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Initial comparison of a Falcon-9 reentry sonic boom with other launch-related noise

Jeffrey Taggart Durrant, Mark C. Anderson, Kent L. Gee, Logan T. Mathews and Grant W. Hart

Department of Physics and Astronomy, Brigham Young University, Provo, UTAH, 84602; taggart.durrant@gmail.com; anderson.mark.az@gmail.com; kentgee@byu.edu; loganmathews103@gmail.com; grant_hart@byu.edu

A downside of landing first-stage boosters of orbital-class launch vehicles, such as the Falcon 9, is the sonic boom associated with reentry and landing. To assess the potential impact of these sonic booms and compare them to launch and landing operations, acoustic data from a Falcon-9 launch and booster landing at Vandenberg Space Force Base are analyzed. The data were collected near Lompoc, CA, at a station 8 km away from the landing site. Because of the booster shape and landing orientation, the measured waveform contains three shocks (a triple boom), rather than the two associated with a traditional N-wave. Waveform and spectral characteristics are examined and various metrics, including A-weighted Sound Exposure Levels, are calculated and compared with those of the launch and landing noise.

**POMA Student Paper Competition Winner*

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1. INTRODUCTION

Current understanding and modeling of rocket launch noise is based on measurements and models made during the Apollo era (1961-1972) on equipment available at the time.[1] New rocket noise research aims to correct and improve our physical understanding and predictive capability of rocket noise.[2,3] Rocket launch noise can disturb wildlife near the launch pad, damage launch pad structures, and lead to community noise exposure and annoyance.[2,4,5] New and improved models of rocket noise will be critical in the coming years,[6] as the number of launches per year across the globe is expected to increase.

Not only are there more rocket launches per year than ever before,[2] but there are now fully-reusable suborbital vehicles and partially-reusable orbital vehicles. Some of these vehicles land on landing pads, while others land on runways, autonomous barges at sea, or other places on land. The first reusable spacecraft was NASA's Space Shuttle, which landed on runways from 1981-2011.[7] Landing launch vehicles or spacecraft back on Earth introduces another noise source: a sonic boom.[8] These launch vehicles tend to be large and heavy, creating loud sonic booms as they land. The most common occurrence of this phenomenon today is SpaceX's Falcon 9 and its famous "triple boom" which is heard on the ground as its first stage booster lands back near the launch pad or on an autonomous barge at sea after delivering a payload to orbit. To the uninformed observer, this sudden, loud sound can be startling, like an explosion. Sonic booms, along with launch and landing engine burn noise, can add to a rocket's environmental effects and community disturbance[9] and need to be understood as rockets with new landing capabilities are launching more often than ever before.

This paper focuses on the launch, sonic boom, and landing noise from a Falcon 9 booster landing recorded at Vandenberg Space Force Base. The "triple boom" waveform is investigated and possible sources for this unique waveform shape are discussed. Additionally, several noise metrics and spectra are compared between the launch, sonic boom, and landing noise.

2. SPACEX FALCON 9

According to the SpaceX website, the Falcon 9 is "a reusable, two-stage rocket designed and manufactured by SpaceX for the reliable and safe transport of people and payloads into Earth orbit and beyond."[10] Fully assembled, the Falcon 9 is about 70 m tall. The bottom part of the rocket is the first stage, or booster, and is about 50 meters tall and has 9 engines. At launch, all 9 engines fire to lift the rocket to a high altitude where the booster then separates from the second stage, which continues to carry the payload into orbit. The booster then flips its orientation and performs a quick reentry burn to slow its velocity as it reenters the atmosphere, using large grid fins to guide its trajectory as it falls at supersonic speeds. The thicker atmosphere at lower altitudes helps slow its descent to subsonic speeds before a single engine fires up, landing legs deploy, and the booster touches down softly at the landing site. Depending on the mission, the booster may either land on an autonomous barge in the ocean or on a landing pad near the launch site.

