

Verification of Ares I Liftoff Acoustic Environments via the Ares I Scale Model Acoustic Test

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ABSTRACT

The Ares I Scale Model Acoustic Test (ASMAT) program was implemented to verify the predicted Ares I liftoff acoustic environments and to determine the acoustic reduction gained by using an above deck water sound suppression system. The test article included a 5% scale Ares I vehicle model and Mobile Launcher with tower. Acoustic and pressure data were measured by over 200 instruments. The ASMAT results are compared to Ares I-X flight data.

KEY WORDS: Liftoff Acoustic Environments, Scale Model Test, Rocket Noise, Ares I, Ares I-X, Water Sound Suppression

SYMBOLS

d_1	= model scale nozzle exit diameter, ft
d_2	= full scale nozzle exit diameter, ft
f_1	= model scale frequency, Hz
f_2	= full scale frequency, Hz
I_1	= model scale intensity, W/m ²
I_2	= full scale intensity, W/m ²
\dot{m}_1	= model scale mass flow, lbm/sec
\dot{m}_2	= full scale mass flow, lbm/sec
R_1	= model scale area, ft ²
R_2	= full scale area, ft ²
SPL_1	= model scale sound pressure level, dB
SPL_2	= full scale sound pressure level, dB
St	= Strouhal number
V_1	= model scale exit velocity, ft/sec
V_2	= full scale exit velocity, ft/sec
W_w	= water mass flow, lbm/sec
W_p	= propellant mass flow, lbm/sec
η_1	= model scale acoustic efficiency
η_2	= full scale acoustic efficiency

INTRODUCTION

One of the goals of the NASA Constellation Program was to develop a new launch vehicle, Ares I, and fly a proof-of-concept vehicle, Ares I-X. Figures 1(a) and 1(b) depict the Ares I and Ares I-X vehicles with their respective launch support structures. The first stage of the Ares I vehicle incorporated a Reusable Solid Rocket Motor V (RSRMV) design, based on the Space Shuttle Reusable Solid Rocket Motor (RSRM). During the Space Shuttle Program, the RSRM has been shown to generate high acoustic levels during vehicle liftoff. These liftoff acoustic (LOA) environments are an important design factor for launch vehicles and are dependent on both the design of the launch vehicle and the ground system. Initial Ares I LOA environments, derived from Saturn V and Space Shuttle flight data, were provided as design criteria for the Ares I vehicle.

The vibroacoustic analysts used those external LOA environments to generate internal responses and corresponding qualification environments for vehicle components. The result was that there were identified risks: cost, schedule and technical, for component qualification. A possible design solution was to reduce the LOA environments via water sound suppression; similar in approach as what was used for the Space Shuttle Program. An implementation of such a system would incur cost, schedule and technical impacts to the Kennedy Space Center (KSC) Ground Systems Program, which was responsible for designing a new Mobile Launcher (ML) system for the Ares I vehicle. The Ares I Scale Model Test (ASMAT) program was implemented to address these programmatic risks and test the proposed water sound suppression system.

The ASMAT objectives were: 1) to obtain data to verify the predicted Ares I LOA environments, 2) determine if the inclusion of a water sound suppression system would reduce the LOA environment and 3) optimize the water sound suppression configuration for LOA noise reduction.

The ASMAT program was performed at the Marshall Space Flight Center (MSFC) East Test Area Test Stand 116. The ASMAT program consisted of 17 hot fires which were conducted in a nine month period from November 2010 to July 2011. The ASMAT configuration included a 5% scale model of the Ares I vehicle, ML (with tower) and launch pad. Figure 1(c) shows the ASMAT test configuration.

