Initial Acoustical Findings of the Space Launch System Measurement

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ABSTRACT

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This thesis documents initial findings from far-field noise measurements made at NASA's Kennedy Space Center during liftoff of the Space Launch System's Artemis I mission, which occurred on November 16, 2022. The vehicle – the most powerful ever successfully launched into orbit – consists of four liquid-fueled RS-25 engines and two five-segment, solid-fuel rocket boosters (SRBs). Because this was the first launch, the noise radiation characteristics of this vehicle were previously unknown. Overall sound pressure levels, waveform characteristics, and spectra are described in the results section at distances ranging from 1.5 to 8.4 km. These are calculated from the pressure waveforms and range from 120-140 dB. The levels due to the SRBs' ignition overpressure are particularly intense in the direction of the flame trench exit. The post-liftoff maximum spectrum has an average peak frequency at 10 Hz. The sound levels distance corrected to 100 nozzle diameters was found to average to 142.6 dB. These findings further the understanding of super heavy-lift rocket acoustics.

Keywords: Space Launch System, Artemis I, rocket acoustics

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Chapter 1

Introduction

The successful launch of NASA's Space Launch System (SLS) as part of the Artemis I mission started a new era of space exploration that aims to return humanity to the moon and beyond. This thesis outlines the data collection and initial analyses of BYU's recent acoustical measurements of the Space Launch System vehicle. An introduction to the mission, launch vehicle, and acoustical impact is given below. A measurement overview and goals of this thesis are also stated.

1.1 Artemis Missions

NASA recently completed the first objective of the Artemis program when the Space Lunch System launched for the first time from Kennedy Space Center. This successful flight marked a huge milestone in accomplishing the goals of the Artemis program: land the first woman and person of color on the moon, explore more of the lunar surface, and with the help of commercial companies, establish a long-term presence on the moon. Artemis I was the first mission of the Artemis program, meant to test NASA's Deep Space Exploration Systems, including the Orion spacecraft, Space Launch System rocket, and newly upgraded Exploration Ground Systems [1]. This was the first time these systems were tested in preparation for the manned missions, Artemis II and Artemis III.

1.2 Space Launch System

The Space Launch System (SLS), Figure 1.1, was built specifically for the completion of the Artemis objectives. On November 16, 2022, at 1:47 AM EST, the SLS lifted off and became the most powerful rocket ever successfully launched into orbit. This rocket is capable of a liftoff thrust of 39.1 meganewtons (MN) giving 13 percent more thrust than the previous most powerful rocket, the Saturn V (used in the Apollo missions). The core stage of the SLS is powered by four Aerojet Rocketdyne RS-25 liquid hydrogen-oxygen engines producing a maximum of 7,200 kilonewtons (kN) of total thrust. The two solid rocket boosters are Northrop Grumman five-segment solid-fueled that each amount to 16,000 kN thrust. Since the boosters produce thrust that is an order of magnitude greater than the main core engines, these are expected to dominate the overall noise radiation at liftoff [2].

1.3 Rocket Noise

Noise generation is an important aspect when designing new rockets, like SLS. Every rocket is different, and these differences influence the sound levels produced. Some factors that affect the generated noise include the number of nozzles, nozzle diameter, or exhaust exit velocity [3]. Upon liftoff, launch vehicles eject super-heated gas at supersonic speeds out of the nozzles that create high-intensity noise, potentially creating negative impacts such as payload damage, structural fatigue, and environmental effects [4]. Since there is a large range of potential impacts, models have been created to predict the generated noise [5] [6] [7]. The current models used are largely empirically-based on data that were taken during the early space program in the 1950's and 1960's. These models were not necessarily derived from a physical understanding, meaning the underlying physics are still unknown concerning the noise propagation. This is due to the many complexities that come with the high-amplitude noise such as nonlinear shocks [8] [9], affecting the frequency

Figure 1.1 SLS rocket at Launch Complex 39B.

content of the noise. This and other effects such as atmospheric attenuation can drastically alter the recorded sound levels, creating impacts that cannot be modeled well as of yet, giving a need for more data to be collected. The purpose of collecting and analyzing noise data is intended to determine the physical processes that occur during propagation.