Figure 1. Left: Photo of a Falcon 9 launch. Photo from NASA/Joel Kowsky, public domain. Right: Photo of a Falcon 9 booster landing. Photo from SpaceX Photos, public domain.

The launch and landing data for this analysis come from the SAOCOM 1A mission out of Vandenberg Space Force Base near Lompoc, California in October 2018. While the research team from Brigham Young University (BYU) has measured several Falcon 9 launches with multiple microphone stations at each launch,[11] this paper focuses on a single microphone for a single launch located 8 km from the launch site. Figure 2 shows a map of the launch area, with the city of Lompoc visible on the right, the microphone location indicated by a blue circle near the top, and the Falcon 9 launch site indicated by a yellow circle on the bottom left. The landing site used for this mission was located a few hundred meters to the west of the launch site. The distance from the launch and landing sites to the microphone location was about 8 km.

Figure 2. Overview of the measurement at Vandenberg Space Force Base near Lompoc, California. The microphone location is indicated by a blue circle near the top, while the launch site is indicated by a yellow circle near the bottom left.

Figure 3 shows the entire recorded waveform from this launch and landing. The recording contains three phases of interest: the launch noise from all 9 engines, the sonic boom from the booster's supersonic descent, and the landing noise from a single engine as the rocket lands. The launch noise starts around 70 seconds into the recording and continues for several hundred seconds. At about 500 seconds into the recording, a sudden sonic boom with a peak overpressure about three times greater than that of the launch is seen, immediately followed by the landing noise.

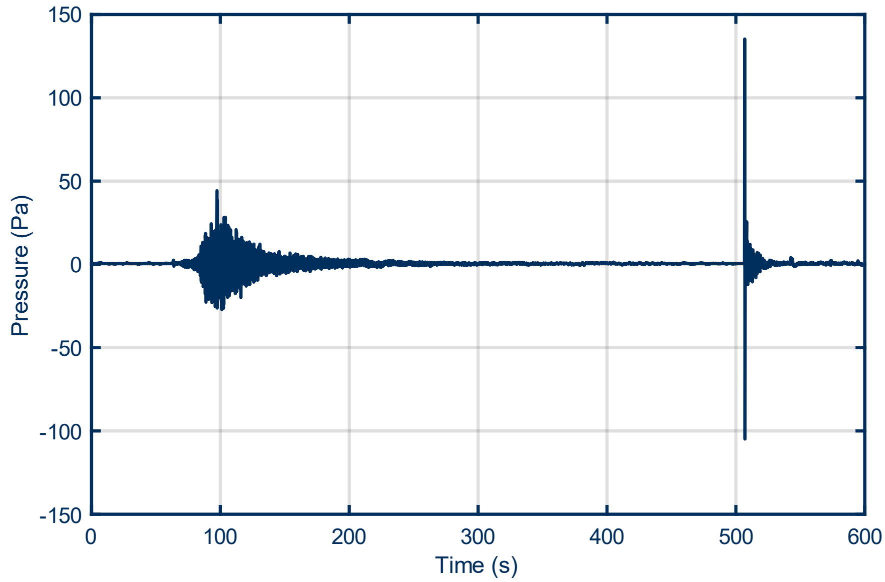

***Figure* 3. Waveform of the entire Falcon 9 launch and landing measurement. The launch noise begins around 70 s into the recording, the sonic boom occurs around 500 s, and the landing noise immediately follows the sonic boom.**

3. THE "TRIPLE BOOM"

Sonic booms are shock waves created by any object that moves faster than the speed of sound.[12] The Falcon 9 booster's sonic boom is unique in that it creates a "triple boom" when observed from the ground, rather than a traditional N-wave. This unique sonic boom signature is audible in many videos of booster landings available online. While a traditional N-wave sonic boom might be described as a "boom-boom" sound, the Falcon 9 "triple boom" sounds more like a "boom buh-boom."[13]

The Steven's Mark VII perceived level of loudness (PL)[14] for this sonic boom was 115 dB, about 40 dB louder than the target level for NASA's X-59,[15] and 10 dB louder than the Concorde.[16] This metric has been shown to correlate well with human perception of sonic booms[17] and can be compared with other transient noises. The PL from these sonic booms, along with several other noise sources, are compared in Figure 4.[18] For more information on the measurements of these noise sources, see Ref. [18].

