POMA Proceedings of Meetings on Acoustics

Volume 51 http://acousticalsociety.org/

184th Meeting of the Acoustical Society of America

Chicago, Illinois

8-12 May 2023

Noise: Paper 1pNS3

# Community-based noise measurements of the Artemis-I mission

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This paper investigates the measured far-field noise from the Space Launch System's Artemis-I mission liftoff. Pressure waveform data were collected at seven locations 12 to 50 kilometers from Kennedy Space Center's (KSC) Launch Complex 39B in Cape Canaveral, Florida. Reported are initial analyses of these measurements outside the perimeter of KSC, including waveform characteristics, overall sound pressure levels, and frequency spectra. Analyses build upon an initial publication [K. L. Gee *et al.*, JASA Exp. Lett. 3, 023601 (2023)] that documented acoustical phenomena at stations 1.5 to 5.2 km from the pad and contributed to a more complete understanding of the noise produced by super heavy-lift launch vehicles. At the stations discussed in this paper, maximum overall sound pressure levels ranged from less than 65 dB to 116 dB with significant variations seen at equidistant locations. As distance increases, one-third-octave band spectra show a significant decrease in peak frequency from 18 Hz down to 3 Hz and a reduction in relative high-frequency content.

Published by the Acoustical Society of America

 https://doi.org/10.1121/2.0001786

## 1. INTRODUCTION

Fifty-seven orbital rockets were launched from Cape Canaveral, Florida in 2022 including forty-eight flights from SpaceX, multiple launches of ULA's Atlas V, and NASA's Space Launch System (SLS) Artemis-I mission. The Apollo program and many American rockets in the early years of the Space Age[1] were launched from Kennedy Space Center (KSC), but today there are nearly thirty active spaceports across the globe. With the launch cadence increasing exponentially during the past five years, a new era of rocket engineering has emerged, resulting in a need for further investigation of the physics behind these powerful systems. A defining characteristic of rocket launches is the sound produced during liftoff. Studying the effects of rocket noise on the vehicle, payloads, launchpads, endangered species, and people is essential to promoting sustainable space exploration.

Many early launch and rocket noise-related studies[2,3,4] were compiled into source modeling approaches found in NASA SP-8072,[5] but subsequent research was relatively limited[6] for decades. Further investigation into rocket noise and its impacts has begun to progress with the development of modern launch vehicles. Current research aims to characterize the sound associated with launch vehicles and build models based on updated knowledge of the noise generation physics.[7] Data from current and historical launches have been evaluated to develop approaches that accurately describe rocket noise and represent acoustic propagation from a launchpad. The findings reported in this article aim to build on past research from various launches, including the Delta IV Heavy,[8] Atlas V,[9] Saturn V,[10] and Falcon 9,[11] and use similar, established methods for far-field rocket noise data analysis. Measuring and analyzing the sound produced by launch vehicles at greater distances furthers an understanding of the noise impacts on surrounding communities.

NASA's SLS completed its successful launch on 16 November 2022 from KSC's Launch Complex 39B (LC-39B). The SLS Artemis-I mission marks NASA's first launch in the Artemis program, which aims to further deep space exploration and land the first woman and person of color on the moon. SLS acoustical measurements were collected and reported in an initial letter published shortly after the launch.[12] Findings from that article include a) the flame trench's role in causing a highly directional ignition overpressure (IOP) event from the solid rocket boosters; b) greater-than-predicted maximum overall sound pressure levels that ranged from 127 to 136 dB (re 20 μPa) at stations 1.4 to 5.2 km from the pad; and c) maximum one-third-octave (OTO) band spectra that peaked around 20 Hz. This prior analysis provided a baseline for further discussion of SLS acoustics, but further work is necessary to more fully understand the noise propagation and prepare for the new generation of super heavy-lift rockets.

This paper evaluates additional analysis made from acoustical measurements gathered during Artemis I. Data are presented from seven community-based measurement stations located 12 to 50 km from the launchpad. Metrics, including maximum overall sound pressure levels and spectra, are compared among the stations that represent a diverse range of distances and natural environments.

## 2. VEHICLE AND LAUNCH DESCRIPTION

SLS is a super heavy-lift launch vehicle whose 8.4 m-diameter core stage is powered by four Aerojet Rocketdyne RS-25 liquid hydrogen-oxygen engines, with two strap-on Northrop Grumman five-segment solid-fuel rocket boosters (SRBs). Including its Orion capsule, SLS stands at 98.1 m tall, with a trans-lunar injection payload capability of 27 metric tons (59,500 lbs).

