Measuring the world's most powerful rocket: Noise from Starship Super Heavy

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ABSTRACT
SpaceX's Starship Super Heavy is the most powerful launch vehicle ever flown, intended to return humans to the moon and reach Mars. After measurements of three test flights (Flights 5, 6, and 9), this paper summarizes the measurements and briefly discusses launch noise and booster flyback boom characteristics. With a planned launch cadence to rival that of the Falcon 9, Starship's noise characterization is critical to determining its impacts and its place relative to other launch vehicles and noise sources. This paper accompanies an Acoustics 2025 plenary talk.

1 INTRODUCTION

The acoustic environment generated by rocket launches continues to be a critical concern in both vehicle design and environmental impact assessment. Far-field noise characterization plays an essential role in validating acoustic propagation models, establishing community exposure levels, and developing mitigation strategies. A growing body of work (e.g., Lubert, 2022; Gee, 2024a) has pointed toward the need to further develop benchmark measurement approaches and improved models of noise source generation, propagation, and reception of noise.

SpaceX's Starship Super Heavy booster represents a major change in launch vehicle acoustics. With 33 Raptor engines producing ~74 MN of thrust at liftoff, Super Heavy operates at scales beyond those considered in prior studies. This includes even NASA's Space Launch System (SLS), which, as the second most powerful rocket flown, has a liftoff thrust of ~39 MN. The far-field acoustics from SLS's Artemis I launch has been studied fairly extensively (Gee, 2023a; Kellison, 2023b; Kellison, 2024; Coyle, 2024; Kellison, 2025), illustrating the high-amplitude, broadband, low peak-frequency, impulsive (i.e., "crackly") noise environment with audibility exceeding 50 km (Kellison, 2023a). On the other hand, there are relatively few studies thus far on the acoustics of Starship. The long-range infrasound study by Pilger and Hupe (2023) is an exception.

This paper, stemming from a plenary talk at the Acoustics 2025 conference, summarizes Brigham Young University's far-field noise measurements of Starship Super Heavy test launches. These measurements build directly from the methodologies that have been used to study the super heavy-lift SLS, but also small- (Firefly Alpha), medium- (Antares 230, Atlas V, and Falcon 9), and heavy-lift (Delta IV Heavy and Falcon Heavy) launch vehicles. Initial analyses of Flights 5 and 6 have been previously published (Gee, 2024b; Gee, 2025). Flight 9 has also been measured at mostly the same locations as Flight 6. By adapting established measurement practices to the spatial and spectral scales of Starship, propagation models can be extended into the Super Heavy regime and a high-fidelity data set curated for additional launch acoustics research. The Starship measurements contribute to the broader effort of refining predictive tools and environmental assessments for next-generation, super-heavy-lift vehicles.

2 MEASUREMENTS

Figure 1 displays Starship Super Heavy (referred to as simply Starship), which consists of the Super Heavy booster, hot staging ring that enables the upper stage's engines to fire prior to booster separation, and the Starship upper stage with its black heat shield tiles. Flight 5 involved the first-ever Super Heavy booster catch, whereas during Flights 6 and 9, the booster was landed in the Gulf to the east after Starship and hot staging ring separation.

Also pictured in Fig. 1 are two measurement stations with line-of-sight to the Starship launch pad. Each measurement station consisted of a weatherproof case containing a computer, GPS clock with microsecond timing accuracy, NI data acquisition module (24 bits, 102.4 kHz or 51.2 kHz sampling at longer range), and a lithium-ion battery. Solar panels were used at stations where access within 24 hours of launch was questionable. Type-1 6.35 mm and 12.7 mm (at longer range) microphones were mounted inverted above a plastic ground plate under a large reticulated foam windscreen. These setups have been used at numerous other launches (e.g., Gee, 2023a) and aircraft sonic boom campaigns. Flight 5 measurements consisted of 8 stations between 10 and 35.5 km whereas for Flights 6 and 9, 21 and 22 stations were respectively deployed from 1.0 – 35.5 km. A map showing the layout from Flight 6 is shown in Fig. 2, where repeated stations from Flight 5 are shown in blue. The Flight 9 layout is similar to Flight 6.

