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Using Firefly Alpha's first-stage anomaly to examine clustered nozzle effects in rocket noise

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The Firefly Alpha launch, featuring an unexpected engine shutdown, offered a unique opportunity to study the acoustic effects of clustered nozzles on rocket noise. Measurements revealed a 0.75 dB drop in overall sound pressure levels (OASPL) and a 30% frequency shift, compared to predictions of 1.2 dB and 20%, respectively. While direct comparisons are limited by the dataset's uniqueness, the results generally align with existing rocket noise models, highlighting areas for refinement. This study provides valuable data for improving noise prediction methods and deepening the understanding of launch vehicle acoustics.

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1. INTRODUCTION

Since the first rocket launch, advancing space technologies has captivated governments and companies worldwide. Recently, the frequency of launches has surged, with projections indicating continued growth. The commercialization of rocket technology, which has led to the development of more launch vehicles capable of entering low earth orbit (LEO), has fed into this increased launch cadence.[1]

As commercial space launches become increasingly common, there is growing concern about the noise generated by these launches. For example, the Space Launch System (SLS), launched by NASA in 2022, recorded a maximum overall sound pressure level (OASPL) of 129 dB re 20 μPa 5.2 km away.[2] The environmental and health impacts of rocket noise are a source of concern.[3] Communities near launch sites may experience an uncomfortable amount of noise pollution, and launch sites near ecologically significant areas raise questions about the impact of the noise on surrounding wildlife.

Much of the current understanding of launch vehicle noise comes from NASA SP-8072, a technical report published in 1971.[4] However, recent research on the Falcon 9 and other modern launch vehicles has expanded upon the understanding of SP-8072.[5, 6]

The launch of the first Firefly Alpha rocket presented a unique opportunity to test current understandings in rocket acoustics. During the launch, an anomaly led to the shutdown of one of its four engines. This unexpected transition from four to three nozzles midflight offered a natural experiment, allowing the validation of predictions related to nozzle effects.

The structure of this paper is as follows: Firefly Aerospace and the Alpha launch vehicle are introduced next, with details about the vehicle's design and first launch attempt. This is followed by an explanation of the acoustic data collection process, including the equipment and setup. Key findings are then analyzed, focusing on waveform patterns, overall sound pressure levels (OASPL), and spectral behavior, with special attention to the effects of the engine anomaly. Finally, the insights gained are summarized, and their implications for rocket noise modeling and future research are discussed.

2. FIREFLY AEROSPACE AND THE ALPHA VEHICLE

Firefly Aerospace was founded in 2017 with the goal of competing in the aerospace market through the development of small launch vehicles. The Firefly Alpha, the company's first launch vehicle, is designed to be a cost-effective solution for relatively light payloads. The Alpha is equipped with four Reaver engines and has an estimated thrust of 801 kN and a maximum payload capacity of 1030 kg to LEO. Its compact size and efficient design make it a compelling option for small satellite launches.[7]

Figure 1. A Firefly Alpha at the SLC-2W launch site in Vandenberg Space Force Base

Firefly Alpha made its first launch attempt on September 2, 2021, from Vandenberg Space Force Base in California. However, approximately 14 seconds into the flight, an anomaly caused one of its four engines to shut down. As the vehicle transitioned into supersonic speeds, it became unstable, eventually leading to a loss of control. The mission was terminated around three minutes into the launch.[8] Despite this setback, the data collected during the flight offers valuable insights for future launches and the continued development of the Alpha launch vehicle.

Brigham Young University (BYU) conducted acoustic measurements of the Alpha launch from 10 different stations. The stations were located at varying distances from the launch pad, with two stations positioned at a distance 95 meters and seven stations on a 300-meter arc. One far-field station was operated approximately 7 km from the launch pad.

Figure 2. Annotated screenshot of Vandenberg Space Force Base, showing the nine near data collection stations, captured from Google Earth Pro. Image © 2022 Maxar Technologies and Google.