***Figure 1. SLS Artemis-I ignition overpressure event (visible cloud at bottom left) during liftoff from LC-39B at Kennedy Space Center. Photo Credit: NASA.***

The SLS launch sequence culminated in the early hours of 16 November 2022. At approximately T-4.5 s, RS-25 engine startup occurred, providing ~18% of the total liftoff thrust needed to take the Orion Capsule into orbit. SRB booster ignition, umbilical separation, and liftoff occurred at 1:47:44 am Eastern Standard Time from LC-39B at Kennedy Space Center. SLS remains the most powerful rocket successfully launched into orbit to date, with a combined liftoff thrust of 39.1 MN ($8.8 \times 10^6$ lbs).

The conditions present during SLS's ignition and liftoff allowed for the visualization of pressure waves propagating away from the rocket.[10] As described in the initial publication,[12] the nighttime launch window, humidity, and backlighting coupled with high-intensity pressure rarefactions caused the local atmospheric pressure to drop below the dew point, creating a rapidly moving cloud. At the bottom left of Figure 1, the IOP's high-amplitude rarefaction is seen propagating away from the rocket in the flame trench's direction. The cloud's movement is captured in a launch video presented in Mm. 1 of Ref. 12.

After liftoff, the vehicle executed a roll maneuver at about T+8 s and did not begin to pitch downrange until about T+20 s into the flight. At approximately T+120 s, the SRBs detached, landing in the Atlantic Ocean, and the core stage separated six minutes later, with the liquid engines falling into the Pacific Ocean. Although trajectory data are not yet available, they are unnecessary for the analyses presented in this paper. Future analyses will incorporate the trajectory's impact on the measurements.

## 3. MEASUREMENT DESCRIPTION

A total of seventeen acoustical measurement stations were configured by a team from Brigham Young University (BYU) and Rollins College, with ten autonomous data collection stations located within KSC and seven manned data collection stations off-Center. While similar analyses have been made for several of the stations on-Center,[12] this paper focuses on the data from the manned stations off-Center located 12 to 50 km from LC-39B.

