marshall Space Flight Center
Huntsville, AL

ABSTRACT

The liftoff phase induces acoustic loading over a broad frequency range for a launch vehicle. These external acoustic environments are then used in the prediction of internal vibration responses of the vehicle and components which result in the qualification levels. Thus, predicting these liftoff acoustic (LOA) environments is critical to the design requirements of any launch vehicle. If there is a significant amount of uncertainty in the predictions or if acoustic mitigation options must be implemented, a subscale acoustic test is a feasible design phase test option to verify the LOA environments.

The NASA Space Launch System (SLS) program initiated the Scale Model Acoustic Test (SMAT) to verify the predicted SLS LOA environments and to determine the acoustic reduction with an above deck water sound suppression system. The SMAT was conducted at Marshall Space Flight Center and the test article included a 5% scale SLS vehicle model, tower and Mobile Launcher. Approximately 250 instruments measured acoustic and pressure data. The SMAT liftoff acoustic results are presented, findings are discussed and a comparison is shown to the Ares I Scale Model Acoustic Test (ASMAT) results.

KEY WORDS:

Liftoff Acoustic Environments, Scale Model Test, Rocket Noise, Space Launch System, Water Sound Suppression

INTRODUCTION

NASA's Space Launch System (SLS) is America's next generation launch vehicle that will carry space explorers safely and reliably into orbit. The launch environments, including the liftoff acoustic (LOA) environments, are important design factors for SLS and are dependent upon the design of both the launch vehicle and the ground systems. Pre-test liftoff environments were predicted with assumptions of the noise reduction based upon both Space Transportation System (STS) and Ares I scale model test water sound suppression data (Counter 2012).

The Space Shuttle and Ares I-X flight vehicles were launched from the same Mobile Launch Pad (MLP). In comparison, there are unique differences in the SLS ground systems including a new Mobile Launcher (ML) with a large exhaust duct at deck zero, a new deflector onto which all of the SLS plumes impinge, and a new layout of the rainbirds for the above deck water sound suppression system. However, the water tower was not upgraded and consequently, the water available for noise suppression is limited when comparing flow rate ratios of water mass flow to propellant mass flow (W_w/W_p). To verify predicted launch environments and the noise attenuation due to the water sound suppression systems, the SLS Scale Model Acoustic Test (SMAT) was implemented. The SMAT objectives were to verify the predicted LOA environments, verify predictions of the ignition overpressure (IOP) environments, evaluate the SLS water sound suppression systems, characterize ground acoustic environments and obtain spatial correlation data for use in vibro-acoustic models.

The following results will be covered in this paper: liftoff acoustic environments, the noise reduction due to the SMAT water sound suppression systems for both hold down and elevated tests and comparisons to other relevant scale model tests.

SCALE MODEL ACOUSTIC TEST CONFIGURATION

The SMAT program was performed at the Marshall Space Flight Center (MSFC) East Test Area Test Stand 116. The SMAT program consisted of 17 hot fires which were conducted over a 9-month period, from April to December 2014.

The SMAT configuration included a five-percent scale model of the SLS Vehicle, Mobile Launcher (ML) with Tower, Launch Pad Trench (LPT), and Main Flame Deflector (MFD), as shown in Figure 1. Tests include firing at multiple vehicle elevations simulating the climb-out trajectory. Two Alliant Techsystems Inc. Rocket Assisted Take-Off (RATO) motors generating ~10,000 lb_f thrust each were used to simulate the SLS solid rocket motors. Four LOX/GH_2 thrusters, with a total thrust of 4,800 lb_f, were used to simulate the SLS RS-25 Core Stage liquid engines.

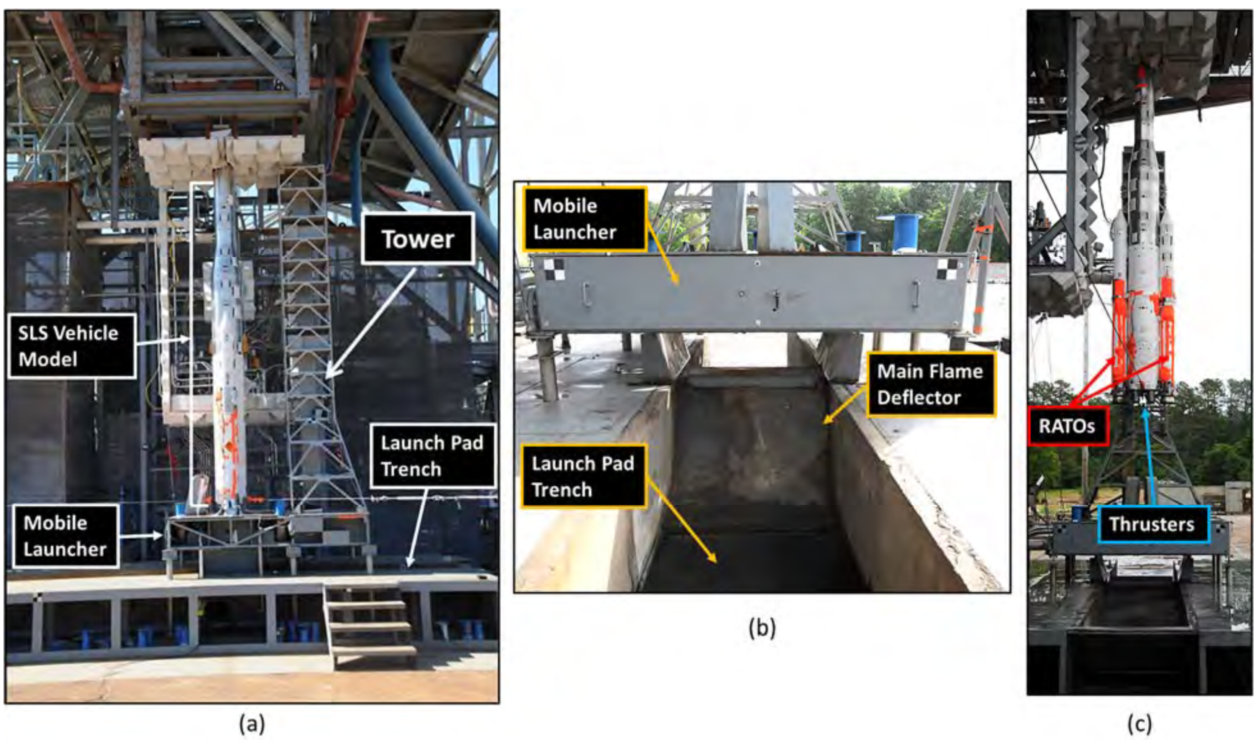


Figure 1: (a) SMAT model and surrounding structures, (b) SMAT mobile launcher, launch pad trench, and main flame deflector, and (c) SMAT model.

Water Sound Suppression Systems

The SLS launchpad will provide several different water sound suppression systems which were simulated in the SMAT configuration. There were two main types of water sound suppression systems in place during the SMAT program. The first was below the main deck and consisted of water below each booster, below the core stage, and in the trench. This system is mainly useful for the "hold down" time period, when the liquid engines are on and the boosters are about to ignite. The second type of water sound suppression system is above the deck, commonly referred to as "rainbirds", and is designed to mitigate noise during liftoff. The different water sound suppression systems are shown in Figure 2a and Figure 2b. Figure 2c shows the nominal rainbird configuration operating.

