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Overview and spectral analysis of the Falcon-9 SARah-1 launch and reentry sonic boom

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The last two years have seen more orbital rocket launches than any period in history, exposing launch pads, natural environments, and communities to large acoustical loads. This paper is part of an ongoing effort by BYU to disseminate the results of acoustical measurements of these launch vehicles. Specifically, this paper summarizes BYU's measurement and analysis of the Falcon-9 SARah-1 launch and landing out of Vandenberg Space Force Base in June 2022. This measurement differs from typical launch measurements due to the sonic boom created by the reentry and landing of the first-stage booster. In total, 9 measurement stations were set up at locations between 400 m and 15000 m from the launch pad, and each station successfully recorded the launch noise and reentry sonic boom. Several metrics are reported for both the launch and sonic boom at each station and compared with a previous measurement. Additionally, spectral analysis shows the sonic booms to peak at a lower frequency than the launch noise, and that they spread cylindrically rather than spherically. No evidence is found of a decrease in peak frequency at stations farther from the pad.

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1. INTRODUCTION

With a new space age starting around the world, more rockets are launching than ever before.[1] These rockets send satellites to orbit, place rovers on the moon and Mars, and launch probes into deep space. NASA even hopes to send astronauts back to the moon this decade, a goal that seems promising after the successful launch of its Space Launch System (SLS) rocket.[2,3] Meanwhile, private companies are developing new technologies (i.e., reusable boosters[4]) that expand the boundaries of aerospace.

While this new age of space exploration is exciting, it introduces many challenges. One such challenge is that with an increasing number of launches comes an increasing amount of environmental and community exposure to the intense acoustics of a rocket launch.[5,6] Rocket launch acoustics[7] are so intense that they can damage launch pads, harm the payloads inside the rocket, impact the environment near the launch pad, and disturb nearby communities.[8] Current research on rocket acoustics aims to improve understanding of rocket noise generation and propagation to create new models and better quantify the impacts of each launch.[9] This research includes understanding the impact of sonic booms[10] from reentry into Earth's atmosphere by space vehicles,[11] which is a major focus of this paper.

Brigham Young University (BYU) has already conducted acoustical measurements and published results from several launch vehicles including Antares,[12] Delta IV Heavy,[13] Firefly Alpha,[14] Atlas V,[15] Falcon-9,[9,11] and NASA SLS,[2] as well as several booster static fire tests.[16] Data from these launches are guiding the development of new noise models and facilitating a new understanding of the generation and propagation of rocket noise. These efforts and novel information can help governments and companies predict and mitigate the impacts of launch acoustics on anthropogenic structures, the environment, and communities around each launch pad. Additionally, publishing these data helps avoid the spreading of acoustics misinformation, as was the case with the Saturn V,[17] and provides a reliable source for other researchers interested in launch vehicle acoustics.

This paper provides a high-level overview and a spectral analysis of acoustical data collected at the Falcon 9 SARah-1 mission[18] from June 2022. This measurement provided a unique opportunity to place microphone setups within several hundred meters of the launch pad to record the launch noise and sonic boom near and far from the pad. Both of these noise sources contribute to the overall noise of the launch and are of concern when quantifying community[19] and environmental[20] impacts of launches. The Falcon-9's reentry sonic boom is unique in that it contains three major shocks or a "triple boom".[21] The cause of this triple boom has been widely debated on internet boards and by space enthusiasts, with several misguided hypotheses gaining significant exposure. A previous paper by Durrant *et al*.[11] analyzed the Falcon-9 triple boom from the SAOCOM 1A mission to identify likely sources of the triple boom. It was found that the triple boom was due to the booster's unique shape and trajectory as it descended at supersonic speeds back to the landing pad (see Figure 1). The results from the current paper support and expand upon the results from Durrant *et al.* [11]

Figure 1. Left: Photo of the Falcon-9 launch for the Demo-2 mission. Right: Falcon-9's first stage lands successfully following a launch. Image credit: NASA.

The rest of this paper is organized into two main sections: a measurement overview with basic waveform analysis and acoustic levels, and a spectral comparison that investigates differences between the launch noise and sonic boom. The sonic boom levels, spectral content, and propagation behavior are compared to the launch noise throughout this paper. While the launch noise and sonic boom are generated by different events and have different durations and waveform properties, they both contribute to the overall noise produced by the vehicle.

2. MEASUREMENT OVERVIEW

SpaceX's Falcon-9 is a medium- to heavy-lift rocket, and it is the most commonly launched vehicle in the world. Falcon-9 rockets are not only reliable enough to send NASA astronauts into space, but they also reduce costs and environmental impact by landing the first stage booster back on Earth near the landing pad or on a drone ship at sea rather than discarding it into the ocean. Landing the booster allows SpaceX to reuse each booster multiple times. During the launch, the first stage booster pushes the payload to high altitudes before separating and returning to the landing pad or drone ship. The supersonic reentry of these boosters creates the famous "triple boom" that can be heard kilometers from the launch pad. Several engine burns help slow down the booster before it touches down gently on the landing pad.