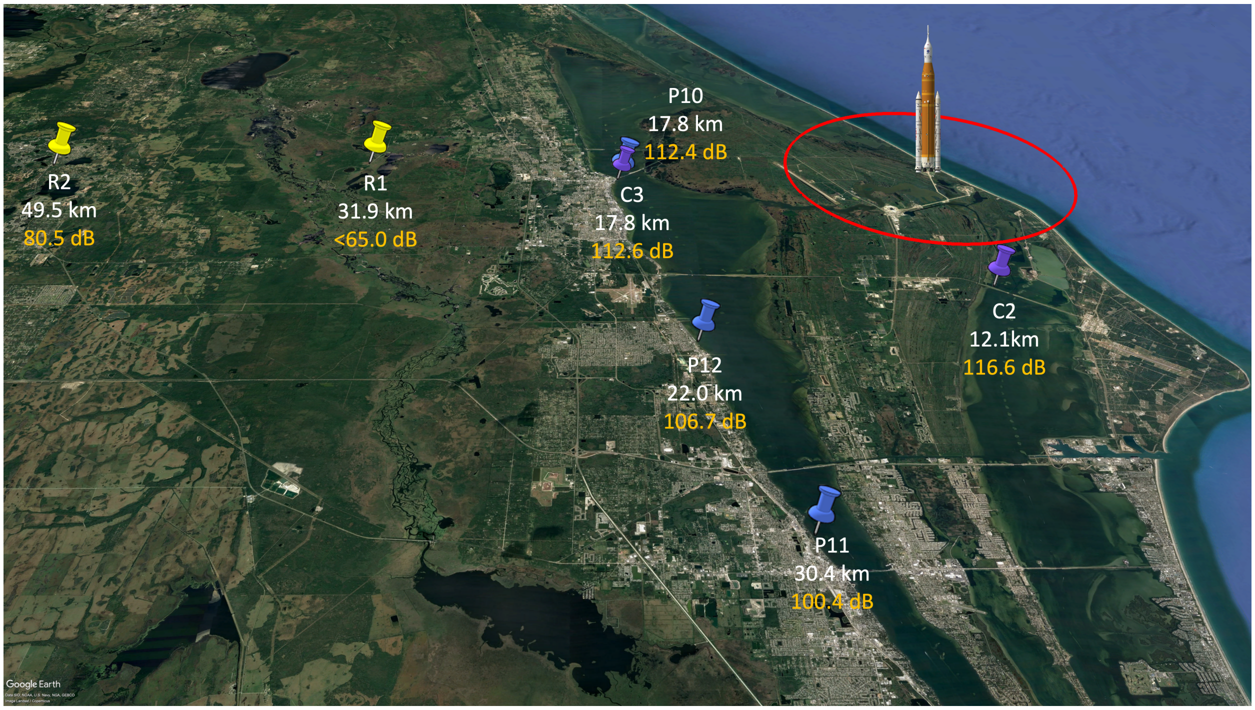


***Figure 2. Seven manned measurement stations are annotated with corresponding distances from LC-39B and maximum overall sound pressure levels. A red circle represents the boundary of the ten autonomous measurement stations configured inside the fence of Kennedy Space Center, not discussed in this paper. SLS is not to scale.***

Three of the seven stations contained hardware identical to the stations located on-Center. Figure 2 shows P10, P12, and P11 (ordered for distance from the pad) located on the Indian River's west bank 17.8, 22.0, and 30.4 km from LC-39B, respectively. Each measurement station consisted of a Portable Unit for Measuring Acoustics (PUMA), which was comprised of a weatherproof case with a ruggedized computer, a GPS time clock for synchronization, NI 9234 24-bit/5-V data acquisition modules sampling at 51.2 kHz, and a lithium-ion battery.[13] Microphones used with the PUMAs were GRAS 12.7 mm (1/2 in) 146AE condenser, free-field microphones (3.15 Hz-20 kHz) that were set up inverted above a 40.6 cm (16 in) plastic circular ground plate under a foam windscreen with a 3.8 cm (1.5 in) uniform thickness. This configuration, nicknamed the Compact Outdoor Unit for Ground-based Acoustical Recordings (COUGAR) at BYU, is seen in Figure 3 and has been successfully utilized at multiple rocket launch,[8,9] sonic boom,[14,15] and jet noise measurements.[16] Several different COUGAR variations have undergone tests to determine the effects of the windscreen thickness and the ground plate's size on the recorded noise.[17] During the Artemis-I launch, a smaller version with a 25.4 cm (10 in) ground plate and a windscreen with a 4.7 cm (1.85 in) thickness was compared to the traditional COUGAR at P10, as shown in Figure 3a. Additionally, Figure 3b shows the P11 PUMA with the COUGARxt, which employs a thinner 40.6 cm (16 in) ground plate and thicker windscreen with a 7.6 cm thickness and a 30.5 cm outer diameter.