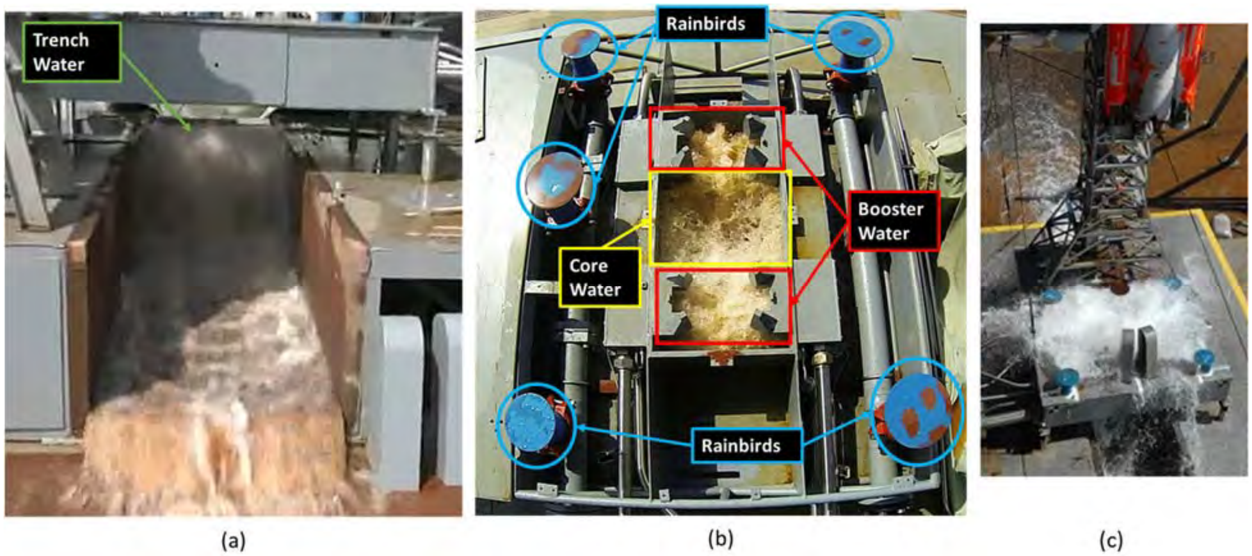


Figure 2: Photo of the (a) trench water suppression system, (b) core and booster water systems and rainbirds, and (c) rainbirds operating.

Instrumentation and Data Acquisition System

The SMAT model was instrumented with approximately 250 transducers of different types and categorized into three main instrumentation suites: LOA, IOP, and spatial correlation (SC). The LOA suite included 27 Bruel & Kjaer Type 4944-B microphones, installed in mounts located along full length of the vehicle. The IOP suite included 83 Kulite XTL-123B-190-30SG pressure transducers mounted on and around the vehicle model, mobile launcher, and trench. The SC suite was made up of 106 Kulite XCEL-12-100-2D pressure transducers mounted in rosette patterns on plates which were located along the full length of the vehicle.

Data were recorded on a DSPcon Piranha III data acquisition system with sample rates of either 256,000 or 4,000 samples per second (sps). Figure 3 shows a rendering of the SMAT vehicle model as well as the location and type of the instruments used in the analysis presented in this paper.

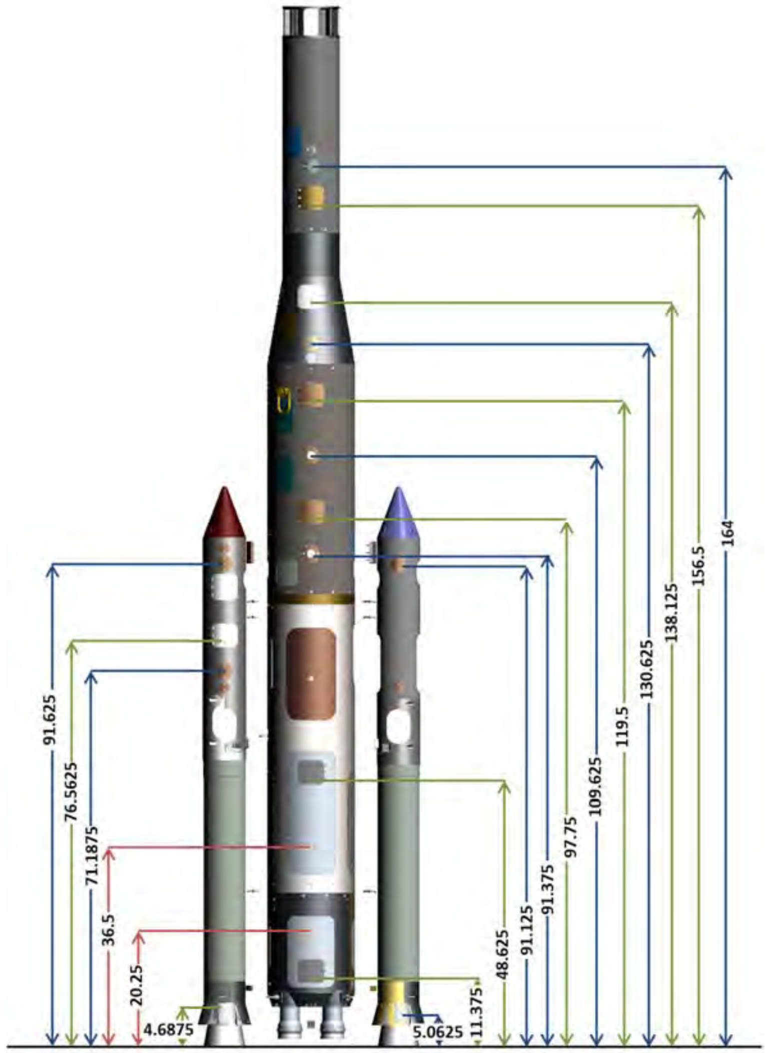


Figure 3: Rendering of SMAT vehicle model and sensor locations (inches). Different colored arrows represent different instrumentation suites: red – IOP, blue – LOA, green – SC.

SCALE MODEL ACOUSTIC TEST OPERATIONS

The SMAT operations included test article positioning, water sound suppression systems operations, and propulsion systems firing.

To simulate liftoff, the SMAT vehicle model was vertically retracted into the test stand by elevating the telescoping cage. This vertical retraction allowed for the vehicle model to be suspended above the launch pad at fixed elevations and test fired. Specific elevations were chosen to create ‘snapshots’ of the vehicle LOA environments at various elevations to be seen in anticipated SLS flight scenarios. Test firings were conducted at elevations of 0, 2.5, 5.0, 7.5 and 9 feet (which correspond to full scale elevations of 0, 50, 100, 150 and 180 feet respectively). Figure 4 shows the vehicle model at the 2.5, 5, 7.5 and 9 foot elevation. In addition to varying the elevation, the vehicle was drifted per the design-to trajectory drift at each elevation. The water sound suppressions systems flow rates were calculated according to each particular vehicle elevation and drift.