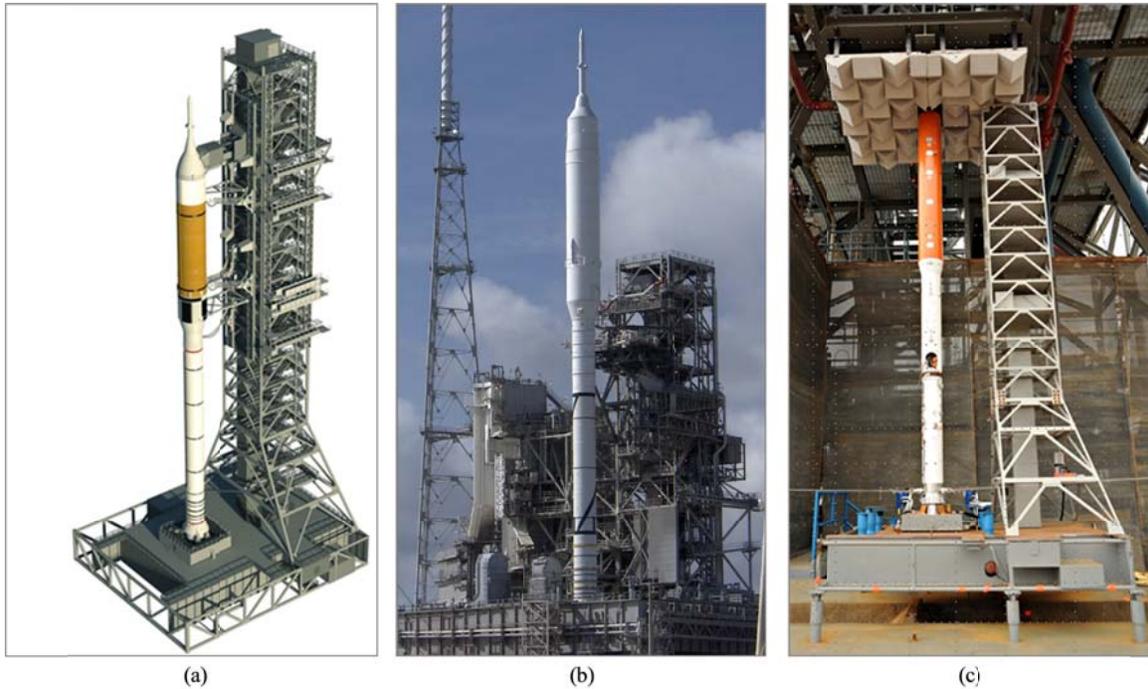


Figure 1: Sketch of Ares I vehicle on Mobile Launcher (a), Ares I-X vehicle at Kennedy Space Center Launch Complex 39B (b) and Ares I Scale Model Acoustic Test article at Marshall Space Flight Center (c).

ASMAT CONFIGURATION

For a subscale model acoustic test to be successful, it must accomplish two interrelated things: 1) capture all relevant full scale noise sources correctly in the subscale configuration, and 2) provide acoustic environments that can accurately be scaled to the full scale environments.

The most critical aspect in simulating the Ares I launch vehicle was to find a comparable solid motor to the Ares I RSRMV. The Alliant Techsystems Inc. (ATK) Rocket Assisted Take-off (RATO) motor was used to represent the Ares I RSRMV. The RATO motor was chosen for two reasons: 1) the motor performance fit within the Test Stand 116 constraints and 2) the nozzle exit diameter, exit velocity and mass flow properties satisfied the model subscale parameter requirements. Using the Strouhal number in equation (1) to determine the frequency scaling, it was found the geometric scale difference between the two models was 5%. This became the design criteria for the ASMAT models.

$$St = \left(\frac{f_1 d_1}{V_1} \right) = \left(\frac{f_2 d_2}{V_2} \right) \quad 1)$$

Once the model scale size had been determined, it was necessary to determine which models needed to be built. The focus was on those systems which affect the noise sources: the geometry of the nozzle exit plane, the deflector upon which the plume impinges, and the reflective surfaces (tower, ML). All these systems were built to 5% scale, referenced to anticipated full scale ground geometries.

Some items were deemed non-critical with respect to the noise source. Omitted geometrical features included the Orion capsule and Ares I protuberances. Additionally, the ASMAT vehicle outer mold line resembled a straight tube except for the transition at the frustum and the first stage aft skirt.

The ASMAT configuration also included an above deck water sound suppression system (commonly referred to as “rainbirds”). Figures 2(a) and 2(b) shows the Space Shuttle above deck water sound suppression system compared to the ASMAT above deck water sound suppression system.



Figure 2: Above deck water sound suppression systems for the Space Shuttle (a) and ASMAT (b).

ASMAT OPERATIONS

The main test operation challenge for ASMAT was to simulate liftoff. The ASMAT vehicle was attached to a thrust plate, which was attached to a telescoping cage. The maximum liftoff acoustic environment is not in the hold down condition but rather at some elevation above the ML. To simulate liftoff, the ASMAT 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 Ares I flight scenarios. Test firings were conducted at elevations of 0, 2.5, 5.0, 7.5 and 10.0 feet (which correspond to full scale elevations of 0, 50, 100, 150 and 200 feet respectively). Figure 3 shows a picture of an ASMAT firing at an elevation of 5 feet.



Figure 3: ASMAT firing at MSFC East Test Area Test Stand 116.

After it was determined which elevation was the maximum liftoff environment (5 feet), the above deck water sound suppression system was tested. During ASMAT, three different ratios of water mass flow to propellant mass flow were tested (2, 3.5 and 4.5).

ASMAT INSTRUMENTATION AND DATA ACQUISITION SYSTEM

Over 200 sensors were required for the ASMAT program, of which the measurement identification ranges, sensor models, sample rate, and locations were captured for each firing in the test definition file. 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). Some monitoring sensors, such as thermocouples, were acquired on the Data Systems Unit at 100 sps. Instrumentation was located on the vehicle, tower, ML (including tower) and launch pad. It is important to note that all the instrumentation remained at their respective locations between tests and were subjected to a variety of outdoor weather conditions during the program's lifetime.

The results presented will focus on the measurements acquired by the Bruel and Kjaer 4944-B microphones that were located on the ASMAT vehicle model. These sensors were located at specific zones that were of interest to the vibroacoustic community.