A. SARAH-1 MEASUREMENT SETUP

The SARah-1 mission lifted off on June 18, 2022, at Vandenberg Space Force Base (VSFB) near Lompoc, California carrying a German government satellite. The launch occurred at 7:19 AM PDT from Space Launch Complex-4, and the booster landed at Landing Zone 4 at 7:27 AM PDT. Nine recording stations referred to as Portable Units for Measuring Acoustics (PUMA) were deployed. The PUMA systems for this launch were outfitted with a NI 9250 low-noise input module[22] and a GRAS 47AC low-frequency response microphone in a ground-based recording system referred to as COUGAR.[23] The PUMAs located nearest to the pad used ¼" microphones with lower sensitivities to avoid clipping the high-amplitude pressures measured near the pad during takeoff and landing. These ¼" microphones have a poorer low-frequency response than the ½" GRAS 47AC and require additional post-processing to correct the waveform and spectral shapes at low frequencies. The PUMA system and COUGAR microphone configuration have been used in many previous measurements of sonic booms[24, 25] and rocket noise.[13- 15] The location of the PUMAs deployed for the SARah-1 launch is given in Figure 2, with the right portion of the figure showing the four farthest PUMAs (which used ½" GRAS 47AC microphones) in a zoomed-out view, and the left portion of the figure showing a close-up of the five PUMAs near the launch and landing pad area (which used ¼" microphones). Note that the launch and landing pads are separated by just 430 m and that PUMAs 1 and 8 were collocated. The launch trajectory was to the south.

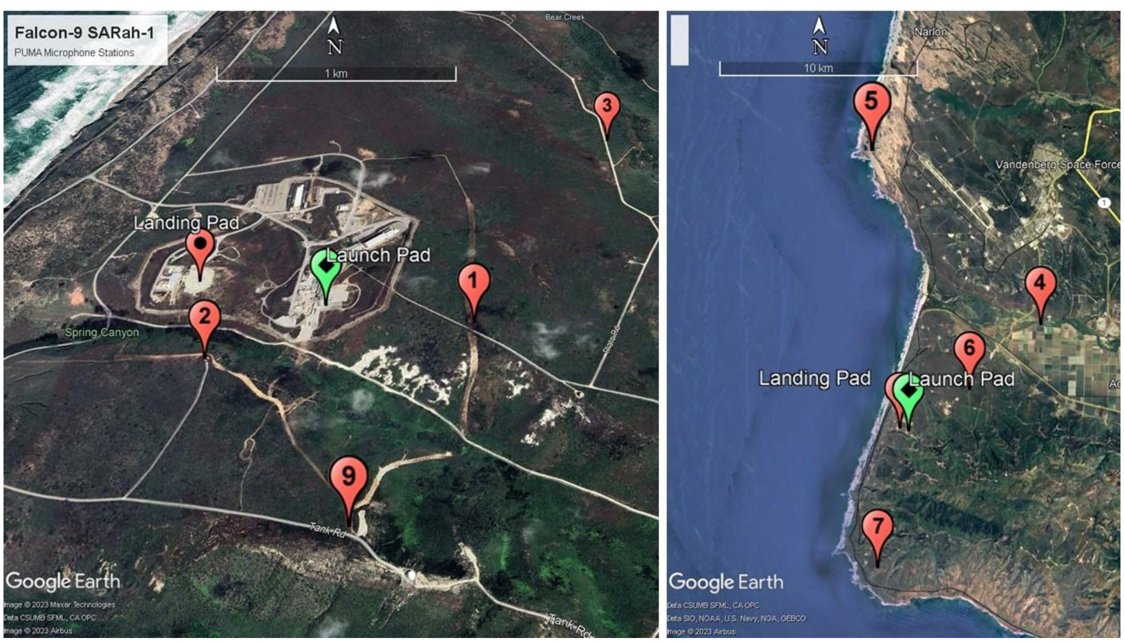

Figure 2. Left: Microphone stations (PUMAs) (PUMAs) near the launch pad (green pin) and landing pad (red pin). Note: PUMAs 1 and 8 were at the same location. Right: Four PUMAs farther from the launch pad.

B. WAVEFORM ANALYSIS

Each PUMA recorded the launch noise, sonic boom, and landing noise. These three acoustic events can be seen below in Figure 3, which plots the full recordings for PUMA 2 (which was 420 m from the pad) and PUMA 4 (which was 8400 m from the pad). In both waveforms, the launch noise is visible, followed by several minutes of mostly inaudible low-frequency noise as the rocket ascends, then a sudden sonic boom followed immediately by the landing burn noise as the first-stage booster touches down on the landing pad. Note that at PUMA 2, the launch noise is of much higher amplitude than the sonic boom, but at PUMA 4, the sonic boom is higher in amplitude. This trend is investigated further in Section 3.