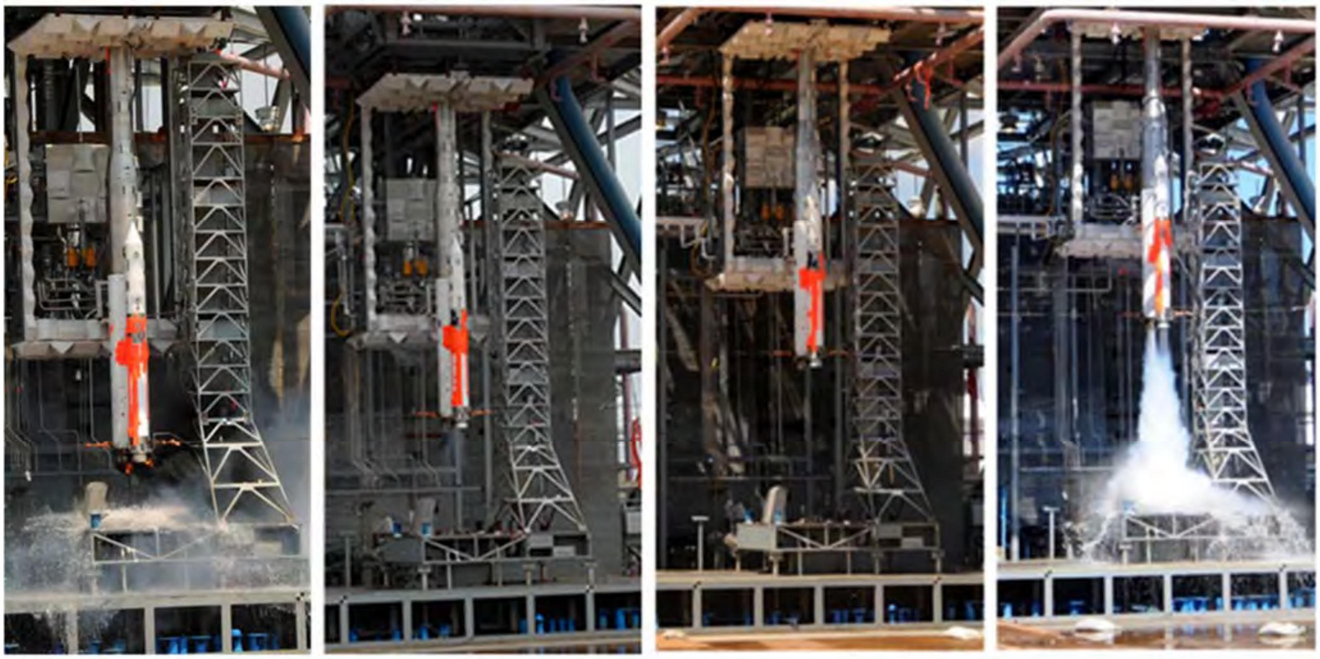


Figure 4: SMAT vehicle climb out simulation.

Figure 5 shows the operation of the propulsion systems: first the water sound suppression systems are turned on, then the liquid engines operate and then the RATOs are ignited and run simultaneously with the liquid engines.

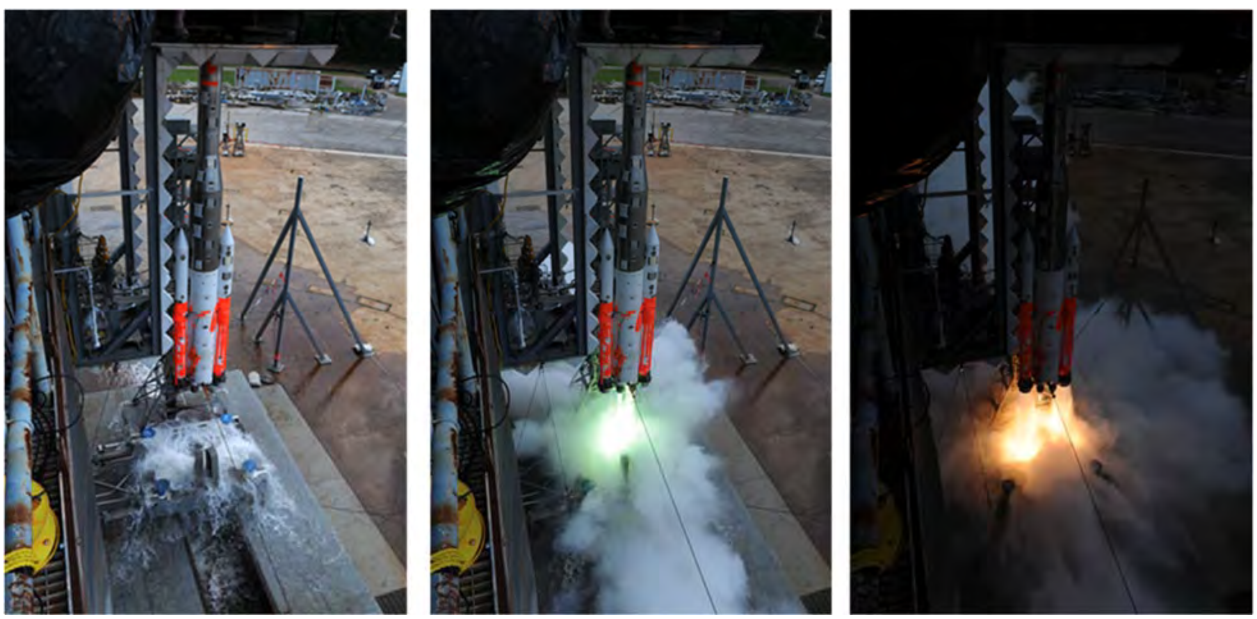


Figure 5: SMAT operation of propulsion systems.

SCALE MODEL ACOUSTIC TESTS

In total, there were 17 firings of the SMAT propulsion systems. The individual firing is a test with a specific objective. In general, there were dedicated tests to determine the elevation at which the maximum sound pressure level (SPL) occurs and tests to determine the noise reduction due to the nominal performance of the rainbirds. Additional testing of the rainbirds occurred for evaluation of different parameters such as number of rainbirds, rainbird height and increased rainbird flow rate.

SCALE MODEL ACOUSTIC TEST RESULTS

The SMAT instrumentation measured the noise during the firings. These narrowband measurements were calculated into 1/3 octave bands over a 1 second data analysis window. These 1/3 octave band results have been compared on a test by test basis in order to determine the SLS design-to liftoff acoustic environments and the noise reduction due to the water sound suppression systems. Finally, the SMAT results were compared to results from other scale model tests.

Liftoff Environments

As the vehicle lifts off the pad, the sound pressure levels will increase until a certain elevation is reached, then sound pressure levels will begin to decrease for higher elevations. Due to this, it is important to determine the elevation at which the maximum sound pressure level occurs in order to capture it in the prediction models. The data in Figure 6 shows that the highest sound pressure levels occur at an elevation of 7.5 feet (150 feet full scale) off the ground. It is important to note that the water sound suppression systems were operating at the corresponding nominal flow rate for each elevation test.