1.4 Measurement Overview

To measure the sound levels produced by the launch, pressure data were recorded by scientific-grade microphones at 10 data collection stations [10] placed at varying distances and angles around the rocket. These different locations were strategically chosen to be able to determine how the sound propagates along different directions. Each station was set up to run independently after initial installation. This was necessary due to the inability to access the equipment near the pad within 24 hours of the launch. Each station, except for Station 10, consisted of at least one GRAS microphone housed in a weather-robust windscreen and ground-plate, computer, data acquisition system, and a solar-charged battery. Station 10 used a 831-C sound level meter with a Piezoelectric 1/2” microphone.

1.5 Thesis Overview

This thesis reports the initial findings given by the data collected during the Artemis I launch. The purpose is to document all of the initial findings for the 10 stations and to do a comparative acoustic analysis relative to other rockets and NASA-predicted levels for the SLS launch at certain locations. Findings include sound pressure levels measured at each station as well as basic spectral analysis. Comparisons are made between stations and a distance correction is used to compare stations located at different distances from the pad. A discussion of the measurement collection system is given to provide an understanding of the veracity of the results.

Figure 1.2 View from the data collection station, Station 02, shown along the coast 4.1 km from the launch pad. The Space Launch System can be seen in the distance near the white dome. Stations include data acquisition devices, under the reflective covering, a solar panel, and microphones that are shielded by a wind screen.

Chapter 2

Measurement Methods

The 10 stations located around the launch pad all recorded data successfully, allowing for a variety of acoustical analyses of the effects of the launch pad environment. It is important to note that the flame trench, a trough used to direct the initial exhaust away from sensitive areas, is pointed toward the north. The stations that best reveal the differences that the flame trench creates are stations 09 and 10. Stations 06, 07, and 05 are the closest locations to the rocket. These stations were placed around the launch pad to determine if there is any difference in the noise radiation at different azimuthal angles. Stations 02, 03, and 04 were placed farther from the pad at 3 to 5 km while 04 was placed near the Saturn V viewing area where patrons could watch SLS launch. Stations 01 and 08 were placed the farthest from the pad to determine noise attenuation in the far field.

2.1 Microphones

The way that data are collected impacts the quality of the information. High-grade equipment leads to more accurate, trustworthy data. Equipment types and sensitivities, especially for microphones, are chosen for specific environments. If the correct sensitivities are not chosen, the signal recorded could be clipped and over-saturated which would make the data unusable. To get the needed