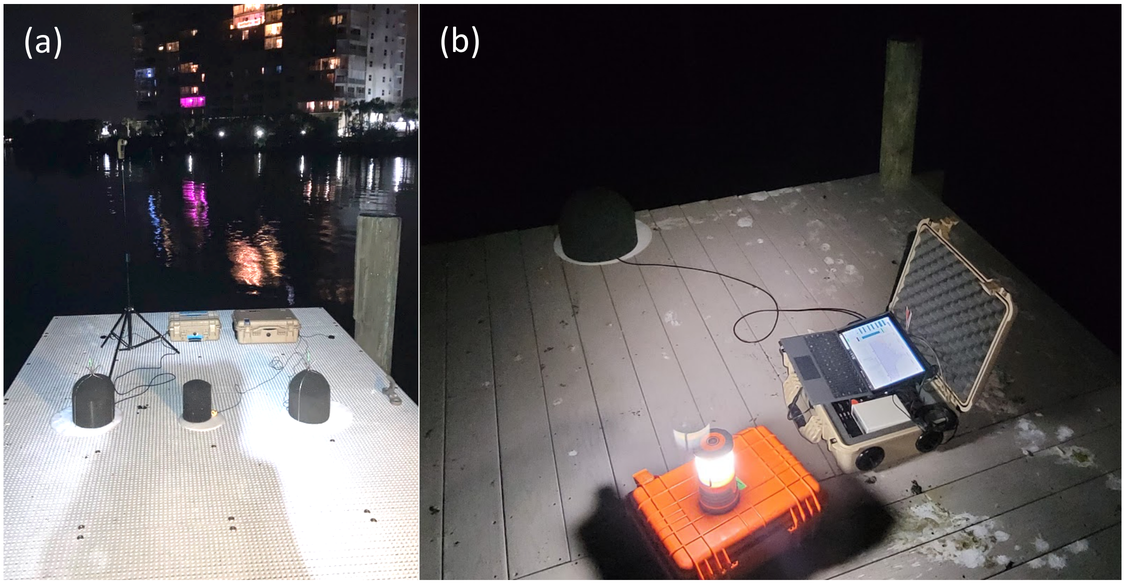


***Figure 3. Three measurement stations reported in this paper. Pictured is the following: a) C3 contains a SLM case (left) with a microphone housed in a COUGAR (left) and P10 contains a PUMA case (right) with two microphones housed in a COUGAR (right) and a small COUGAR prototype (middle), b) P11 contains a PUMA case (brown) with a microphone housed in a COUGARxt.***

The third COUGAR at P10 (far left of Figure 3a) housed a PCB 377B02 12.7 mm (1/2 in) free-field prepolarized condenser microphone connected to a Larson Davis SoundAdvisor 831C Class 1 sound level meter (SLM) sampling at 51.2 kHz. This system was used previously for rocket launch measurements in Ref. 18 and was being tested for comparison to data collected by the original P10 COUGAR configuration, on the far right in Figure 3a. Three SLMs were used during SLS's launch, with two stations off-Center at manned measurement stations.

The remaining two far-field stations in Figure 2, R1 and R2, were placed along an approximate radial directly to the west of the pad. These locations included ACO Pacific 12.7 mm (1/2 in) free-field microphones (2 Hz-120 kHz) with WS1 standard windscreens and a PS9200 ACOustical Interface system contained in a custom-designed storage kit. Measurements were collected at a 40kHz sample rate and stored on a computer for later analysis. At R1, the microphone was approximately 2.4 m (8 ft) above the ground and placed in direct line-of-sight to the launch pad. At R2, the microphone was approximately 1.5 m (5 ft) above the ground with trees that obstructed a view of the pad. The microphones were pointed towards the launchpad and located 31.9 km (R1) and 49.5 km (R2) from LC-39B, as seen in Figure 2.

## 4. ANALYSIS

This analysis provides an initial assessment of far-field data from the seven manned measurement stations during SLS's launch. Findings discussed include waveform characteristics, overall sound pressure levels (OASPL), and narrowband and OTO band spectra.

### A. SOUND PRESSURE LEVELS

#### I. PUMA STATIONS

Waveforms and corresponding OASPLs for P10, 12, and 11 are displayed in Figure 4a, 4b, and 4c where the stations were located on the Indian River in an approximate diagonal southwest of LC-39B. The manned stations' ambient environments differed significantly, which is reflected in their prelaunch noise levels. P10 and P12 had ambient levels of ~70 dB due to nearby traffic noise and celebrations. However, P11 was in a residential neighborhood where ambient noise levels were ~55 dB prior to the launch. In Figure 4a, the SRB's ignition overpressure at P10 is observed in both the pressure waveform and the 1-s averaged OASPL, marked by a sharp peak in sound levels around 50 s after liftoff. However, because the IOP was directed north toward the flame trench, at P12 and P11, located southwest of the pad, there is only a slight peak in levels. Although maximum post-liftoff levels decreased as measurement locations moved farther to the south, the largest difference between ambient and maximum levels was observed at P11 because of its low-level ambient environment, as shown in the OASPL comparison plot in Figure 4f. Understanding the difference between ambient and launch levels for SLS is important for community noise considerations in Cape Canaveral and surrounding areas on Florida's Atlantic Coast.