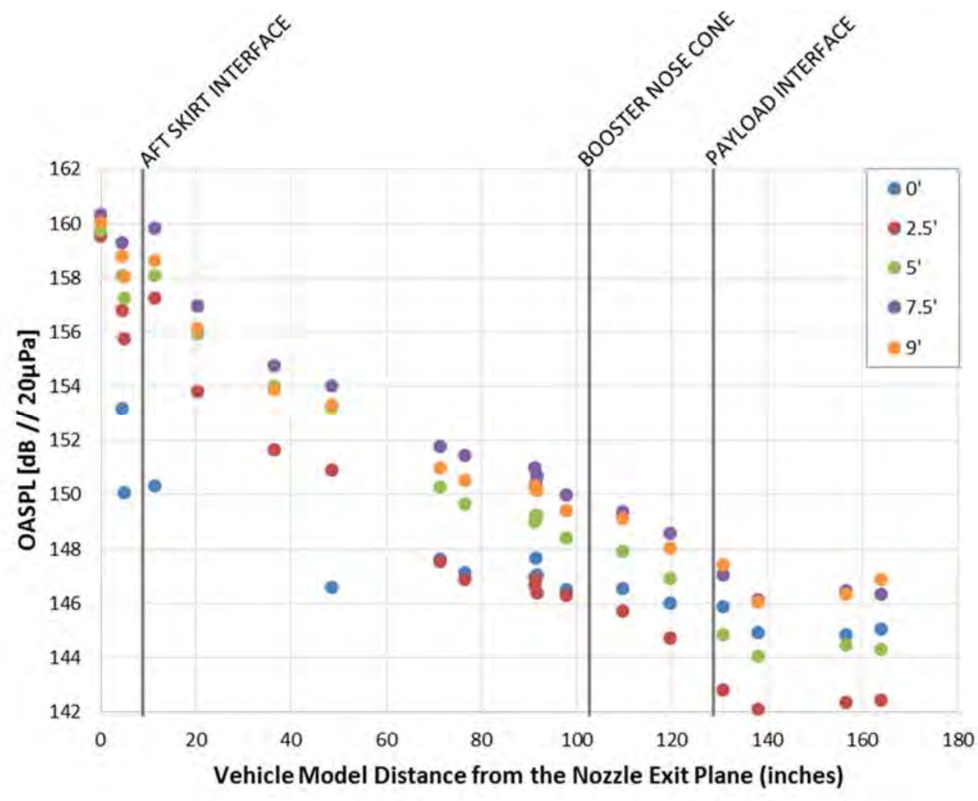


Figure 6: Comparison of different elevations for similar liftoff trajectories and water suppression (0' – blue, 2.5' – red, 5' – green, 7.5' – purple, 9' – orange).

Noise Reduction

There are two main types of water sound suppression systems: below and above deck ("rainbirds"). The below deck system is effective at suppressing noise during the hold down period, when the liquid engines are operational and prior to booster ignition and liftoff. There were dedicated tests in the hold down position in order to measure the pre-launch environments. These environments are useful when evaluating ground system components such as umbilicals.

The effect of the below deck water system was investigated by having an initial test with no water at all, and two subsequent tests which included the same amount of water for each water system to determine the repeatability. The "hold down" environment is characterized by analyzing the time period when only the liquids are firing. This is due to the fact that for a real vehicle, liftoff begins as soon as the boosters fire. Figure 7 shows the liquid engines only noise levels with and without the below deck water sound suppression systems operating. As can be seen in Figure 7, the dry test is 6 dB higher at the aft skirt, and 10 dB higher over the rest of the vehicle model. The two wet tests, performed on different days, show very good repeatability.

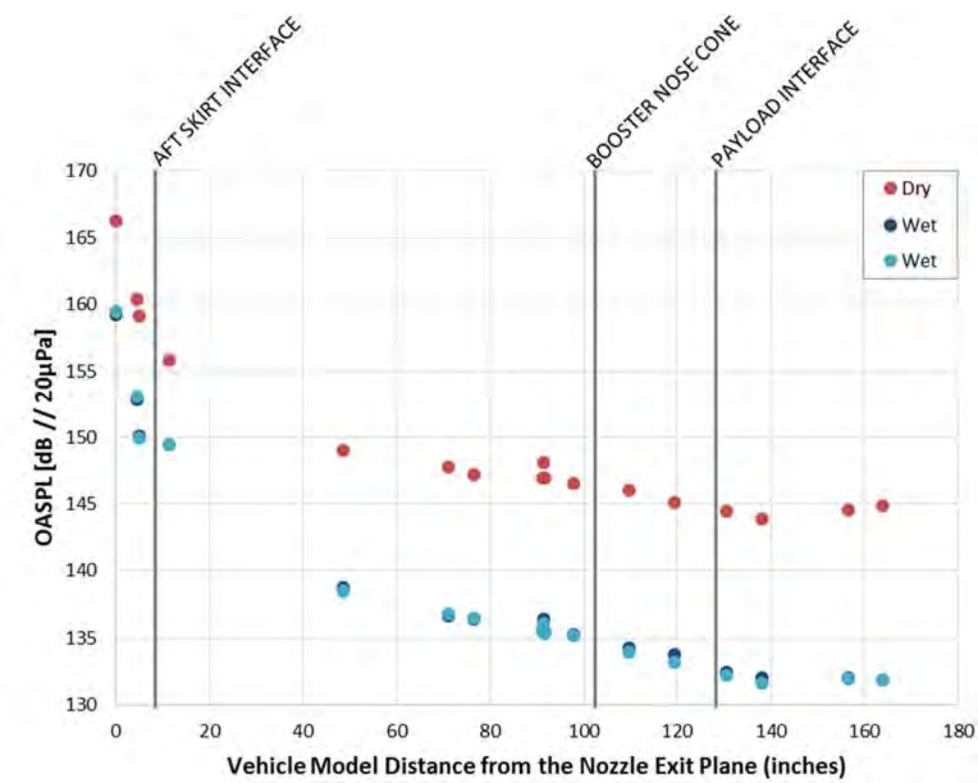


Figure 7: Comparison of dry (red) and wet (blue, turquoise) tests for the hold down tests.

To determine the effectiveness of rainbirds for SLS, tests were done with and without rainbirds (above deck water sound suppression). It is important to note that the below deck water sound suppression systems are operational during all of the rainbird testing. There were also several tests done with different rainbird configurations to determine which was the most effective. Finally, a higher flow rate ratio was investigated.

The first question to answer was whether rainbirds provided any kind of sound suppression at all. For the baseline configuration, a water mass flow to propellant mass flow ratio (W_w/W_p) of 1.9

was tested. Figure 8 shows that rainbirds in general provide about 2-3 dB of sound suppression for most of the vehicle except the aft skirt region. Questions arose about how to optimize these results within the design trade space: decrease number of rainbirds and implement taller rainbirds.

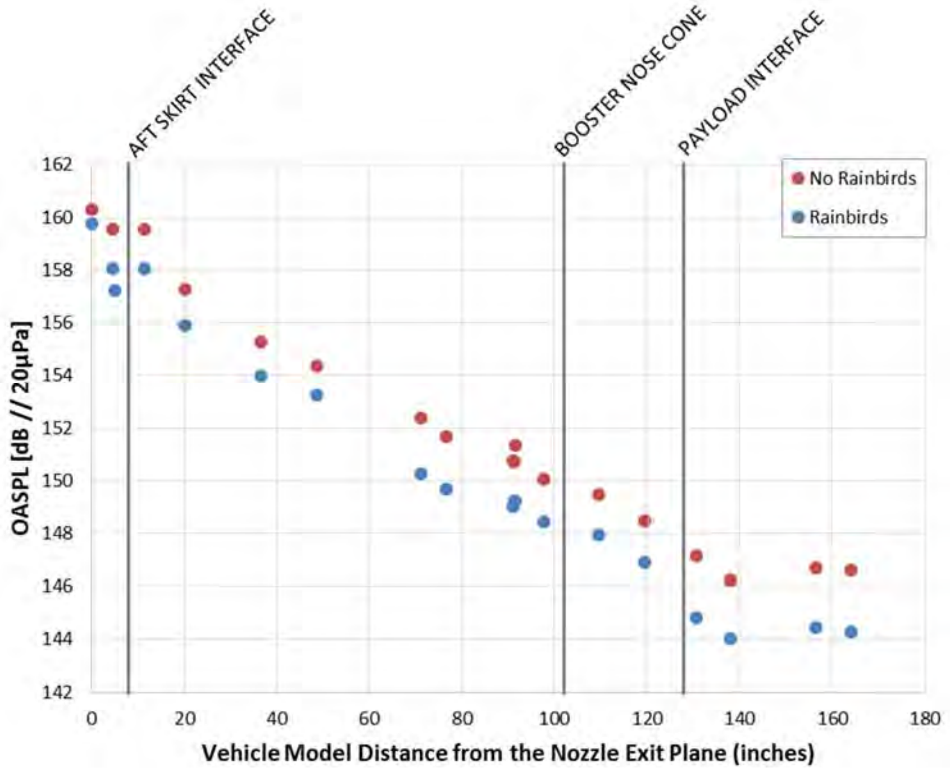


Figure 8: Comparison of rainbird (blue) and no rainbird (red) tests.