ASMAT RESULTS

Data Processing

A typical ASMAT pressure time history is shown in Figure 4(a). Dynamic pressure amplitudes show relatively steady levels up to approximately 2 seconds into the firing. This timeframe is when the RATO motor approximately reaches steady state chamber pressure and corresponding thrust operation. For spectral analyses of the ASMAT acoustic data, an analysis window was chosen within the 2 seconds for each test. A consistent analysis window was identified for each test by bounding the timeframe in which the RATO chamber pressure was within 10% of the maximum chamber pressure value. Figure 4(b) shows the analysis window overlaid on ASMAT Test #5's RATO chamber pressure measurement and Root Mean Square (RMS) – based Overall Sound Pressure Level (OASPL) time history. The maximum acoustic level essentially corresponds to the maximum chamber pressure level. The corresponding one-third octave band spectral analysis was performed on this analysis window as seen in Figure 5. All spectral analyses were conducted on 256,000 sps data using a rectangular window. The combination of the data sample rate and chosen analysis window yielded the number of spectral averages to equal seven.

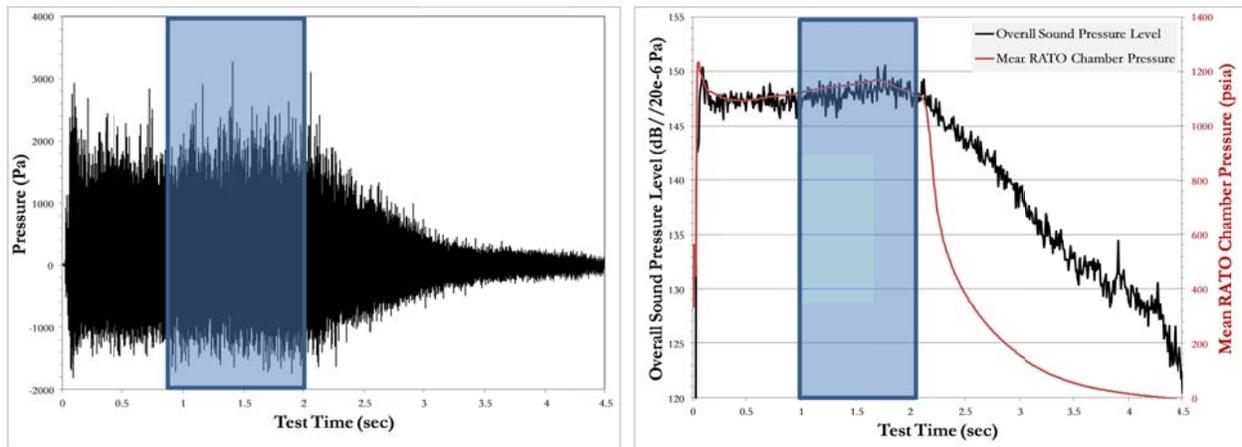


Figure 4: Typical ASMAT pressure time history (a) and analysis window overlaid on a RATO chamber pressure measurement and RMS OASPL time history (b).

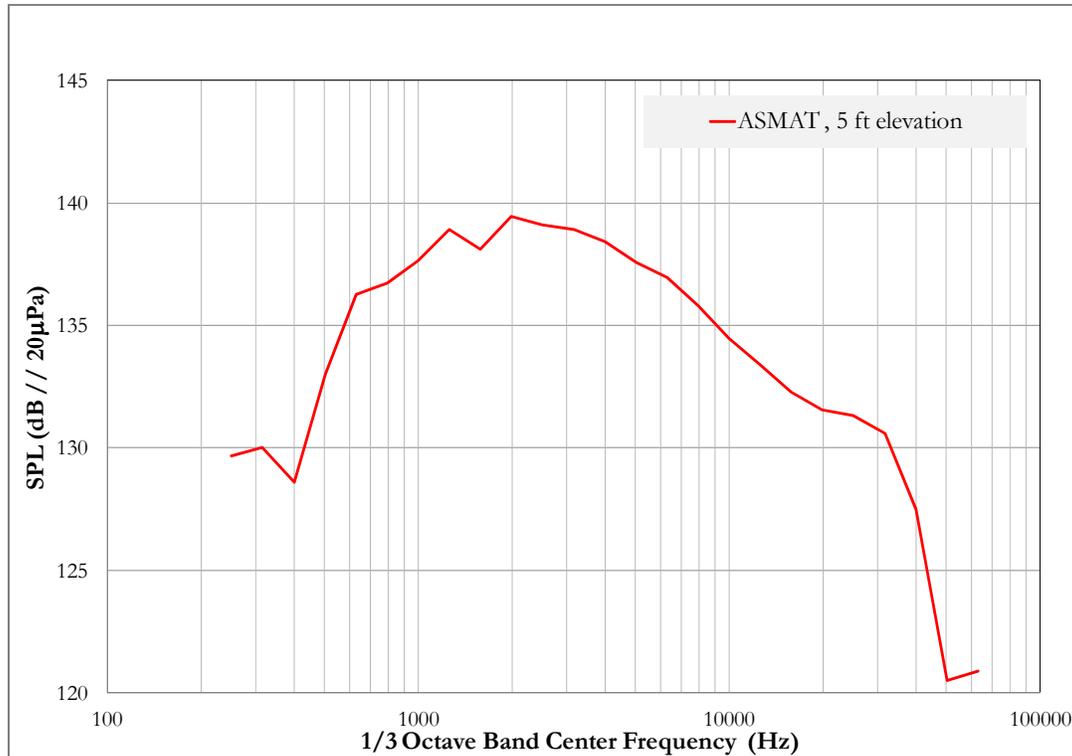


Figure 5: ASMAT 1/3 octave band analysis.