Figure 1. Left and right: Measurement stations set up in view of the Starship Super Heavy (center) launch pad.

3 Representative Waveforms

Shown in Fig. 3 are the waveforms during the three flights at a measurement station 10.5 km from the launch pad (station 13 in Fig. 2). Along with the pressure in pascals is the 1-s running overall sound pressure level (OASPL) in decibels. The ambient sound levels prior to launch are substantially less for Flight 5, which was 7:25 am local time on a Sunday. The variability during the maximum noise period is striking, with the level envelope having a different shape for each launch and maximum levels reached at different times. However, the maximum 1-s OASPL, $\mathrm{OASPL}_{\mathrm{max}}$ is similar: Flight 9 briefly had the greatest level of around 123 dB whereas Flights 5 and 6 were both approximately 121 dB. For all three launches, after the maximum launch noise period, there was a slow decay in level during the vehicle's ascent. Gee et al. (2024b) discuss how it took 16-17 minutes for the unweighted, low-frequency sound levels to return to ambient after Flight 5 liftoff. For Flights 6 and 9, it took less time to return to ambient, but both of these flights were late afternoon with increased ambient noise levels.

Despite the overall similarities in the launch noise characteristics at this station, they differ greatly in terms of the flyback characteristics. Flight 5 involved a booster catch with flyback sonic boom, precatch landing burn, and a hot staging ring sonic boom. Although the Super Heavy booster was landed in the ocean for Flights 6 and 9, both the flyback sonic boom and hot staging ring boom were detected at several microphones. These events are shown with arrows in Fig. 3. Note that the landing engine burn and the booster explosion were not detected at this station but are being investigated for other, more coastal stations. For Flight 6, the level was relatively low and barely detectable above the ambient levels. However, for Flight 9, both events were clearly above the ambient sound environment.