Initially, five rainbirds were positioned around the ML deck (2 on the south side, 3 on the north side). One question posed was whether the center rainbird on the north side was more detrimental than helpful, because it was not providing water directly into the booster plumes and was essentially taking water away from the two corner rainbirds on that side. The first modification that was made to the rainbird system was to have 4 rainbirds, all with equal amounts of water flowing. The results of this are shown in Figure 9, and show that changing the configuration from 5 rainbirds to 4 rainbirds has no effect on the sound pressure level.

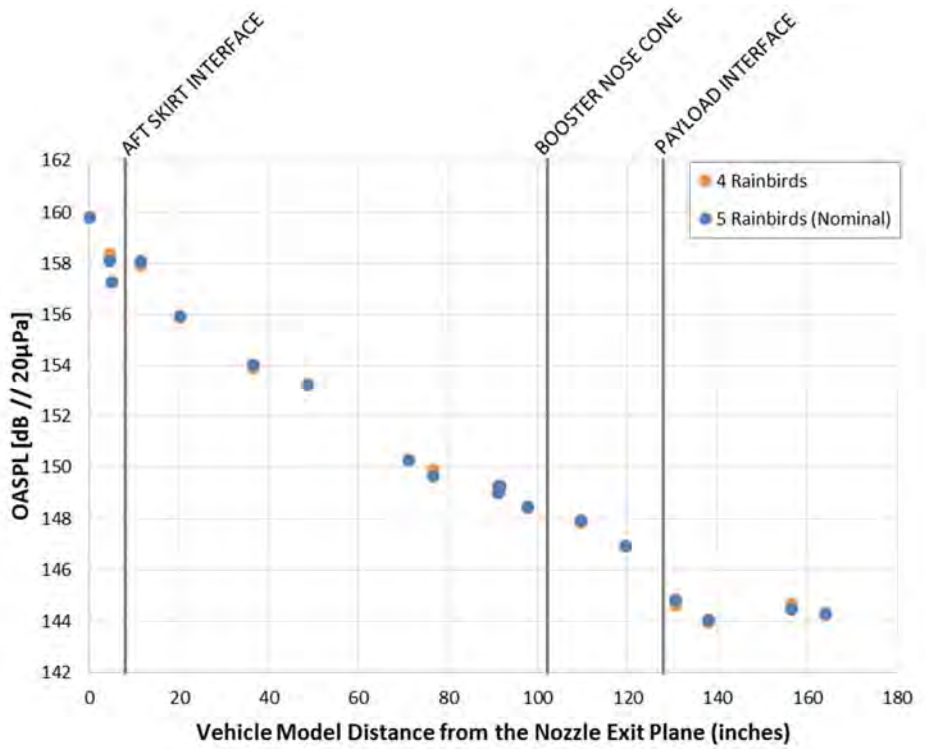


Figure 9: Comparison of 5-rainbird configuration (blue) and 4-rainbird configuration (orange).

The second modification was to determine whether taller rainbirds would be helpful, as they would come in contact with the plumes earlier than the shorter rainbirds. This was slightly more effective than the regular baseline, as shown in Figure 10, but not enough to warrant a change in configuration for the SLS.

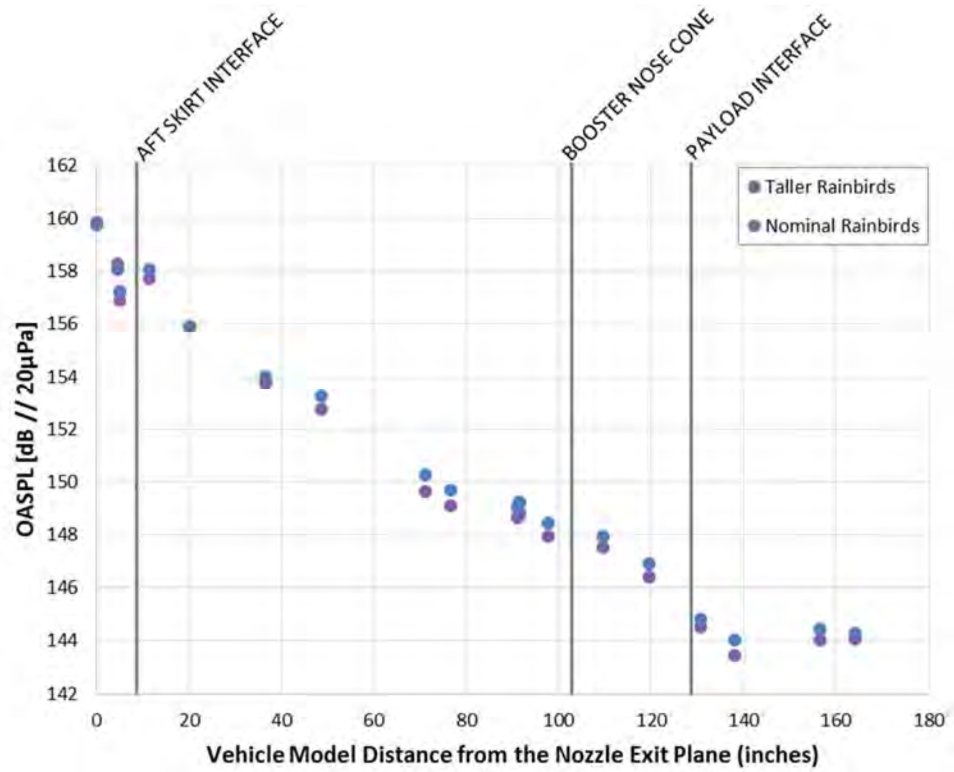


Figure 10: Comparison of nominal height rainbirds (blue) and taller rainbirds (purple).

The last modification was to increase the water flow rate of the rainbirds. Higher flow rates were tested in several scale model tests previously and it is known that there is a point where increasing the water flow rate no longer increases sound suppression. During SMAT, the highest ratio of water flow rate to propellant flow rate tested was 3.5. Though there is an obvious increase in sound suppression, as seen in Figure 11, this cannot be implemented for the SLS due to water constraints at Kennedy Space Center (KSC).

