Comparative Analysis of Two Firefly Alpha launches

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ABSTRACT

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Firefly Aerospace conducted the first flight of its Firefly Alpha rocket in 2020 (FLTA001), during which an anomaly occurred, causing one of the four engines to shut down. In contrast, the fifth Alpha launch in 2024 (FLTA005) proceeded without anomalies. Current rocket and jet noise models primarily emphasize the influence of effective nozzle diameter and mechanical power on launch noise. This comparative analysis of the anomalous FLTA001 and nominal FLTA005 provides a unique opportunity to evaluate these parameters' impact on noise generation, offering insights to refine existing acoustic models and improve noise prediction for future launches.

Model predictions anticipated a 1.2 dB drop in overall sound pressure level (OASPL) and a 20% increase in peak frequency due to the anomaly. However, FLTA001 data showed greater than a 2.5 dB OASPL reduction and a 50% increase in preak frequency near $t = 14$ s. While these discrepancies may be partially attributed to atmospheric conditions or trajectory differences, they suggest additional factors may influence launch acoustics beyond nozzle geometry and mechanical power. Nonetheless, the results affirm that current models are trending in the right direction and provide valuable data for further refinement.

Keywords: Rocket noise, Engine shutdown, Launch acoustics, Sound pressure, Frequency shift, Firefly Alpha, Nozzle effects, Rocket launch, Anomaly, Noise prediction

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To my family, thank you for believing in me even when I doubted myself. Your unwavering support has carried me further than I could have gone alone.

To Arielle—thank you for standing next to me. Your presence has meant more than words can say.

Above all, I thank my God, who lends me breath. None of this would be possible without Him.

Contents

Chapter 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 129dB re 20μPa (a reference pressure of 20μPa) 5.2 km away [2]. The environmental and health impacts of rocket noise are a source of concern [3]. At 129 dB re 20 μPa, the recorded sound pressure level was nearly eight times more intense than that of a typical rock concert (approximately 120 dB), and perceived as roughly twice as loud. Communities near launch sites may be subjected to uncomfortable levels of noise pollution, and facilities located near ecologically sensitive areas raise important concerns about the potential impact of such intense 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 mid flight offered a natural experiment. Comparing the noise generated by the anomalous first flight to a later successful launch provides an opportunity to validate current rocket noise models regarding nozzle and mechanical power effects.

The structure of this thesis is as follows: Firefly Aerospace and the Alpha launch vehicle are introduced, along with an overview of two launches and their corresponding datasets. This is followed by a description of the measurement setup, including equipment, weather, and trajectory. Key findings are then presented, first focusing on general rocket acoustics—waveform patterns, OASPL, and spectral content—and later examining the engine anomaly, including the OASPL drop and frequency shift. The thesis concludes with a summary of results and their implications for rocket noise modeling.

1.1 Firefly Aerospace and the Alpha Vehicle

Firefly Aerospace was founded in 2017 with the goal of competing in the aerospace market through the small launch vehicles development. The Firefly Alpha (shown in Fig. 1.1) 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 which provide an estimated combined thrust of 801 kN and a maximum payload capacity of 1030 kg to LEO. Alpha's compact size and efficient design make it a compelling option for small satellite launches [7].

Our team measured Firefly Alpha'a first launch attempt (FLTA001) 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 setbacks during its first launch, Firefly Aerospace has achieved multiple successful launches since. Our team was able to collect data from the fifth Alpha launch (FLTA005) on July 3, 2024, which lifted off from the same location as FLTA001. This new dataset provides a valuable opportunity to compare acoustic signatures between launches.

Figure 1.1 A Firefly Alpha at the SLC-2W launch site at Vandenberg Space Force Base. The Alpha rocket and launch tower stand at the center of the image, surrounded by floodlights in preparation for a night launch.

Chapter 2

Measurements

Brigham Young University (BYU) conducted acoustic measurements of FLTA001 from 10 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 7km from the launch pad. FLTA005 was recorded using 14 station, with a majority located 300 – 1000m from the launch pad (Fig. 2.1).

For the comparative analyses in this study, we focus on the four stations that have matching locations across both launches (Fig. 2.2). These stations provide a consistent basis for evaluating differences between FLTA001 and FLTA005 while minimizing variability due to location-dependent factors.