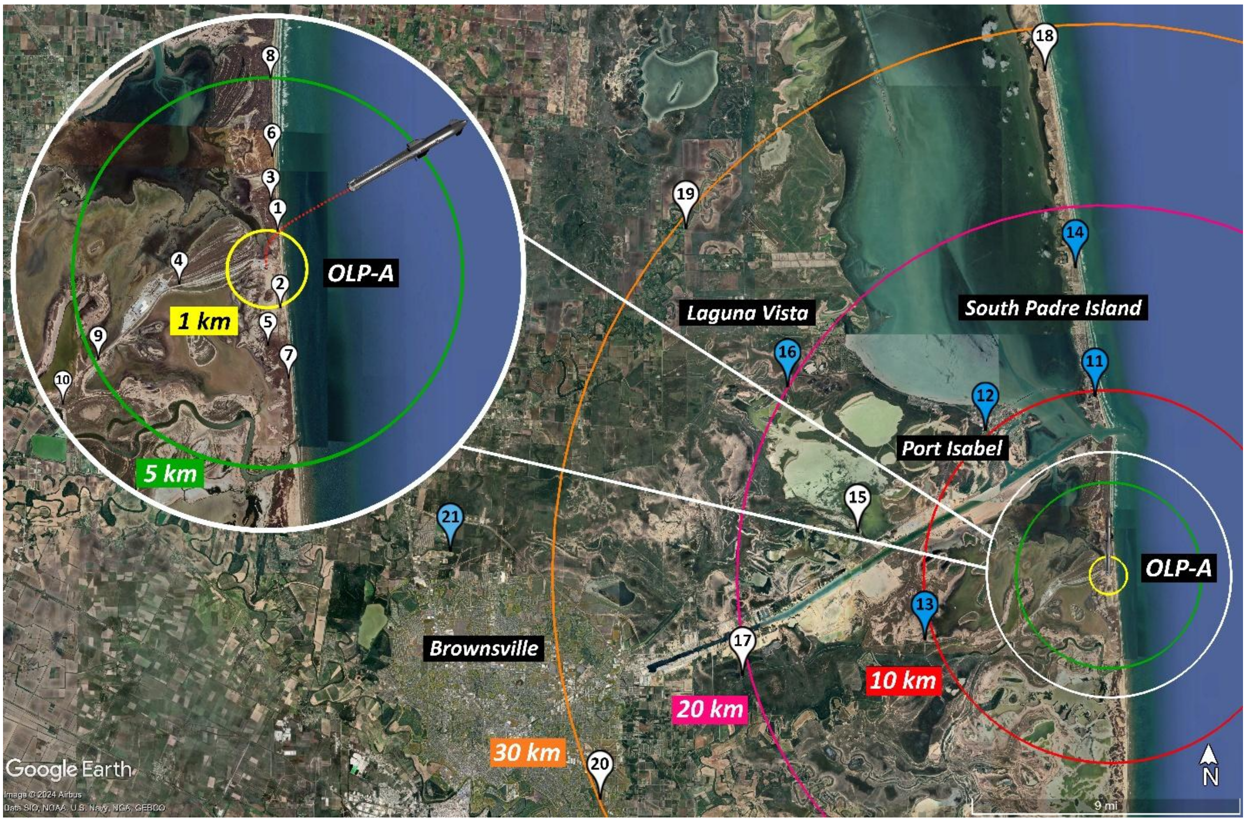

Figure 2. Map showing microphone deployment for Flight 6. Blue markers indicate repeated stations from Flight 5. Figure from (Gee, 2025).

