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An application of aircraft noise metrics to the Artemis-I launch

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ABSTRACT

In aerospace and acoustical research, there has been significant focus on understanding the negative effects of noise from jet aircraft and flyover vehicles. However, there has been relatively little investigation into the specific noise impacts of launch vehicles. Despite a considerable rise in the number of launches from various spaceports globally in the past decade, there appears to be poor understanding of the potential harm these increasing launches could pose to nearby communities, including both humans and wildlife. This paper aims to apply established noise metrics such as overall sound pressure level, sound exposure level, and effective perceived noise level, commonly used in aircraft policy, to quantify the potential noise impact of launch vehicles, using measurements from the Artemis-I mission as a case study.

1. INTRODUCTION

Decades of research have been dedicated to quantifying and qualifying aircraft noise, leading to the development of numerous metrics that aid researchers, manufacturers, and policymakers in understanding its impact. However, despite the increasing frequency of rocket launches worldwide, there has been a notable absence of investigation into the adverse effects of launch vehicle noise on surrounding communities, including both humans and wildlife.

This paper will delve into several key metrics used in this field, including Overall Sound Pressure Level (OASPL), Sound Exposure Level (SEL), and Effective Perceived Noise Level (EPNL) [1]. These metrics vary in their basis, some rooted in physics while others in human perception, all aiming to provide a quantifiable means of assessing potential annoyance levels. They can be categorized into frequency-weighted sound pressure levels (OASPL), computed loudness-based metrics (EPNL), and an average energy level metric (SEL).

2. BACKGROUND

In 2023, Kennedy Space Center in Merritt Island, Florida, USA, conducted a total of sixty-nine launches [2]. This rise in launch frequency, coupled with the accompanying noise, including

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booster landing noise, underscores the need for a deeper understanding of the environmental and population impacts in the vicinity of the launch pads.

The United States NASA report known as SP 8072 detailing the early launch vehicle noise predictions (from the 1960s) was meant to aid in understanding noise generated from launch vehicles during the space race and to offer guidance on noise limit criteria surrounding launch pads [3]. Since this report, there have been a few other large environmental studies at KSC [4, 5] but they seem limited in scope and only offer a few simple metrics and predicted levels on base and in the close surrounding community. Recently, in an effort to improve reporting on launch vehicle acoustics, researchers compiled the work of the past fifty years. The article thoroughly detailed to better understand the how, why, and what do we do about noise from launch vehicles since the seminal SP 8072 report [6]. However, this review article did not address noise metrics akin to those mentioned in the current work.

While many metrics exist, many are more subjective and describe human annoyance or perception, the study of which (for launch vehicles) is left for future work. The next few sections will offer more background on the following metrics:

- OASPL: an objective numerical result describing the level of the launch noise at any particular instant, or averaged over a period of time.

- SEL, EPNL: metrics that describe the noise exposure, perceived noisiness and in some cases, annoyance.

Regardless, all of these metrics are in some way related to the effect of the noise levels on humans and depend largely on the hearing thresholds of humans both in level (pascals) and frequency (hertz).

2.1. Overall Sound Pressure Level

Overall Sound Pressure Level (OASPL) is perhaps the most well known and easily calculated metric available for noise quantification. OASPL is reported using a variety of different frequency weightings depending on the noise level and frequency range, some of which are Z, A, C, D, or G. Figure 1 shows the weighting curves A, C, and G on a scaled access ranging from 0 Hz to 10^4 Hz. The A-weighted OASPL, reported in dBA, is the most widely used weighting curve as it is the weighting that best approximates the response of the human ear. The C-weighting curve has a different shape and is said to be used for noises that are high level (greater than 100 dB). D-weighting is no longer included in standards but was in the past used for aircraft noise as well [1]. Less-known G-weighting was designed for use in infrasound applications, sounds below 20 Hz [7]. There is a rapid roll-off in the weighting curve both above and below 10 Hz [8].

2.2. Sound Exposure Level

Sound Exposure Level (SEL) represents the energy in a signal and considers the received level of sound and duration of exposure. SEL is an objective measurement of the cumulative amount of exposure a subject would endure at the receiving location and is a useful metric since with this, sound exposures of different duration can be related to one another based on the total acoustic energy measured [10].