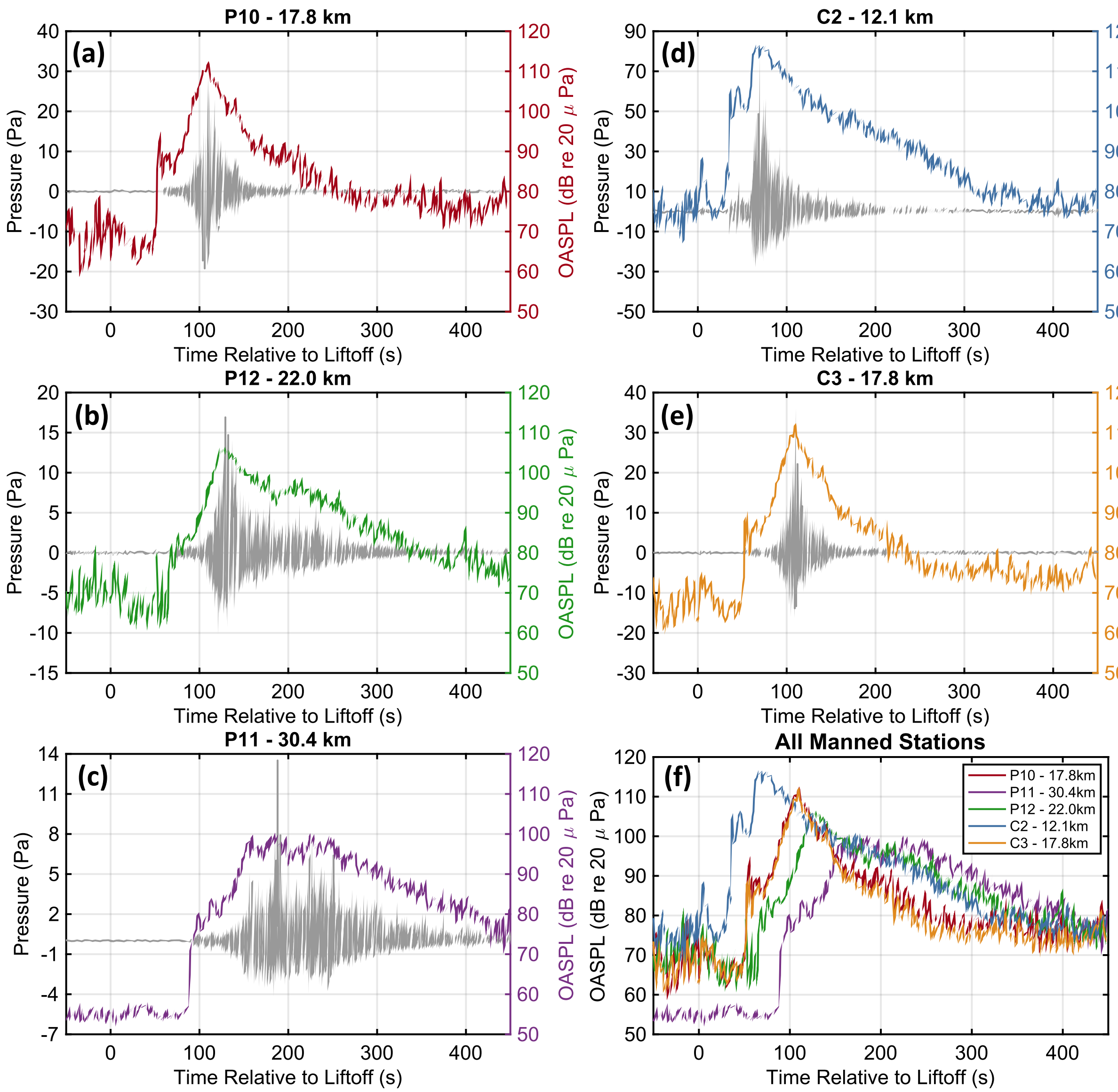


***Figure 4. Measured waveforms and corresponding maximum OASPL for stations P10 (COUGAR), P12, P11, C2, and C3 listed in order of increasing distance from the pad. Plots on the left contain waveform segments from PUMA stations and plots on the right contain waveform segments from SLM stations. All measured OASPL curves are plotted in (f).***

Waveform characteristics from P10, P12, and P11 all differ significantly and reflect the variation in distance from the launchpad. Figure 4a displays the rocket noise from SLS recorded at P10 containing a sharp peak around 110 s and then a gradual decline from the maximum level. Figure 4b shows a similar peak at ~120 s and a corresponding decline for P12, but this waveform peaks a second time at ~210 s. In Figure 4c, the waveform for P11 has a significantly different shape with a more gradual increase in sound levels and flat maximum region from ~150 – 250 s, except for a singular bang of nearly 14 Pa. These overall level trends will eventually be analyzed in conjunction with trajectory and weather data.