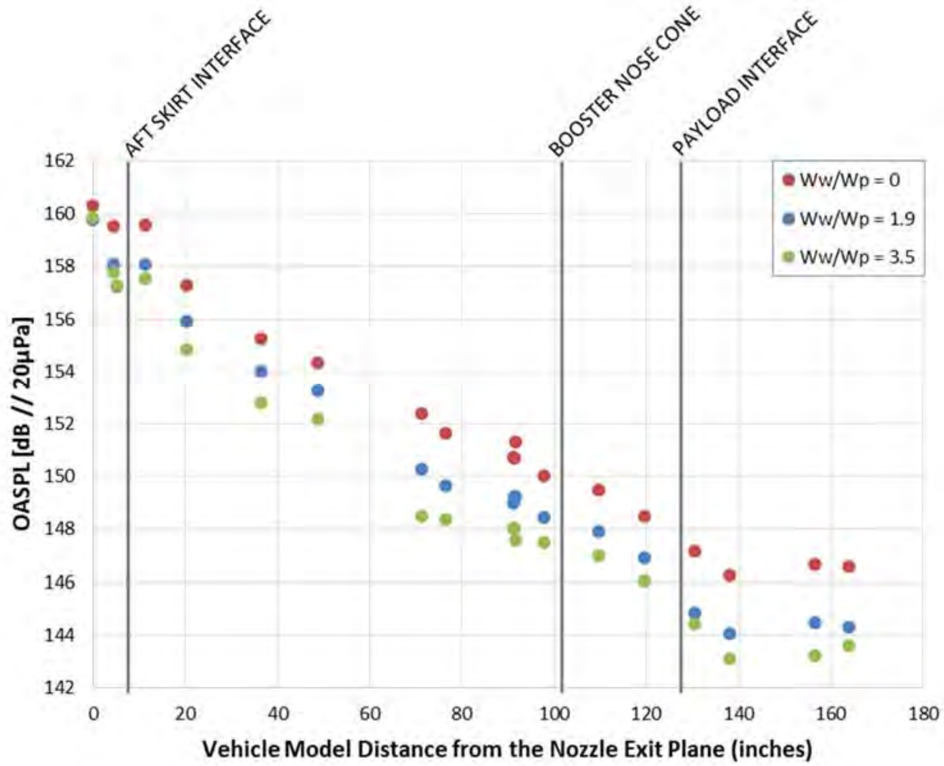


Figure 11: Comparison of different rainbird flow rates (no water – red, $W_w/W_p = 1.9$ – blue, $W_w/W_p = 3.5$ – green).

Comparisons to other Scale Model Tests

MSFC has a long history conducting scale model tests of launch vehicles including the STS, the Ares I, and the SLS. Figure 12 shows scale model testing of these three vehicles, with the actual geometric scales listed.

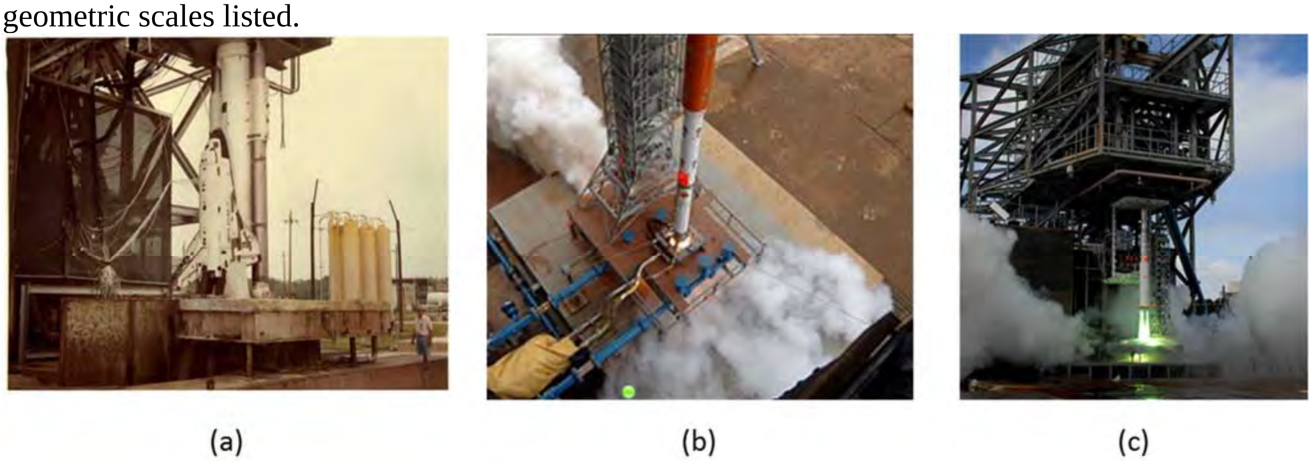


Figure 12: Pictures of Acoustic Scale Model Tests of (a) STS (6.4% scale) (b) Ares I (5% scale), and (c) SLS (5% scale)

There are differences in the launch configurations: single stack versus multi-body launch vehicles. Also, the launch pad facilities are different. However, there is information to be gleaned in the trends. A comparison of where the sensors were located for the ASMAT and SMAT vehicle models is shown in Figure 13. The SMAT results were compared to the 6.4% Space Shuttle and ASMAT results.

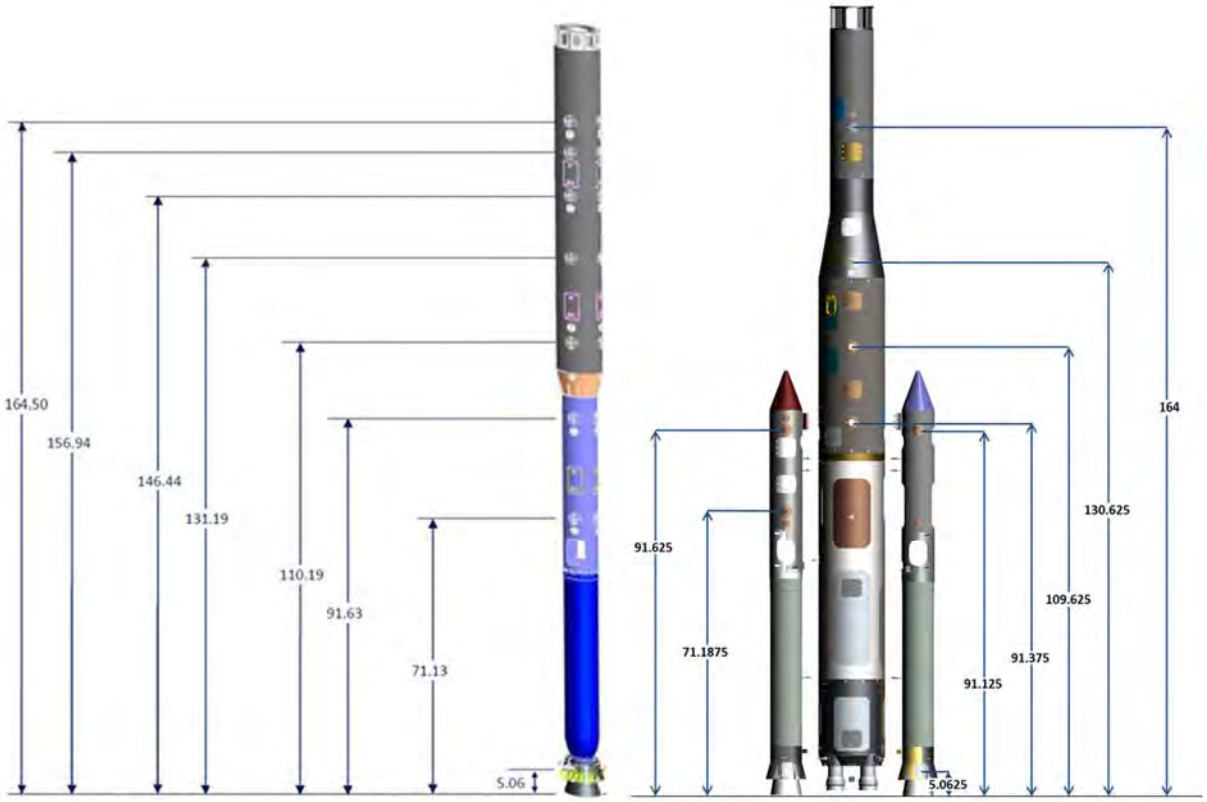


Figure 13: Comparison of microphone locations for ASMAT and SMAT in inches.

Figure 14 shows a comparison of the noise reduction measured for various mass flow rate ratios during the various scale model tests. As seen in Figure 14, more flow rates were tested for the Space Shuttle. It can be seen that an increased flow rate ratio results in increased noise reduction.