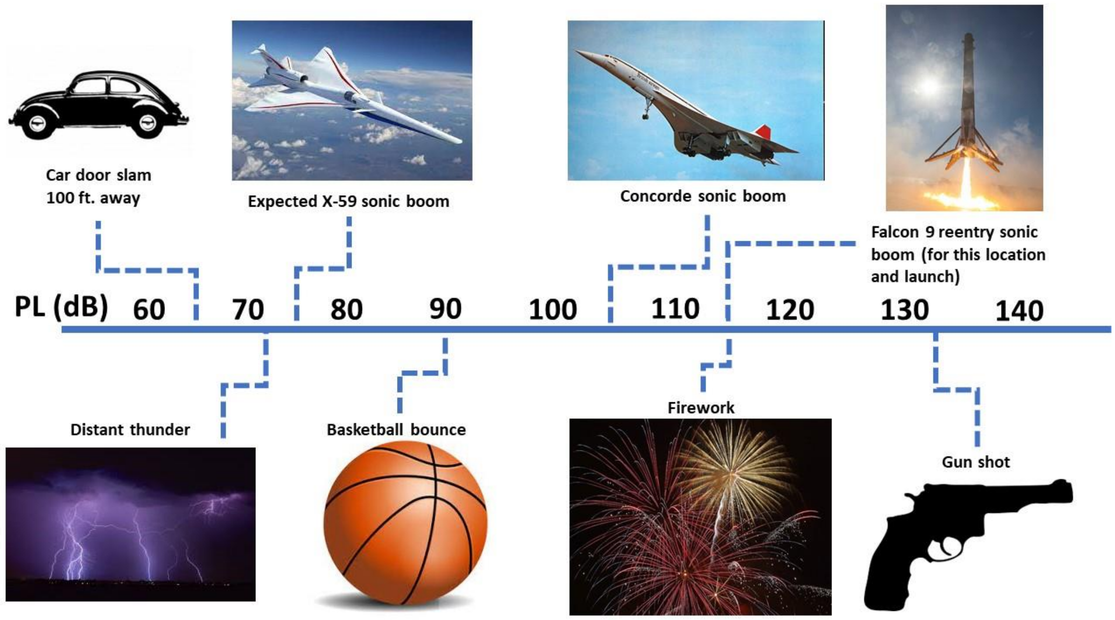

Figure 4. The PL values of different noise sources are compared. Three supersonic vehicles are included, with NASA's X-59 expected to be the quietest at 75 dB. The Concorde's sonic booms were much louder at 105 dB, and the Falcon 9 sonic boom for this location and launch was even louder at 115 dB. For more details of these measurements, see Ref. [18].

Figure 5 shows the sonic boom waveform from this recording cropped to a 650 ms window, as is customary for sonic boom analysis.[19,20] The three distinct shocks that make up the triple boom are visible in the waveform, with the first and largest shock being further ahead of the second two. This is consistent with the "boom buh-boom" timing heard by observers on the ground.