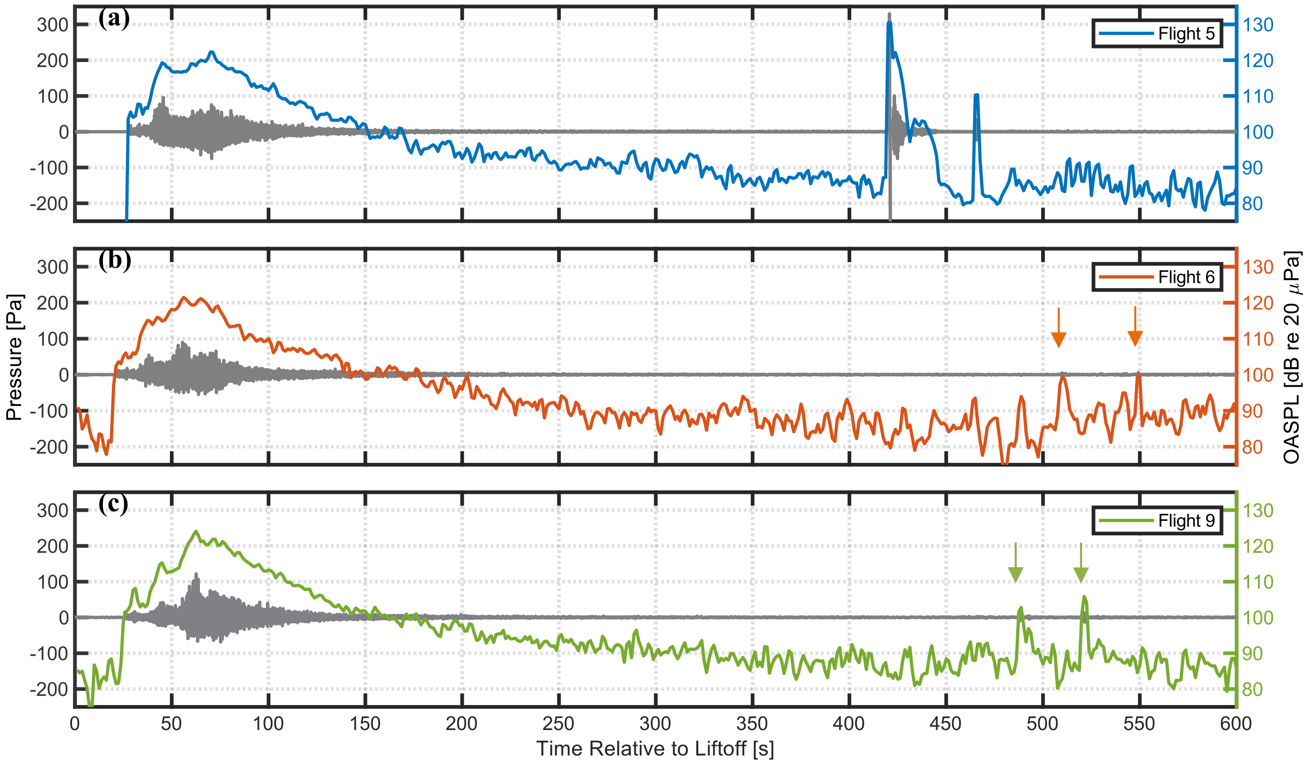

Figure 3. Pressure waveform and running 1-s overall sound pressure level (OASPL) at a station 10.5 km from the Starship launch pad for a) Flight 5, b) Flight 6, and c) Flight 9.

Figure 4 shows zoomed waveform segments from Flights 5 and 9. Figure 4(a) and (c) show the launch noise centred around the waveform peak level. The waveform characteristics reveal the cause of the crackling sound quality as there are numerous shocks present in the signature. Although the physical and perceptual characteristics of crackle have been studied in relatively great detail for high-performance military aircraft (Gee, 2007; Gee, 2016; Gee, 2018; Swift, 2022), the perception of crackle-containing rocket noise remains an open research question important to determining noise-related policies.

Figures 4(b) and 4(d) show the flyback and hot staging ring booms for Flights 5 and 9. In Fig. 4(b), the booster catch during Flight 5 resulted in a flyback boom with an overpressure exceeding 300 Pa (6 psf). After the boom, the landing burn is followed by a lower amplitude noise event from 432—445 seconds. The cause of this noise has not been explored. Finally, the hot staging ring sonic boom arrives. In Fig.4(d), the flyback sonic boom is substantially lower because the booster landed several kilometres in the ocean. (Acoustically determining the sonic boom origin and booster landing location is an ongoing research topic.) It is possible that the noise around 492 s is part of a landing burn but the low amplitude makes this difficult to confirm. Just after 520 s, the hot staging ring boom is clear and is of similar amplitude as the ring boom during Flight 5. Overall, the waveforms help reveal several acoustically significant events associated with a Starship launch.