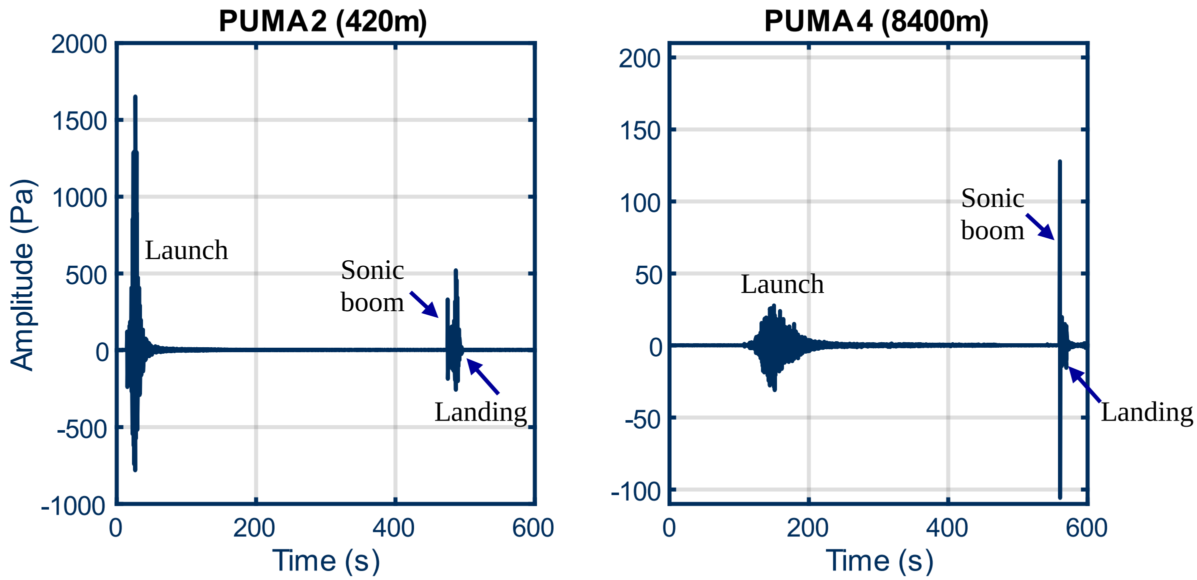

Figure 3. Full waveforms for PUMA microphone stations 2 and 4, showing the launch, sonic boom, and landing noise. Note the difference in the y-axis scale for the two waveforms.

Inspecting the launch and sonic boom portions of the waveform from PUMA 2 helps identify acoustical differences between the two noise sources. The launch noise, which is primarily due to the mixing of the supersonic, superheated jet of gas exiting the rocket engine nozzle and mixing with the ambient air downstream,[26,27] contains many high-amplitude shocks (>1500 Pa). These loud shocks are the audible “crackle”[28] associated with rocket and jet noise. The sonic boom is also primarily made up of shocks, but they are more spread out than the launch noise. This particular sonic boom waveform is also significant because it was recorded closer to the landing pad than previous measurements of Falcon-9 sonic booms. Most Falcon-9 sonic booms consist of three main shocks (hence the term “triple boom”), but this sonic boom appears at first to have more than three shocks. However, whether these shocks are part of the sonic boom or landing noise is unclear because there is little or no gap between the two. Further complicating the issue, the landing noise at this location is around the same amplitude as the sonic boom and also contains large shocks.

For all sonic booms in this analysis, a digital pole-shift filter is used to improve the low-frequency response of the measured waveforms.[29,30] This correction is mostly needed at PUMAs 1, 2, 3, 8, and 9, which used ¼” microphones. For each recording, the pole-shift filter is adjusted until the ramp portions of the sonic boom waveforms approximate the shape of waveforms measured at PUMAs that used microphones with better low-frequency responses. This digital pole-shift filter significantly alters the shape of the waveform and its low-frequency energy, which affects its spectra and overall levels reported in Subsection C and Section 3.

