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**Far-field acoustic variability across twelve Falcon 9 launches near
Vandenberg Space Force Base**

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This study presents a comparative analysis of far-field acoustic measurements from twelve SpaceX Falcon 9 launches conducted near Vandenberg Space Force Base. Acoustic data were collected at a fixed location 8.45 km from the launch pad as part of an ongoing ecology-motivated effort to characterize the launch noise environment. Maximum overall sound pressure levels (OASPL), one-third-octave spectra, pressure-time waveforms, and running pressure-derivative skewness were examined to assess launch-to-launch variability. Results show a spread of approximately 4.7 dB in maximum flat-weighted OASPL and over 10 dBA across the dataset, despite consistent vehicle configuration and similar ascent trajectories. Detailed comparisons of three representative launches reveal substantial differences in waveform structure, dominant spectral content, and crackle-related metrics. The period of maximum OASPL does not coincide with the period of maximum derivative skewness, and the launch with the greatest OASPL contains the least amount of crackle content. Understanding of this launch-to-launch variability, likely driven by local meteorology, is critical for accurate rocket noise modeling and environmental impact assessment.

1. INTRODUCTION

The SpaceX Falcon 9 rocket is a two-stage launch vehicle that has become a key player in modern space exploration due to its re-usability and cost-effectiveness. Designed for the reliable and safe transport of satellites, cargo, and astronauts, Falcon 9 has completed numerous missions for both commercial and government clients. As of February 4, 2026, 177 Falcon 9 launches have taken place from Space Launch Complex (SLC)-4E at Vandenberg Space Force Base (VSFB). Each launch has the potential to impact the surrounding environment. This study is part of a collaborative eco-acoustic project to better understand the VSFB launch noise environment at nests of endangered bird species located on base beaches, a topic that has caught the interest to the local population and media^{1,2}. Despite the rocket's success and widespread use, the acoustic properties of Falcon 9 remain relatively unexplored, aside from early studies that used limited data^{3,4}. Additionally, there is still much to be understood about the acoustics of supersonic flow from launch vehicles^{5,6}. Understanding the noise generated by the rocket during launch, especially how it varies from launch to launch, is crucial in modeling rocket noise and assessing the environmental impact^{6,7}. This paper reports on twelve measurements of Falcon 9 launches at a location 8.45 km from the launch pad. Individual launches were measured at varying times of year and day, occurring during various local weather conditions.

In this paper, maximum overall sound pressure levels (OASPL) across all twelve launches are compared. The pressure-time waveforms, running OASPL, maximum one-third octave (OTO) spectra, and running derivative skewness (dSk) of three specific launches are discussed. OASPL values are reported in flat-weighted decibels, dB, and A-weighted decibels, dBA, both relative to 20 μ Pa. Both are included because A-weighting is used in environmental assessment modeling. Although A-weighting is intended to mimic the audio response for the average human ear for moderate sound levels, rocket noise is low-frequency and high-level, resulting in A-weighted values that may not accurately reflect what an observer would experience during a rocket launch.

Overall, results show a 4.7 dB spread (10.9 dBA) in maximum OASPL across twelve different Falcon 9 launches. For three launches studied in more detail, the period of maximum level varies considerably, with a one-octave variation in peak frequency. Finally, the period of maximum OASPL does not correlate to the period of maximum dSk nor does the pressure amplitude relate to the maximum dSk level. These analyses show that variation across the multiple launches is evident despite the same fuel type and thrust capacities. Payload weight may vary across launch but will not affect the metrics used in this study. Also, trajectory remains similar during this time period of launch, meaning that variation is likely due to atmospheric propagation effects. Understanding this significant variation can better inform models that predict levels during launches.

2. METHODS

A. MISSIONS OVERVIEW

Table 1 provides an overview of all twelve launches measured with local launch date and time, weather conditions, maximum OASPL both unweighted and A-weighted. All launches were measured from the location nicknamed "North Field", shown relative to the launch pad in Figure 1 (This is the same as the "North" location described by Mathews et al.⁴). Local weather conditions during launch were gathered from SpaceX launch recordings as well as data collected from weather balloons launched twice daily from VSFB.

Table 1. Overview of twelve individual launches measured for this study, their launch data and time, weather conditions during launch, and maximum OASPL unweighted and A-weighted levels recorded during launch.