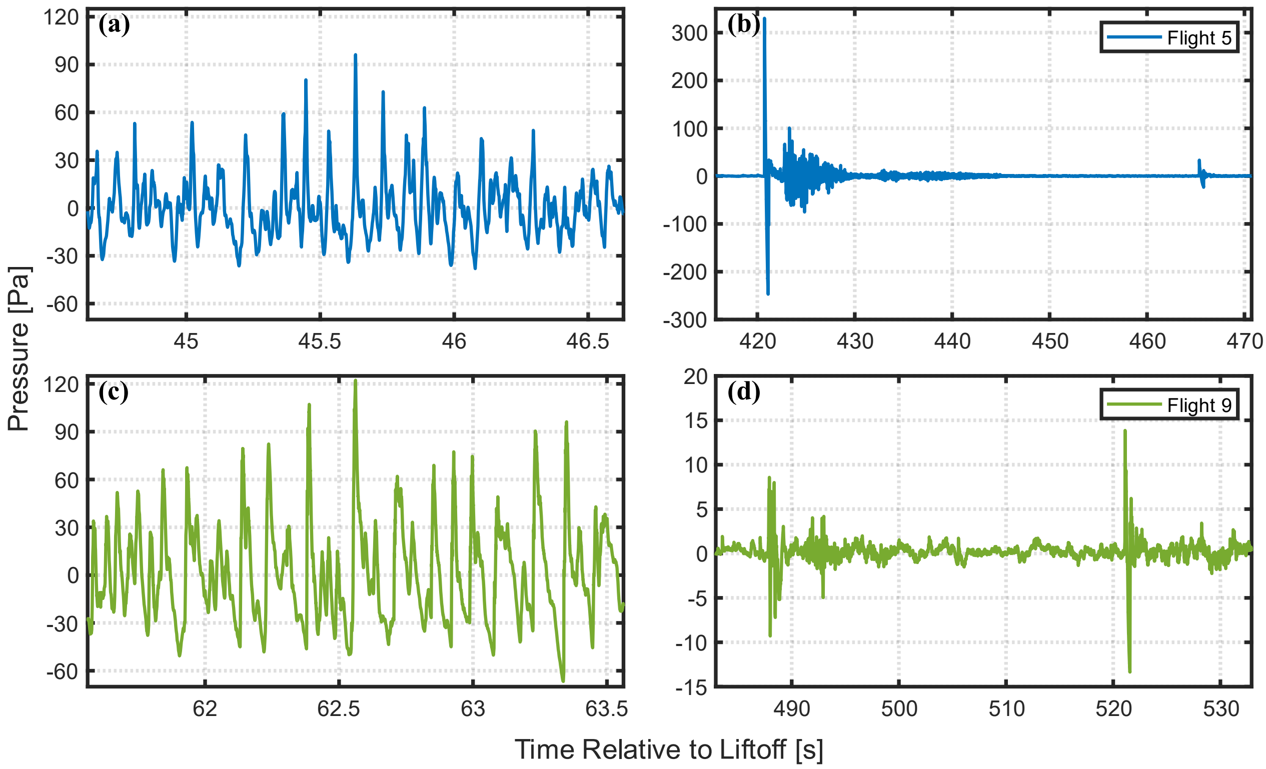

Figure 4. At the same station as Fig. 2, a) two seconds of the launch noise waveform, centered around the peak OASPL from Flight 5, b) the flyback sonic boom, landing noise, and hot-staging ring boom; c) and d) same as a) and b), but for Flight 9.

4 OVERALL LEVELS

Gee et al. (2025) compare unweighted and A-weighted maximum and sound exposure levels for all measurements during Flights 5 and 6. A similar figure is shown in Fig. 5. They reveal the near spherical sound level decay out to 10 km and then more sporadic decay beyond this distance. The longer-range behaviour illustrates changes due to meteorology and propagation direction as discussed by the authors. Gee et al. (2025) then used the set of four metrics at 1 km to compare to Falcon 9 and to SLS at the same distance. They concluded that one Starship launch was equivalent to approximately 2.2 SLS launches and ~11 Falcon 9 launches.

How do the maximum levels compare to a relatively simple empirical model by Mathews and Gee (2025), which builds on prior work by McInerny (1996)? For an assumed peak directivity index of 5 dB and measurements made over hard ground (+6 dB re free field), Mathews and Gee's model can be reduced to

$$\mathrm{OASPL_{max}} = 10\log_{10}\left(\frac{\eta F U}{r^2}\right) + 117\ \mathrm{dB}, \quad (1)$$