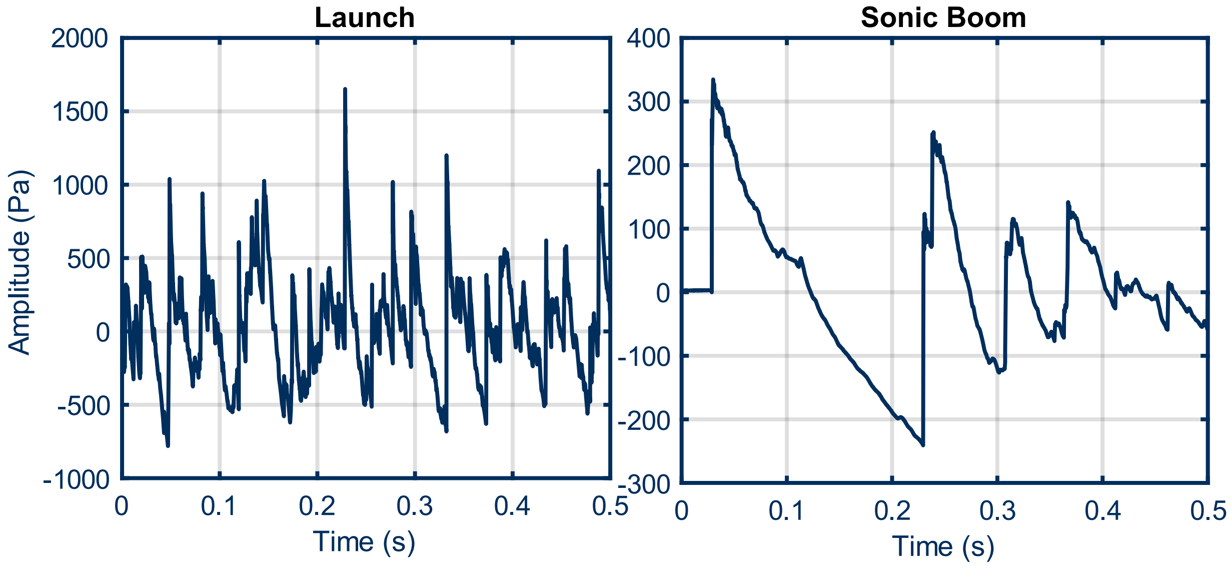

Figure 4. Waveform snippets of the launch (left) and sonic boom (right) from PUMA 2. Note the difference in the y-axis scale for the two plots.

At PUMAs farther from the pad, the sonic boom appears more similar to other Falcon-9 triple boom measurements, with just three main shocks visible. Figure 5 plots the sonic boom waveforms at PUMAs 2 and 4, which differ in amplitude and shape. At PUMA 4, the boom has smoothed out and several shocks have coalesced. Additionally, at this PUMA, the landing noise immediately following the boom is not as significant as at PUMA 2.

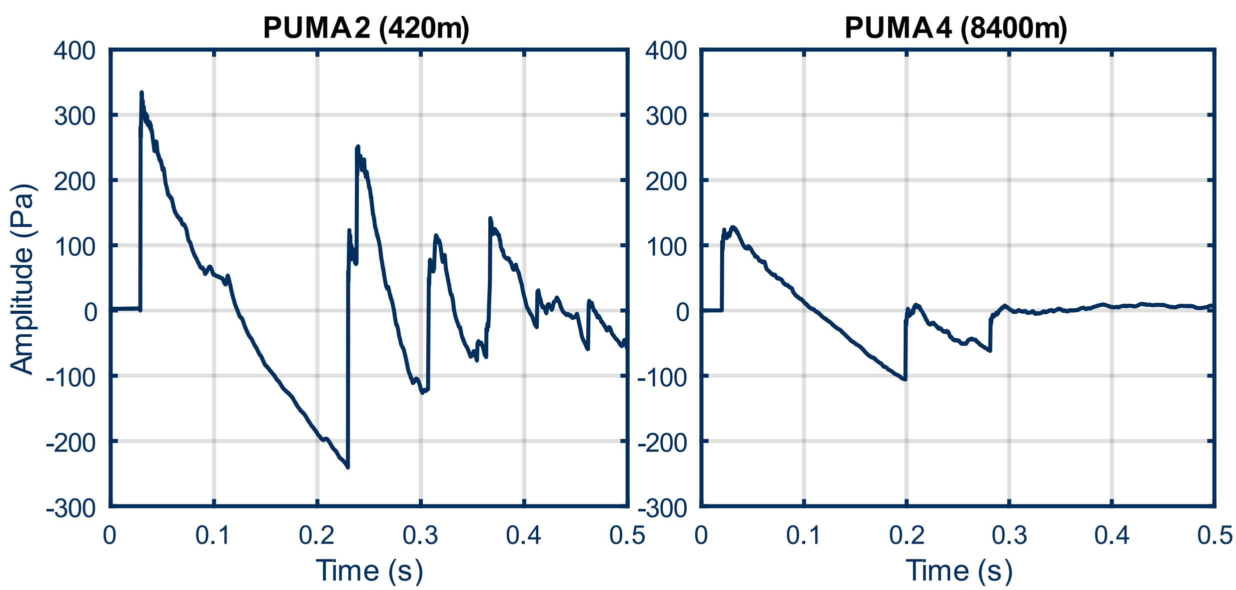

Figure 5. Sonic boom waveforms at PUMA 2 and PUMA 4 show that the sonic boom coalesces into three main shocks at distances farther from the pad.