Mission Name	Launch Date & Time (Pacific Time)	Weather Conditions	Max OASPL (dB)	Max OASPL (dBA)
IRIDIUM 7	25 July 2018 4:39AM	Fog & Clouds	114.7	92.6
SAOCOM 1A	8 October 2018 7:21PM	Clear	115.4	97.6
RADARSAT	12 June 2019 7:17AM	Fog & Clouds	113.0	91.6
SARah-1	18 June 2022 7:19AM	Fog	114.2	93.4
Transporter 8	12 June 2023 2:35PM	Clouds	117.2	93.7
Starlink 5-13	7 July 2023 12:29PM	Fog & Clouds	113.9	93.7
Starlink 6-15	20 July 2023 9:09PM	Fog & Clouds	113.3	86.7
Tranche 0B	2 September 2023 7:23AM	Clouds	113.7	95.3
Korea 425	1 December 2023 10:19AM	Clear	117.7	92.3
Starlink 7-10	14 January 2024 12:49AM	Clouds	113.6	95.7
USSF-62	11 April 2024 7:24AM	Clear	114.5	95.3
WorldVIEW	2 May 2024 11:36AM	Clear	115.6	95.5

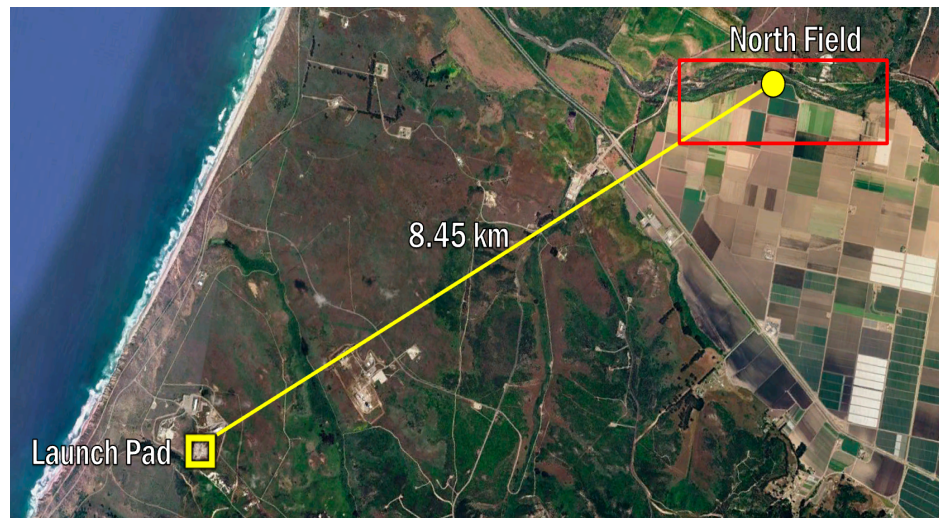


Figure 1. Satellite imagery of VAFB showing the Falcon 9 launch pad at SLC-6 and the measurement location North Field, 8.45 km away. Image from Google Earth Pro, Image © 2026 Google

A. DATA COLLECTION

Measurements were made using a data acquisition system developed at Brigham Young University known as the Portable Unit for Measuring Acoustics (PUMA), used in other recent papers published on rocket measurements^{7,8}. The PUMA consists of microphones connected into a ruggedized data acquisition (DAQ) system consisting of a computer, GPS, and external power. Collection methods vary in microphone type, sample rate, data acquisition system, and microphone deployment. Microphone types used include half-inch GRAS 46AE, 146AE, 46BD 46AO and AO-S5. The various microphone types results in a range of microphone sensitivities from 4 to 56 millivolts per Pascal (mV/Pa). The National Instruments (NI)-9250 (102.4 kHz sample rate, ± 5 V, 0.43 Hz cutoff) and NI-9232 (51.2 kHz sample rate, ± 5 V, 0.13 Hz cutoff) were used as 24-bit DAQ systems. The microphone was inverted over a hard plastic ground plate and surrounded by an acoustically transparent wind screen, as described by Anderson et al.⁸. At any single launch, anywhere between one and fifteen microphones were deployed in sufficient proximity to be essentially collocated relative to the launch vehicle. A multimicrophone set up is pictured in Figure 2.



Figure 2. a) An example measurement set-up. b) PUMA computer and DAQ system. c) COUGAR windscreens and microphone deployment.

B. DATA ANALYSIS METHODS

The analysis details are as follows. The waveform is trimmed by finding the ignition overpressure (IOP) event, then including the previous 10 seconds of ambient noise. In this paper, 10 s before ignition is denoted as 0 seconds. The running OASPL is then computed over a 1-second sliding window over the entire waveform. The maximum OASPL refers to the absolute maximum value taken from the running OASPL. The OTO spectra are calculated over the 3-dB down range, relative to the maximum OASPL. To calculate the running dSk, a 1-second sliding window is used, similar to calculating running OASPL.