2.1 Equipment

A variety of equipment was used to measure the Alpha launches (Fig. 2.3). To collect the acoustic noise data generated by the launch, National Instruments (NI) 9250, 9232, and 9234 24-bit data acquisition modules were used in conjunction with 6.35 mm GRAS (brand name) 46BG, 46BD, and 46BE microphones, as well as 12.7 mm 47AC, 46A0-S5, and 46A0 microphones. The microphones

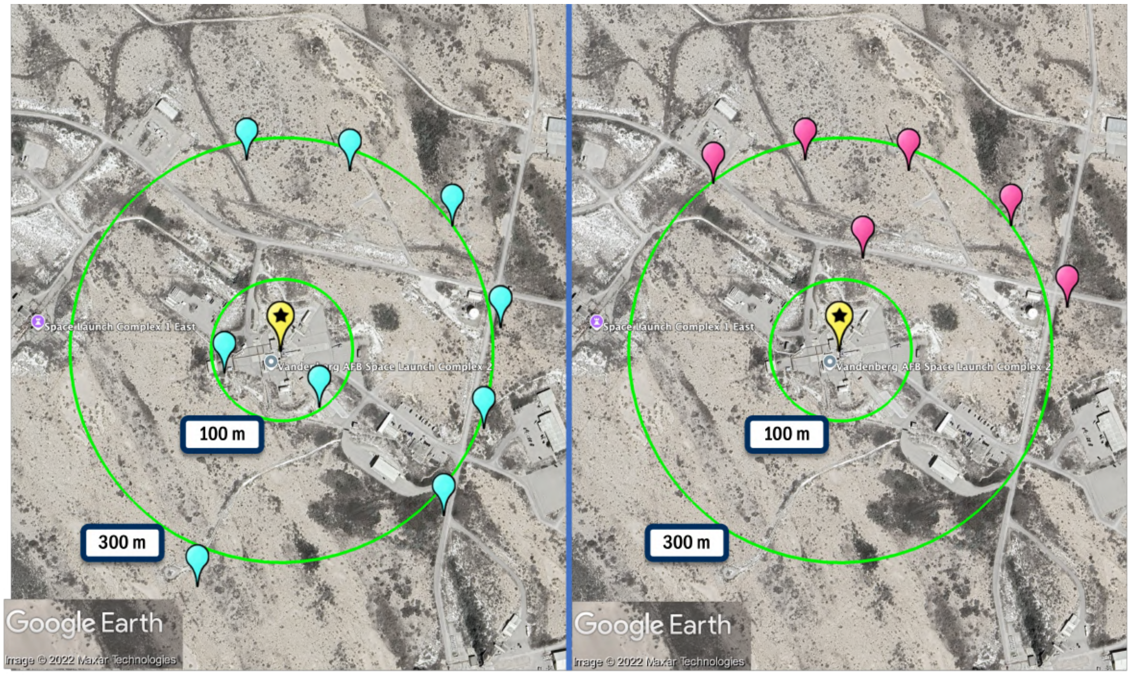

Figure 2.1 Map showing measurement stations for FLTA001 (left/blue) and FLTA005 (right/pink). The yellow star pin marks the launch pad. Green circles indicate 100-meter and 300-meter distances, as labeled in the image.

were housed in a windscreen and ground-plate setup developed by BYU and Blue Ridge Research and Consulting LLC, often refered to as a 'Compact Outdoor Unit for Ground-based Acoustical Recordings', or COUGAR for short [9]. The measurements were synchronized using GPS clocks for accurate time stamping. The equipment was housed in a waterproof case and operated using Surface Pro tablets for FLTA0001 while LattePandas and Cincoze ruggedized PCs for FLTA0005.

2.2 Weather

Although weather conditions are not directly incorporated into the analysis, it is important to acknowledge the atmospheric differences between the two launches. Historical weather data from Santa Maria, CA—approximately 15 miles from Vandenberg Space Force Base—was used as a proxy [10] (see Table 2.1). While not a perfect representation of conditions at the launch site, this