Scaling the Data

The acquired ASMAT data represents LOA environments for the 5% scale model. Representative one-third octave band spectra were scaled using Strouhal number as defined in equation (1) and seen in Figure 6. To make this data “full scale”, i.e. relevant to a launch vehicle, the Sound Pressure Levels (SPLs) are scaled by the ratio of intensities defined in equations (2) and (3). For equation (2), the acoustic efficiencies, η_1 and η_2 , were assumed to be equal. The result is a delta ($SPL_2 - SPL_1$) of -0.5 dB for the ASMAT subscale data to full scale.

$$\frac{I_2}{I_1} = \left(\frac{\eta_2}{\eta_1} \right) \left(\frac{\dot{m}_2}{\dot{m}_1} \right) \left(\frac{V_2}{V_1} \right)^2 \left(\frac{R_1}{R_2} \right)^2 \quad (2)$$

$$SPL_2 = 10 \log \left(10^{\frac{SPL_1}{10}} \left(\frac{I_2}{I_1} \right) \right) \quad (3)$$

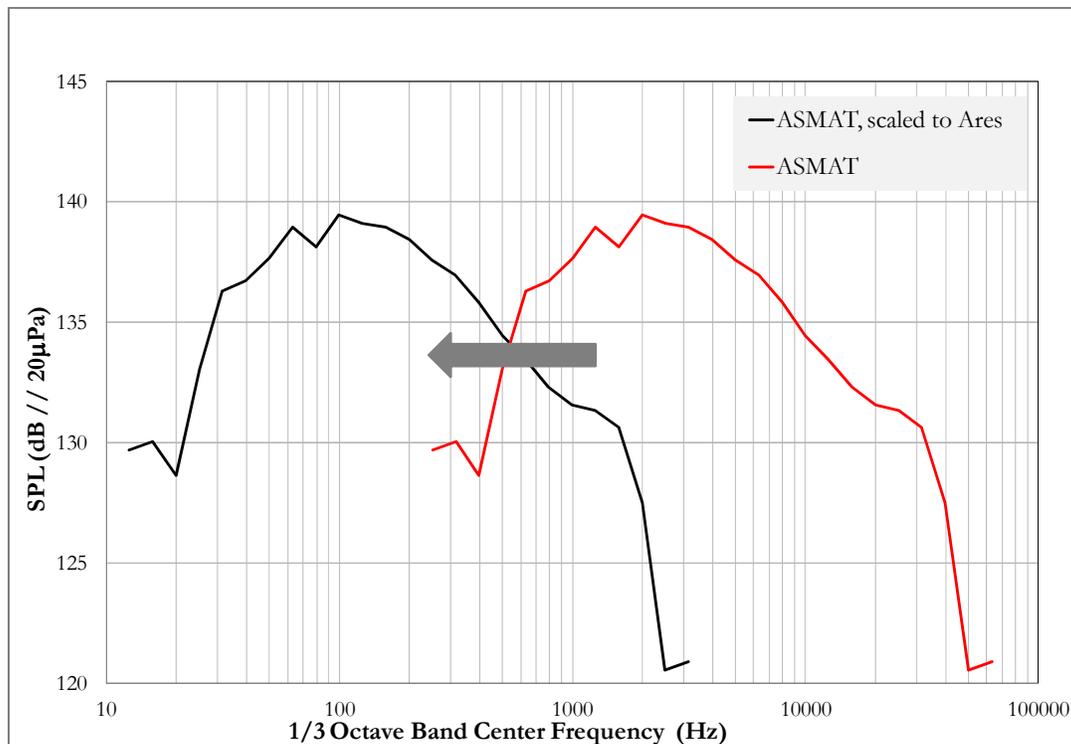


Figure 6: Scaling ASMAT frequencies to full scale.

ASMAT compared to Ares I-X flight data

The Ares I-X was an early proof-of-concept development flight for the Ares I vehicle within the NASA Constellation Program. Measured vehicle acoustic data from the Ares I-X flight presented a unique opportunity to compare the ASMAT results with flight data. Differences between the Ares I-X vehicle and launch support structures and the ASMAT configuration were deemed insignificant when comparing external acoustic environment measurements.

The Ares I-X data was processed using similar spectral resolution and number of averages as with the ASMAT data. The Ares I-X one-third octave band SPLs were determined by averaging the data over 1 second time slices. Data comparisons between the Ares I-X and ASMAT measurements were done at similar vehicle elevations, sensor locations, and at a defined data analysis window that corresponded to the maximum sound level. The Ares I-X time slices that produced the loudest noise levels were typically between 4.5 to 5.5 seconds after solid rocket motor ignition.

A comparison of Ares I-X and ASMAT SPLs are shown in Figures 7 and 8. The ASMAT data from tests designated ‘Vert #5,’ ‘Vert #7,’ and ‘Vert #11’ were scaled to the Ares I-X vehicle. Specifically, the ASMAT measurement located at 9.18 feet on the model is compared to three Ares I-X measurements located at 182.3, 185.3 and 185.9 feet on the vehicle. The ASMAT measurement at 13.7 feet on the model is compared to four Ares I-X measurements at two locations; 272.6 and 274.8 feet on the vehicle. Figures 7 and 8 show excellent agreement for

SPL vs. frequency between Ares I-X data and scaled ASMAT data. The ASMAT data also shows good repeatability between the three tests. Figure 9 shows the OASPLs and the continued trend of good comparison between the ASMAT and Ares I-X data along the height of the vehicle. However, note at around 100 inches, the Ares I-X and ASMAT data “pop out” of the general linear trend. This increase in OASPL is due to the angled surface of the frustum effecting the acoustic wave propagation.