C. ACOUSTIC LEVELS

The launch noise and sonic boom from Falcon-9 launches are difficult to compare due to their difference in duration, so several different metrics are used here, similar to Durrant *et al.*[11] Table 1 lists the acoustic levels for both the launch phase and the sonic boom at each PUMA, along with the distance from each PUMA to the launch pad. Distances are reported with only two significant figures because the launch and landing pad are separated by 430 m and the sound source location for both sonic boom and launch noise is not constant. Three metrics are compared: the 1-second maximum equivalent level (Leq), A-weighted sound exposure level (ASEL), and

Maximum Overpressure. For the launch noise, the 6 dB-down period is used to calculate the ASEL (except PUMA 7, which uses the 3 dB-down period due to significant wind noise) whereas the sonic boom ASEL is calculated over a 650-ms window. The general trend is that farther PUMAs record lower levels as expected, but it is also apparent that the sonic boom attenuates less at farther PUMAs than the launch noise. For example, at PUMA 2, the launch Leq is 9 dB higher than the sonic boom Leq, but at PUMA 4 the sonic boom Leq is 11 dB louder than the launch Leq. However, because the landing burn noise immediately follows the sonic boom noise at PUMAs close to the pad, the reported sonic boom Leq and ASEL values may include a small portion of the landing noise. All sonic booms recorded at this launch were extremely loud compared to typical aircraft-produced sonic booms. At PUMA 4, the Perceived Level (PL),[31,32] a common metric for human perception of sonic booms, was 115 dB. This means that this Falcon-9 sonic boom at this location is 40 dB louder than the NASA low-boom flight demonstrator, the X-59, is predicted to be.[33]

Table 1. The launch noise and sonic boom metrics from the SARah-1 launch are compared at each PUMA. The 1-second maximum equivalent level (Leq) is given for each phase, along with the ASEL over the given time interval and the maximum overpressure.

Distance from Launch Pad	PUMA #	Launch Maximum Leq (dB)	Sonic Boom Leq (dB)	Launch 6 dB-down ASEL (dB)	Sonic Boom ASEL (dB)	Launch Maximum Overpressure (Pa)	Sonic Boom Maximum Overpressure (Pa)
420 m	**2**	**143**	**134**	**137** (7 s)	**109** (650 ms)	**1652**	**345**
500 m	**1**	**140**	**134**	**132** (9 s)	**108** (650 ms)	**895**	**311**
500 m	**8**	**139**	**132**	**133** (9 s)	**110** (650 ms)	**929**	**378**
850 m	**9**	**136**	**135**	**130** (12 s)	**107** (650 ms)	**726**	**323**
1200 m	**3**	**131**	**132**	**122** (15 s)	**109** (650 ms)	**282**	**310**
3600 m	**6**	**123**	**130**	**116** (26 s)	**101** (650 ms)	**165**	**272**
7000 m	**7**	**114**	**126**	**102** (26 s)	**96** (650 ms)	**34**	**182**
8400 m	**4**	**113**	**124**	**100** (31 s)	**98** (650 ms)	**28**	**130**
14000 m	**5**	**111**	**122**	**92** (16 s)	**91** (650 ms)	**25**	**92**

These results build on those from the SAOCOM 1A Falcon-9 launch reported by Durrant *et al.*[11] that provided the same metrics for the launch and sonic boom, but used only a single microphone station at the same location as PUMA 4 from the SARah-1 launch. Comparing the levels from PUMA 4 in Table 1 to those from the SAOCOM 1A launch show remarkably similar levels in the sonic boom metrics. At SAOCOM 1A, the sonic boom Leq was reported as 124 dB, the ASEL was 99 dB, and the maximum overpressure was 130 Pa, all of which match those from PUMA 4 for this launch exactly, except the ASEL is lower by 1 dB. The launch noise Leq from SAOCOM 1A was 115 dB, the ASEL was 100 dB, and the maximum overpressure was 45 Pa. These levels are similar to the levels recorded at PUMA 4, except that the maximum overpressure for this launch is 17 Pa lower. Such close agreement between the SARah-1 and SAOCOM 1A measurements builds confidence in the results of these measurements. Additionally, the extra PUMA stations deployed at the SARah-1 launch show how the launch and sonic boom metrics vary as they propagate farther from the pad and in different directions. As more measurements are made of Falcon-9 launches and landings at these locations, additional insights and analyses can help determine the effect of trajectory, meteorology, and terrain on the launch and sonic boom waveforms, metrics, and spectra.

3. SPECTRAL ANALYSIS

In addition to time waveform analysis, spectral analysis is useful to compare the launch noise and sonic boom from the SARah-1 mission. Figure 6 compares the one-third octave band (OTO) spectra for both the launch and sonic boom at each PUMA, along with the associated SEL. For the launch phase, the 6-dB down period at each PUMA is calculated and used to calculate spectra and levels. For the sonic boom, a 650 ms window is used, with the peak of the boom 0.1 s into the recording. The sonic boom spectra are zero-padded to smooth out the low frequencies.[34] Both the launch and sonic boom spectra tend to follow a characteristic 10 dB per decade roll-off[35,36] from about 100-10,000 Hz, although several PUMAs located farther from the launch pad roll off at a higher rate. The data from this plot can be compared with the map of PUMAs in Figure 2 to discover several trends with spectra and max level as a function of distance. The next few figures break down important information from these plots into several key takeaways.