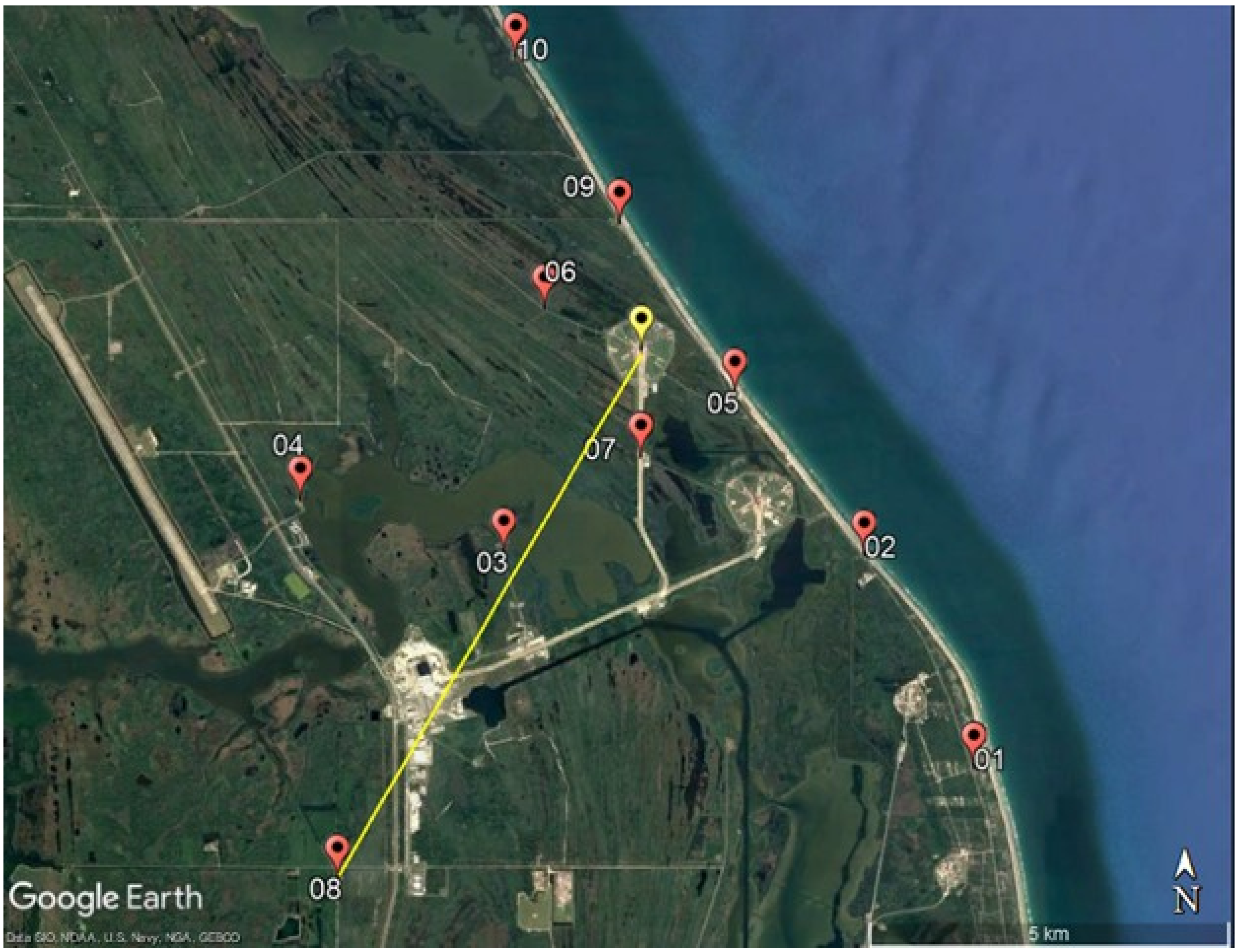

Figure 2.1 Image showing the relative range and varying station locations surrounding the launch pad. The maximum distance of 8.5 km is shown by the yellow line leading from the pad to Station 08. Google Earth Pro. (28° 37’ 35.92”N, 80° 37’ 14.47”W, Eye alt 16.95 km. V 7.3.6.9345) Accessed 02/11/2023.

information from the noise, the equipment and microphones need to be carefully selected and calibrated for their particular location and expected noise levels. In general, microphones capable of measuring infrasound (<20 Hz) are necessary to record rocket launches, as this is where a significant portion of the acoustical energy is present. The stations closest to the pad are the most likely to clip the data, as this is where pressure levels are the highest. At these locations, ¼" GRAS 40BD microphones were used to record the high amplitude pressure waves. These microphones are laboratory grade and have the needed sensitivities to record the high pressures that the rocket produces without clipping. At farther stations, the microphones need to be more sensitive to pick up the lower-amplitude noise farther from the pad. The microphones used at some of the farther stations were free-field ½" GRAS 46BE. The specific choice of microphones near and far from the pad enables the recordings to collect the needed data accurately at varying distances.