In Figure 3, an example waveform is shown to illustrate the waveform characteristics and the reason for shock-related dSk calculations. The waveform in Figure 3a) emphasizes positive pressure outliers during the maximum-amplitude portion of the launch. Figure 3b) shows a single second of data at 85 s (75 s after ignition). The data in Figure 3b) are used to calculate histograms for the pressure (Figure 3c) and the pressure time derivative, calculated from a simple first-order difference (Figure 3d). Counts in both plots are shown on a logarithmic scale to emphasize low-probability outliers. While the pressure histogram in Figure 3c) appears slightly skewed, the histogram in Figure 3d) is much more positively skewed, emphasizing the waveform steepening and shock-like characteristics that give rise to crackle perception. Because they have been associated with increased annoyance in jet noise, understanding shocks and crackle is important in studies of high-amplitude sound such as rocket noise⁹⁻¹².

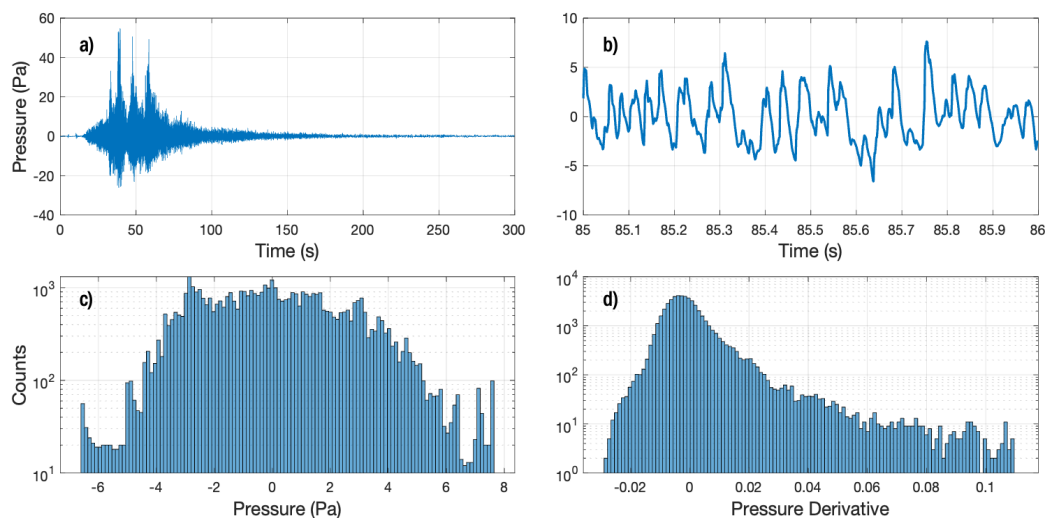


Figure 3. Example pressure-time waveform. b) A one-second pressure-time waveform. c) A one-second interval histogram. d) A histogram from the one-second derivative interval.

3. RESULTS

A. MAXIMUM OVERALL LEVELS

Table 1 reports the maximum flat and A-weighted OASPL measured during each launch. Flat-weighted levels are always higher than A-weighted, due to the low-frequency nature of rocket noise. Based on our analysis thus far, there is no correlation between maximum level and time of day or weather condition. Figure 4 represents the launch and maximum flat-weighted level graphically, ordering the launches from lowest to highest average maximum flat-weighted OASPL. The RADARSAT, USSF-62, and Transporter launches are chosen for later in-depth comparison. The Tranche 0B, USSF-62, and WorldVIEW launches had a total of 15 microphones present with 50 ft spacing between each microphone to create a 500 ft linear array, which provides insights into uncertainty based on atmospheric turbulence affecting sound propagation. Within a single launch, the largest spread of maximum OASPL ranged from 114.2 dB to 116.9 dB at the WorldVIEW launch, a total spread of 2.7 dB. Across all launches, there was a spread of 4.7 dB and 11.3 dBA in the maximum flat- and A-weighted OASPLs, respectively. With 6 dB being equivalent to a doubling of pressure, a spread of 4.7 dB indicates a noticeable variation in acoustic energy. Similarly, an increase in 11.3 dBA results in more than a doubling in perceived loudness, meaning that people and communities can experience launches that sound twice as loud as others despite the same rocket and trajectory being flown.