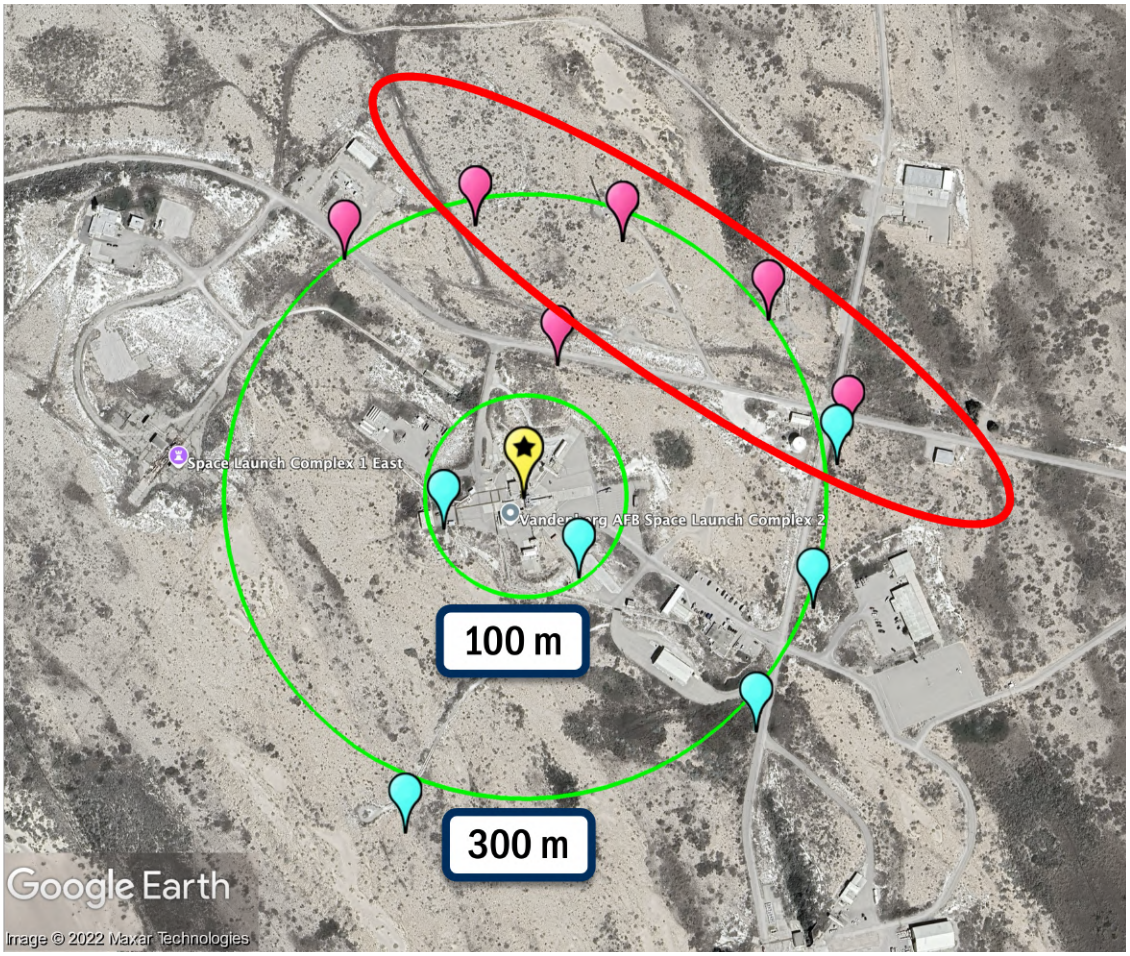

Figure 2.2 Map of station locations for FLTA001 (blue) and FLTA005 (pink). The red ellipse highlights the four stations common to both launches, which will be used for comparison. Note that three of the blue pins in the red ellipse are in the exact same locations as their pink counterparts and are obscured in the image.

data serves as a reasonable substitute in the absence of more localized measurements. Additionally, we observed fog during the second launch, a condition that was not present during the first.

2.3 Trajectory

The trajectory data for both launches was provided by Firefly Aerospace. While we are unable to present the raw data, it is important to note that FLTA005 experienced a faster ascent compared

Figure 2.3 Data collection equipment at FLTA0001 with Alpha in background. (1) Firefly Alpha, (2) windscreen and ground plate housing microphone (COUGAR), (3) solar panel, (4) weatherproof case housing the data acquisition system.

	FLTA001	**FLTA005**
Launch Time (PT)	6 : 59 PM	9 : 04 PM
Temperature (F)	61°	61°
Rel. Humidity	72%	90%

Table 2.1 Historic weather data 15 miles away from the launch site, it is important to note that fog was present during the second launch.

to FLTA001 due to the latter losing the use of one of its engines. While this variation in trajectory alone does not alter how the noise is generated, it does influence how we compare the acoustic data between the two launches

Chapter 3

Preliminary Analysis

Chapter 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. The analysis in this section will be conducted using one station from the first launch, located 300 meters from the launch pad, and will be used to highlight the key characteristics of rocket launch noise.

3.1 Waveform and OASPL

Figure 3.1 illustrates key moments in the FLTA001 launch. At $t = 0$, the typical ignition overpressure from the launch vehicle startup, including the Reaver LOX engines, is observed. Around 7 seconds after ignition, the maximum 1-second averaged Overall Sound Pressure Level (OASPL), or equivalent level (LEQ), is recorded at approximately 135 dB re 20μPa dB, with a peak sound pressure level of around 135 dB (600 Pa). For comparison, an F-22 with one engine at afterburner reaches around 122 dB, while the F-35 is also around 122 dB [11, 12]. Despite being a relatively small launch vehicle, the Alpha generates sound levels roughly 10 dB higher than these aircraft.