2.3. Perceived Noise Level, Effective Perceived Noise Level

Perceived Noise Level (PNL) represents the the potential annoyance to a listener and used in the calculation for the more often reported Effective Perceived Noise Level (EPNL) [1]. EPNL is a single number measure of an aircraft noise event, a measure of relative noisiness and is reported in EPNdB. Manufacturers use the calculated EPNL for noise certifications and the metric applies

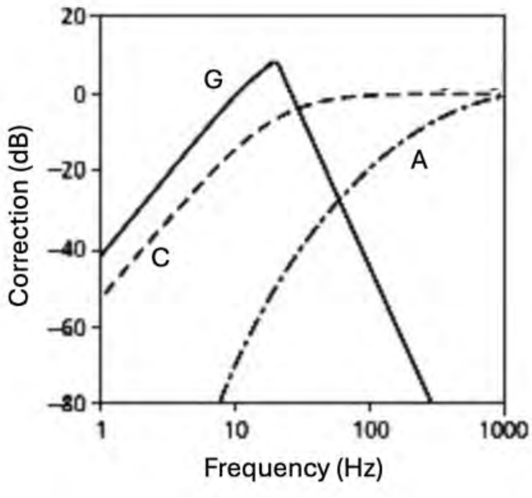


Figure 1: The weighting curves A, C, G to be applied to raw OASPL based on the intended use (adapted from [9]).

to an individual aircraft as opposed to an event [11]. This metric assumes that the noise event in question is pass-by or fly-over.

2.4. Paper outline

In the subsequent sections we will offer a description of the Artemis-I launch, equipment used, and data gathered. We will then further detail a selection of applicable measurement stations used for this paper's analysis and report the results for this launch to make comparisons to the values in literature for known aircraft. Finally, we will provide a discussion on the usefulness of these particular metrics moving forward and suggest a call to action for policy makers and researchers regarding the necessary direction for the future of launch vehicle noise metrics.

3. LAUNCH AND MEASUREMENT DESCRIPTION

Space Launch System's (SLS) Artemis I mission successfully launched in November of 2022 [12–14]. The following sections will describe the launch and rocket environment as well as provide details of the equipment used to measure the low-frequency, high-intensity sound from the launch.

3.1. Launch description

The Artemis-I mission launched from Launch Complex 39B (LC-39B) at KSC. The core stage of SLS was powered by four Aerojet Rocketdyne RS-25 liquid hydrogen-oxygen engines. On opposite sides of the core stage were two Northrop Grumman five-segment solid-fuel rocket boosters (SRBs). Figure 2 shows a depiction of the full space launch system expanded featuring the white SRBs on the sides of the core stage and the four RS-25 engines at the bottom.

3.2. Measurement description

Acoustic data were collected at several far-field sites surrounding LC-39B, both inside and outside of KSC, from a blast radius limit of 1.4-km to nearly 40-km from the pad. The data analyzed here are from a small subset of the total stations located at environmentally interesting locations around the pad. The goal for this paper was to choose sites that would be in the community or of interest from an ecological standpoint. Shown in Fig. 3 are station numbers and distances from

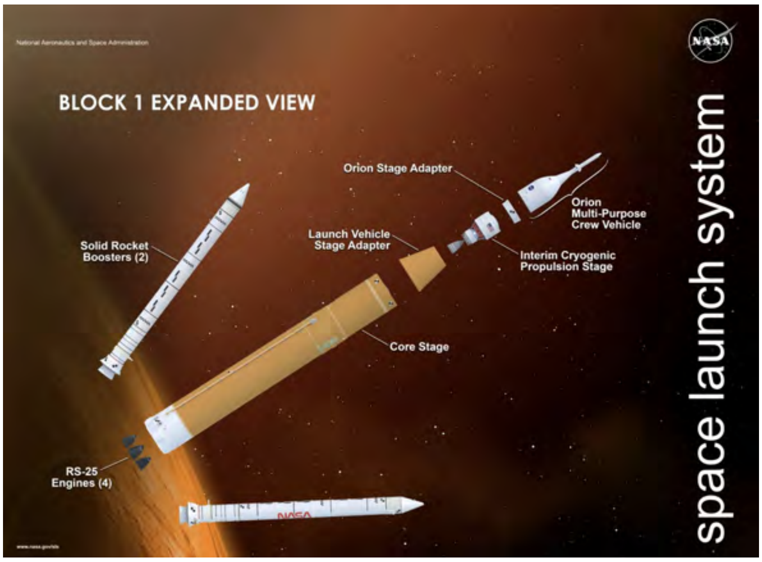


Figure 2: NASA graphic of the SLS showing the SRBs (detached, in white) and the RS-25 engines (detached, in black). Image credit: NASA.