A variety of equipment was used to measure to measure the Alpha launch. National Instruments (NI) 9250, 9232, and 9234 24-bit data acquisition modules were used in conjunction with 6.35 mm GRAS 46BG, 46BD, and 46BE microphones, as well as 12.7 mm 47AC microphones, to collect data on the acoustic noise generated by the launch. The microphones were housed in a windscreen and ground-plate setup developed by BYU and Blue Ridge Research and Consulting LLC.[9] The measurements were synchronized using GPS clocks for accurate timestamping. The equipment was housed in a waterproof case and operated using Surface Pro tablets.

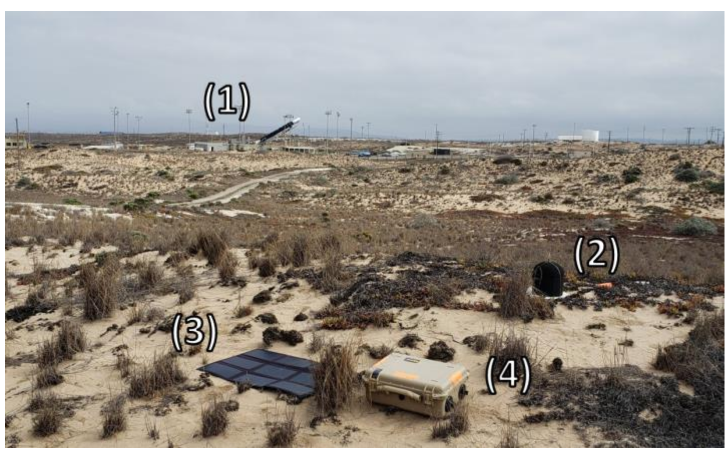

Figure 3. Data collection equipment at Station 9 with Alpha in background. (1) Firefly Alpha, (2) windscreen and ground plate housing microphone, (3) solar panel, (4) weatherproof case.

3. PRELIMINARY ANALYSIS

Section 3 presents the preliminary analysis of the acoustic data from the Firefly Alpha launch. It includes an examination of the waveform, overall sound pressure levels (OASPL), and the spectral data. The section also highlights key acoustic events and analyzes the frequency characteristics observed during the launch.

I. WAVEFORM AND OASPL

Figure 4, derived from Station 3's data, located approximately 300 m from the launch pad, illustrates key moments in the Firefly Alpha launch. The typical ignition overpressure seen in launch vehicle startup, including the Reaver LOX engines, is observed at $T = 0$. About 7 seconds after ignition, the maximum 1-second averaged Overall Sound Pressure Level (OASPL), or equivalent level (LEQ), is recorded around 133 dB, with a peak sound pressure level of 146 dB (400 Pa). For comparison, at similar distances, an F-22 with one engine at afterburner is around 121 dB, and the F-35 is around 122 dB.[10, 11] Even though the Alpha is a relatively small launch vehicle, it still produces sound levels roughly 10 dB more than these aircraft.

Using the same data as Figure 4, Figure 5 focuses on the period of maximum overall sound pressure. Approximately 14.48 seconds after the ignition, shocks can be observed, a characteristic trait of the expected nonlinear acoustics of this high sound level.[12]

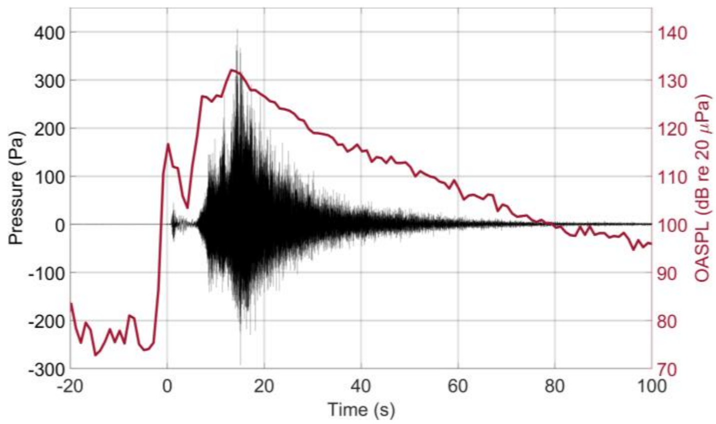

Figure 4. Waveform and OASPL measured from Station 3.