2.2 Data Acquisition Equipment

At each location, a Portable Unit for Measuring Acoustics (PUMA) [10] was used to collect data. A PUMA is capable of recording independently for more than 24 hours after its initial installation due to its solar charging capability. An example PUMA setup is shown in Fig. 2.2. Inside each PUMA case, a ruggedized computer was used because of the high temperatures common in Florida. National Instrument data acquisition cards and chassis connected the ruggedized computer to the microphones outside of the case. A program designed specifically for acoustics recordings, named the Acoustic Field Recorder, was used to convert the analog signals to digital binary files. A Compact Outdoor Unit for Ground-based Acoustical Recordings (COUGAR) houses each microphone. These COUGARs consist of a ground plate which mitigates the impact of ground reflections and a windscreen to filter out wind noise. These types of setups have been researched thoroughly by Anderson et al., [10] and are now a staple of any BYU rocket measurement.

Figure 2.2 An example setup of data collection stations. Left: Station 07, Right: Station 03

Chapter 3

Results

This chapter reports and discusses the initial findings from the Space Launch System acoustical measurement. These findings include overall sound pressure levels (OASPL) and spectra from several locations to understand the levels and frequency content of the sound at different distances and angles from the rocket. Important features of the levels and spectra are discussed throughout.

3.1 Overall Sound Pressure Level

In the field of acoustics, different weightings are used to characterize the sound for different scenarios. The most common type of weighting, A-weighting, is used to simulate the response of the human ear based on the equal loudness contour of 40 phon. This contour effectively filters out sound that does not fall within the range of human hearing. While useful for correlating certain sounds with human perception, it is less useful for rocket noise because much of the rocket's acoustical energy is at frequencies lower than are audible to the human ear (infrasound). This weighting is also said to be standard for whisper-like noises. Rockets are much louder than a whisper. As such, for this analysis a flat weighting, or no weighting, is used to create the OASPL and spectra plots to avoid this loss of frequency information. This better characterizes the noise

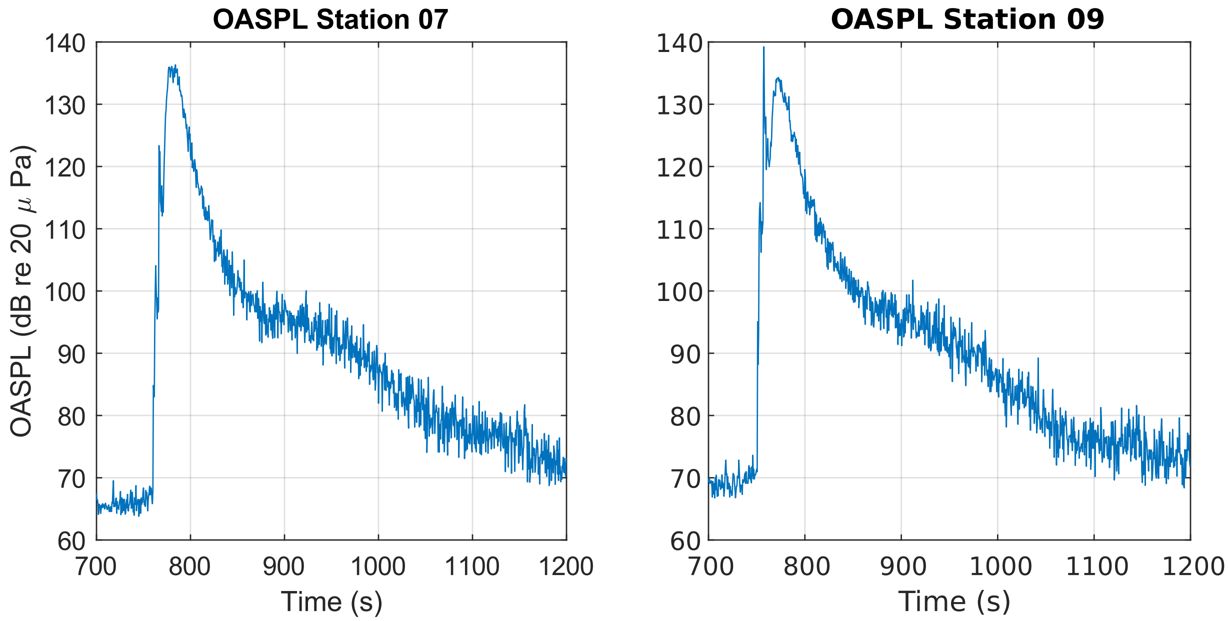

Figure 3.1 Plots of the overall sound pressure level from the Northern (Station 09) and Southern (Station 07) locations that are nearest to the launch site. Station 07 is 1.4 km away and Station 09 is 1.9 km away.