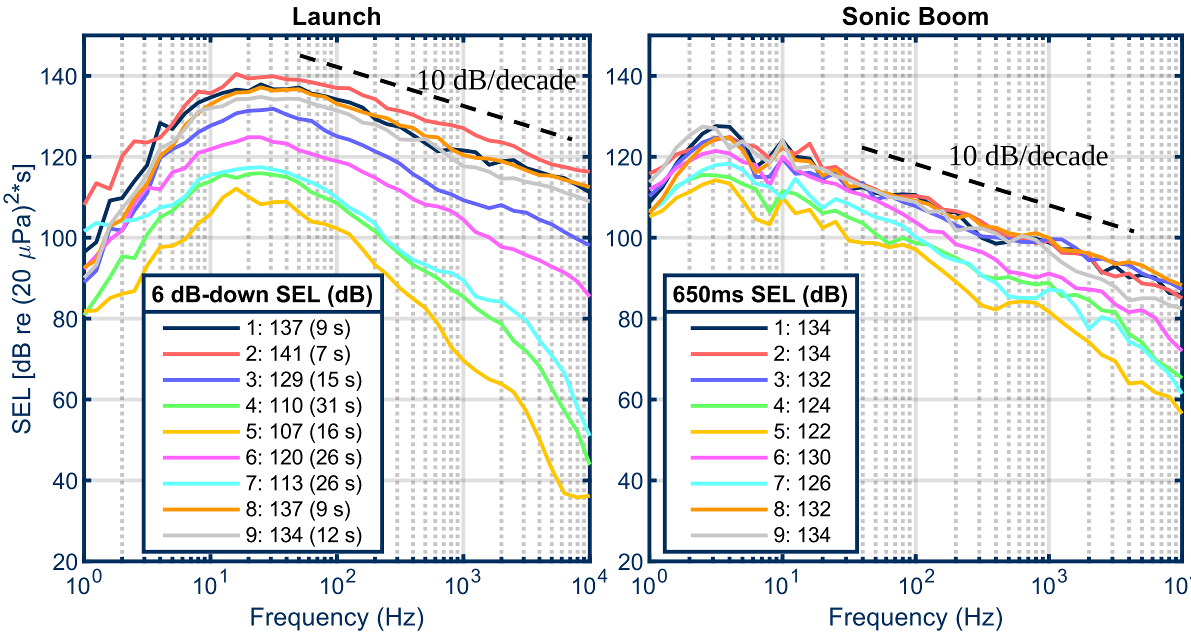

Figure 6. One-third octave spectra and SEL for every PUMA microphone station for both the launch (trimmed to 6 dB-down points) and sonic boom.

The first spectral analysis takeaway comes from calculating the relative spectra of the launch and sonic boom. Comparing these two noise sources' spectra, like comparing their noise metrics, is difficult because the two noise sources are considerably different both in character and in signal duration. The purpose of this comparison is to determine the significance of the sound exposure at each frequency from a short-duration sonic boom when compared to the loudest portion of the launch phase. This is shown in Figure 7, where the launch spectra are subtracted from the sonic boom spectra to obtain the relative OTO level at each frequency. At frequencies below 10 Hz, the sonic boom is up to 26 dB higher than the launch noise. However, at frequencies above 10 Hz, the launch noise is louder than the sonic boom at all PUMAs except three, which had higher sonic boom levels at some frequencies above 500 Hz. These three PUMAs (4, 5, and 7) were the farthest PUMAs from the launch pad. Thus, at larger distances, the sonic boom levels are higher than the launch phase at higher frequencies, while the opposite is true for PUMAs near the pad.