the center of LC-39B. Data were collected using an in-house system referred to as the Portable Unit for Measuring Acoustics (PUMA), which consisted of a ruggedized computer, a GPS time clock for synchronization, NI 9250 24-bit/5-V data acquisition modules sampling at 102.4 kHz, and a lithium-ion battery housed in a weatherproof case with a solar charging system [15]. Microphones used with the PUMAs were condenser, free-field microphones: 6.35 mm (1/4 in.) diameter GRAS 46BE (4 Hz–80 kHz) [15–17].

4. METRICS - DEFINITIONS AND EQUATIONS, DISCUSSION AND ANALYSIS OF SLS DATA

4.1. OASPL

Figure 4a shows the overall sound pressure level and pressure waveform measured at station P01 which was the furthest station on the coast from the launch pad. The event beginning at 0-seconds represents the signaled liftoff. Figure 4b shows the spectrum at the same location both narrow band and OTO band. Notice that the peak frequency at this station was around 12 Hz.

More OASPL results and comparisons between stations were made in recent publications [12, 13]. Figure 5a shows the 1/3 octave band spectrum from station 12 using four different weighting curves: dBA, dBZ, dBC, dBG. Notice that the dBZ weighted curve represents the true peak frequency being around 10 Hz and the only curve to give the correct importance in that frequency range is the dBG curve. While there are not many agencies and researchers publishing G-weighted results, a 2004 conference proceedings paper on the assessment of low-frequency noise reported measurements of noise inside offices near two noisy areas (i) a sewage works pumping station and a blast furnace in a steel works plant. The results were given in 1/3rd octave band sound pressure levels in the range 2 Hz to 100 Hz. Levels reported for the pumping station show, for example, 78 dBG at 10 Hz (zero gain in G-weighting) and 83 dBG at 79 Hz. Whereas, at 100 Hz, with a -44 dB gain in G-weighting, would result in a level of 54 dBG. For the blast furnace, a 10 Hz the level was 93 dBG and at 20 Hz (with the highest gain of +9dB) the level was 106 dBG.

A Boeing report from 1986 listed the maximum level, L_{max} of a Boeing 707 from 4000 ft (≈1200 m) at various levels of thrust between 67-85 dBA [18]. Table 1 shows the A-weighted levels from each station mentioned. For comparison, station P01 had a maximum level of 99.8 dBA and station P12, at a distance of 22 km from the launch pad had a maximum level of 79.3 dBA.