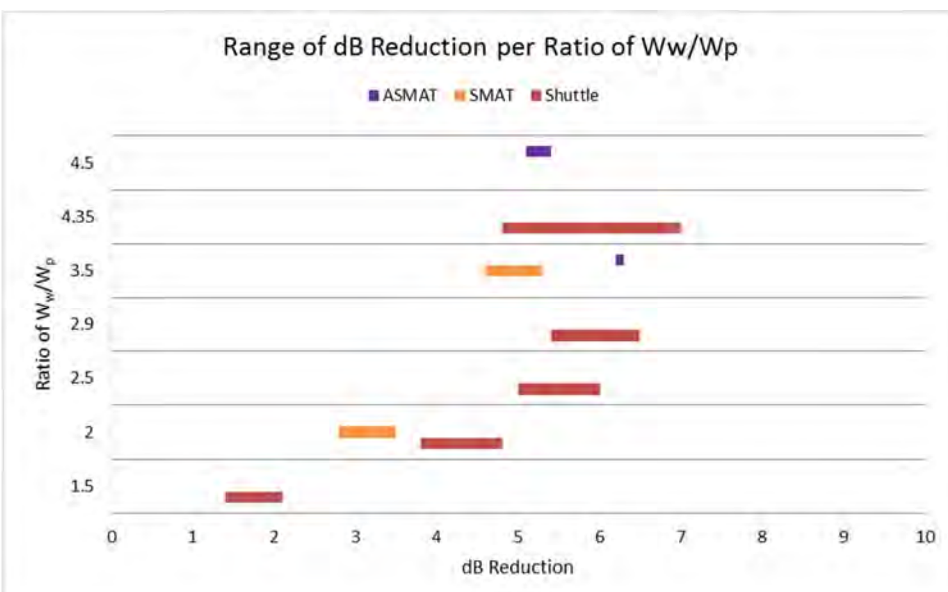
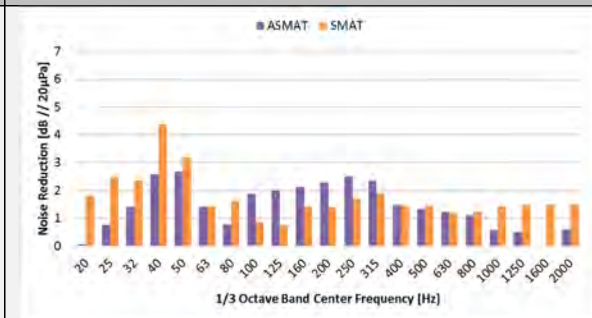
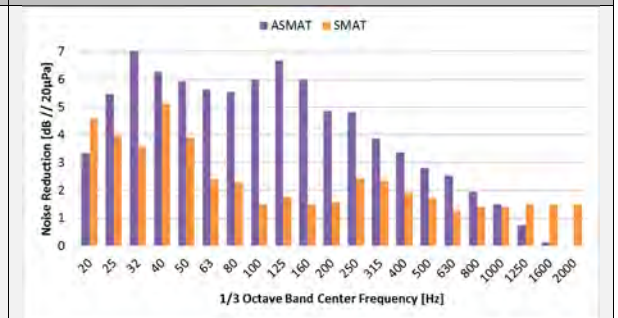
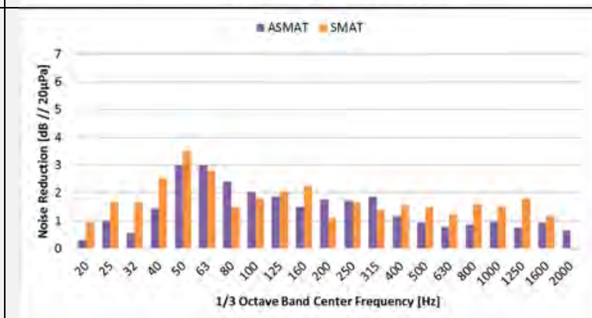
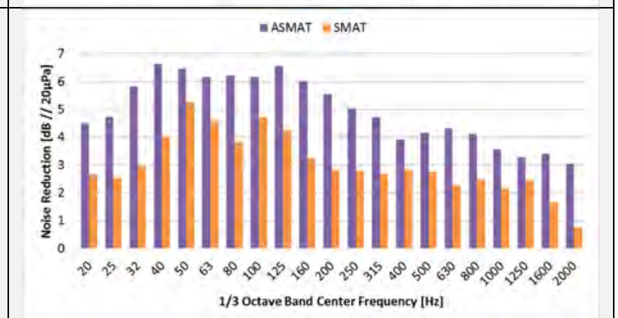
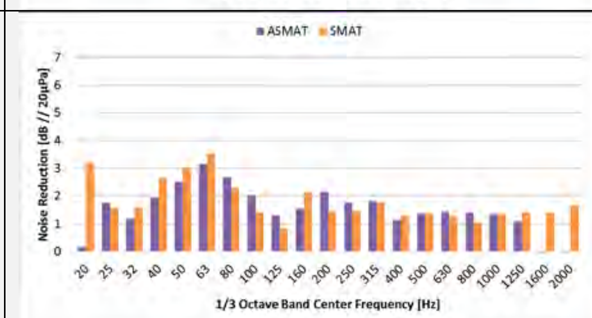
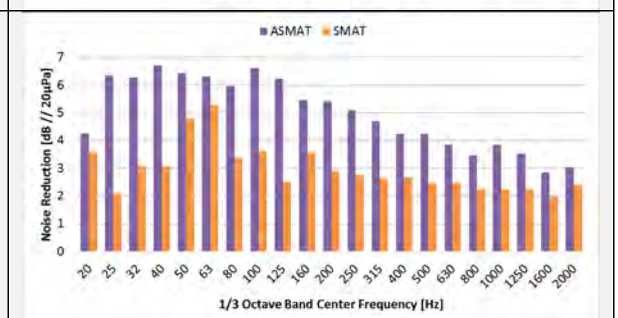
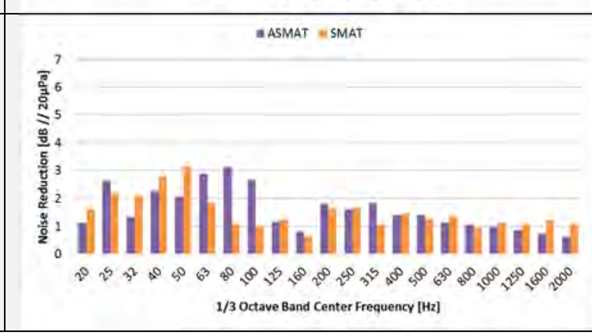
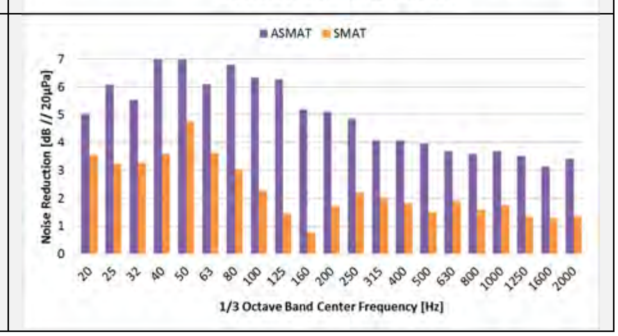
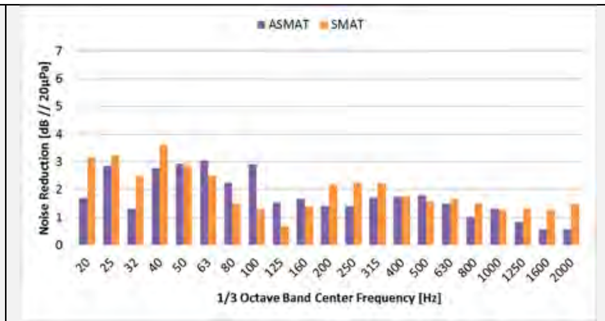
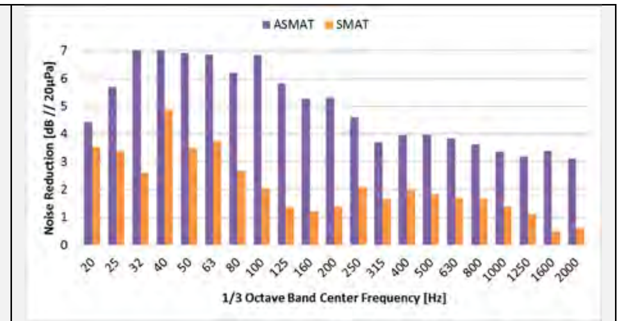
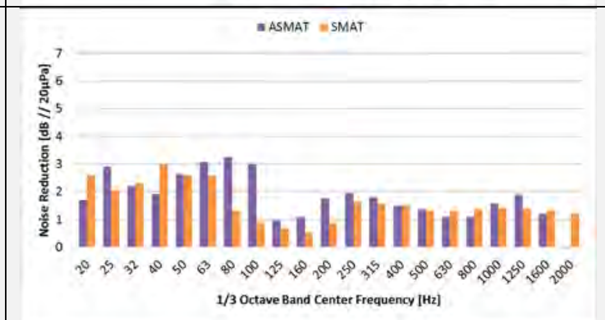
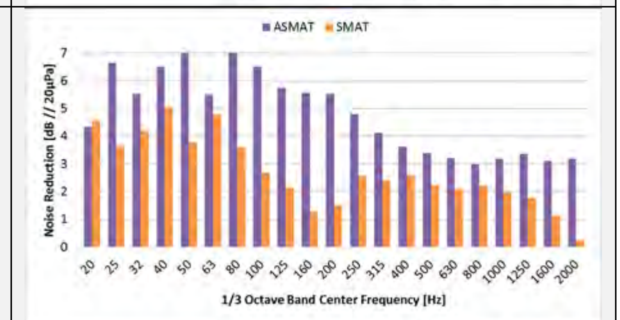
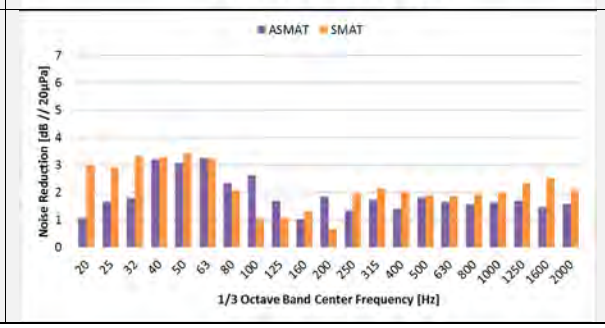
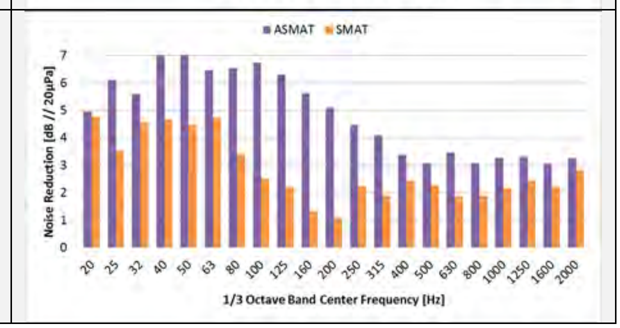