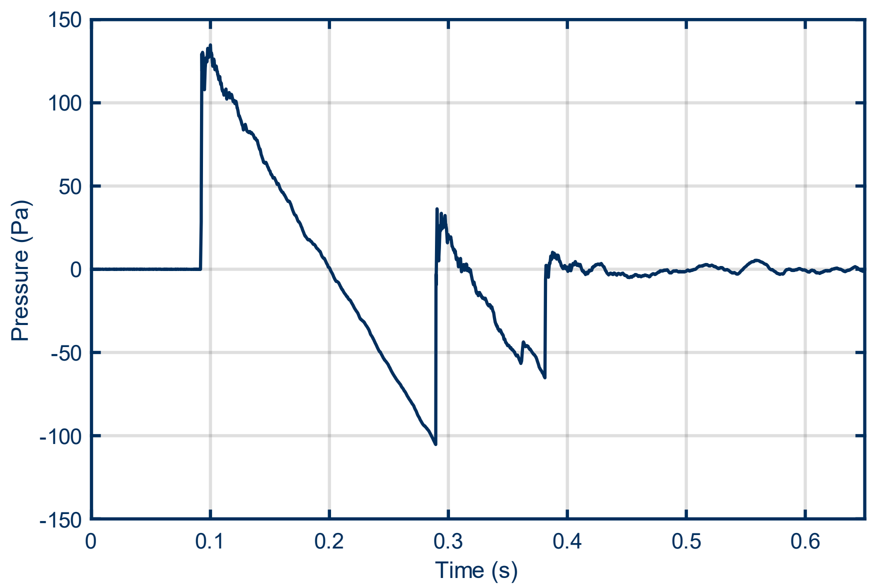

Figure 5. Falcon 9 booster landing sonic boom waveform. The maximum amplitude is 130 pascals.

The cause of the Falcon 9 triple boom has been a source of confusion amongst the general public and internet discussion boards. Some explanations have been as misguided as claiming that the deployment of grid fins and landing legs cause the triple boom. This is false, as the grid fins deploy while the rocket is still coasting upward in the upper fringes of the atmosphere and the landing legs deploy at subsonic speeds seconds before the booster lands. A more official explanation comes from the SpaceX Communications director, who said "[the] first boom is from the aft end (engines), [the] second boom is from the landing legs at the widest point going up the side of the rocket. [The] third boom is from the fins near the forward end.”[21]

Further investigation into sonic boom shock origination points can be done by aligning a schematic of the vehicle with the time waveform of the sonic boom recording, a method that has been used to identify shock origination points of other supersonic vehicles in years past. One drawback of this method is that it requires near-field measurements, close enough that the shocks don’t coalesce due to nonlinear propagation.[12] These types of measurements are unavailable for this paper, as the measurements for this analysis come from 8 km away from the landing site. Additionally, the altitude at which the shocks were produced is unknown, as the booster is supersonic up until it is about 6 km from the ground. This makes using alignment with a time waveform more difficult, but some insights can still be gained from this technique, as long as propagation effects are considered.

Figure 6 aligns the booster, which is about 50 m tall, with the time waveform to estimate the shock origination points. The top end of the booster is aligned with the third and final shock, where the pressure collapses back to ambient pressure as the vehicle passes. Just before the third shock, a smaller bump in the waveform is visible, likely from the grid fins, which line up directly below it. This bump is visible in recordings from multiple Falcon 9 booster sonic boom recordings made by BYU. The second shock appears to originate from somewhere along the body of the rocket, close to the landing legs. This shock could be in part due to the orientation of the booster, as it descends at a slight angle, causing air to flow horizontally over the folded landing legs and body of the rocket. Computational Fluid Dynamics (CFD) simulation by Ecker et al. lends additional information into the airflow over the descending booster, both with and without the engine firing.[22] The first shock, however, does not line up with the bottom end of the booster. There could be several explanations for this, the first being that the plume from the engines pushes the bow shock in front of the vehicle. CFD from Ecker et al. shows that the firing engine could push the bow shock a significant distance in front of the descending booster. However, this is only relevant if the boom originates from the time when the engines are firing. Another possible reason is that nonlinear propagation from this large overpressure shock causes it to travel faster and arrive sooner than the two following shocks. Nonlinear effects are strongest with sound waves of large amplitude, like the first shock in Figure 6, but could make it difficult to line up the booster with the time waveform of any of the three shocks. The exact origin and cause of this unique triple boom can’t be stated for certain from the available data, but it is likely due to the unique shape and orientation of the booster as it returns to the landing pad.