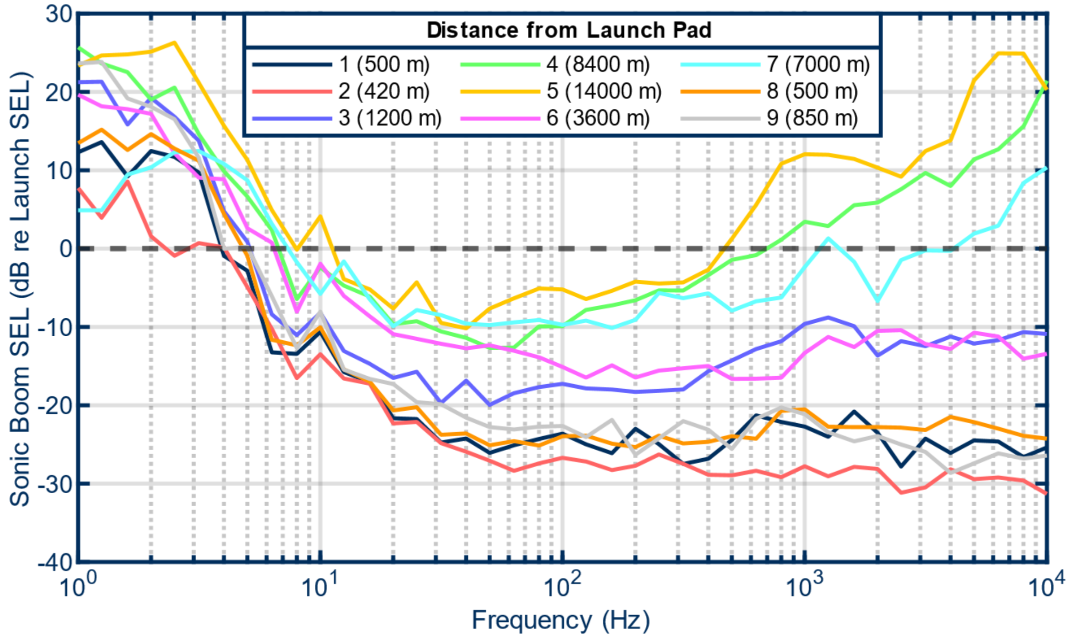

Figure 7. Sonic boom OTO spectra relative to the launch OTO spectra for every PUMA.

A. PROPAGATION EFFECTS

To investigate whether the sonic boom may spread differently and maintain more energy than the launch noise, Figure 8 plots the Leq for both sources as a function of distance. Both noises appear to be rolling off somewhat linearly when distance is plotted on a logarithmic scale. The sonic boom, though lower in level near the pad, rolls off at ~10 dB per decade and thus is higher in level at PUMAs farther from the pad. The launch noise, though higher in level near the pad, rolls off at ~20 dB per decade and thus is lower in level at PUMAs farther from the pad. This suggests that the two noise sources are spreading differently, with the sonic boom spreading cylindrically and the launch noise spreading spherically. However, it is important to note that the rocket is moving during both the launch and the sonic boom, so the exact emission location of the noises is uncertain. The location of sonic boom emission is difficult to identify without exact trajectory data because the booster is moving at supersonic speeds for most of its return descent to the landing pad. Additionally, the sonic boom is generated from high above the pad, likely making the closest PUMAs to the pad nearly equidistant from the sonic boom emission location. This uncertainty in emission location relative to each PUMA could influence the apparent spreading seen in Figure 8, especially with the PUMAs near the pad.

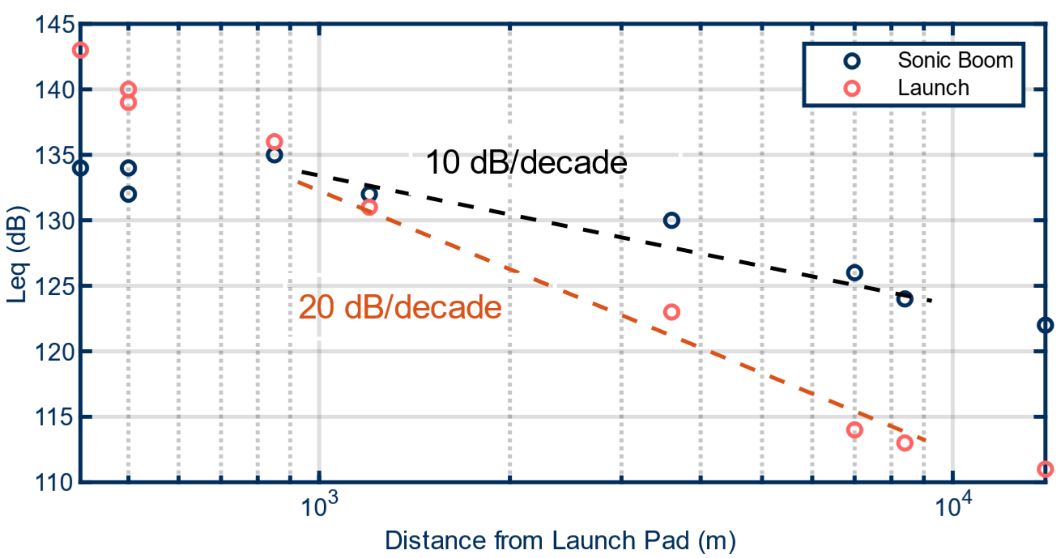

Figure 8. 1-second maximum equivalent level (Leq) as a function of distance, showing the launch spreads spherically, and the sonic boom cylindrically.