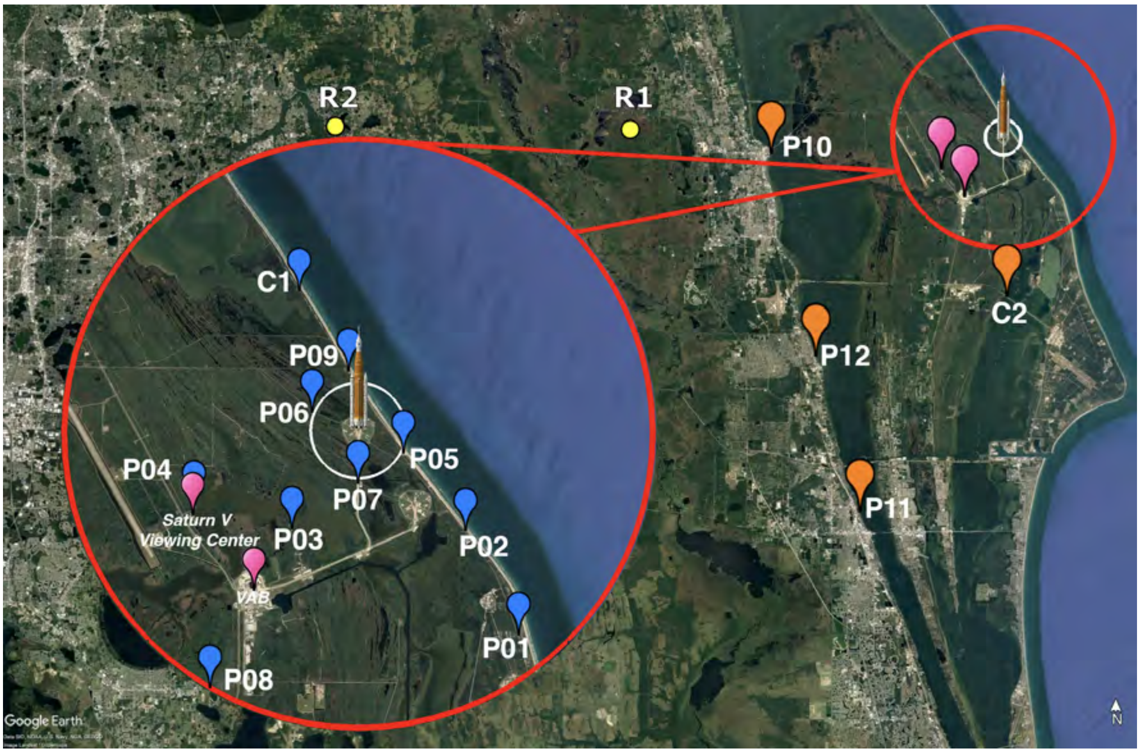


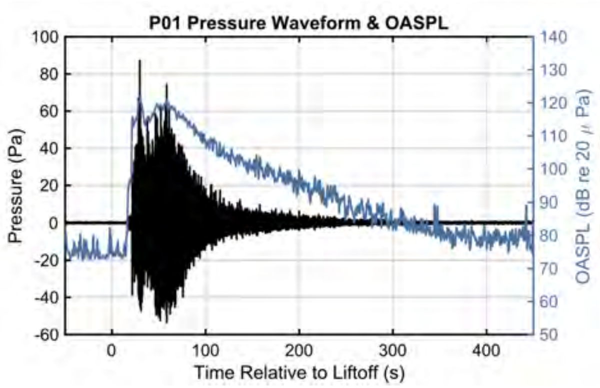
Figure 3: Cape Canaveral and Kennedy Space Center Base in Cape Canaveral, Florida USA. Launch Complex 39B circled in white. On base stations circled in Red. Community/off-base stations signified by orange markers. Stations P07 (close to Pad), P12 (community station), and P01 (coastal station) will be discussed.

Table 1: OASPL and SEL values using different weighting functions for three different stations, P01, P07 and P12.

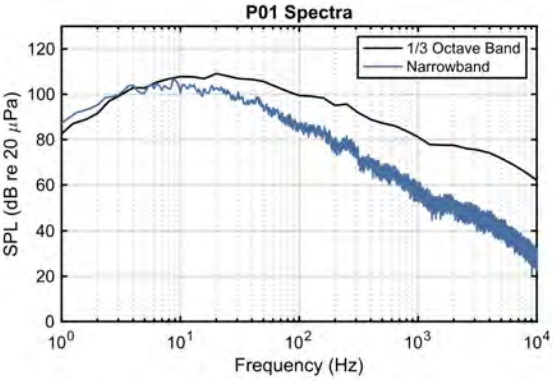
Station	Dist. from Pad (km)	dBZ	dBA	dBC	dBG	SEL dBZ	SEL dBA	SEL dBC	SEL dBG
P01	7.4	122.3	99.8	116.2	128.9	135.8	111.9	129.7	26.8
P07	1.49	136.6	116.9	133.6	164.7	147.3	127.2	143.0	467.1
P12	22	107.3	79.3	100.4	100.7	121.3	86.6	111.7	22.4

4.2. SEL

The sound exposure level calculated at stations P01, P12, P07 are shown in Table 1. Notice when comparing to the maximum OASPL found in the same table, the SEL is normalized to one second and its value will always be larger than the maximum OASPL. In a sense, SEL condenses the entire measured event into one second. According to the Federal Aviation Administration (FAA), SEL is normally 7 - 12 dB higher than the maximum level. Long, slow, quieter aircraft can yield the same or higher SEL values than faster (shorter duration exposure), louder aircraft [19]. The results in Table 1 exhibit this behavior, Station P01 OASPL was 99.8 dBA and the SEL_A was 111.9 dBA for a difference of 12 dBA. The highest SEL from these three stations was of course the closest station, station 7, at a level of 127.2 dBA. For comparison, an 1986 FAA report listed the SEL_A of a Boeing 707 of 85 dBA at maximum thrust measured at 1400 m [18].