While there is likely still significant low-frequency rocket noise recorded beyond the abscissa limit in Figure 4, all waveforms were trimmed at 450 s due to noise contamination from surrounding crowds. As seen in Figure 4f, the three PUMA stations reach sound levels of ~75 – 80 dB at the end of the observed window, and none of these stations had returned to their prelaunch ambient levels. Although microphones were initially placed a significant distance from observers, data collected at manned stations are often limited by spectators, traffic, etc. that interfere with late-launch recordings.

Results from the P10 COUGAR microphone are shown in Figure 4a; the smaller COUGAR prototype results are not shown because they are nearly identical – maximum levels differed by 0.1 dB. This provides further evidence beyond Ref. 17 that the windscreen thickness and plate size have little effect on the recorded measurement and advances the concept of a more compact measurement system for future field tests. Additional comparisons between the OASPL from P10 and C3 were made, and maximum levels differed by 0.2 dB. The differences recorded between these three configurations pictured in Figure 3a are insignificant when compared to the distance these stations were from the pad, minor setup differences including proximity to dock pilings, and any slight microphone calibration variations. The SLM at C3 requires less setup and the smaller COUGAR prototype is more transportable than the original COUGAR, but all three configurations provided accurate data for analysis and can be used independently at future launch measurements.

### II. SLM STATONS

Pressure waveforms and the time-dependent OASPL from the SLMs used at stations C2 and C3 are included in Figure 4d and 4e. Prelaunch ambient levels at C2 (as seen in Figure 4d) were notably louder than the other manned stations due to this microphone's proximity to a crowd of observers. This station's waveform shows a sharp peak in levels at 0 s that is from cheering and not rocket noise, given that C2 was placed 12.1 km from the pad and the IOP took about 36 s to arrive.

The SLM at C3 also detected the SRB ignition, similar to the P10 COUGAR and smaller COUGAR prototype configured in the same location. Waveform characteristics from C3 in Figure 4e are nearly identical to P10 in Figure 4a due to the collocation of these measurement stations. Both SLM stations returned to post-launch levels at a rate similar to the PUMA stations at 450 s, as seen in Figure 4f.

### III. ROLLINS STATIONS

The "R"-labeled stations in Figure 2 were recorded by students and faculty from Rollins College and are referred to as Rollins stations in this section of the paper. Whereas the maximum OASPL at C2 reached 116.6 dB at a distance of 12.1 km, at R2 levels reached 80.5 dB nearly 50 km from the pad. This level is significantly less than predicted when using a simple spherical spreading model that uses measurements made on-Center, closer to the pad. The closest autonomous measurement station (Station 7) during SLS's launch was 1.48 km from the pad and recorded levels of 136.1 dB.[12] Employing spherical spreading from this measurement station, levels should be 118 dB at 12.1 km and 106 dB at 49.5 km, revealing that there is an additional, substantial loss in low-frequency acoustic energy as the sound waves propagate from the source. However, given vehicle motion and trajectory and atmospheric variability and absorption, it is reasonable that a simple spherical spreading model does not hold. More detailed atmospheric propagation analyses, including numerical modeling, will be the subject of further investigation.

As further evidence of complex atmospheric propagation, the sound levels observed at P11 and R1 were markedly different. Both stations were located approximately 30 km away from LC-39B, with R1 located due west and P11 southwest of the pad. The maximum OASPL at P11 was 100.4 dB, but R1 levels did not exceed 65 dB, the maximum level associated with the prelaunch ambient noise. Observers at R1 reported only hearing a brief low-frequency thumping and no additional rocket noise, providing further support for the recorded low levels. With a source level of 136.1 dB at 1.48 km from the pad,[12] a 26 dB decrease in measured level should occur 30 km from the pad. Although this is a simplified model, the maximum OASPL measurements at P11 and R1 would both be 110 dB. While P11 is ~10 dB lower, R1 is at least 45 dB lower than this prediction. It is notable the launch was clearly audible (maximum level of 80.5 dB) 20 km farther west at R2, evidence that there are complex meteorological effects influencing the propagation. Although an explanation is still being sought, one possible contributor is that the path toward P11 from the launchpad was mostly over the Indian River, while there was mostly dense vegetation and urban areas between the pad and R1. Differences in near-ground temperature gradients across these propagation paths could begin to offer a possible explanation for the variation in level at R1 and P11.