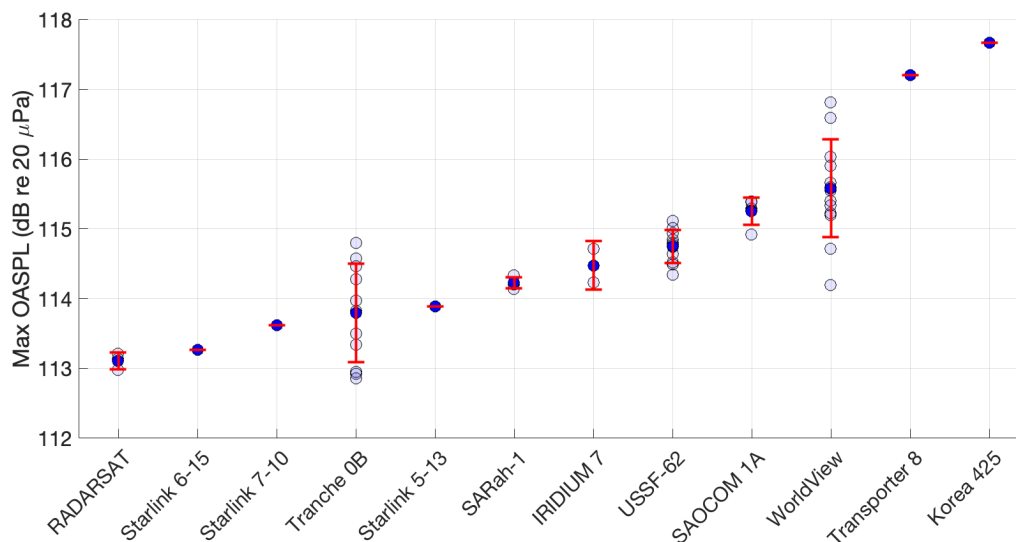


Figure 4. The calculated maximum OASPL of each mic (pale blue), the average level of all microphones at a single launch (dark blue) and error bar (red), which is the standard deviation of that launch's dataset.

C. PRESSURE WAVEFORM AND RUNNING OASPL COMPARISON

Three launches are chosen for further analysis. USSF-62 is chosen to represent an average launch. RADARSAT represents a below-average launch, having the lowest maximum flat-weighted level. Transporter 8 represents an above-average launch with one of the highest maximum flat-weighted levels and interesting characteristics noticeable in the waveform. As an example, compare the USSF-62 launch in Figure 5 to the Transporter 8 launch in Figure 6. Visually, the pressure-time waveform shown in blue looks different between the launches shown. The USSF-62 shows a smooth build-up of launch noise, followed by a gradual roll-off, whereas Transporter 8 exhibits four distinct, sharp peaks throughout the launch period. Those shapes can also be seen in the running OASPL. USSF-62 had a maximum OASPL of 114.5 dB and 95.3 dBA. Transporter 8 had a maximum of 117.2 dB and 93.7 dBA. Transporter 8's maximum unweighted level was 2.7 dB higher than USSF-62 while the maximum A-weighted level 1.6 dBA lower than USSF-62. For both launches, the period of maximum OASPL occurred approximately 40 seconds from $t=0$.

Figure 7 depicts the same metrics but for the RADARSAT launch. Here is another smooth waveform apart from a small undulation from 10 to 25 seconds. RADARSAT's waveform is similar in shape to USSF-62's waveform. RADARSAT had the lowest maximum OASPL of 113.0 dB and 91.6 dBA, which is 1.5 dB (3.7 dBA) below USSF-62 and 4.2 dB (2.1 dBA) below Transporter 8. The maximum OASPL occurred around 50 seconds into this launch, 10 seconds later than the other two launches. Figure 8 shows a three-launch overlay,

zoomed into the time period of maximum OASPL. The level of ignition varies from 92 dB at RADARSAT, to 96 dB at USSF 62, and 90 dB at Transporter 8.