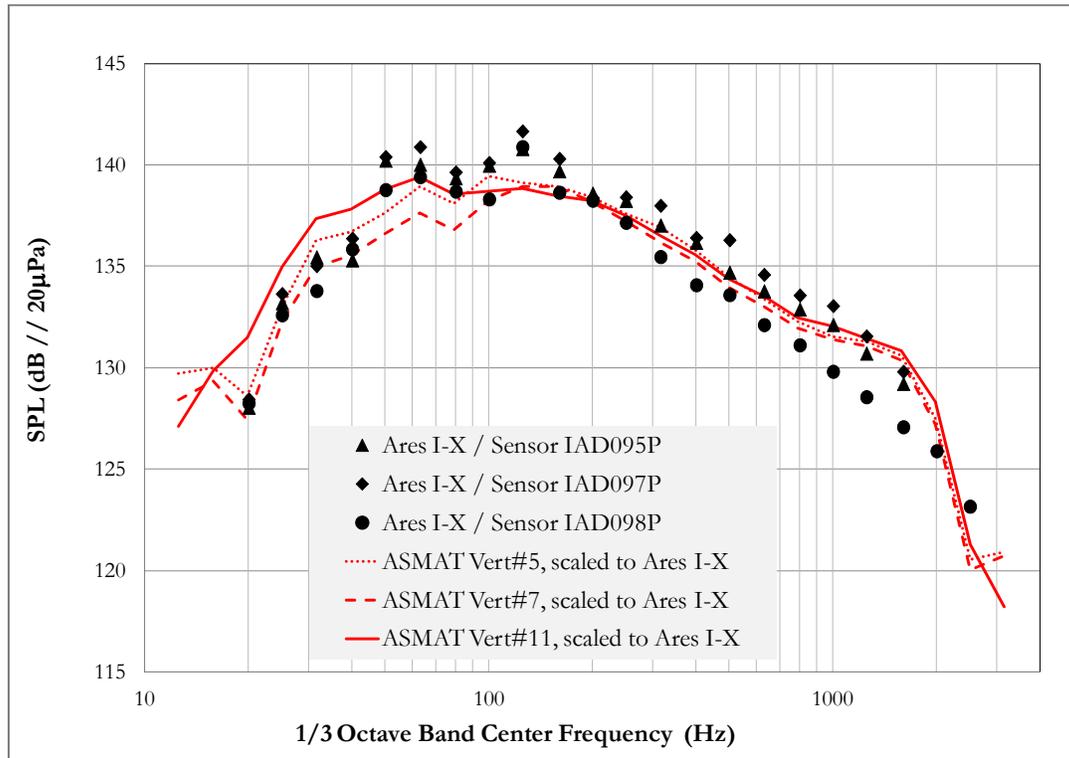


Figure 7: ASMAT versus Ares I-X at ~ 185 feet (full scale) from the nozzle exit plane.