and is better used to create physics-based models. The stations selected for this analysis are the two closest stations that are north and south of the rocket, and the farthest stations north and south. These give an initial understanding of the sound generation near the launch vehicle, how the sound attenuates in the far field, and the importance of noise directionality.

The overall shapes of the OASPL for stations 07 and 09 are similar, which is expected because they are roughly the same distance away from the launch site.**??** The interesting results are where the graphs diverge. Station 09 as seen in Fig.3.1 has a spike around 760 seconds from the beginning of the recording that nears 139 dB. A similar yet less intense peak is seen from Station 07. This spike is evidence of asymmetry in the propagated sound. As previously stated, Station 09 is to the north of Station 07 and the launch pad, in the same direction of the flame trench exit. The spike seen from Station 09 at 760 seconds from the beginning of the recording is determined to be from the ignition of the solid rocket boosters because of how close it is to the beginning of the impulse

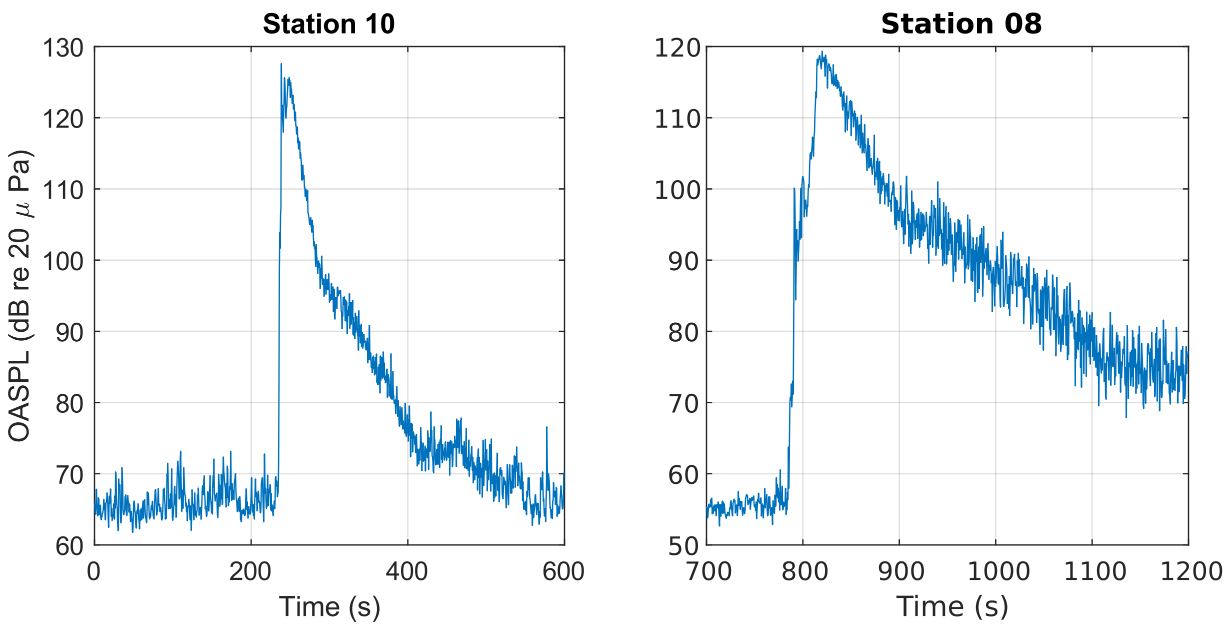

Figure 3.2 Plots of the overall sound pressure levels from the Northern (Station10) and Southern (Station 08) locations. Station 10 is 4.5 km away and Station 08 is 8.5 km away.

from ambient noise. This initial spike in pressure is known as the "ignition overpressure", caused by the ignition of the solid rocket boosters on the vehicle. This spike shows that the flame trench affected the directionality of the sound, funneling more of the sound in the northward direction when compared to Station 07, which is located at a similar distance but on the opposite side of the launch site. After the maximum level, both of these plots appear to die out at the same rate and there are no other major differences to note.