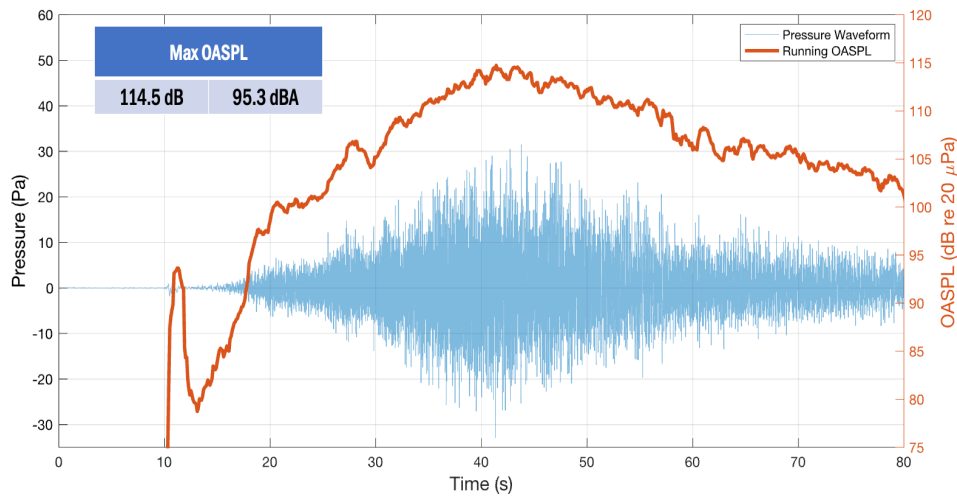


Figure 5. USSF-62 pressure-time waveform (blue) and running OASPL (red) with pressure on the left y-axis and OASPL in dB on the right y-axis, maximum values in the top left. Note the smooth rise in level from ambient to maximum from 10 seconds to 45 seconds.

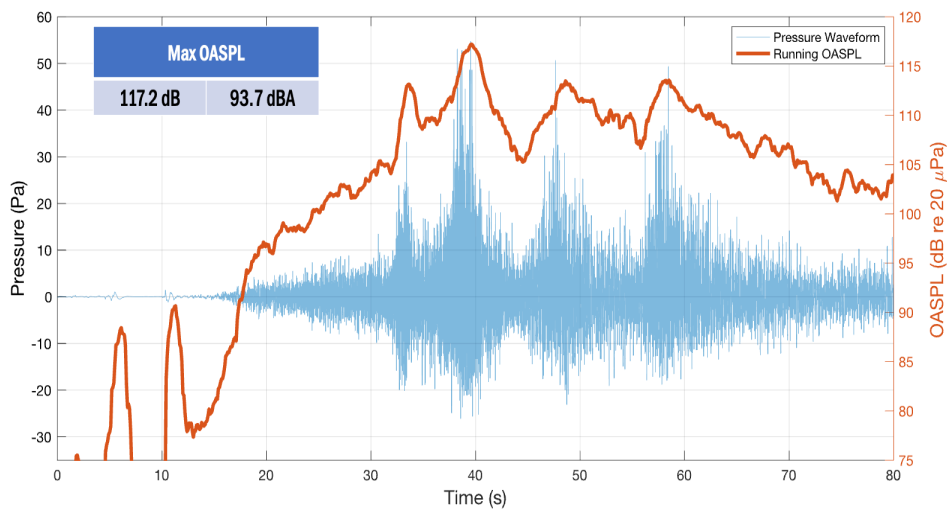


Figure 6. Transporter 8 pressure-time waveform (blue) and running OASPL (red) with pressure on the left y-axis and OASPL in dB on the right y-axis, maximum values in the top left. There are 4 distinct peaks, resulting in jumps in OASPL of 10 dB from peak to trough.

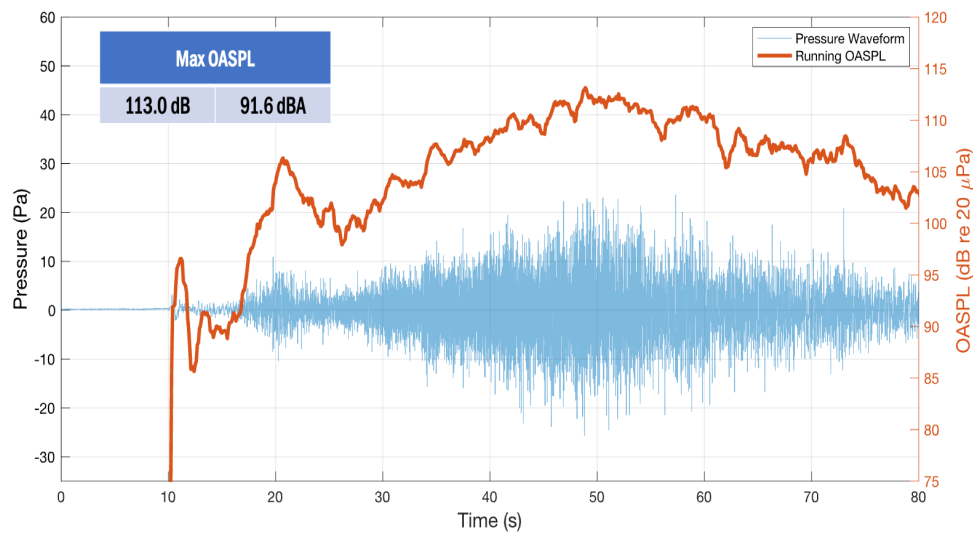


Figure 7. *RADARSAT pressure-time waveform (blue) and running OASPL (red) with pressure on the left y-axis and OASPL in dB on the right y-axis, maximum values in the top left. This waveform is smoother than that of Transporter 8's, but there are two smaller envelopes between 15-20 seconds and 30-70 seconds.*