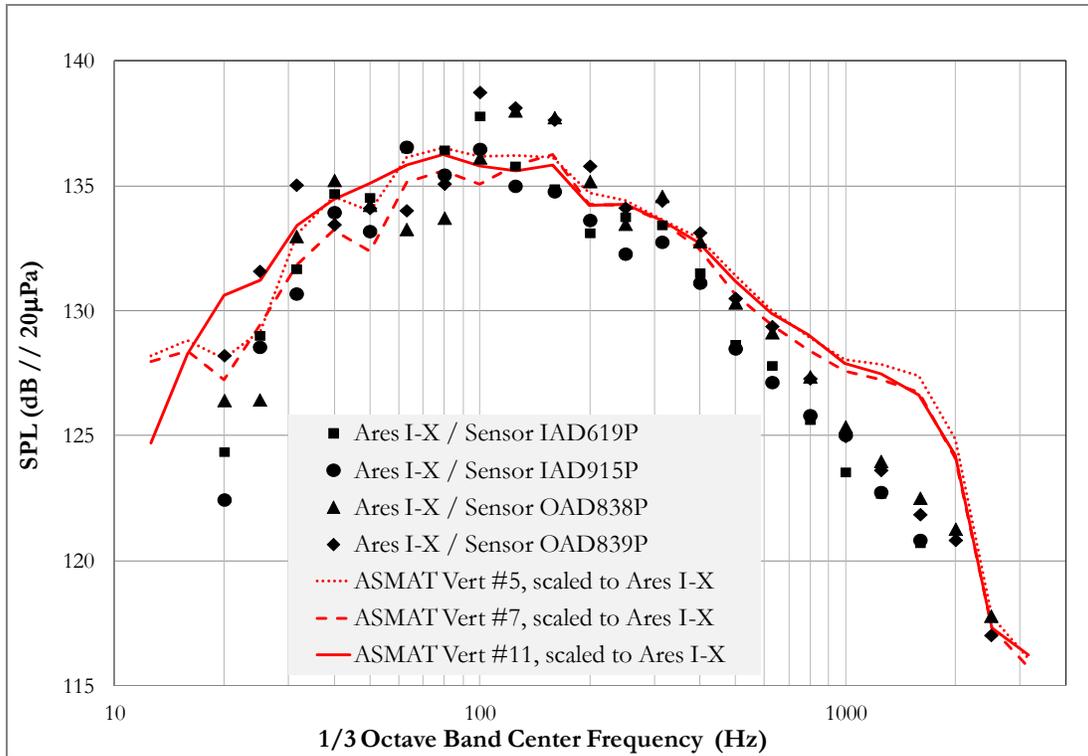


Figure 8: ASMAT versus Ares I-X at ~ 275 feet (full scale) from the nozzle exit plane.

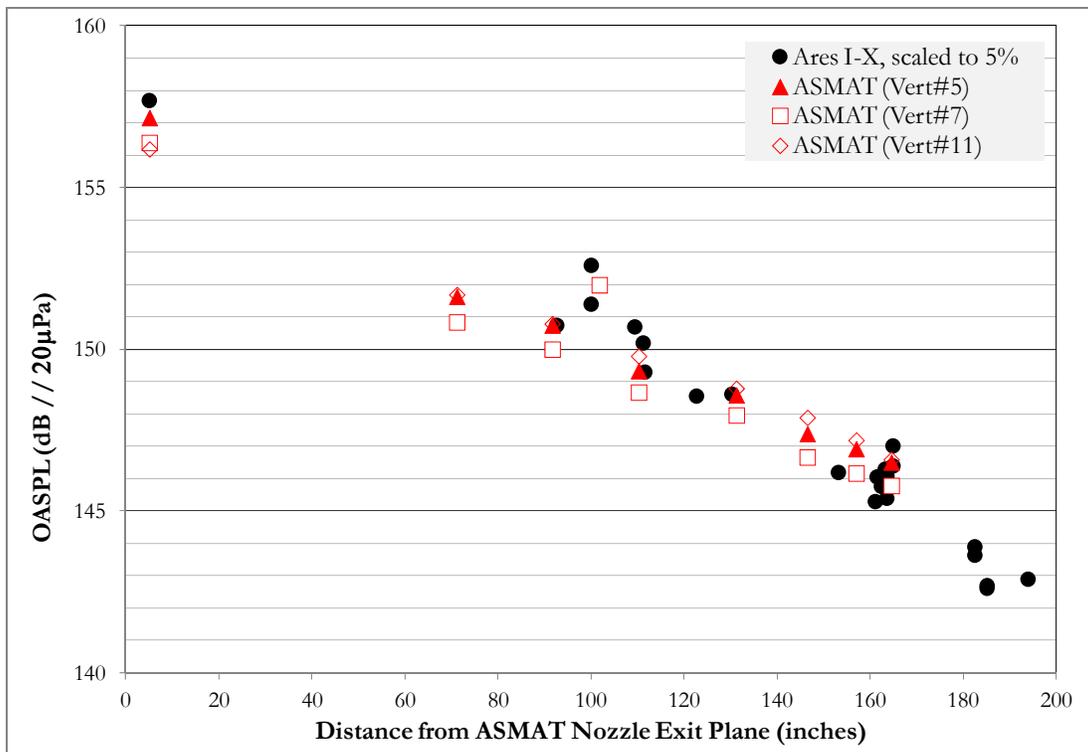


Figure 9: Overall Sound Pressure Levels for ASMAT and Ares I-X.

ASMAT above deck water sound suppression system performance

The ASMAT above deck water sound suppression system was based on the KSC design for the Space Shuttle Program. To assess the effectiveness of the water sound suppression system, the ASMAT program conducted tests with several combinations of water flow rates and vehicle elevations.

Figure 10 shows a comparison of the SPLs with and without above deck water sound suppression, scaled to the Ares vehicle frequency range. The data reflects the test case with the above deck water sound suppression at a water mass flow to propellant mass flow ratio (W_w/W_p) of 3.5, which was shown to provide the best noise reduction. The SPL with rainbirds is significantly lower than without rainbirds.