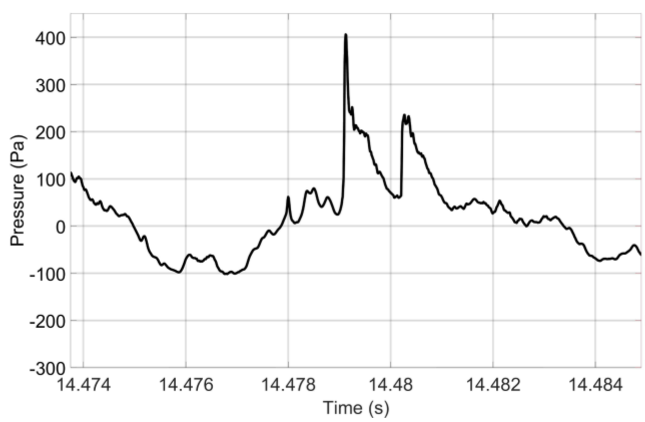

Figure 5. Waveform from Station 3, near the peak of maximum sound pressure.

II. SPECTRUM

Using data from Station 3, Figure 6 presents a spectrum centered on the peak OASPL with a 10-millisecond sample width, determined by the 3 dB down points. For comparisons, an ambient spectrum sampled from before the launch is provided. Note the 20 dB per decade roll off after 100 Hz; this is a key trait of nonlinear propagation.[13]

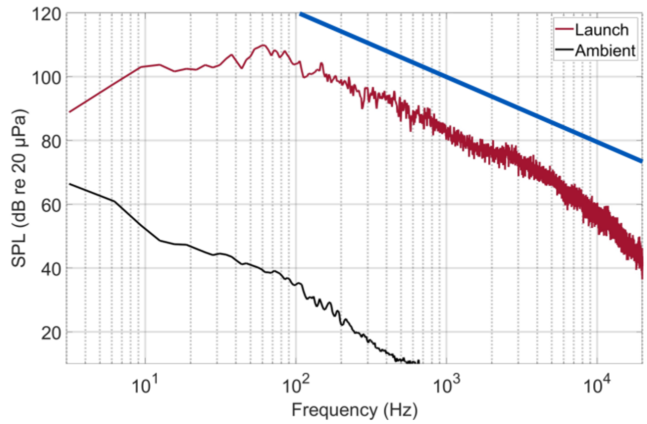

Figure 6. Spectra from Station 3 during the period of peak OASPL with a 10-millisecond sample width determined by the 3 dB down points. The blue line represents the 20 dB per decade roll-off.

4. ANOMALY AND ACOUSTICAL IMPLICATIONS

Rocket noise is primarily generated from the turbulent mixing of the plume with the atmosphere. Current noise models depend on two main factors: the total mechanical power of the rocket and the effective nozzle diameter.[1] In this first launch of the Firefly Alpha rocket, one of the four engines shut off unexpectedly around 14 seconds after liftoff. With this anomaly, both parameters were affected. The anomaly thus provides an opportunity to test and refine our understanding.