where η is the acoustic efficiency (the ratio of the acoustic to mechanical powers), F is thrust in newtons, U is exit velocity, and r is the distance from rocket to receiver at the peak directivity angle. Assuming $\eta = 0.0035$ (0.35%) based on our other recent work (Kellison, 2023b; Mathews, 2025), $F = 74$ MN, $U = 3.2$ km/s, and peak noise emission when the vehicle is 20° above the horizon, the expected $\mathrm{OASPL_{max}}$ at a horizontal range of 1 km is 145.6 dB. This is excellent agreement with the measured levels of 145.7 dB. Moving out to 5 km, the expected $\mathrm{OASPL_{max}}$ is 132.2 dB, whereas the measured level is 131.5 dB. Finally, at 10 km, the predicted $\mathrm{OASPL_{max}}$ is 125.6 dB whereas the Flight 5 measured levels are 125.2 dB. Thus, the Starship measurements help confirm the validity of a simple model for the maximum noise level. However, note that Flight 6's measured levels were nearly 3 dB lower at 10 km, likely due to meteorology (Gee, 2025). Understanding and accounting for meteorology in rocket liftoff acoustics remains an open research topic.

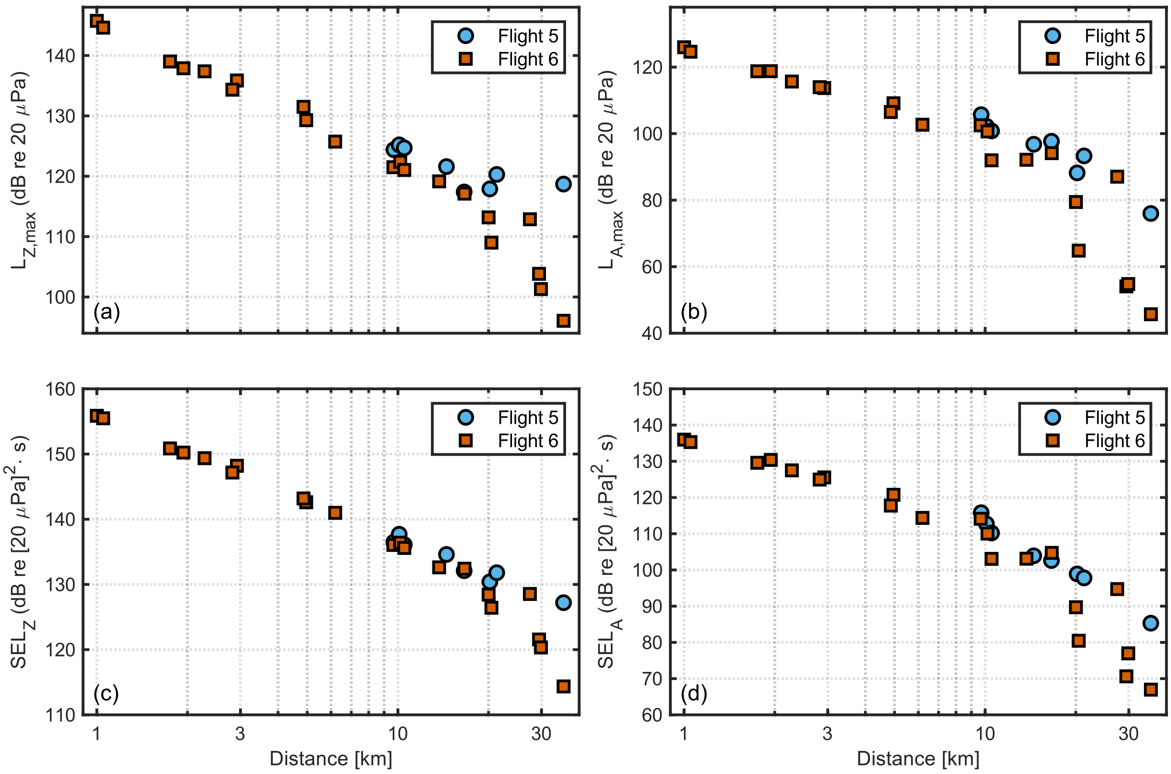

Figure 5. Unweighted (Z-weighted) and A-weighted maximum and sound exposure levels for Starship Flights 5 and 6 as a function of distance from the launchpad. Flight 9 data will be added in future publications.