The dissimilarities in the far stations compared to the nearer stations are found in the roll off time of the launch and the maximum levels. To compare max level comparison with distance, Station 08 is twice as far away as Station 10 in Fig. 3.2 and has a 10-dB difference in recorded maximum levels. These stations are shown to characterize how the sound pressure levels change over distance. Station 08 has much lower values compared to any other station due to its distance. Station 10 is closer to the nearer stations but also has lower values. These four stations best characterize how the flame trench affects the sound in the North and South locations.

Figure 3.3 This map shows the maximum sound pressure levels at each station. The yellow marker indicates the location of the launch site, LC-39B. Google Earth Pro. (28° 37’ 35.92”N, 80° 37’ 14.47”W, Eye alt 16.95 km. V 7.3.6.9345) Accessed 02/11/2023.

Station	Max OASPL dBZ	Max OASPL dBA
01	122.4	99.7
02	128.0	106.2
03	130.1	111.9
04	129.1	108.2
05	138.3	119.6
06	138.2	119.1
07	136.2	117.0
08	119.6	98.8
09	138.8	117.0
10	129.5	106.1

Table 3.1 This table shows the maximum overall sound pressure levels of each station that are Z-weighted and A-weighted.

The sound levels at all the other stations are also important and classify the attenuation speed of the noise through the atmosphere. Figure 3.3 shows a map of every station with its corresponding distance and maximum sound pressure level. As has been noticed, the larger the distance, the lower the maximum sound level. The reasoning behind why Station 03 and Station 04 are only 1 dB apart but differ in distance by nearly 2 km will be studied in a later paper.

As stated previously, many in the field of acoustics use A-weighted levels. To compare to other measurements that NASA or other contractors have made, the A-weighted maximum levels are calculated and shown in Table 3.1. The Z-weighted and A-weighted levels show max differences reaching to as much as 23 dB. This is why Z-weighting is used to understand the physics behind the generated sound rather than having an industry standard of A-weighting.