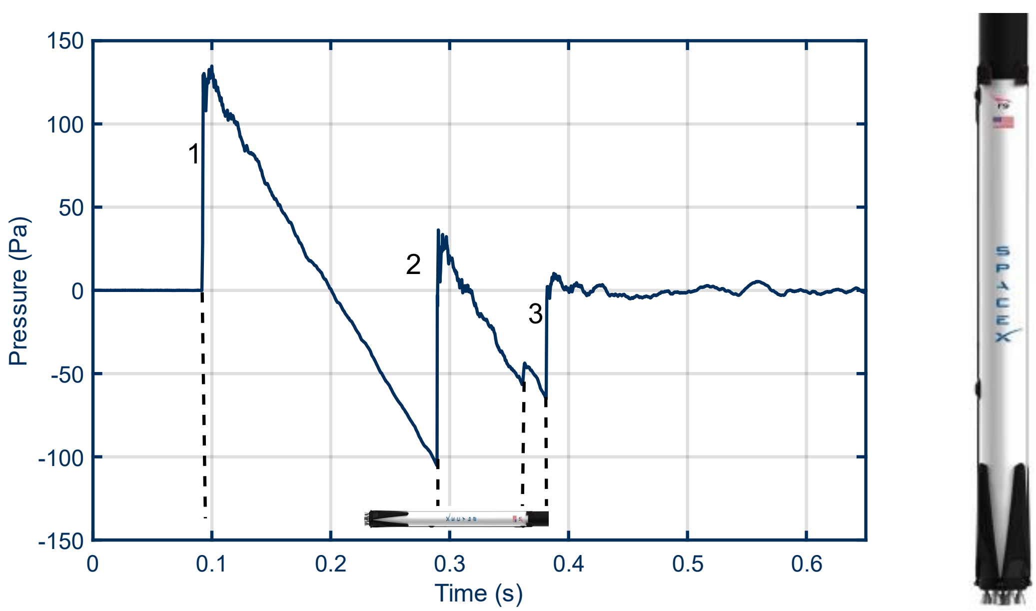

Figure 6. The Falcon 9 booster is aligned below the time waveform of the associated sonic boom to estimate possible shock origination points. Photo from Ref. [23].

4. METRIC AND SPECTRAL COMPARISONS

Several metrics could be used to compare the loudness of the sonic boom with that of the launch and landing engine noise. For this paper, maximum overpressure, A-weighted Sound Exposure Level (A-SEL), and the 1 second maximum equivalent continuous sound level (Leq) are used for comparison. The A-SEL metric is used over a longer period of each phase, integrating the sound levels to determine the total sound exposure. This metric has been used for rocket noise and sonic booms at Vandenberg Space Force Base in previous studies.[5] The maximum Leq quantifies the loudest second of each phase, and the maximum overpressure provides the amplitude of the largest shock from each phase.

The metric values for each of the three phases (launch, sonic boom, and landing) are given in Table 1, where the rows contain the metrics, and the columns contain the three phases. The sonic boom is shown to have the largest Leq at 124 dB, much louder than the launch Leq of 115 dB and the landing Leq of 109 dB. The sonic boom also has the largest maximum overpressure at 130 Pascals (Pa), almost three times as large as the launch maximum overpressure of 45 Pa. Perhaps most interestingly, the launch and sonic boom are seen to have similar A-SEL values at 100 and 99 dB, respectively, when the launch noise is trimmed to the 6 dB-down points (to capture the loudest portion of the launch phase). This shows that an observer on the ground 8 km away receives a similar sound exposure from a 650 ms sonic boom and the loudest 27 seconds of launch noise. The landing noise is also trimmed to the 6 dB-down points, and is seen to have an A-SEL of 85 dB.

Table 1. Falcon 9 Launch, Sonic Boom, and Landing metrics, with time intervals used for calculation in parentheses.