### B. SPECTRA

Spectra are briefly discussed from six manned measurement stations (P10, P12, P11, C2, C3, and R2) to complete this paper's analyses. Figure 5 displays the narrowband and OTO band spectra calculated using the waveform segment corresponding to the 3 dB-down period relative to the maximum OASPL. Because the narrowband and OTO spectra follow the same overall trends, the narrowband spectra are shown but the discussion is restricted to the OTO spectra. It is noteworthy that the P12 spectra in Figure 5b show a peak at ~3 kHz that is uncharacteristic of rocket noise and likely indicates environmental noise at this manned measurement station.

Two observations are made from the OTO spectral comparison in Figure 5f. First, the high-frequency energy present in the spectra steadily decreases with distance. Whereas the on-Center measurements[12] had a 10 dB/decade high-frequency roll-off characteristic of significant shock content, the manned stations' spectra contain less high-frequency energy. This relative reduction in high-frequency content means that shocks have significantly thickened by the time the sound reaches these stations. These deviations become more prominent as distance increases, with C2 at 12.1 km containing more notable shocks (more high-frequency content) and P11 at 30.4 km containing very little shock content. However, nonlinear propagation events are still observed at these locations. At P12, the continuous rumble was accompanied by discrete "thumps" that signaled the arrival of significantly thickened shocks.