The loss of one engine leads to a reduction in the mechanical power to three-fourths of the original. Since current models show that acoustical power is proportional to mechanical power, an estimated drop of 1.2 dB is expected.[1]

Current models predict that the spectrum is invariant when scaled with the Strouhal number (St). The Strouhal number is defined as $St = \frac{f\, d_{eff}}{U}$ where f is the frequency, d_{eff} is the effective nozzle diameter, and U is the engine exit velocity.[1] Therefore, the expected spectrum as a function of frequency is $f = St\, \frac{U}{d_{eff}}$. The effective diameter is a method of approximating a multi-nozzle system as a single nozzle and is defined such that the effective nozzle has the same area as the multi-nozzle system. This approach to clustered nozzles of the same type was adopted in NASA SP-8072, and has even been successfully adopted for SLS, which has two solid boosters and four liquid engines.[14] With the case of the Alpha anomaly, suddenly losing one of the four nozzles would reduce the area by a factor of ¾, which would scale d_{eff} by a factor of $\sqrt{3/4}$, suggesting that the spectral peak frequency would scale by a factor of $\sqrt{4/3}$. This translates to roughly a 20% increase in frequency.

I. OASPL DROP

The radiated sound from a rocket is highly directional. As the rocket rises, the microphones measure the changes in the sound as the lobe of sound radiation sweeps past it. In general, peak rocket sound directivity occurs around 65° to 70° relative to the plume.[1]

The goal becomes to place when the anomaly occurred with respect to the directivity. Analyzing the trajectory, along with a careful consideration for sound propagation, as well as GPS timing and location of the stations led to inconvenient results.

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The data shown below were taken from the seven stations on the 300-meter arc. Examining the OASPL with a 1-second window, the anomaly occurs at $T = 13\ s$. The propagation delay to the stations has been removed from these plots. To remove the decreasing OASPL resulting from the directivity, a linear fit was performed using the data collected between 20 and 40 seconds (Figure 7a). Since this linear decrease in OASPL occurs well after the anomaly, subtracting the averaged OASPL from the linear fit should isolate the anomaly's effect and provide valuable insights (Figure 7b).

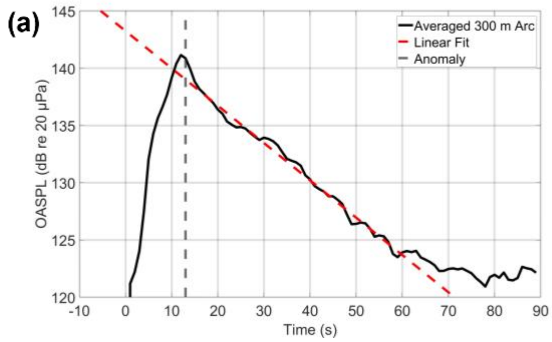

Figure 7a: Averaged OASPL from the 95 m arc, $T = 0$ being ignition. b: Averaged OASPL from the 95 m arc with the linear fit subtracted

Figure 8 shows the data from Figure 7b before it was averaged, note that the OASPL is still subtracted from the linear fit found in Figure 7a. In Figure 8, the maximum and minimum values from among the 7 stations are represented by the blue shaded regions. Though there are many fluctuations, the only period where every station has a drop in OASPL is immediately following the anomaly. This hints that the drop of 0.75 dB immediately following the anomaly in Figure 7b, is likely caused by the reduction in mechanical power.