Metric	Launch	Sonic Boom	Landing
A-SEL (dB)	**100** (27 s)	**99** (650 ms)	**85** (4 s)
Maximum Leq (dB)	**115** (1 s)	**124** (1 s)	**109** (1 s)
Maximum overpressure (Pa)	**45**	**130**	**27**

Before calculating the spectra during each of the phases, it is useful to take a closer look at the waveforms from the launch and landing phases. Figure 7 shows half-second snippets of the launch and landing waveforms to make the individual shocks visible. The launch phase has many shocks that are both steep and high in amplitude, which are audible as "crackle."[24] The landing phase also contains shocks, but they are of smaller amplitude.

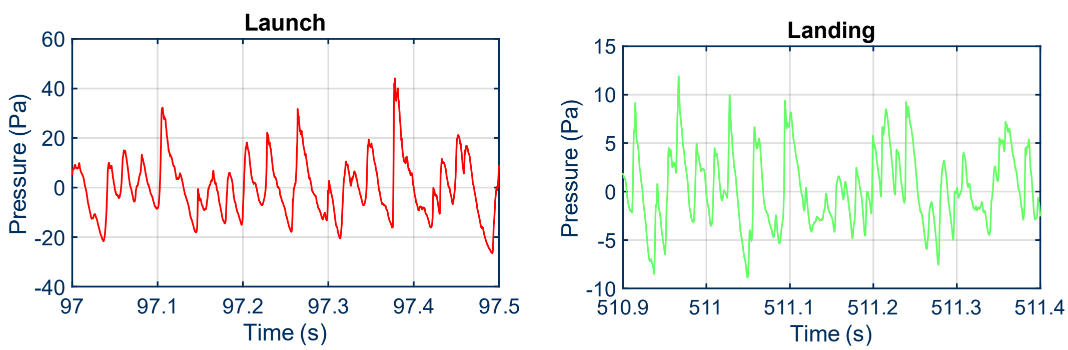

Figure 7. Zoomed in half-second snippets of the launch (left) and landing (right) waveforms. Both snippets contain shocks, but the launch contains shocks of higher amplitude than the landing shocks.

Figure 8 contains the one-third octave (OTO) band spectra of the launch, sonic boom, and landing, along with each phase's flat-weighted SEL. The 6 dB-down points are again used to trim the launch and landing waveforms to the loudest portion of each phase. The sonic boom is trimmed to a 650 ms window. Similar to the A-SEL shown previously, the flat-weighted SEL for the 650 ms sonic boom is just 1 dB quieter than the loudest 27 seconds of launch noise. The sonic boom spectrum peaks around 3 Hz, lower than the peak frequency for the launch and landing, which both peak around 10-20 Hz. This low-frequency noise, while inaudible to humans, can cause buildings to rattle.[12] Additionally, the sonic boom spectrum follows a 10 dB per decade roll-off[25,26] up to about 1 kHz, while the launch spectrum starts rolling off faster at frequencies below 100 Hz, and the landing rolls off faster than the launch at high frequencies. This shows that the sonic boom contains the most shock content and that the launch shock content is higher than the landing shock content.