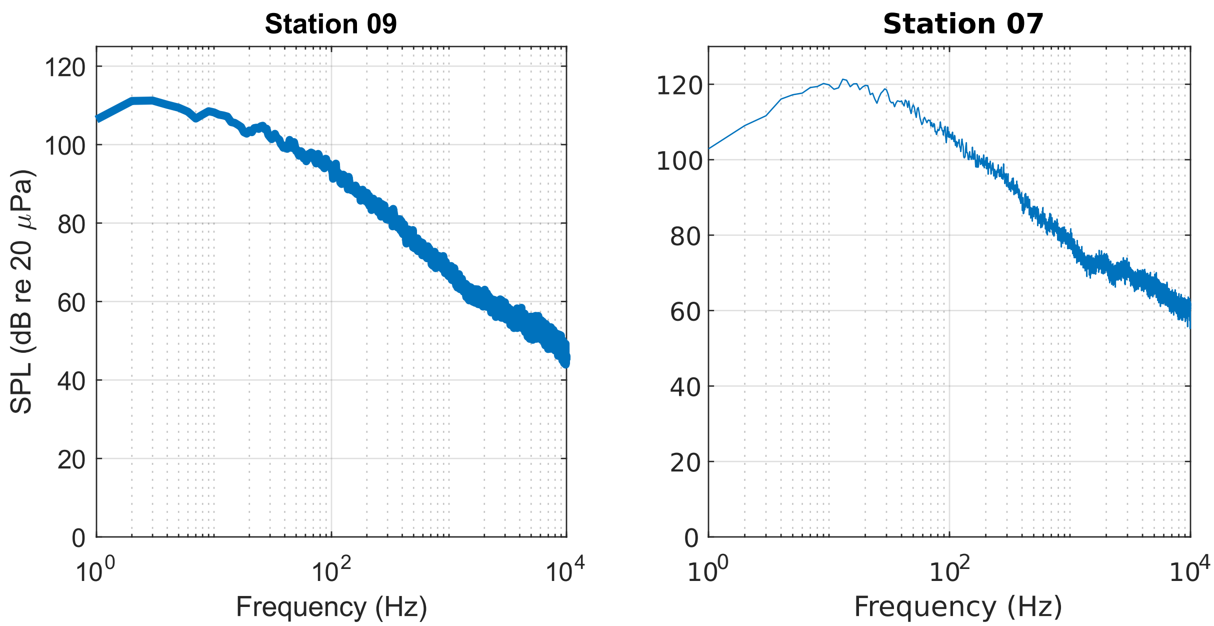

Figure 3.4 Shows spectra from Station 09 and Station 07. The peak frequency for Station 07 is 10 Hz and Station 09 is 2 Hz.

3.2 Narrowband Spectra

A Fourier transform was applied to the recordings to determine the spectral characteristics of the noise. It is important to see at which frequencies the sound is the loudest because the nominal frequency range for the average human is 20 Hz to 20 kHz.

As shown in Fig. 3.3, the highest sound pressure levels for the Artemis I launch are found to be outside the human range of hearing. The peak frequency for this station is 10 Hz, which is in the range of infrasound. Even though humans are not able to hear infrasound under normal conditions, these frequencies have the ability to shake and vibrate structures within the range of the noise. It even has the ability to damage structures. A level of 120 dB is seen at the peak frequency of 10 Hz, showing that a lot of energy is placed below the range of human hearing.

Figure 3.4 has some interesting characteristics. Station 10 has an abnormal shape around its peak frequency and then has some nulls that are around 100-200 Hz. The causes of these are still