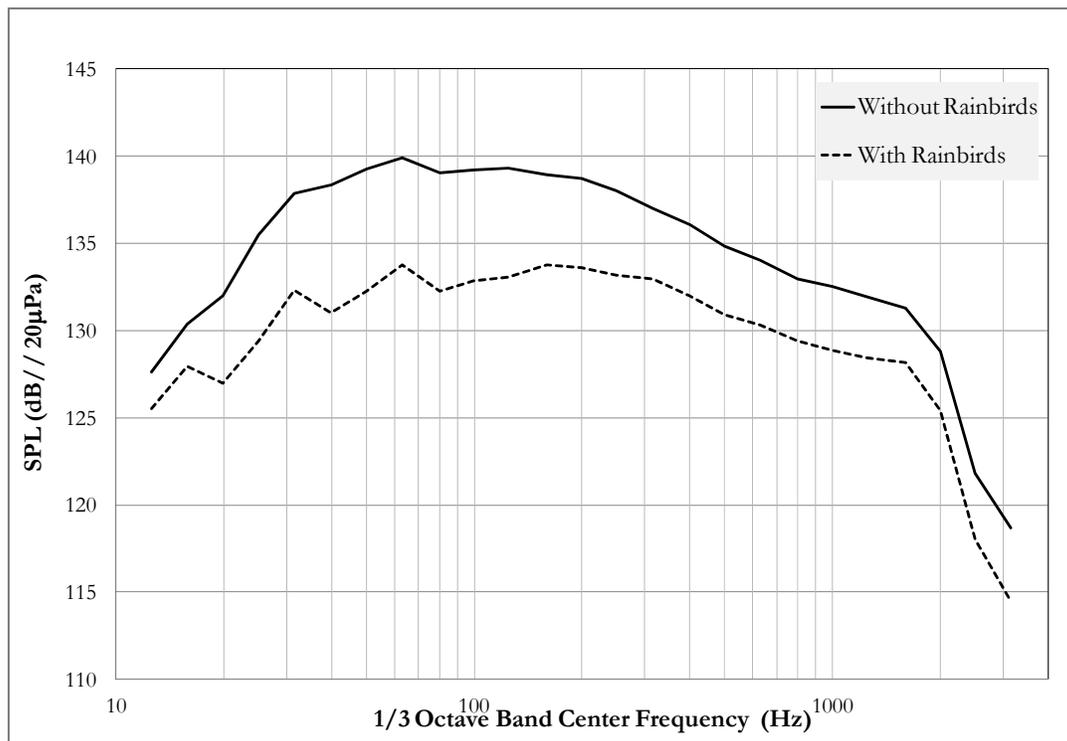


Figure 10: Sounds Pressure Levels versus 1/3 octave band center frequencies with and without above deck water sound suppression.

Figure 11 shows the corresponding noise reduction relevant to the Ares vehicle for each 1/3 octave band center frequencies from 20 to 2000 Hz. These results highlight the fact that the noise reduction is frequency dependent, with the largest reduction of ~5-7 dB in the 20-200 Hz range with the reduction decreasing to ~3-4 dB in the 250 to 2000 Hz range.

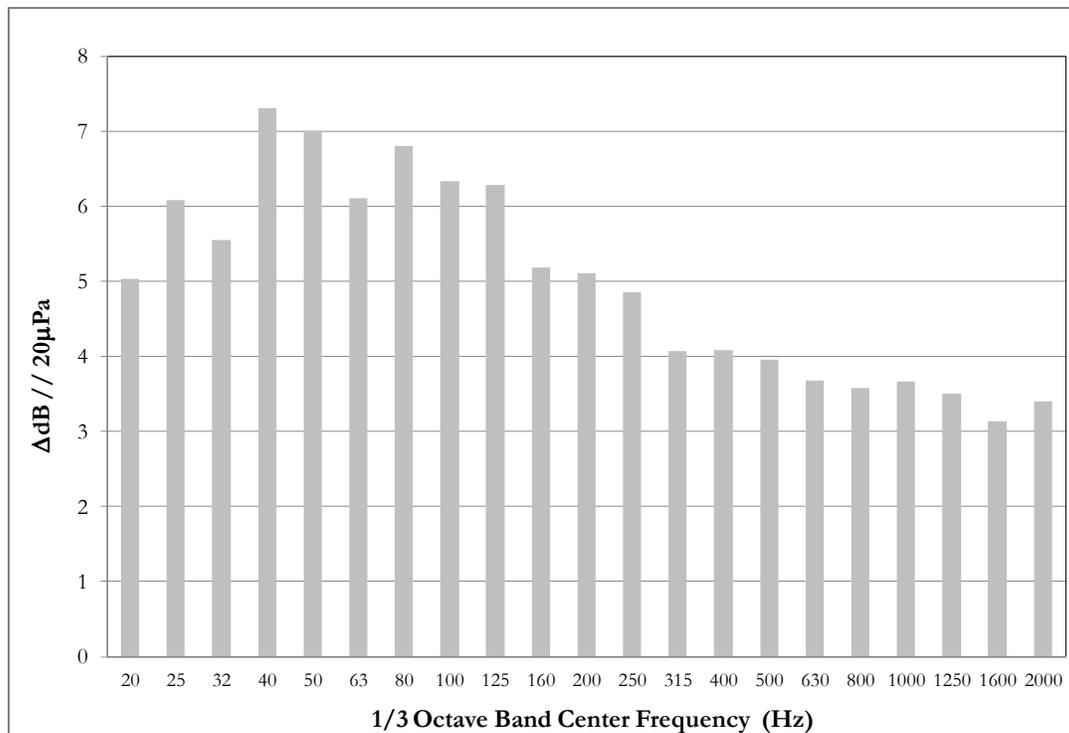


Figure 11: Noise reduction versus 1/3 octave band center frequencies.

The OASPLs are plotted versus the model scale distance on the vehicle from the nozzle exit plane in Figure 12. The figure shows that the OASPL was reduced by ~ 5 dB with rainbirds at a flow rate ratio of 3.5. It also shows that the noise reduction appears to be consistent along the vehicle model.