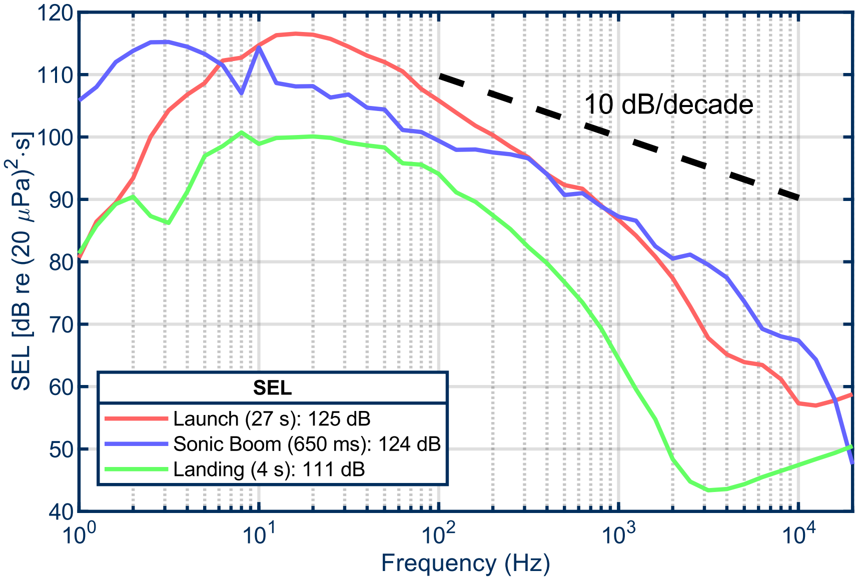

Figure 8. OTO spectral comparison between the launch, sonic boom, and landing noise, with the total SEL values included for each phase and time intervals used for calculation after trimming to 6 dB-down points.

5. CONCLUSIONS

To further understanding of rocket launch and landing noise, this paper has investigated several characteristics of a Falcon 9 launch and booster reentry sonic boom, including its unique "triple boom." The sonic boom measured at this location for this launch had a PL of 115 dB, which is 10 dB louder than the Concorde's sonic boom and 40 dB louder than the expected X-59 sonic boom. The exact cause of the triple boom waveform is hard to identify, but it is likely due to the booster's unique shape and orientation as it falls at supersonic speeds toward the landing pad. Further investigation into this unique sonic boom could include ray tracing, CFD, or other techniques to confirm the exact origin and cause of the triple boom.

Several metrics have been used to compare the three phases (launch, sonic boom, and landing). The sonic boom had the highest maximum overpressure and Leq, and its A-SEL of 99 dB over 650 ms was almost as high as the 100 dB A-SEL from the loudest 27 seconds of the launch phase. Spectral analysis showed the sonic boom to contain the most shock content and peak at a lower frequency than the launch. These metric and spectral comparisons show that sonic boom contributes a large amount of noise, similar to that of the launch phase, and should be considered when studying the effects of rocket launches on communities and environments.

REFERENCES

1 Eldred, K. M. (1971). "Acoustic loads generated by the propulsion system," NASA SP-8072, Washington, DC.

2 C. P. Lubert, K. L. Gee, S. Tsustumi, "Supersonic jet noise from launch vehicles: 50 years since NASA SP-8072," The Journal of the Acoustical Society of America. 151, 752 (2022). https://doi.org/10.1121/10.0009160

3 L. T. Mathews, K. L. Gee, G. W. Hart, "Characterization of Falcon 9 launch vehicle noise from far-field measurements." The Journal of the Acoustical Society of America. The Journal of the Acoustical Society of America 150, 620 (2021); https://doi.org/10.1121/10.0005658

4 Gee, K. L., Lubert, C. P., Wall, A. T., & Tsutsumi, S. (2017). Summary of "Supersonic Jet and Rocket Noise". Proceedings of Meetings on Acoustics (Vol. 31, No. 1, p. 040002). ASA. https://doi.org/10.1121/2.0000655

5 Bradley, K.A. 2016a. Noise Assessment of Falcon 9 (3 Engine Thrust) Landing at Vandenberg AFB. Arlington, VA: Wyle Aerospace Environmental and Energy, Prepared for Space Exploration Technologies

6 K. Tran et al., "Noise and Sonic Boom Analysis from Rocket Launches," 2018 AIAA/CEAS Aeroacoustics Conference, DOI:10.2514/6.2018-2816

7 Space Shuttle Era, https://www.nasa.gov/mission_pages/shuttle/flyout/index.html, accessed 06/09/2022.

8 NASA Armstrong Fact Sheet: Sonic Booms, https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-016-DFRC.html, accessed 06/09/2022.