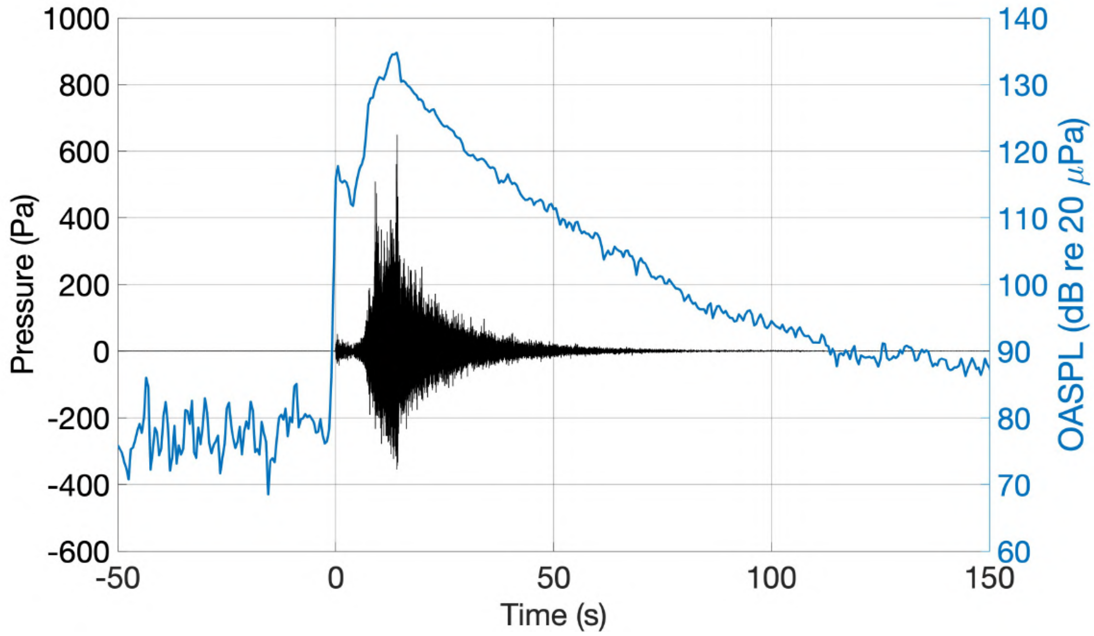

Figure 3.1 Key moments in the FLTA001 launch. At $t = 0$, ignition overpressure from the Reaver LOX engines is observed. Approximately 7 seconds post-ignition, the maximum 1-second averaged Overall Sound Pressure Level (OASPL) reaches 135 dB re 20μPa, with a peak pressure of around 620 Pa.

Using the same data as Figure 3.1, Figure 3.2 highlights the period of maximum overall sound pressure. Many sharp pressure spikes—some of which are marked by orange arrows—are visible in the waveform. These spikes represent shock waves, a characteristic feature of the nonlinear acoustic behavior expected at high sound levels [13].

3.2 Spectrum

Figure 3.3 presents a spectrum centered on the peak OASPL with a 10 second sample width. 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 and shocks [14].