Figure 14: Range of dB Reduction based on water to propellant ratio for ASMAT (purple), SMAT (orange), and 6.4% Space Shuttle (red).

The effectiveness of rainbirds as a function of frequency between ASMAT and SMAT are compared in Table 1.

Table 1: Comparison of flow rate results from ASMAT and SMAT

X-station	Flow Rate Ratio = 2	Flow Rate Ratio = 3.5
Aft Skirt		
71 inches		
92 inches		
113 inches		

132 inches		
158 inches		
166 inches		

SUMMARY AND CONCLUSIONS

The previous Ares I Scale Model Acoustic Test and the Ares I-X measurements showed good correlation and provided further confidence that scale model acoustic testing is useful to verify liftoff acoustic environments prior to launch (Counter 2012). Consequently, the SLS program initiated the SMAT. The SLS liftoff acoustic design-to environments were verified and updated due to the measured increases in the lower frequencies (100 Hertz and below) in the lower vehicle zones. Simulating lift-off conditions allowed for determining at which elevation the maximum sound pressure for SLS would occur.

The noise reduction due to the water sound suppression systems was quantified and it appeared to be consistent in all vehicle zones. It was found that, compared to ASMAT and Space Shuttle 6.4%, the rainbirds are slightly less effective for the SLS vehicle when comparing to similar flow rates. The above deck water sound suppression system “rainbirds” at a W_w/W_p of 2.0 reduced the OASPL by 1.5 dB (1-3 dB depending upon frequency). With an increased ratio of 3.5, there is increased reduction of the OASPL to 2.5 dB (2-5 dB reduction depending on frequency). In general, it is recommended that a ratio (W_w/W_p) of 3.5 should be used. For the specific SLS-configuration, results indicated that taller rainbirds would be more effective. While possible in the limited design space, it was not recommended to implement the taller rainbirds due to the potential cost impact.

Different rainbird configurations did not have a significant effect on the noise reduction provided. Decreasing the number of rainbird nozzles from five to four (to increase flow rate in the rainbirds) did not have a significant effect. Installing taller rainbirds provided a slight decrease of the OASPL at all locations on the vehicle.

The Scale Model Acoustic Test data provided useful results for the NASA SLS program and future launch vehicles. Subscale acoustic testing is necessary for future vehicle environment verification and to verify water suppression design. It is recommended that water sound suppression systems are part of any launch facility.

REFERENCES

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BIOGRAPHIES

Mr. Counter is a senior acoustics analyst for the Bevilacqua Research Corporation in Huntsville, Alabama.. Mr. Counter has over 30 years of experience in aerospace, ranging from acoustic testing, scale model testing, data analysis, on-orbit noise, and far field acoustic rocket noise. Mr. Counter served as the technical lead for the Space Launch Systems Scale Model Acoustic Test and is responsible for the liftoff acoustic environment for the SLS program. He holds a BS degree in Mechanical Engineering from the University of Alabama.

Ms. Houston is a launch vehicle acoustics engineer for NASA Marshall Space Flight Center. Ms. Houston has 20+ years of experience in aerospace, ranging from the development of microgravity payloads for the NASA DC-9, KC 135 Reduced Gravity Flights and the Conquest I sounding rocket, performing microgravity tests for the International Space Station program in Italy and Germany, and participating in the Ares I Scale Model Acoustic Test. She has participated in more than 25 solid rocket motor tests at various test facilities including ATK test grounds in Utah, Mid-Atlantic Regions Spaceport, Naval Surface Warfare Center at Indian Head, and the Ares I-X flight at KSC. Her work has resulted in two patents. Currently, she is the liftoff environments sub-discipline lead engineer for SLS and she participated in the Space Launch Systems Scale Model Acoustic Test. Ms. Houston holds a BS degree in Astronomy and Physics from the University of Arizona.

Ms. Giacomoni is an acoustics analyst for All Points Logistics in Huntsville, Alabama. Ms. Giacomoni received a BS in Acoustical Engineering & Music from the University of Hartford and a MS in Engineering from Purdue University. She has worked 2 years in the aerospace industry for NASA at Marshall Space Flight Center. She was responsible for the liftoff acoustic instrumentation and data analysis for the Space Launch System Scale Model Acoustic Test.