9 U.S. Air Force, "Application for incidental take regulations and letters of authorization; U.S. Air Force launches, aircraft and helicopter operations at Vandenberg Air Force Base, California." https://media.fisheries.noaa.gov/dam-migration/vandenberg_2019loa_app2_opr1.pdf

10 Falcon 9, https://www.spacex.com/vehicles/falcon-9/, accessed June 9, 2022.

11 Mathews et al., "Comparative analysis of noise from three Falcon 9 launches," The Journal of the Acoustical Society of Korea. 39(4):322-330 DOI:10.7776/ASK.2020.39.4.322

12 D. J. Maglieri, P. J. Bobbitt, K. J. Plotkin, K. P. Shepherd, P. G. Coen, D. M. Richwine, "Sonic Boom: Six Decades of Research," NASA/SP-2014-622 (2014).

13 J. T. Durrant, K. L. Gee, M. C. Anderson, L. T. Mathews, G. W. Hart, "Boom Buh-Boom! A brief analysis of a Falcon-9 booster landing," Acoustical Society of America, https://acoustics.org/2apaa6-boom-buh-boom-a-brief-analysis-of-a-falcon-9-booster-landing/

14 Stevens, S. S. (1972). "Perceived level of noise by Mark VII and decibels (E)," J. Acoust. Soc. Am. 51(2B), 575–601.

15 L.P. Ozoroski, et al., NASA Community Test Workshop 2, (2021); https://ntrs.nasa.gov/citations/20210025956

16 Sonic Boom Heads for a Thump, https://www.nasa.gov/topics/aeronautics/features/sonic_boom_thump.html, accessed June 9, 2022.

17 A. Loubeau, S. R. Wilson, J. Rathsam, (2018). "Updated evaluation of sonic boom noise metrics," The Journal of the Acoustical Society of America 144, 1706 (2018); https://doi.org/10.1121/1.5067578

18 W. J. Doebler, J. Rathsam, "How Loud is X-59's Shaped Sonic Boom?" Proceedings of Meetings on Acoustics (POMA), 36,1 DOI: 10.1121/2.0001265

19 J. A. Page et al., "Waveforms and Sonic Boom Perception and Response (WSPR): Low-Boom Community Response Program Pilot Test Design, Execution, and Analysis," (2014) https://ntrs.nasa.gov/citations/20140002785

20 J. A. Page et al., "Quiet Supersonic Flights 2018 (QSF18) Test: Galveston, Texas Risk Reduction for Future Community Testing with a Low-Boom Flight Demonstration Vehicle," (2020) https://ntrs.nasa.gov/citations/20200003224

21 Scott Johnson, 07/27/2016, From double to triple: why the landing Falcon 9 creates three sonic booms, https://www.spaceflightinsider.com/organizations/space-exploration-technologies/double-triple-landing-falcon-9-creates-three-sonic-booms/, accessed June 9, 2022.

22 Tobias Ecker, Sebastian Karl, Etienne Dumont, Sven Stappert and Daniel Krause, "A Numerical Study on the Thermal Loads during a Supersonic Rocket Retro-propulsion Maneuver," AIAA 2017-4878. https://doi.org/10.2514/6.2017-4878

23 Falcon User's Guide, https://www.spacex.com/media/falcon-users-guide-2021-09.pdf, accessed 06/13/2022.

24 K. Gee, V. Sparrow, A. Atchley, T. Gabrielson, "On the Perception of Crackle in Noise Radiated from Military Jet Aircraft," 12th AIAA/CEAS Aeroacoustics Conference (27th AIAA Aeroacoustics Conference) (2006). https://doi.org/10.2514/6.2006-2530

25 S. N. Gurbatov and O. V. Rudenko, "Statistical phenomena," in Nonlinear Acoustics, edited by M. F. Hamilton and D. T. Blackstock Academic, San Diego, 1998, Chap. 13, pp. 377–398.

26 S. M. Young, K. L. Gee, T. B. Neilsen, K. M. Leete, "Outdoor measurements of spherical acoustic shock decay," The Journal of the Acoustical Society of America 138, EL305 (2015); https://doi.org/10.1121/1.4929928