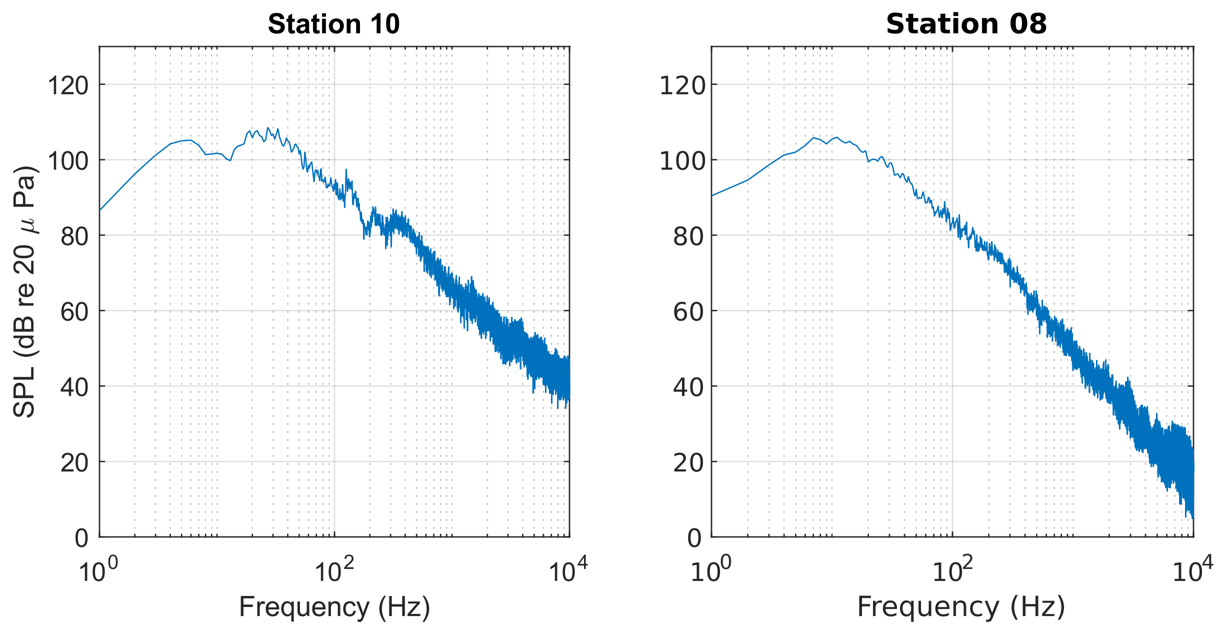

Figure 3.5 Shows spectra from Station 10 and Station 08. The peak frequency for these stations are both around 10 Hz.

unknown but the main takeaway from these graphs is to show that although the stations are at a farther distance, the peak frequencies have not changed. This again shows that the generated noise is within the infrasound range both near and far from the pad.

3.3 Comparative Analysis

Due to the wide variety of launch vehicles, a robust acoustical model is desired to be applicable to all vehicles no matter the configuration. To begin with this process, data are collected from various vehicles and are scaled as to be comparative one with another. This scaling is applied to the data to shift the sound levels of all stations to a single location. The scaling distance from the source used in this thesis is 100 effective nozzle diameters. The effective nozzle area is found by taking the area of each engine exhaust nozzle and combining them as if they were a single nozzle with the total area equal to the sum of the individual nozzles' areas. The effective nozzle diameter of the

Station	Distance-Corrected Max OASPL dBZ
01	142.8
02	143.4
03	143.7
04	146.3
05	144.4
06	144.5
07	142.6
08	141.1
09	142.1
10	145.4
Mean	143.6
STDV	1.6

Table 3.2 This table shows the maximum overall sound pressure levels of each station that are distance corrected to 100 effective nozzle diameters.

SLS vehicle is 7.07 m, making the distance of 100 effective nozzle diameters is calculated to be 707 m. The sound levels from each station will be corrected to this distance to be comparable to each other as well as other launch vehicles. The average sound level correction for all 10 stations at the distance of 100 effective nozzle diameters is 143.6 dB [11] with a standard deviation of 1.6 dB. The values for each station can be seen in Table 3.2.

Another quantitative comparison between different launch vehicles is the calculation of the Strouhal number [12]. This is a nondimensional number that is based on the exit velocity of the plume, Ue, peak frequency, f, and exit diameter of the nozzle, De.

$$Sr = f * De/Ue \tag{3.1}$$

The idea of the Strouhal number is to determine the peak frequency of the generated noise, given the known parameters of the rocket. This number has the potential to be able to scale frequencies determined by vehicle parameters. From the spectrum analysis in 3.2, the peak frequency for all the stations is found to be around 10 Hz. Using this number, the peak Strouhal number is calculated to be 0.059. This number will be used in future comparative work of other launch vehicles.

3.4 Conclusion

These results are just the beginning of what will be done with these data. As discussed, there are interesting characteristics that can be seen as distance and direction from the launch site is changed. As found in the OASPL and spectra plots, there is a clear difference in pressure levels moving azimuthally around the launch site. These changes were caused in part by the flame trench directing the sound northward, resulting in the higher sound levels. The atmospheric attenuation is also seen as it propagates to the farther stations. The average sound level corrected to 100 nozzle diameters was calculated to be 143.6 dB with a standard deviation of 1.6 dB. The peak frequency for all the stations was found to be near 10 Hz. This frequency was used to calculate the peak Strouhal number which is reported to be 0.059. These values of OASPL, spectra and Strouhal number show the strength and characteristics of the sound that is generated by the Space Launch System vehicle. Further analyses will be done to determine the sound power produced by the vehicle and the peak directivity angle of the noise. Other areas of interest that will be studied are the nonlinear properties of the shock content in the noise and the effects of weather on the noise attenuation.

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