Lastly, spectral analysis identifies changing frequency content as the launch noise and sonic boom propagate through the atmosphere. Launch noise and sonic booms propagate nonlinearly, so shock coalescence and waveform period lengthening, which would lead to a downward shift in spectral peak frequency, might be expected for both events. A decrease in peak frequency could impact the human perception of the noise farther from the pad, as most human annoyance metrics more heavily weigh higher frequencies (usually near 3 kHz). However, the lower frequencies still contribute to building vibration and rattle.[37] To investigate this possibility for this launch, Figure 9 plots the measured peak OTO frequency as a function of distance from the pad. The sonic boom peaks around 2-4 Hz and has no noticeable downward shift in peak frequency. The launch noise peaks around 20-30 Hz and also has no noticeable shift, which contrasts with the recent analysis of NASA's SLS launch, which showed the launch noise decreased in peak frequency at stations placed farther from the pad in the nearby community.[38]Additional data collection efforts farther from the launch pad are needed to determine if the same trend is present for these Falcon-9 launches, as the data from these stations do not show this propagation effect.

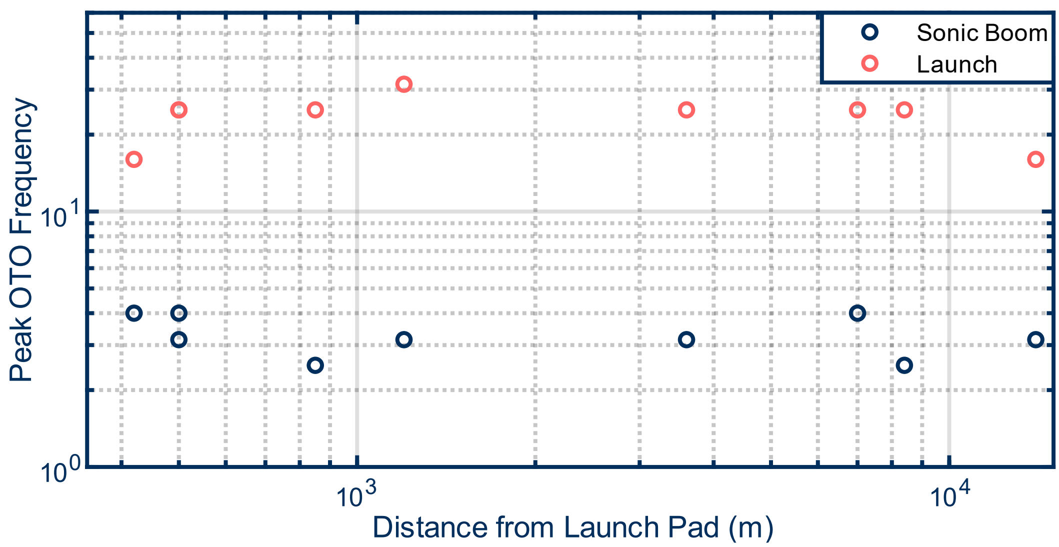

Figure 9. Peak frequency plotted as a function of distance for both the launch noise and the sonic boom.

4. CONCLUSION

In conclusion, nine PUMA stations successfully recorded the acoustics of the Falcon-9 SARah-1 launch and sonic boom at locations in and around VSFB. Several metrics at each PUMA were provided for both the launch noise and sonic boom, which were compared with results from a previous Falcon-9 launch at VSFB. PUMAs near the pad recorded a sonic boom with more than three shocks, while PUMAs farther from the pad recorded the expected triple boom. However, identifying the number of shocks due to the sonic boom near the pad is difficult due to the landing noise that immediately follows the sonic boom. Additionally, the sonic booms farther from the pad contained higher peak overpressures than the launch noise, while the opposite was true near the pad.

Spectral analysis yielded several interesting insights. First, the relative OTO spectra showed the sonic boom SEL spectra to be higher than the launch noise at frequencies below 10 Hz, but lower than the launch nose at frequencies above 10 Hz. The exception to this observation was the three PUMAs located farthest from the pad, where the sonic boom was louder at some frequencies above 500 Hz. This difference in spreading between the two noise sources was also observed in the max levels plotted as a function of distance, which showed the sonic boom spread cylindrically while the launch noise spread spherically. Lastly, the launch noise peaked at higher frequencies than the sonic boom, but neither could be determined to increase or decrease in peak frequency as they propagated.

Overall, this paper provides a high-level overview of BYU's measurement of the SARah-1 launch as well as a spectral comparison between the launch noise and sonic boom. Future work will further analyze the sonic boom propagation behavior, taking advantage of the sonic boom recordings from all nine PUMAs used at the launch. When combined with launch and reentry trajectory data, measurements like this could shed further light on the triple sonic boom, its origination point, and propagation behavior. Learning more about sonic booms from booster reentries will help scientists, companies, and governments create accurate models and mitigate the acoustical impact of reusable launch vehicles.

ACKNOWLEDGMENTS

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