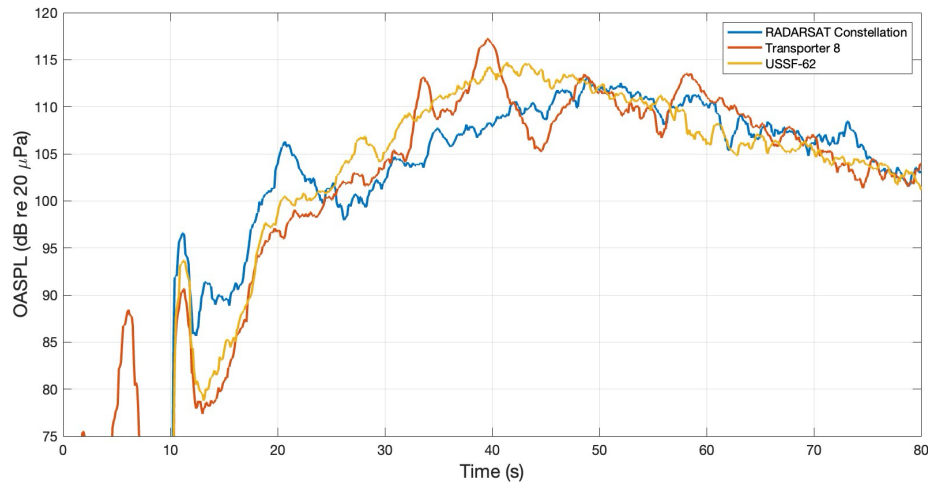


Figure 8. *USSF-62, Transporter 8, and RADARSAT launches running OASPL overlay. Note the peak and dip from 117 dB to 105 dB in the Transporter 8 data compared to the smoother rise and fall of RADARSAT and USSF-62.*

B. MAXIMUM OTO SPECTRUM

The maximum OTO spectrum refers to the spectrum during the period of peak OASPL, including ± 3 dB around the absolute peak, as done in other recent papers on rocket acoustics⁷. The three spectra are compared in Figure 9. USSF-2 and RADARSAT have peak frequencies of 10-30 Hz, and Transporter 8 around 30 Hz. Transporter 8's peak frequency was 5 dB higher than USSF-62's and almost 10 dB higher than RADARSAT. Separation between the three launches reaches a maximum of 15 dB at a frequency of 61 Hz. At 400 Hz, Transporter 8 levels start to diminish, and USSF-62 has the highest level from 400 Hz and on. This decay of Transporter 8's high-frequency content explains why the A-weighted values for Transporter 8 were lower than those of RADARSAT and USSF-62.

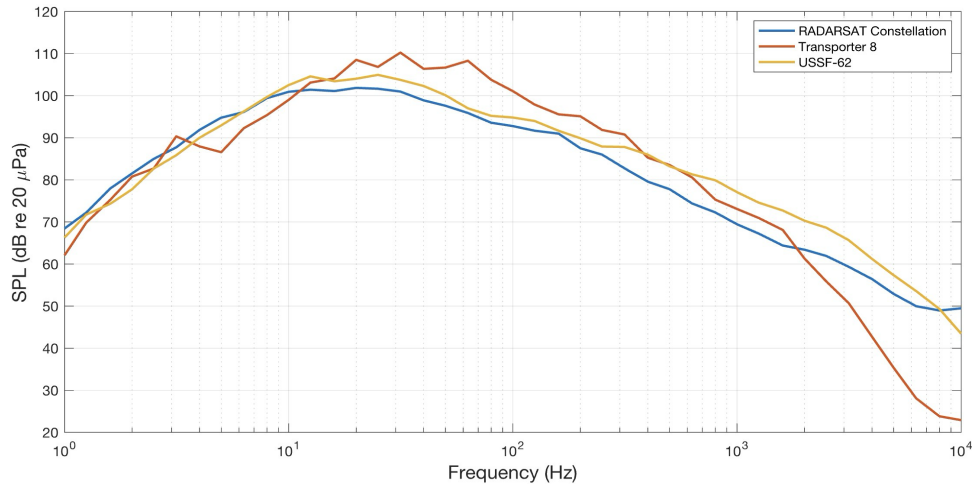


Figure 9. Maximum OTO spectra comparison of the USSF-62, Transporter 8, and RADARSAT launches. RADARSAT’s peak frequency is 20 Hz. Transporter 8’s peak frequency is 30 Hz. USSF-62’s peak frequency is between 10 and 20 Hz. From about 10 – 400 Hz, Transporter 8 had the highest levels. From 400 Hz on, USSF-62 dominates with the highest levels. RADARSAT’s levels stay consistently below the other two until 2000 Hz.