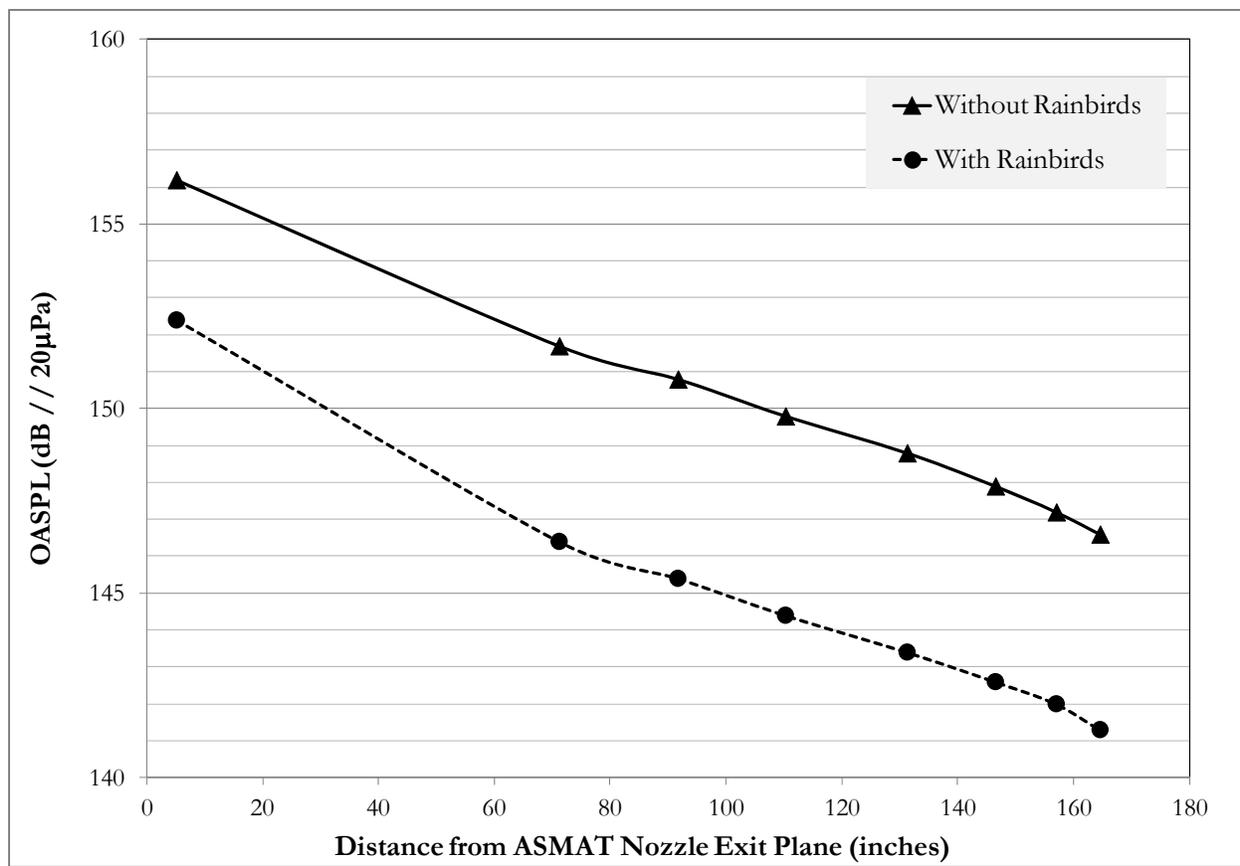


Figure 12: Comparison of Overall Sound Pressure Levels with and without rainbirds.

SUMMARY & CONCLUSION

The results of the Ares I Scale Model Acoustic test conclusively show that the scaling methodology works if care is taken to accurately identify the important variables used to define the scaling parameters. In the case of ASMAT, the relevant variables were nozzle exit diameter, exit velocity and mass flow which were used to scale model Sound Pressure Level measurements to full scale vehicle predictions. The ASMAT data set compares well to the Ares I-X liftoff acoustic flight data. Additionally, the ASMAT data set replicated the Ares I-X measurement which showed that a change in the outer mold line of the frustum yielded an increase in sound pressure level. Conclusively, the Ares I-X flight data validated the ASMAT liftoff acoustic results.

Scale model acoustic testing is an effective method to test mitigation solutions to reduce the LOA environment. ASMAT specifically tested above deck water sound suppression systems at different flow rates. The ASMAT results showed that the above deck water sound suppression systems provided significant reduction, ~5 dB, in the Overall Sound Pressure Levels of the LOA environments and that the best noise reduction occurred with a flow rate ratio of 3.5. It is

recommended that above deck water sound suppression systems be incorporated on future launch systems.

In conclusion, results from ASMAT will be used to determine LOA environments for future vehicles such as NASA's Space Launch System (SLS). The SLS Program has implemented the recommendation to incorporate an above deck water sound suppression system.

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BIOGRAPHIES

Mr. Counter is an aerospace engineer for NASA Marshall Space Flight Center. 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. Currently, Mr. Counter is serving 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 the Technical Fellow in Acoustics for Jacobs Technology in Huntsville, Alabama. 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 test integration engineer for the Space Launch Systems Scale Model Acoustic Test. Ms. Houston holds a BS degree in Astronomy and Physics from the University of Arizona.