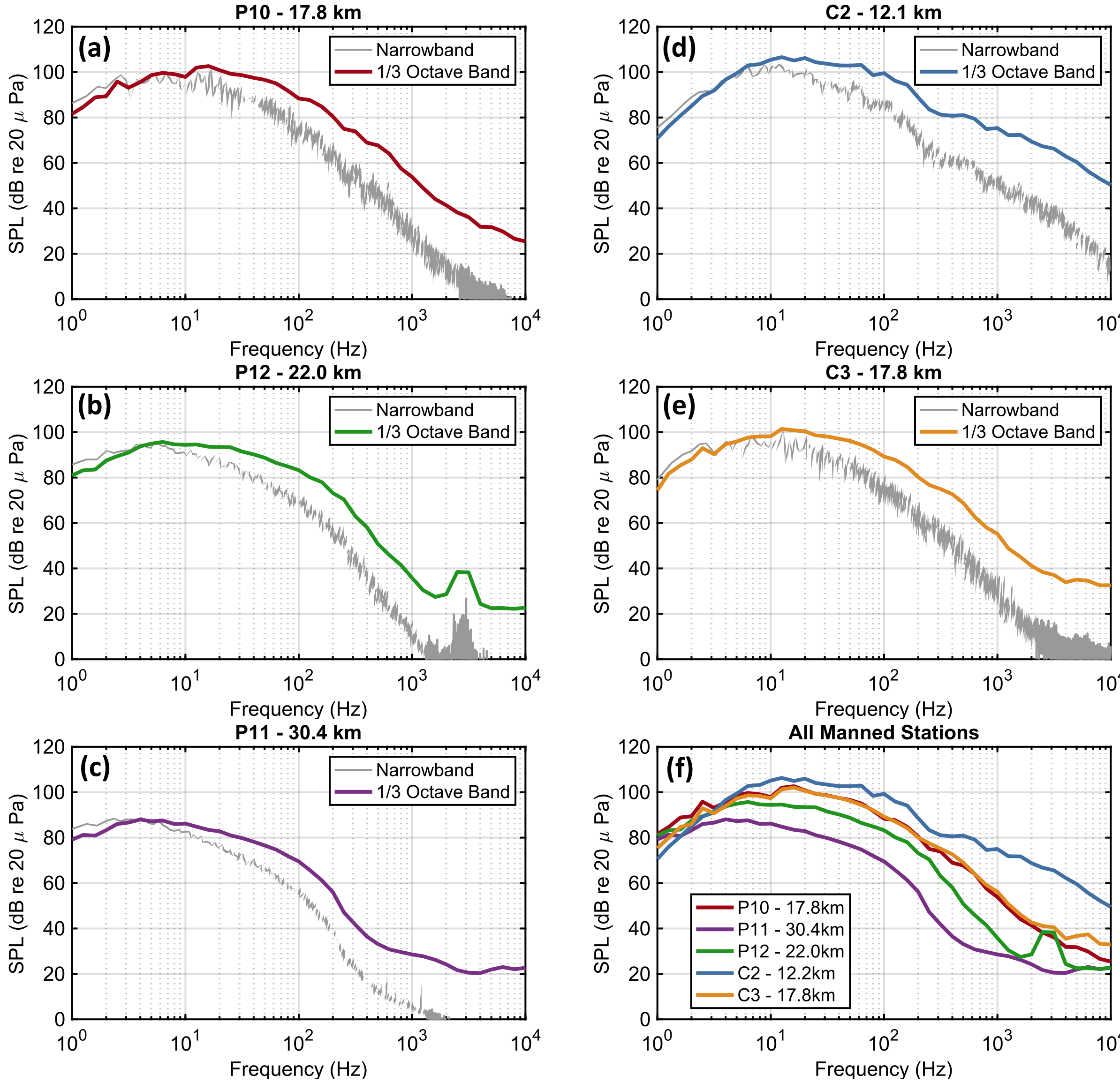


***Figure 5. Narrowband and one-third-octave band spectra for P10 (COUGAR), P12, P11, C2, and C3 listed in order of increasing distance from the pad. Plots on the left contain spectra from PUMA stations and plots on the right contain spectra from SLM stations. All one-third-octave band spectra are plotted in (f).***

The second observation regards the spectral peak frequency. The OTO spectra from the on-Center stations' analyzed in Ref. 12 all peaked at around 20 Hz, but off-Center there is a steady decrease in peak frequency with distance. Peak frequency was extracted from the OTO spectra by using a second-order polynomial fit around the 6 dB-down region of the spectrum. Figure 5f shows slight differences in low-frequency behavior at collocated stations C3 and P10 and, given that values were rounded to the nearest hertz, this accounts for the 2 Hz discrepancy in peak frequency. Table 1 displays these OTO peak-frequency values, which range from 18 Hz at C2 and 3 Hz at R2. The reason for this peak-frequency shift could include vehicle trajectory, nonlinear propagation phenomena, and greater-than-expected atmospheric attenuation. For the nominal near-ground atmospheric conditions during the launch, much less than 1 dB in ordinary atmospheric absorption is expected over 50 km below 10 Hz. This downward shift in peak frequency will be the subject of further analysis because of its implications for community-impact assessment.

***Table 1. Peak-frequency values extracted from OTO spectra at manned measurement stations during the launch of SLS Artemis I.***

| Station | Distance from LC-39B (km) | Peak Frequency (Hz) |
|---|---|---|
| C2 | 12.1 | 18 |
| C3 | 17.8 | 16 |
| P10 | 17.8 | 14 |
| P12 | 22.0 | 10 |
| P11 | 30.4 | 6 |
| R2 | 49.5 | 3 |

## 5. CONCLUSION

This paper has reported further findings of acoustical measurements from NASA's SLS Artemis-I mission, with a focus on the data collected at manned stations off-Center. At 12.1 km from the launchpad, maximum overall sound pressure levels (OASPL) reached 116.6 dB, while 49.5 km from the pad, a maximum level of 80.5 dB was observed. Notably, at one intermediate location (R1, 31.9 km from the pad), the launch was barely audible, suggesting complex atmospheric propagation effects. A spectral analysis has shown that the relative high-frequency content diminishes with distance, suggesting thickening of shocks present in the propagating noise. Spectra also show a downward shift in peak frequency with increasing distance between the station and pad. The range of peak values is lower when compared to measurement stations on-Center[12], which had a fairly consistent peak around 20 Hz; here, peak frequencies of 18 Hz at 12.1 km and only 3 Hz at 49.5 km were observed. Further data analysis will be completed once SLS's trajectory data are available, including sound power and rocket directivity.

NASA's successful Artemis-I mission marks the beginning of a new era in American space exploration. This paper's results will aid in preparations for acoustical measurements of Artemis II, which is scheduled to launch four astronauts around the moon in 2024. And, as the global space industry continues to expand at a rapid rate, investigation of super heavy-lift launch vehicle noise radiation, propagation, and reception will help determine its impacts on launch facilities, surrounding communities, and natural habitats.


## ACKNOWLEDGMENTS

The authors would like to acknowledge Mark C. Anderson, J. Taggart Durrant, Levi T. Moats, Logan T. Mathews, and Michael S. Bassett for their contributions to the measurements described in this paper.


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