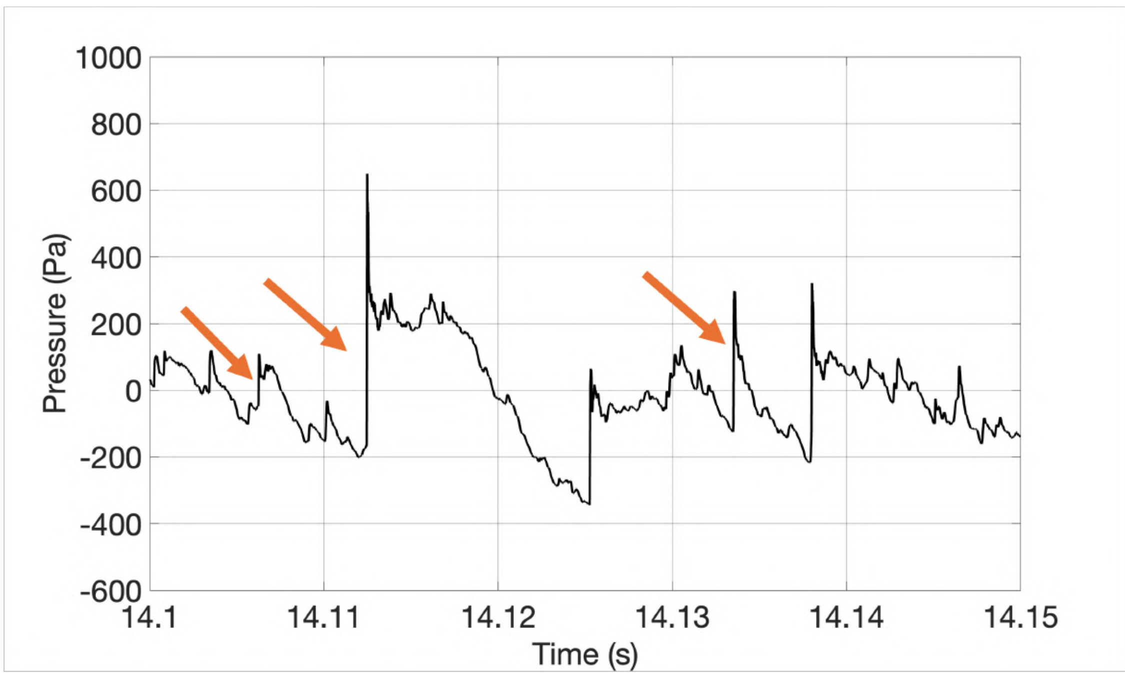

Figure 3.2 Zoomed-in view of the period of maximum overall sound pressure during the FLTA001 launch. The waveform shows multiple sharp pressure spikes—some of which are marked by orange arrows—that indicate the presence of shock waves, a signature of nonlinear acoustic behavior typical at high sound levels.

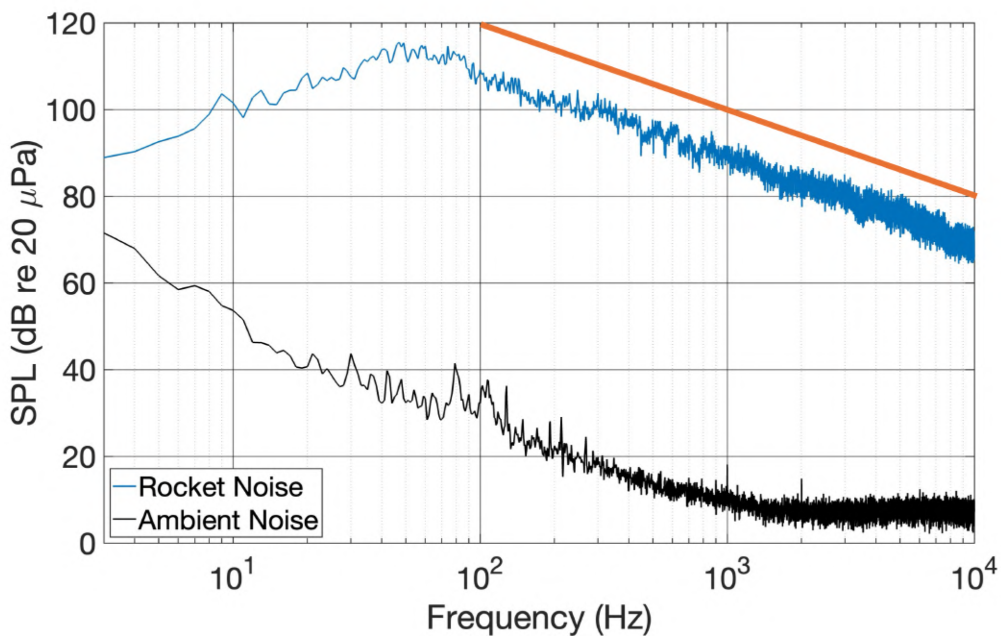

Figure 3.3 Spectrum centered on the peak OASPL with a 10-second sample window. An ambient spectrum from before the launch is included for comparison. The orange line highlights the characteristic 20 dB per decade roll-off beyond 100 Hz—a key indicator of nonlinear propagation and shocks.

Chapter 4

Results: 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 reduces the mechanical power output to three-fourths of its original value. Since current models suggest that acoustical power scales proportionally with mechanical power, this corresponds to an estimated sound level drop of approximately 1.2 dB [1]:

$$10\log_{10}\left(\frac{3}{4}\right) \approx -1.2.$$

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 the Space Launch System (SLS), which has two solid boosters and four liquid engines [15]. With the case of the Alpha anomaly, suddenly losing one of the four nozzles would reduce the area by a factor of $3/4$ 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.

4.1 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 determine when the anomaly occurred with respect to the directivity. Analyzing the trajectory—along with careful consideration of sound propagation, GPS timing, and the locations of the stations—led to inconvenient results. Specifically, the anomaly occurred when the rocket was positioned at an angle between 65 and 70 degrees, an unfortunate region where it became difficult to distinguish whether the observed OASPL drop was due to natural directivity effects or the anomaly itself.

The data shown below were collected from four stations located along the 300-meter arc common to both launches (Fig. 2.2). Using a 1-second moving window to examine the Overall Sound Pressure Level (OASPL), we can compare the two launches—FLTA001 (blue) and FLTA005 (orange)—via a polar plot (Fig. 4.1). Note that 90 degrees corresponds to the microphone being perpendicular to the rocket early in the launch. The angle at which the anomaly occurred is indicated by the green line. A distinct difference in OASPL is observed following the anomaly, with FLTA001 exhibiting lower levels compared to FLTA005, as expected.