5 SPECTRA

Given the brevity of the initial Flight 5 (Gee, 2024b) and Flight 6 (Gee, 2025) analyses, launch noise spectra were not shown. Figure 6 shows maximum one-third octave band spectra (within 3 dB of the maximum overall level) for the three waveforms in Fig. 3. At 10.5 km, the broad spectral peak falls between 4 and 16 Hz and is fairly consistent across the three launches. However, the high-frequency rolloff point differ. Flight 5 has the most spectral energy at high frequencies, whereas Flight 9 is similar to Flight 6, which had the least. Again, meteorological differences could account for this change in high-frequency decay slope, as Flight 5 was in the morning just after sunrise, and the other two flights were in the afternoon with greater wind and presumably turbulence. The high-frequency spectral shape, with the quasi power-law decay and then the sharp knee at around 10 kHz, is the combined result of nonlinear propagation and atmospheric effects. But in the power-law part of the spectral rolloff, energy rolls off faster than the 10 dB/decade expected from weak shock theory. This additional energy loss suggests other atmospheric effects are in play beyond ordinary atmospheric absorption. Detailed analyses of spectral characteristics and the role of nonlinear propagation is an important research topic, especially since the high-frequency portion of the spectrum is directly related to the crackling sound quality.

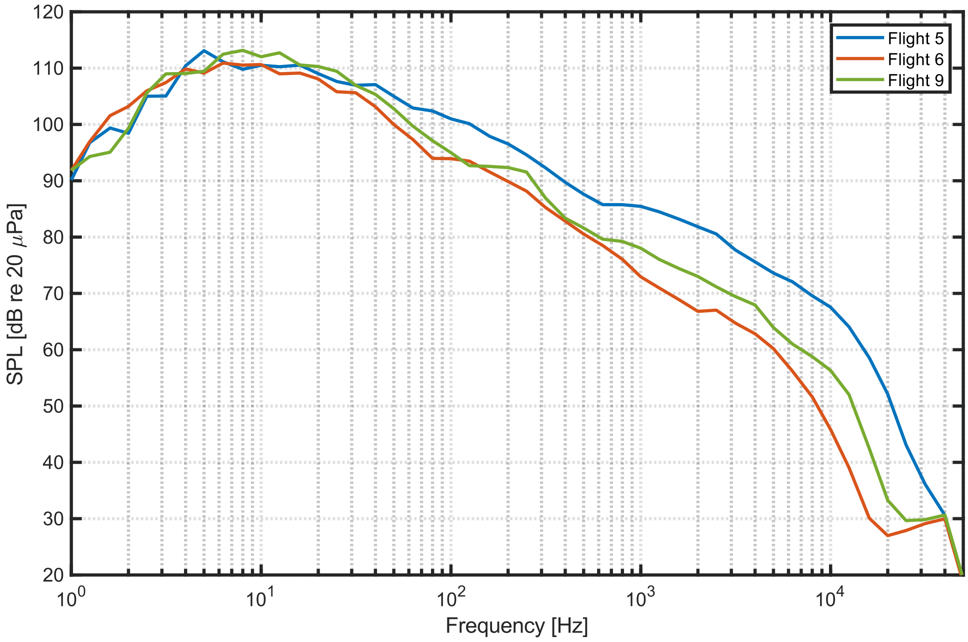

Figure 6. One-third octave band spectra from the 10.5 km station during the maximum 3-dB period from the recorded Starship launch noise waveforms in Fig. 2.

6 STARSHIP CONTEXT

It is difficult to conceptualize the sound levels associated with a large rocket launch. To conclude, we try to put some of these numbers in context. A Starship launch has been put in context with a Falcon 9 and SLS, which may be helpful for those living in California or Floria. But what about other noise sources that might be more applicable to an Australian audience or includes every-day sounds? This section contains a few citable comparisons that may serve helpful.