C. RUNNING DERIVATIVE SKEWNESS

Derivative skewness is directly related to the waveform’s crackle content in that greater perception of crackle has been correlated with greater dSk. This measurement is often used in military jet noise analyses. A dSk of 3 is considered continuous crackle and a value above 9 is denoted as intensely crackling^{11,13}. High dSk implies significant shock content, which is linked to high-frequency events. Low dSk suggests less high-frequency content^{14,15}. In Figure 9, the maximum spectra, Transporter 8’s high frequency roll off occurs at a faster rate than the other two launches. This roll off is reflected in the maximum dSk value for Transporter 8 of 6, compared to the values of 32 and 33 of USSF-62 and RADARSAT respectively. Previously, the dSk of other rockets has been reported, with maximum values ranging from 40 to 100 for a static firing of a GEM 63 solid booster, 7.1 to 7.7 for Delta, 3.6 to 6.9 for Scout, 7.7 to 9.6 for Peacekeeper, and 1.7 to 17 for Titan IV^{11,13}. It should be noted that that sampling frequency affects dSk values as higher sample rates can better capture shock rise time^{16,17}.

The USSF-62 launch shown in Figure 10 had the smoothest pressure-time waveform and reached a maximum dSk of 32 approximately 48 seconds into the launch. The launch with the greatest maximum OASPL, Transporter 8, with the four distinct sharp peaks in the pressure-time waveform, reached a maximum dSk of 6, also about 48 seconds into the launch shown in Figure 11. RADARSAT, the launch with the lowest maximum OASPL and a relatively smooth pressure-time waveform, reached a maximum dSk of 33, occurring 55 seconds into the launch shown in Figure 12. The period of maximum dSk does not overlap with the period of maximum OASPL for this dataset.

Table 2. Summary of timing of values and timing maximum OASPL and dSk for 3 launches.

Mission Name	Value of Max OASPL (dB re 20 μPa)	Time of OASPL (seconds into launch)	Max dSk	Time of Max dSk (seconds from t = 0)
USSF-62	114.5	41	32	48
Transporter 8	117.2	39	6	47
RADARSAT	113.0	48	33	55

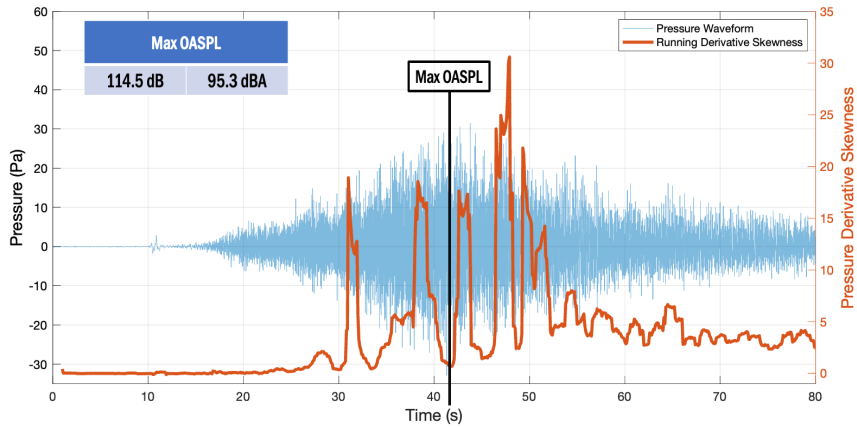


Figure 10. USSF-62 pressure-time waveform (blue) and running pressure derivative skewness (red) with pressure in Pa on the left y-axis and pressure derivative skewness on the right y-axis, maximum OASPL values in the top left.