To better compare the differences, the next plot shows the same data on a Cartesian axis (Fig. 4.2). We observe the same distinct drop in OASPL for FLTA001 following the anomaly. This representation makes it easier to quantify the reduction: approximately 2.5 dB early on, increasing to a maximum difference of around 7.5 dB later in the flight. While both values exceed the predicted 1.2 dB difference, the key takeaway is that a noticeable change did occur.

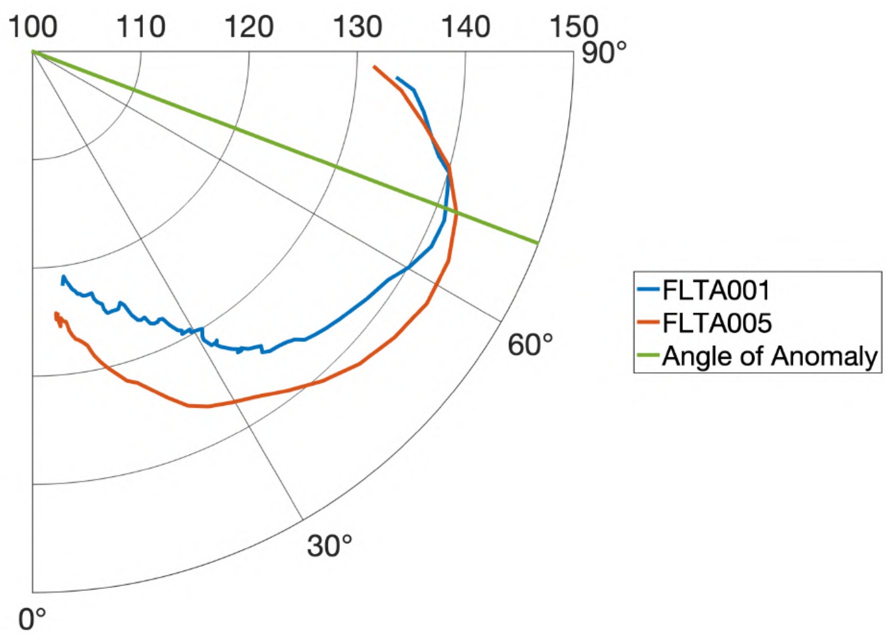

Figure 4.1 Polar plot of OASPL measured at four stations along a 300-meter arc for launches FLTA001 (blue) and FLTA005 (orange). Data are averaged using a 1-second moving window. The green line marks the angle at which the anomaly occurred. Note that 90° corresponds to a microphone position perpendicular to the rocket during early ascent.

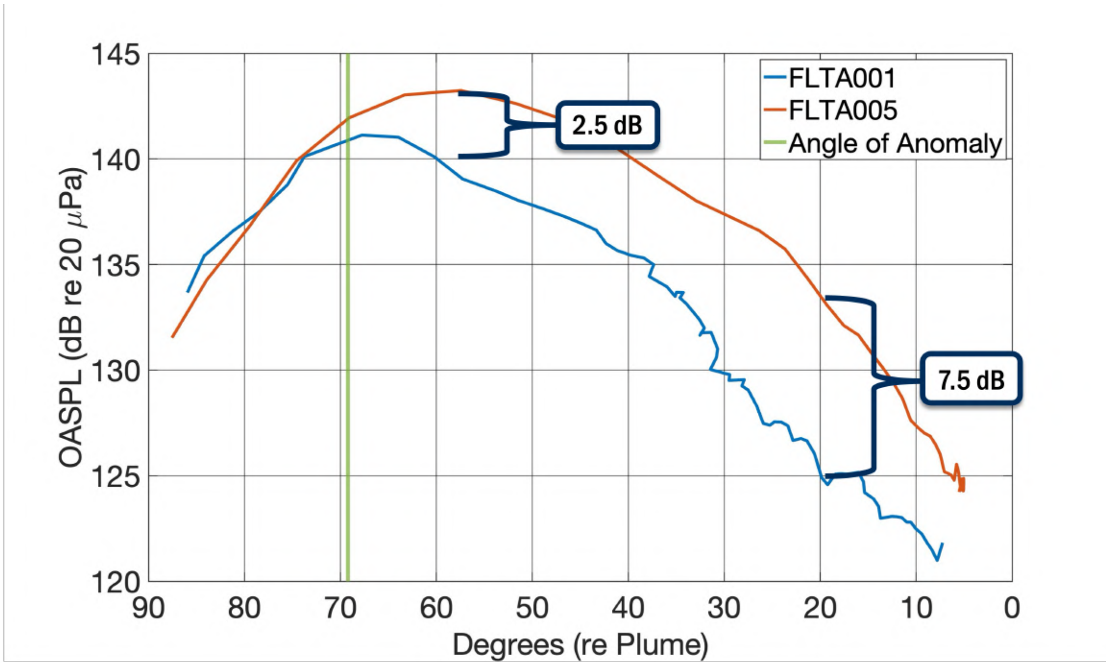

Figure 4.2 Cartesian plot of OASPL versus angle for launches FLTA001 (blue) and FLTA005 (orange), using the same data as in Figure 4.1. This view highlights the post-anomaly reduction in OASPL for FLTA001, with differences beginning around 2.5 dB and reaching up to approximately 7.5 dB difference later on in the flight.