First, noise impacts in relation to Australian spaceports may be of interest (Gee, 2023b). Gilmour Space Technologies recently test-launched their Eris rocket from Bowen Spaceport. Although we have not made acoustical measurements of Eris, we can make reasonable approximations to estimate $\mathrm{OASPL}_{\mathrm{max}}$ using Eq. (1). Using $F =$ 460 kN, $U =$ 3 km/s, $\eta = 0.0035$, and a peak sound emission at an elevation angle of 20°, we estimate $\mathrm{OASPL}_{\mathrm{max}}$ of 123 dB at 1 km. Compared to an $\mathrm{OASPL}_{\mathrm{max}}$ of 145.7 dB for Starship, this suggests one Starship launch is the equivalent of 150-200 Eris launches. This may provide context for noise impacts from super heavy- versus small-lift vehicles.

Second, Starship can be compared against the F-35 Joint Strike Fighter, advanced fifth-generation fighter jet aircraft used both by the U.S. and Australian Air Forces. The F-35's maximum OASPL at 305 m is nearly 123 dB (Reichman, 2022). Extrapolation to 1 km using spherical spreading results in a level of 112.5 dB. Contrast this with an $\mathrm{OASPL}_{\mathrm{max}}$ of 145.7 dB for Starship. At this distance, and for this metric, a single Starship launch from this distance looks like the equivalent of ~2000 F-35s. Per Google, fewer than 1300 F-35s have been built to date, perhaps providing some context regarding what effort is required using advanced military aircraft to create the equivalent acoustic power produced during a Starship launch.

Third, a Starship launch has an A-weighted SEL of ~115 dBA at 10 km. Per the EASA (2023) aircraft noise database, the Boeing 777-300ER has a departure thrust of 97,000 lbs and an $\mathrm{SEL}_{\mathrm{A}}$ of 85 dBA. A 30 dB increase means that a Starship launch, at this distance, and for this metric, is equivalent to 1,000 large airliner departures.

Fourth, the impulsive quality due to the shock-containing noise merits comparison to a jackhammer. Per Berger et al. (2016), a large jackhammer produces an A-weighted level of 108 dBA at the operator position. Therefore, the maximum level during a Starship launch around 5 km is equivalent to the noise experienced by a jackhammer operator, per this metric. This likely informs hearing protection requirements for those relatively close to a large rocket launch.

Finally, while this paper has summarized the launch noise, some context regarding the Flight 5 flyback sonic boom in Figs. 3 and 4 is also worthwhile. As discussed by Gee et al. (2024b), the flyback boom produces an average overpressure at 10 km of around 450 Pa (9 psf), corresponding to a perceived level (PL) of around 125 dB. At 20 km from the pad, the PL was 110 dB. According to Doebler and Rathsam (2020), 125–135 dB represents a gunshot recorded at 2 ft, 115 dB is like a firework at 500 ft, and 103 dB is the PL of “nearby thunder.” A comparison with a renowned supersonic aircraft is possible. A Concorde cruising supersonically at 18 km produced a sonic boom at the ground with a PL of ∼105 dB. This 5 dB increase for Starship’s boom for similar distances suggests a Starship flyback boom at 20 km is 1.5 times the loudness of the Concorde boom (where 9 dB represents a loudness doubling for PL).

7 FINAL REMARKS

This paper accompanies a plenary talk given at Acoustics 2025 and hopefully serves as a useful entry point to some of the ongoing research into Starship acoustics. As the largest, most powerful rocket ever flown, Starship unquestionably produces the most acoustic energy of any rocket during launch. Also, booster flyback is a mode of operation that potentially increases the noise impacts. There is much to continue to learn about the fundamental physics of noise propagation, and about tying the noise to impacts through meaningful metrics and thresholds. For our part, we have been fortunate to have made measurements of Starship amid the backdrop of other launch acoustics work that includes NASA Space Launch System acoustical environments, assessment of launch activity-related ecological impacts at Vandenberg Space Force Base, and measurement and simulation of launch vehicle ascent sonic booms. This has broadened our understanding of launch vehicle noise in general, allowing us to more readily interpret some Starship findings.

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