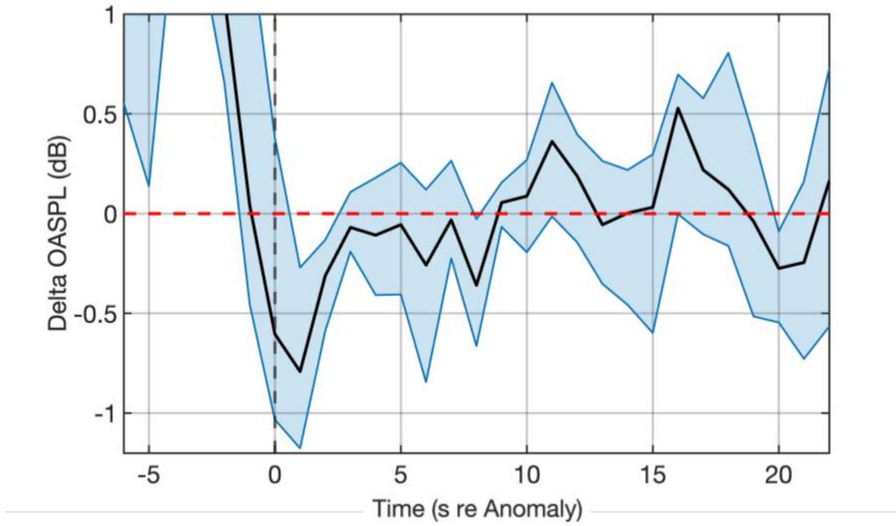

Figure 8: Same data as Figure 7b, blue shaded region represents the maximum and minimum change in OASPL measured at each station. Time axis adjusted to align with anomaly.

II. FREQUENCY SHIFT

In order to examine the frequencies during the launch, spectra from the stations located at 300 m were generated throughout the launch period using 2-second blocks spaced an eighth of a second apart. The spectra were averaged across stations and fit to a 5th-order polynomial. The resulting peak frequencies were plotted with respect to the center of the spectral window.

In Figure 9, $t = 0$ signifies the moment the anomaly was detected at the 300 m arc. The signals were synchronized using GPS data, with adjustments made for sound propagation times based on trajectory data. During a launch of a rocket, the peak frequency generally decreases due to the directivity of frequencies coming from the plume.[15] Since the anomaly occurs relatively early into the launch, the rising peak frequency from -8 to -4 seconds is likely due to pad and environment effects. Around $t = -4$ seconds, the vehicle presumably rises high enough that the pad and environmental effects become insignificant. After $t = -4$ seconds, the peak frequency decreases as expected until around and just after t = 0.

The black vertical line represents the first peak frequency where the entire spectral window occurs after the anomaly. The orange dashed lines represent the boundaries of the window. The red line estimates the change in peak frequency that would be anticipated from a typical rocket, based off other observations BYU researchers have made.[15] With this rough estimate, the peak frequency potentially rose by 20 Hz or 28%. It is important to note that the observed rise in peak frequency one second before the anomaly is likely a result of the 2-second sample windowing, which was centered on each time point and spanned 1 second before and after.

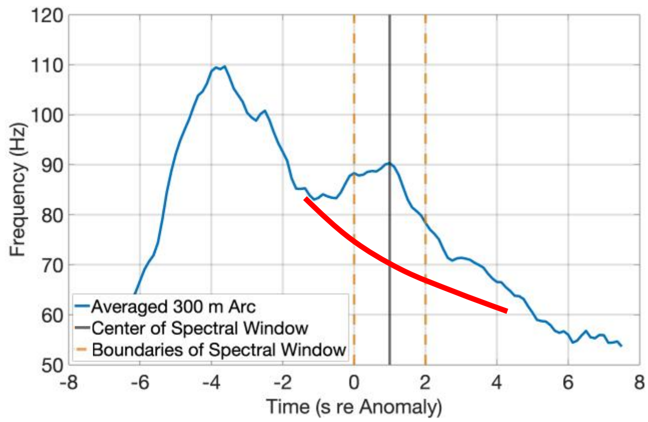

Figure 9. Average peak frequency measured from stations at 300m. The red line represents an estimate of the peak frequency change without the anomaly.

5. CONCLUSION

The Firefly Alpha launch, marked by an unexpected engine shutdown, provided a unique natural experiment for investigating the effects of clustered nozzles on launch vehicle acoustics. The measurements revealed slight disparities between predicted and observed effects in overall sound pressure level (OASPL) and frequency shift due to the anomaly.

While challenges to direct numerical comparison exist due to the unique nature of the dataset, the study suggests that current rocket noise models generally align with observed trends. The 0.75 dB drop in OASPL, compared to the predicted 1.2 dB, and the 28% frequency shift, exceeding the predicted 20%, are consistent with the limitations of the measurements.

In essence, the Firefly Alpha launch contributes valuable data to the ongoing development of rocket noise models. The observed deviations highlight potential areas for improvement, guiding future research toward a more accurate understanding of the launch vehicle noise.

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