4.2 Frequency Shift

In order to examine the frequencies during the launch, spectra from the four matching stations located at 300 m (Fig. 2.2) 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 polynomial. The resulting peak frequencies were plotted with respect to the left of the spectral window.

In Figure 4.3, $t = 0$ marks the beginning of the launch. The signals were synchronized using GPS data, with adjustments made for sound propagation times based on trajectory information. During a rocket launch, the peak frequency generally decreases due to the directional characteristics of frequencies emitted from the plume [16]. Since the anomaly occurs relatively early in the launch, the rising peak frequency from $t = 0$ to $t = 7$ seconds is likely attributable to pad and environmental effects. Around $t = 7$ seconds, the vehicle likely ascends high enough that these effects become negligible. After this point, the peak frequency decreases as expected until just after $t = 12$ seconds.

The orange dashed vertical line indicates the first peak frequency measurement where the spectral window contains the anomaly. The green solid line marks time of the anomaly. When comparing the two launches, we observe a maximum difference of approximately 30 Hz in peak frequency around $t = 14$ seconds. This corresponds to a 50% change, while a 20% change was anticipated. Given more time, it would have been beneficial to analyze the peak frequency with respect to the angle relative to the plume, similar to the OASPL analysis. Doing so would ensure that we are comparing similar regions of the plume during each launch, providing a more accurate representation of peak frequency shifts. While it is difficult to determine the exact extent to which the frequency increased, it is important to note that there is convincing evidence that the anomaly caused an increase in peak frequency during FLTA001.

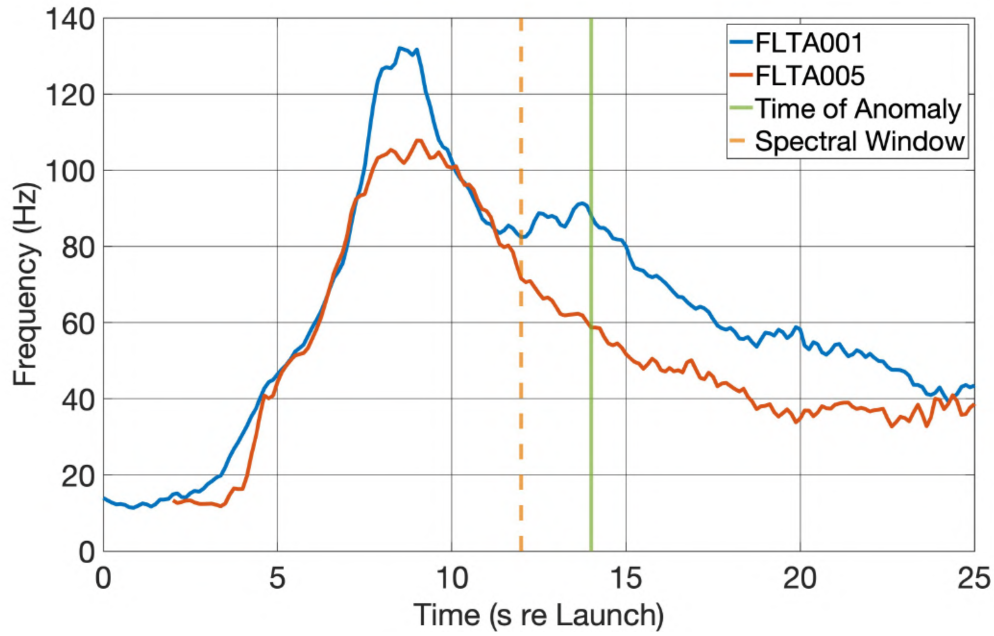

Figure 4.3 Peak frequency over time for two Alpha launches. The green solid vertical line indicates the time of the anomaly, while the orange dashed line marks the first peak frequency measurement where the spectral window contains the anomaly. A maximum difference of approximately 30 Hz in peak frequency is observed around t = 14 seconds, corresponding to a 50% change, while only a 20% change was expected. This suggests that the anomaly likely contributed to the increase in peak frequency observed during FLTA001.