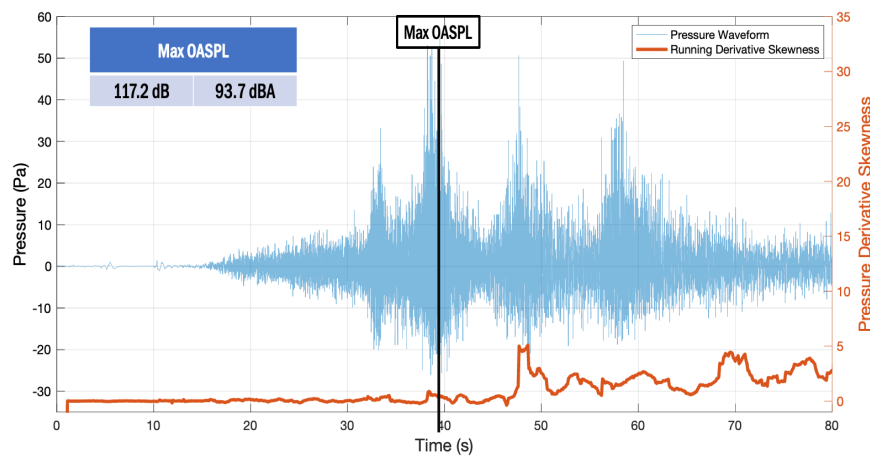


Figure 11. Transporter 8 pressure-time waveform (blue) and running pressure derivative skewness (red) with pressure in Pa on the left y-axis and pressure derivative skewness on the right y-axis, maximum OASPL values in the top left.

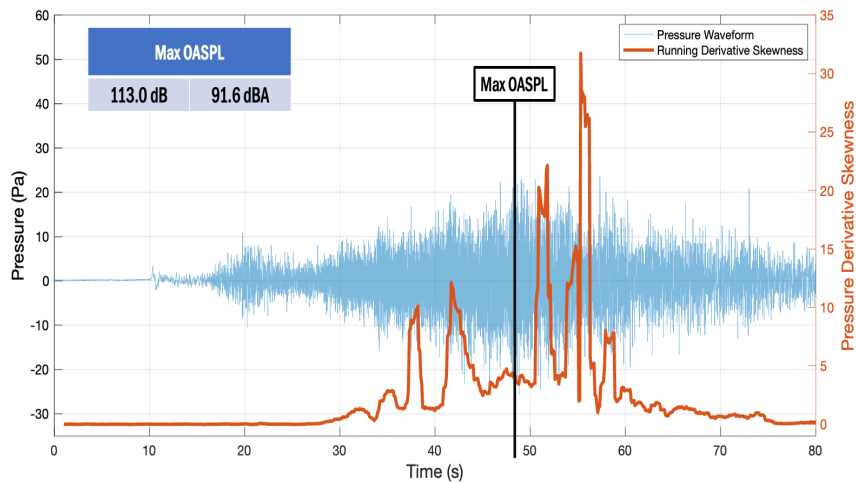


Figure 12. RADARSAT pressure-time waveform (blue) and running pressure derivative skewness (red) with pressure in Pa on the left y-axis and pressure derivative skewness on the right y-axis, maximum OASPL values in the top left.

4. CONCLUSIONS

Acoustic data were collected at the same location 8.45 km from the launch pad during twelve different Falcon 9 rocket launches. Across the twelve launches, a spread of 4.7 dB (10.9 dBA) in the maximum OASPL was found. This indicates a notable variation in peak acoustic levels between different launches. Additionally, for the WorldVIEW launch, a spread of 2.7 dB (11.3 dBA) maximum OASPL across a 500 ft linear array, indicating significant variation even within the same launch. Across all twelve launches, a spread of 4.7 dB and 10.9 dBA was found. This variation introduces challenges to modeling sound levels from future rocket launches. When examining the peak frequency across three launches, a spread of 20 Hz was found. Therefore, there is variability in the dominant noise signature's dominant frequency. The period of maximum OASPL did not correlate with the period of maximum derivative skewness. This suggests that there are complex changes in noise characteristics over the launch duration. Lastly, the launch with the highest maximum OASPL, Transporter 8, had the lowest maximum derivative skewness. Inversely, the quietest launch, RADARSAT, had the highest maximum dSk.

In the future, a similar analysis will be conducted for data recorded at a much closer distance to the rocket during takeoff for the same launches discussed here and more. Preliminary indications suggest that the noise metrics and conclusions for these closer recordings will differ from those obtained in this analysis. The variation from launch to launch are attributable to sound propagation effects through the atmosphere. Variations in atmospheric conditions, both within a single launch and between different launches, likely play a significant role in these differences. The atmospheric environment is one factor that varies while other launch aspects remain relatively consistent, highlighting the critical role of atmospheric propagation in shaping the acoustic environment. To further improve studies such as this one, more launch data from multiple locations are being collected, contributing to a large data set with statistically significant results.

ACKNOWLEDGMENTS

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