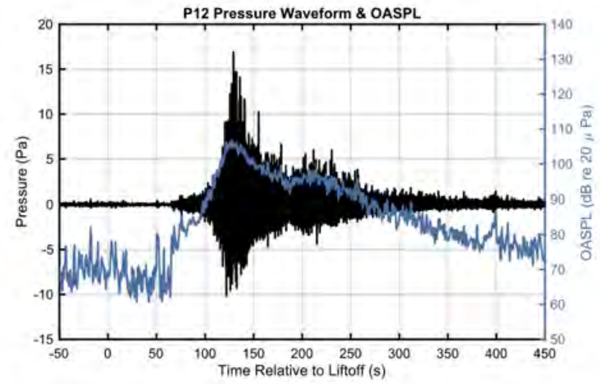


(a) Running OASPL (in blue) in dBZ at Station P01. Pressure waveform (black) in Pa.

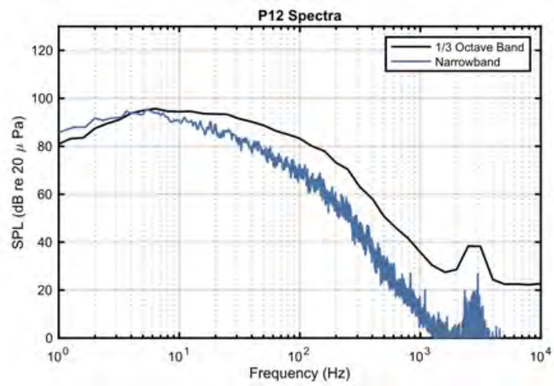


(b) Frequency spectrum, both narrow band and one-third octave band are shown for Station P01.

Figure 4: Station 01, 7.4 km from launch pad.



(a) Running OASPL (in blue) in dBZ at Station P12. Pressure waveform (black) in Pa.



(b) Frequency spectrum, both narrow band and one-third octave band are shown for Station P12.

Figure 5: Station 12, 22 km from launch pad.

4.3. EPNL

The perceived noise level (PNL) and tone-corrected perceived noise level are used to calculate the effective perceived noise level (EPNL). EPNL at stations P01, P07, P12 was 120.7, 156.6, 80.3 EPNdB respectively. For comparison, an 1986 FAA report listed the EPNL of a Boeing 707 of 98.4 EPNdB at maximum thrust measured at 1200 m [18]. For other aircraft, found in 1997 report, the highest EPNL value reported was around 110 EPNdB [20]. Since EPNL is a measure of the relative noisiness of an individual aircraft pass-by event, if we are comparing the two (Boeing 707 and SLS), the EPNL for SLS is significantly greater.

Since station P12 was in the community and exhibited significantly lower levels than other stations, an EPNL value would be interesting. Again, EPNL at station P12 was 80.3 EPNdB compared with the 98.4 EPNdB of the Boeing 707 (at 1200 m). Recall, however, that EPNL is supposed to characterize a fly-over or pass-by event of an aircraft which would be of shorter duration than rocket launches. Further, recall that EPNL is calculated through the use of A-weighted OASPL, which as already mentioned, may not be appropriate to classify launch vehicle noise.

5. DISCUSSION AND CONCLUSIONS

This paper has introduced a few metrics available for assessing community noise impact from aircraft and applied them to the sound measurements from the SLS/Artemis-I mission. Due to the high-levels, low peak frequencies, and assumed rarity of the rocket launches, the metrics available to policy makers may not be suited to accurately determine the resulting impact. This work is not meant to offer new metrics at this time; this is left for future work either for this group or others. This is merely a gentle call to action for those making policy and estimating the potential harm that could come from the increase in rocket launches around the world. Based on this preliminary work G-weighted OASPL is likely the best physics based metric to use when calculating and reporting SEL and EPNL. Since EPNL is defined as a flyover metric, as currently defined it may not be the best choice to classify launch vehicles. Lastly, as launch duration seems to be long in comparison to aircraft flyovers, SEL_G may be a good option to quantify an average exposure.

ACKNOWLEDGEMENTS

We gratefully acknowledge the funding from the National Science Foundation Award 2109932 and the Utah Space Grant. Thanks also to G. Hart, M. Anderson, M. Kellison, and L. Mathews for, among other things, fruitful conversations and computational support.

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