Chapter 5

Conclusion

FLTA001, marked by an unexpected engine shutdown, offered a rare opportunity to investigate the acoustic effects of clustered nozzles under anomalous conditions. Analysis of the overall sound pressure level (OASPL) and peak frequency across two launches revealed deviations from model predictions, offering insights into how such anomalies may alter launch acoustics.

OASPL analysis showed at least a 2.5 dB decrease post-anomaly, compared to the predicted 1.2 dB, indicating a measurable, though smaller-than-expected, drop in acoustic energy. Similarly, a maximum difference of approximately 30 Hz in peak frequency was observed around $t = 14$ seconds, corresponding to a 50% increase—substantially higher than the predicted 20%. This difference first appeared in the spectral window containing the anomaly and persisted afterward, suggesting a strong correlation between the anomaly and the frequency shift.

Given more time, a more detailed analysis of peak frequency relative to plume angle—mirroring the approach taken with OASPL—would have enhanced the comparison between launches and provided greater confidence in interpreting the data. Nonetheless, the evidence strongly suggests that the anomaly during FLTA001 contributed to both a reduction in OASPL and a rise in peak frequency, aligning with standard model predictions.

Overall, the Firefly Alpha dataset contributes valuable insights toward the refinement of rocket noise models. The observed deviations highlight the need for continued improvement, particularly in modeling frequency content and directional acoustic behavior as a function of effective nozzle diameter.

Bibliography

[1] C. P. Lubert, K. L. Gee, and S. Tsutsumi, "Supersonic jet noise from launch vehicles: 50 years since NASA SP-8072," Journal of the Acoustical Society of America 151 (2022).

[2] K. L. Gee *et al.*, "Space Launch System acoustics: Far-field noise measurements of the Artemis-I launch," JASA Express Letters 3 (2023).

[3] N. Jones, "Does the roar of rocket launches harm wildlife? These scientists seek answers," Nature **618,** 16–17 (2023).

[4] K. M. Eldred, "Acoustic loads generated by the propulsion system," NASA SP-8072 (1971).

[5] L. T. Mathews, K. L. Gee, G. W. Hart, R. D. Rasband, D. J. Novakovich, F. I. Irarrazabal, A. B. Vaughn, and P. Nelson, "An overview of acoustical measurements made of the Atlas V JPSS-2 rocket launch," Proceedings of Meetings on Acoustics (2023).

[6] L. T. Mathews, K. L. Gee, G. W. Hart, R. D. Rasband, D. J. Novakovich, F. I. Irarrazabal, A. B. Vaughn, and P. Nelson, "Comparative analysis of noise from three Falcon 9 launches," J. Acoust. Soc. Korea **39,** 322–330 (2020).

[7] F. Aerospace, "Alpha launch vehicle,", 2024, accessed: 2024-12-21.

[8] M. Wall, "Firefly Aerospace traces rocket launch failure to premature engine shutdown. Space.com,", 2021, accessed: 2024-12-21.

[9] Z. Jones, M. R. Cook, K. L. Gee, M. K. Transtrum, S. V. Lympany, M. F. Calton, and M. M. James, “Examining wind noise reduction effects of windscreens and microphone elevation in outdoor acoustical measurements,” Proceedings of Meetings on Acoustics 42 (2020).

[10] “Santa Maria, CA Weather History,”, 2024, accessed: 2025-03-15.

[11] K. L. Gee, V. W. Sparrow, M. M. James, J. M. Downing, C. M. Hobbs, T. B. Gabrielson, and A. A. Atchley, “The role of nonlinear effects in the propagation of noise from high-power jet aircraft,” The Journal of the Acoustical Society of America **123,** 4082 – 4093 (2008).

[12] B. O. Reichman, K. L. Gee, T. B. Neilsen, S. H. Swift, A. T. Wall, J. M. Downing, and M. M. James, “Acoustic shock formation in noise propagation during military aircraft ground run-up operations,” AIAA Journal **60,** 4081 – 4090 (2022).

[13] S. A. McInerny and S. M. Ölçmen, “High-intensity rocket noise: Nonlinear propagation, atmospheric absorption, and characterization,” The Journal of the Acoustical Society of America **117,** 578 – 591 (2005).

[14] S. N. Gurbatov and O. V. Rudenko, in *Nonlinear Acoustics: Nonlinear Acoustics (Chap. 13)*, D. T. B. M. F. Hamilton, ed., (Springer, Cham, 1998), pp. 377 – 398.

[15] M. S. Kellison, K. L. Gee, W. L. Coyle, M. C. Anderson, L. T. Mathews, and G. W. Hart, “Aeroacoustic analysis of NASA’s Space Launch System Artemis-I mission,” 30th AIAA/CEAS Aeroacoustics Conference (2024).

[16] G. Hart, K. Gee, and M. Cook, “Corrected frequency-dependent directivity indices for high-power jet noise,” Proceedings of Meetings on Acoustics (2023).